



Developing the behavioural repertoire of a robot assistant for professional painters

June 2026

Geert Hansma

Chairs:
Dr.ing. M.C. Rozendaal
Dr. J.H. Boyle

 TU Delft

Developing the behavioural repertoire of a robot assistant for professional painters

MSc. Graduation Thesis
June, 2026

Author

Geert Hansma
Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Chair

Dr.ing. M.C. Rozendaal

Mentor

Dr. J.H. Boyle



This work is licensed under CC BY 4.0. To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

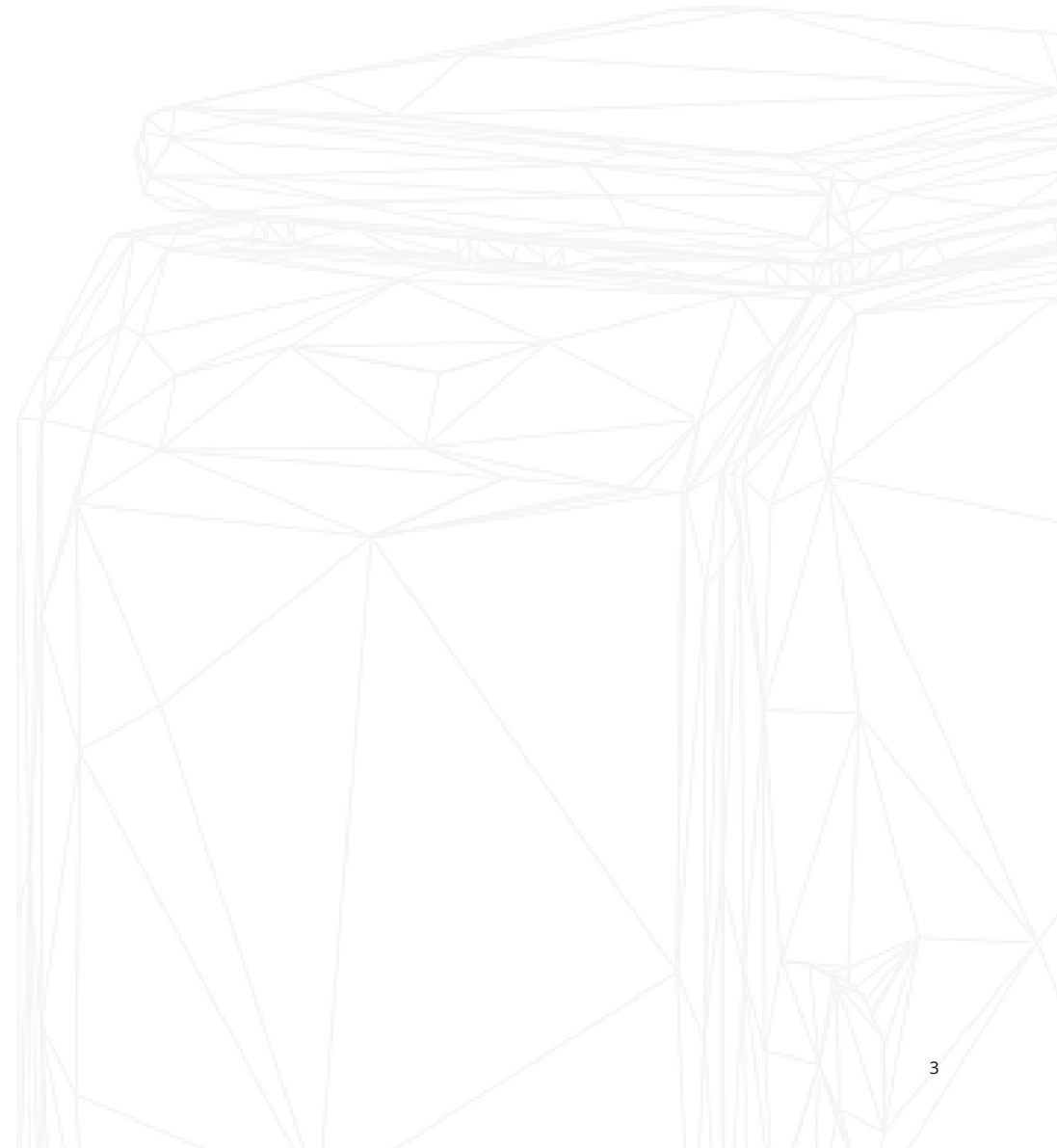
Abstract

Professional painting is a physically demanding job that frequently leads to long-term health issues. To reduce this physical strain, prior research developed a motorized robot cart assistant. However, this prototype lacked a defined behavioural repertoire, limiting its practical usability regarding control, feedback, and autonomy. This thesis addresses this gap by exploring how this robot can be transformed into a transparent and collaborative tool through appropriate autonomy design and multimodal interaction.

The research followed a Double Diamond design process, combining literature research, a benchmark of existing autonomous systems, and stakeholder input. These insights were subsequently explored in an exploratory field study with professional painters using a Wizard-of-Oz approach. The findings demonstrated a clear user preference for the robot to function as a responsive, predictable tool carrier rather than a proactive autonomous collaborator. Furthermore, the study highlighted the strict necessity for simple, physically grounded interaction over complex digital interfaces, as painters must maintain visual focus on their work. Based on these insights, the project scope was refined to focus specifically on the active work scenario within a constrained, one-dimensional workspace alongside a wall.

A functional motorized prototype was developed to evaluate the proposed interaction concepts in practice. The system incorporated a Time-of-Flight sensor for distance regulation, three distinct behavioural modes (Manual, Continuous Follow, and Segmented Follow), a wearable tactile remote, and a digital dashboard. A validation user study was then conducted, comparing the autonomous prototype against a manual cart baseline using abstract wall-based tasks and NASA-TLX workload assessments. The results showed that autonomous assistance successfully reduced physical effort but redistributed the workload by increasing cognitive demand, as users initially needed to monitor the robot's state. Additionally, the autonomous cart induced a shift in user workflow from sequential task execution to more efficient batch-processing strategies.

To address the observed increase in cognitive load, the interfaces were redesigned to include distinct tactile buttons, a physical mode slider, haptic vibration feedback, and a simplified dashboard. An extended familiarisation study was subsequently conducted to investigate interaction over repeated trials. This follow-up study revealed that the previously elevated mental workload was primarily a temporary learning effect. With repeated exposure, this participant's perceived mental demand dropped significantly, interaction efficiency improved, and they successfully adapted their workflow to naturally integrate the autonomous system. The thesis concludes that effective robotic assistance in this context depends on predictable robot behaviour, explicit state communication, and a shared-control approach that enables simple tactile interaction and immediate physical user override.



Acknowledgements

I would like to thank everyone who supported me throughout this graduation project.

First, I would like to thank the representatives of SUSAG and OnderhoudNL for providing an interesting and relevant design case for this thesis. I would also like to thank Fleur Jansen and Jesper van Zoest for the work they contributed to the project and for providing a solid concept from which this thesis could develop.

A special thank you goes to my chair, Associate Professor Dr.ing. Marco Rozendaal, and my mentor, Assistant Professor Dr. Jordan Boyle. Your feedback, trust, and enthusiasm made it possible to explore this project in depth. I greatly appreciated being supervised by a team that approaches robotics from both technical and human perspectives.

I would like to thank all participants in my studies for their time and for the valuable feedback they provided.

I also want to thank the Delft Design Lab on Human–Robot Interaction. The biweekly meetings were a valuable place to exchange ideas and learn from the work of others. The Graduation Launchpad group was equally important. Beginning our theses at roughly the same time meant that we could share the uncertainties, practical challenges, and milestones that come with a graduation project.

I am grateful to the people at StudioLab for their great company during my thesis. In particular, I would like to thank Aadjan van der Helm for providing me with a desk space at StudioLab.

Finally, I am grateful to my family and friends for supporting me throughout this period. My parents have supported me not only during this thesis, but throughout my entire education. Lastly, I would like to thank my girlfriend for her constant support and encouragement throughout this project.

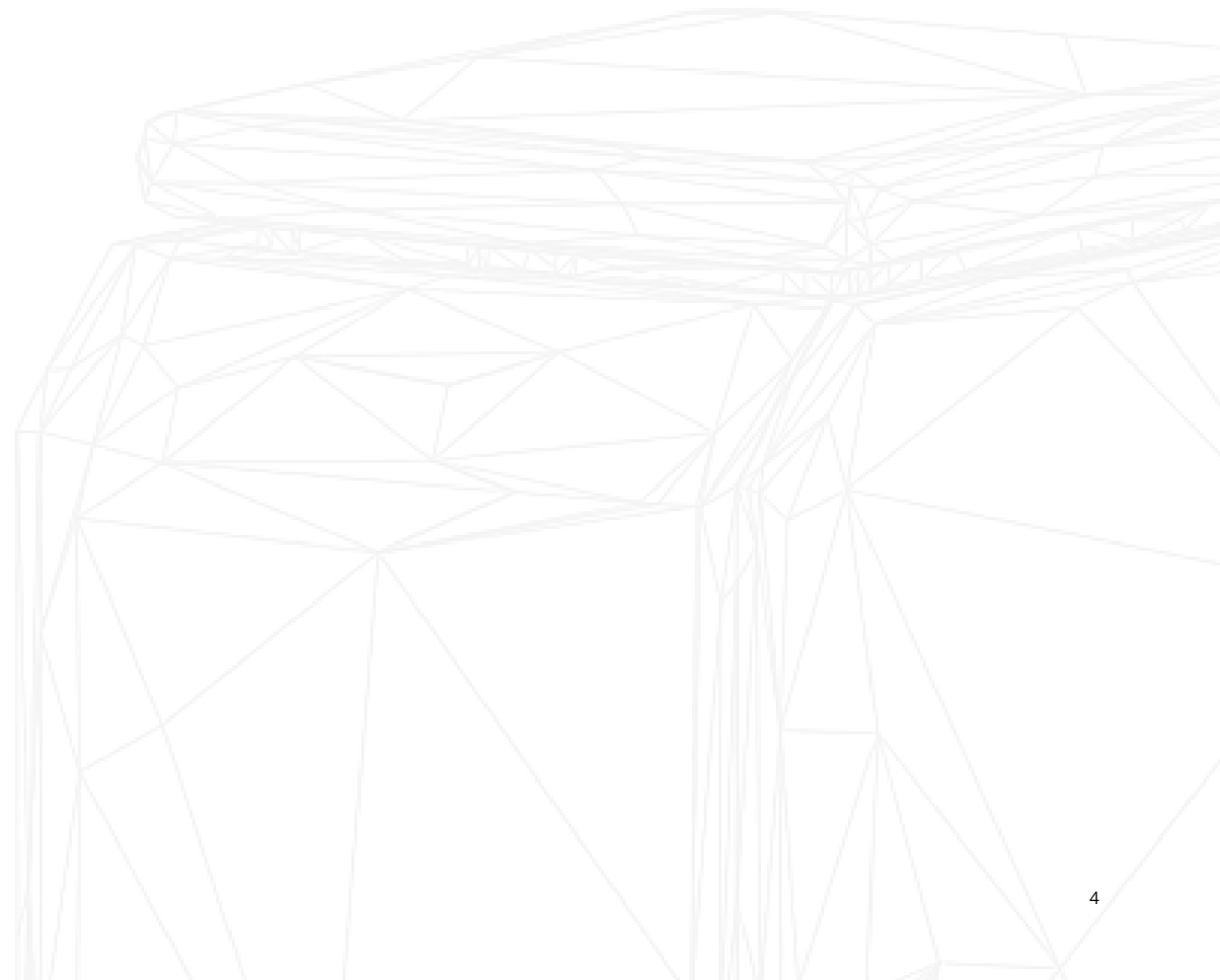


Table of contents

Chapter 1: Introduction	6
1.1 Context	7
1.2 Current state of concept	7
1.3 Goal	8
1.4 Research questions	8
1.5 Project scope	8
Chapter 2: Background	9
2.1 Literature review	10
2.2 Conclusion	14
2.3 Takeaways	14
Chapter 3: State of the Art	14
3.1 Benchmark	15
3.2 Autonomy	15
3.3 Interaction design	19
Chapter 4: Interaction Exploration	22
4.1 Stakeholder and user feedback	23
4.2 Functionality cards	25
Chapter 5: Field test	27
5.1 Explorative user field test	28
5.2 Test procedure and scenarios	29
5.3 Results	30
Chapter 6: Narrowed scope	34
6.1 Narrowed scope	35
6.2 Determining autonomy level	36
6.3 Findings from talks with experts	37
6.4 Workflow scenario	38
Chapter 7: Building the platform	39
7.1 Platform base	40
7.2 Sensing and control	41
7.3 Prototype assembly	42
7.4 Behaviour modes	43

7.5 Wearable remote	44
7.6 Dashboard interface	46
7.7 Overview of system	48
Chapter 8: Validation test	48
8.1 Validation in a one-dimensional workspace	50
8.2 Results validation test	54
8.3 Takeaways	60
8.4 Limitations	60
Chapter 9: Updates from feedback	61
9.1 Updated remote control design	62
9.2 Updated dashboard design	63
Chapter 10: Familiarisation study	64
10.1 Investigating familiarisation effects	65
10.2 Results	68
10.3 Takeaways	73
10.4 Limitations	73
Chapter 11: Closing	74
11.1 Discussion	75
11.2 Conclusion	77
11.3 Limitations	78
11.4 Future work	78
Chapter 12: References	79
Al disclosure	80
References	80
Chapter 13: Appendix	83
Appendix A: ISO design principles	83
Appendix B: Interview questions	84
Appendix C: HREC	86
Appendix D: Data	90
Appendix E: Project Proposal form	101

Chapter 1

Introduction

Context

Current state of concept

Goal

Research questions

Project scope

Context

This project builds on a collaboration between SUSAG and the Delft Design Lab on Human-Robot Interaction at TU Delft. The broader project by SUSAG is part of the Dutch government's Sustainable Employability and Early Retirement Arrangement (MDIEU) program, which invests in sustainable employability to help people reach retirement in good health. Driven by this goal, the concept of a robot assistant emerged as a practical solution to reduce the physical strain on professional painters.

To make sure the technology actually fits the users, the social design agency Muzus first gathered insights into the daily needs of professional painters [18]. These insights were

then used in the Advanced Concept Design course at TU Delft. Students developed various concepts for smart tools, and the mobile robot cart designed by Hoogendijk [13] was selected as the most promising concept for further research.

In her master's thesis, Jansen [14] further developed the concept by researching the user-experience and functionalities through site visits, co-creation, and user evaluations. After that, van Zoest [30] worked on the exterior design and feasibility. This resulted in a high-fidelity prototype that is now integrated with a robotic platform developed by a student team at RoboHouse.

Current state of concept

This project represents the concluding phase of the development cycle of a robot cart for professional painters, building upon a series of foundational research and design iterations conducted by previous students. The most up-to-date advancement of the physical hardware was developed by van Zoest [30], while the foundational user experience and use-case scenarios were conceptualized by Jansen [14]. The concept in its current form (illustrated in Figure 1) is a robust mobile trolley designed to function as an autonomous mobile workbench for professional painters.

To address the physical strain of painting, the top of the cart features a platform that can be raised to the user's desired working height, significantly reducing the need to repeatedly bend down for tools and materials. The interior of the trolley provides organized storage for daily equipment. Based on Jansen's initial concepts, this interior space is designed to securely lock valuable tools during breaks or overnight, and includes integrated capabilities to charge power tools while stored, see Figure 2. The exterior is designed with modularity in mind, accommodating

various add-ons, such as exterior shelving to transport bulky items like ladders and flat sheets, as well as customizable hooks for smaller, frequently used tools, see Figure 4.

To navigate the demanding and often cluttered environment of a construction site, the cart is equipped with a heavy-duty drivetrain featuring rugged wheels and skid-steering. This allows the robot to smoothly handle uneven surfaces, debris, and small curbs. Furthermore, the base of the cart is integrated with comprehensive sensors, including cameras, ultrasonic sensors, and LiDAR, see Figure 3. These sensors are intended for autonomy, like giving the robot the ability to follow the painter to the work area, dynamically stay close to the user while they are painting, fetch specific tools, and autonomously navigate across the site to deliver items to a colleague.

The next step is determining how the painter will actually control the robot, its expressive capabilities and how these autonomous features should work in practice: figuring out its behavioural repertoire.



Figure 1: Renders of hardware prototype, by van Zoest [30]



Figure 2: Paint storage inside the cart, by van Zoest [30]



Figure 3: Drivetrain and sensors of prototype, by van Zoest [30]

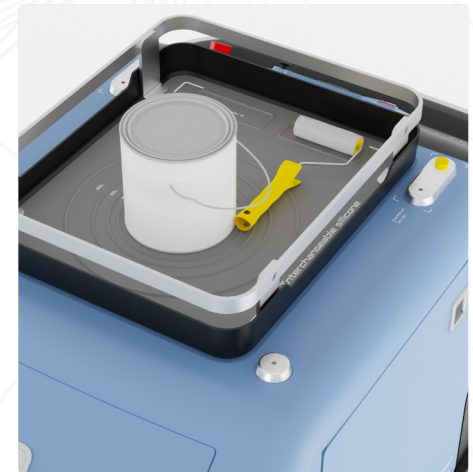


Figure 4: Paint storage on top of the cart, by van Zoest [30]

Goal

This project focuses on the interaction layer of the existing robot cart prototype, specifically how painters can effectively control, understand, and work alongside the system during use. While previous work established the physical design and overall concept, the interaction between user and robot remained underdefined, particularly in relation to autonomy, control, and feedback.

While the existing robot cart prototype already supports teleoperated movement and basic sensing of its environment, there was still limited definition of how painters should interact with it during use, how the robot should express its intentions, and how autonomy should be structured in practice. This created a gap between the system's physical capabilities and its usability as a supportive tool in a real workflow

The goal of this project is to close this gap by designing and implementing a coherent

behavioural repertoire for the robot cart. This includes defining how the robot moves, how it is controlled, and how it gives feedback. A central focus is the definition of an appropriate level of autonomy within a shared workspace, and how this autonomy can be made understandable and usable for painters during operation.

This involves designing how users can control and override the system, how the robot communicates its state and intent through multimodal feedback (motion, sound, and visual interface), and how different behavioural modes influence interaction in practice.

The outcome of this work is a validated prototype of a mobile robot cart, demonstrating how autonomy, feedback, and control can be combined into a usable and interpretable system for during professional painting.

Research questions

To structure the design of the robot cart's behavioural repertoire, three research directions are formulated, each with a corresponding research question.

Robot control input

1. "How can multimodal interaction enable intuitive control of an (semi-)autonomous robot in the complex operational environment of painting job sites?"

Robot feedback/transparency output

2. "How can multimodal feedback and expressive behaviours enable a robot cart to communicate intentions, capabilities, and operational state without demanding continuous visual attention from painters?"

Robot autonomous behaviour autonomy

3. "How can a robot cart's autonomy be structured along a sliding scale to provide appropriate assistance while preserving intuitive human oversight and intervention?"

Project scope

This project represents the final phase in the development cycle of the robot cart for professional painters. The scope is focused on the design and implementation of the interaction layer of the robot, including its behavioural repertoire, control methods, and feedback. The final deliverable is a validated prototype demonstrating how users can interact with the robot in a realistic context.

The project follows the Double Diamond design process (see Figure 5), structured across four phases:

Discover, Define, Develop, and Deliver.

In the Discover phase, relevant prior work and literature on human-robot interaction were reviewed, supported by a benchmark of existing robots and precedent mapping to identify established solutions.

In the Define phase, insights were translated into initial interaction possibilities. These were explored through an exploratory field test with professional painters, which informed the formulation of key requirements for further development.

The Develop phase focused on narrowing the scope to the workspace and translating the design directions from the Define phase into a functional prototype concept. This phase included building a prototype of the robot platform, control interface, and feedback, which together formed the basis for validating the prototype.

In the Deliver phase, the final concept was implemented as an integrated prototype and evaluated in a concluding user study. This validated the interaction design in terms of usability, workload, and control methods.

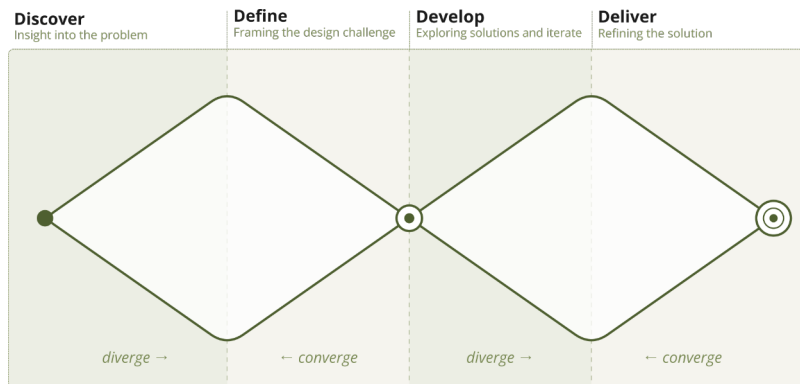


Figure 5: Development cycle project: Double diamond approach

Chapter 2

Background

Literature review

Conclusion

Takeaways

Literature review

This section presents the literature review that forms the theoretical foundation of this project. It discusses existing research relevant to human–robot interaction in professional work environments, with a focus on interface design, robot control, transparency, autonomy, and environmental constraints. The reviewed literature is used to identify design principles and theoretical foundations that inform the development of the behavioural repertoire of the robot cart.

Robots in the workspace

For robots in the workspace, Cila [3] argues for moving beyond utilitarian relations, like viewing technology as just a tool, toward viewing robots as partners or otherware, the application of social metaphors to human–technology interaction. Seeing a robot as a co-worker is also useful for operators who work on the work floor with these robots. They often express fear for robots stealing their jobs, with the image of fully automated factories. The co-worker model can help reduce this fear as the robot is seen as a colleague that is helping the operator. However, people developing software for such robots strongly resist anthropomorphism for these robots. They prefer it to view the robots as machines, devices or tools to maintain a clear understanding of the robot's technical reality [2]. De-anthropomorphizing the robot helps understand its limitations. Show the technical status of the robot without hiding it behind unclear words. Depending on what is needed, there is a level of automation that is suitable for the robot cart. The question is whether to go into the direction of viewing the robot as a co-worker or talking about the robot as a tool. This is something that has to be figured out for the specific use case and its users.

While social framing of robots can be appealing, research in industrial settings has questioned whether human-like qualities are actually beneficial in practice. Onnäs and Hildebrandt [22] challenge the benefit of anthropomorphism, arguing that in industrial settings, human-like features can actually decrease perceived reliability compared to a functional, machine-like design. Furthermore, their study revealed that these features act as distractions, significantly drawing the operator's visual attention away from safety and critical task areas. For a robot that helps painters, where the user must focus on the

physical wall and the paint application this is quite relevant. The robot's interface should prioritize functional clarity over social character design to prevent distracting the painter from their work and be safer.

Beyond interaction design, the broader integration of robots into construction work raises organizational and safety-related challenges. According to Masri et al. [17] robotics in construction (RiC) requires a holistic understanding that considers technological and environmental constraints, as well as the interplay between these factors. Currently there are no standardized practices specific to RiC, which could negatively affect its adoption in the workplace. Safe interaction between robots and humans is important and requires further research and development

Interface design and usability principles

Designing an effective human–robot interface requires making decisions in established usability frameworks rather than intuition alone. Based on user-centred design in mobile human-robot cooperation, Colceriu recommends the application of ISO design principles for designing user interfaces [5]. Particularly, ISO 9241-110, 9241-112 and 9241-13 [32] (see Appendix A). These standards provide a framework for applying those interaction principles and the general design recommendations for interactive systems.

Colceriu applied a design method where a concept is made based on user analysis which is then checked against the ISO-standards. For designing the HRI for the robot cart utilizing this method could prevent making assumptions about how the interface should look and build on tested guidelines. Nielsen's 10 Usability Heuristics for User Interface Design [19] provide a validated, scientifically

derived framework for detecting serious safety and interaction flaws before you even test with users (see Figure 6).

A challenge in interaction design for robots is managing how much information the robot should present and when.

Matthews et al. [9] describe five notification levels for displays to categorize information importance based on required user attention. It ranges from:

Ignore: Information is considered unimportant and should not be displayed.

Change Blind: Information is of marginal importance and is displayed so that it consumes no conscious awareness.

Make Aware: Information is important enough to consume some conscious effort but does not fully distract the user from their primary task.

Interrupt: The information is critical enough to temporarily divert users from their primary activity.

Demand Action: Critical information requires the user to perform an explicit action to dismiss the alert

This framework should be considered for the robot for painters, as the user's visual focus must remain on their work. By applying these levels, the robot can communicate routine updates peripherally while reserving intrusive notifications only for important issues.

Complementing these notification levels, Ebusi et al. [4] found a distinct trade-off in robot displays. Animated visuals increase user trust, while static icons result in faster reaction times and clarity. This implies that different communication goals require distinct visual strategies. For example, routine updates could utilize subtle animations to increase trust, but critical alerts should use high-contrast, static symbols.

Nielsen's Ten Usability Heuristics



Figure 6: Nielsen's Ten Usability Heuristics [9].

Multimodal feedback

In the context of HRI, transparency refers to the system's ability to clearly communicate its internal state, current actions, and future intentions to the operator, ensuring the human understands not only what the robot is doing, but why it is doing it. To achieve this, Schött et al. [25] provide a structured overview of how transparency in HRI is achieved and distinguishes three approaches, see Figure 7. Transparency can be achieved through the robot itself by leveraging cues such as movement or orientation, using the robot, through integrated communication channels like screens, lights, or speech, and on the robot, via external visualizations such as projections or augmented reality overlays. This categorization helps clarify how different transparency strategies align with the robot's physical presence and interaction context.

The authors observe that most existing work relies on simple visual or verbal communication, where especially text and speech offer high information density and precise explanations. However, haptic feedback and non-speech audio cues are

largely underexplored. Schött et al. suggest that future studies should investigate these alternative modalities in human-robot interaction. For a construction robot operating in a visually demanding environment like painting, such modalities could communicate the robot's intent without competing for visual attention or increasing the user's cognitive load excessively.

Dei et al. [7] demonstrate that multimodal feedback by combining light and sound serves a dual purpose in industrial HRI. It reinforces message clarity through redundancy and improves accessibility for neurodivergent operators. However, their empirical testing revealed limitations in abstract multimodal feedback. Red lights and warning sounds for alarm states were intuitive, but complex robot states, like 'searching', paired with abstract sounds were frequently misinterpreted. Participants explicitly suggested that the acoustic component of multimodal interfaces would be more effective if it was verbal speech rather than abstract tones to reduce ambiguity.

Integration	Tool	Approach	Communicative purpose
Transparency through robot	robot itself	natural movement trajectories	to clarify robot behaviour & intentions of where it is moving
		facial expressions	to show internal states
		robot gaze	to make task delegation intelligible via shared attention
Transparency using the robot	projector or AR interface	light projections & labels	to communicate behaviour, intent & capabilities
	speakers	first-person explanations (researcher perspective)	to clarify robot decision making, intent, beliefs & cause of failure
	haptic device	feedback via touching the robot (premapped)	to communicate intent, behaviour & capabilities
	integrated screen	visualisations, single words, facial expressions	to clarify capabilities & intent
Transparency on robot	external interface	videos of researcher, text, environment visualisations	to explain behaviour, environment & decision making
	researcher	verbal third-person explanations	to explain robot capabilities & purpose

Figure 7: Robot transparency classification [25].

Robot control

How users prefer to control a robot is dependent on the working conditions of a construction site. Lee et al. [15] found that voice control is preferred for its efficiency when it does have a high accuracy, because it does not interrupt workflow. However, when recognition accuracy dropped (for example on a noisy construction site), users shifted their preference to gestures. Gestures did reduce acceptance because issuing gestures was perceived to break task flow. Furthermore, they caution against redundant multimodal inputs like having simultaneous voice and gesture controls, noting that it reduces acceptance and can increase cognitive load.

When it is a noisy construction site where gestures come in handy, Qi et al. [24] provide the technical framework for implementing this modality. Qi et al. argue that sensor-based methods in wearables are restrictive and require setup. Vision-based methods using cameras allow for natural human-robot interaction, without requiring the worker to wear extra equipment. On a construction site, requiring a painter to wear delicate electronic gloves is likely impractical, a camera on the robot is a more robust solution. For this, an RGB-D (Depth) camera is strongly advised. Standard 2D images struggle with depth. RGB-D cameras provide depth maps that allow for easier segmentation of the hand from complex backgrounds, though it still faces challenges regarding lighting variations and occlusion from the frame.

Beyond direct control, there are also approaches that allow workers to teach or plan robot behaviour more intuitively. Zhang et al. [29] discuss approaches for HRI in construction. One approach is walk-through

programming, which allows users to physically guide the robot to record a trajectory that it can reproduce. This method supports direct, hands-on teaching of movement workflows of the robot at specific places. The second approach is to manage complex on-site tasks. Zhang et al. propose a Digital Twin framework that connects the robot's physical system with a virtual model. A Building Information Modelling (BIM) can be integrated to enable virtual task allocation, workflow planning, and data-driven decision-making. This involves the robot sending data back to a digital model of the building to update progress.

To address the limitations of graphical interfaces in physically demanding environments, Ma et al. [16] propose a Tangible Interaction Framework. They argue that traditional interfaces, which separate digital programming from physical execution, have a high cognitive load. In contrast, Tangible User Interfaces allow users to leverage their existing physical skills and intuitive understanding of the world to control complex systems.

Ma et al. demonstrated this through a "Smart Pen" controller for welding robots, where users defined robot paths by physically "drawing" on the workpiece rather than inputting coordinates on a screen [16]. This controller incorporated multimodal feedback, a retractable point provided tactile confirmation of data entry, while integrated LED indicators signalled the system's status. These input tools could function as an addition to the painter's existing equipment, rather than abstract digital menus to control the robot breaking their workflow.

Regulations and EU law

When designing the robot's behavioural repertoire it should also comply with strict requirements of the European safety law. The current Directive 2006/42/EC [31] and its replacement Machinery Regulation (EU) 2023/1230 [35], explicitly address autonomous human-machine interaction. Under its new ergonomics requirements, autonomous machinery must respond to people appropriately using verbal or non-verbal cues, such as gestures or movement. It must also comprehensibly communicate its planned actions and reasoning. This legally reinforces the need for the multimodal communication and readable motion strategies discussed earlier, ensuring the robot's intent remains transparent.

As autonomous mobile machines operate in dynamic environments, the robot cart must adhere to strict movement and supervision mechanisms. It must be equipped with sensors or cameras to detect humans, animals, and obstacles to actively prevent collisions. Additionally, the regulation mandates a remote supervisory function allowing a human supervisor to receive alerts, halt the robot, or return it to a safe state. The robot is legally prohibited from operating if this supervision is inactive.

To ensure clear authority, the regulation dictates specific control requirements. The robot must feature a clearly identifiable mode selector that overrides all other control modes, removing operational ambiguity. The only exception is the emergency stop system, which must immediately cut energy to the actuators to avert danger. These measures are essential because the law requires risk prevention for both direct human-machine

interaction and general coexistence in shared spaces. Consequently, the cart's path planning and safety buffers must protect both the interacting painter and uninvolved bystanders.

Finally, the directive addresses digital security. The robot's control architecture must withstand intended and unintended external influences, including foreseeable malicious attempts like hacking. Therefore, all hardware and software critical to the robot's safety must be protected against accidental or intentional corruption.



Robot behaviour and autonomy

Even without a screen, a robot's physical movement itself can communicate information to the user. Takayama and Dooley [26] emphasize the importance of readable motion to prevent robots from looking like black boxes. They propose applying animation principles such as forethought, signalling intent before movement, and reaction to task outcomes. This could mean expressive behaviours, like orienting wheels or pulsing lights while planning a path. By making internal states like "thinking" or "error" observable through physical cues, the robot could reduce the painter's cognitive load and allowing the user to intuitively predict the machine's next move.

While transparency in human-robot interaction often focuses on communicating the robot's current status, this alone can be insufficient for robots operating in busy workspaces. Cleaver et al. [4] argue that although humans can observe a robot's present position, its intended trajectory is often unclear, requiring users to guess where the robot is going. This uncertainty increases cognitive load and complicates safety. To address this, Cleaver et al. propose path visualization, in which the robot visually projects its planned movement trajectory into the environment. However, the authors note that displaying the full planned path at all times can introduce visual clutter, particularly in complex environments. To prevent this, they introduce a dynamic path visualization method, where the length of the projected path adapts to the complexity of the robot's path. This allows enough information to be communicated while avoiding unnecessary distraction.

Autonomy is a central concept in human-robot interaction and in this research project, as it determines how responsibilities are divided between the user and the robot.

There are multiple interpretations of autonomy but Beer et al. [1] synthesizes and organizes multiple existing views of autonomy in HRI and define autonomy as:

"The extent to which a robot can sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal without external control"

Rather than viewing autonomy as a binary distinction between manual control and full automation, autonomy exists on a spectrum. Determining the appropriate level of autonomy is therefore not simply a question of what a robot can do, but rather what it should do within a particular context [1].

Levels of autonomy

There are different levels of automation based on the combination of human and computer. Endsley [9] explains that it moves from a manual control, where the human performs all aspects of tasks, all the way to full automation, where the computer carries out all aspects of the task. Endsley also talks about guidelines for the design of human-robot systems. For example, provide automation transparency. The system should be transparent in its functioning, making it clearly apparent not only what the system is currently doing but also why it is doing it and what it will do next. These guidelines Endsley wrote down are noteworthy when deciding how much autonomy robot cart should have and how to communicate that.

Building on these earlier levels of automation, Beer et al. [1] adapted the framework from Endsley [9] specifically for human-robot interaction, see Figure 8. Their work emphasizes that robot autonomy should not only be considered from a technical perspective, but also from the perspective of interaction. Within HRI, two perspectives exist regarding autonomy. The first suggests that increasing autonomy reduces the need for human intervention, allowing the robot to operate independently for longer periods [28]. This view is reflected in the concept of neglect tolerance, which describes how long a robot can continue to perform effectively without human attention [6]. Robots with higher autonomy can generally be neglected for longer periods while maintaining performance. The second perspective argues that increasing autonomy requires more sophisticated forms of interaction, as users must understand, supervise, and coordinate with increasingly capable robotic systems [10].

An important contribution of Beer et al. is the recognition that autonomy is not necessarily fixed. Rather than occupying a single level of autonomy, a robot's autonomy may fluctuate depending on the environment, task, and interaction context. This challenges traditional notions and acknowledges that semi-autonomous systems often move between different levels of autonomy during operation. Beer et al. therefore describe autonomy as a fluid characteristic rather than a static property of a robot [1].

This dynamic view of autonomy is reflected in the Sliding Scale Autonomy (SSA) framework proposed by Desai and Yanco [8]. Rather than completely transferring control between the user and the robot, SSA blends user input with robot autonomy. Desai and Yanco describe Virtual Force Fields, which can act as invisible barriers around obstacles. For example, protecting a freshly painted wall, the robot's autonomy overrides that specific movement to prevent contact, while still allowing the user to drive parallel to the wall. Similarly, the authors introduce an autonomous speed limiter that prevents the risks of colliding or cargo falling off. In narrow or cluttered hallways, the robot can autonomously limit the speed down of the user's maximum speed input, ensuring that even if a painter pushes the joystick to full throttle, the machine physically refuses to move at unsafe speeds. Finally, SSA addresses the clunky nature of discrete control handovers. By allowing the robot to gradually shift autonomy levels based on environmental difficulty, ensuring the painter remains physically engaged in the control loop without being overburdened during complex manoeuvres.

Taxonomy of Levels of Robot Autonomy

Level	Level of Automation	Sense	Plan	Act	Description
1	Manual	👤	👤	👤	The human performs all aspects of the task including sensing the environment, generating plans/options/goals, and implementing processes.
2	Tele-operation	👤 / 🤖	👤	👤 / 🤖	The robot assists the human with action implementation. However, sensing and planning is allocated to the human. For example, a human may teleoperate a robot, but the human may choose to prompt the robot to assist with some aspects of a task (e.g., gripping objects).
3	Assisted Tele-operation	👤 / 🤖	👤	👤 / 🤖	The human assists with all aspects of the task. However, the robot senses the environment and chooses to intervene with task. For example, if the user navigates the robot too close to an obstacle, the robot will automatically steer to avoid collision.
4	Batch Processing	👤 / 🤖	👤	🤖	Both the human and robot monitor and sense the environment. The human, however, determines the goals and plans of the task. The robot then implements the task.
5	Decision Support	👤 / 🤖	👤 / 🤖	🤖	Both the human and robot sense the environment and generate a task plan. However, the human chooses the task plan and commands the robot to implement actions.
6	Shared Control With Human Initiative	👤 / 🤖	👤 / 🤖	🤖	The robot autonomously senses the environment, develops plans and goals, and implements actions. However, the human monitors the robot's progress and may intervene and influence the robot with new goals and plans if the robot is having difficulty.
7	Shared Control With Robot Initiative	👤 / 🤖	👤 / 🤖	🤖	The robot performs all aspects of the task (sense, plan, act). If the robot encounters difficulty, it can prompt the human for assistance in setting new goals and plans.
8	Executive Control	🤖	👤 / 🤖	🤖	The human may give an abstract high-level goal (e.g., navigate in environment to a specified location). The robot autonomously senses environment, sets the plan, and implements action.
9	Supervisory Control	👤 / 🤖	🤖	🤖	The robot performs all aspects of task, but the human continuously monitors the robot, environment, and task. The human has override capability and may set a new goal and plan. In this case, the autonomy would shift to executive control, shared control, or decision support.
10	Full Autonomy	🤖	🤖	🤖	The robot performs all aspects of a task autonomously without human intervention with sensing, planning, or implementing action.

Figure 8: Taxonomy of Levels of Robot Autonomy, adapted from Beer et al. [1].

👤 = human 🤖 = robot

Conclusion

This literature review explored research on human-robot interaction, interface design, robot control, transparency, autonomy, and regulatory requirements relevant to the development of a robot cart for painters.

It shows that designing robots for professional work environments requires a careful balance between usability, transparency, and safety. Several studies discuss whether robots should be framed as co-workers or as tools. While the co-worker perspective can increase acceptance, research in industrial settings consistently argues against anthropomorphic design. Human-like features can distract users and reduce perceived reliability, particularly in visually demanding tasks. For the painter robot cart, this implies that interaction design should remain functionally oriented, clearly communicating system status, intent, and limitations without unnecessary social cues.

There are several user-centred design principles to take into consideration. Standards such as ISO 9241 and Nielsen's usability heuristics provide guidelines for the interface design and evaluating it. Managing the user's attention is important. Since painters must remain visually focused on their work surface, the robot should communicate routine information peripherally and reserve intrusive notifications for safety-critical or action-demanding situations.

Multimodal communication is a promising way to increase robustness and accessibility in

noisy and complex environments. However, existing studies show that abstract feedback can be misinterpreted, suggesting the need for simple, intuitive communication of robot states and feedback modalities. Non-visual channels such as sound, haptics, and expressive movement are opportunities to communicate intent without competing for visual attention.

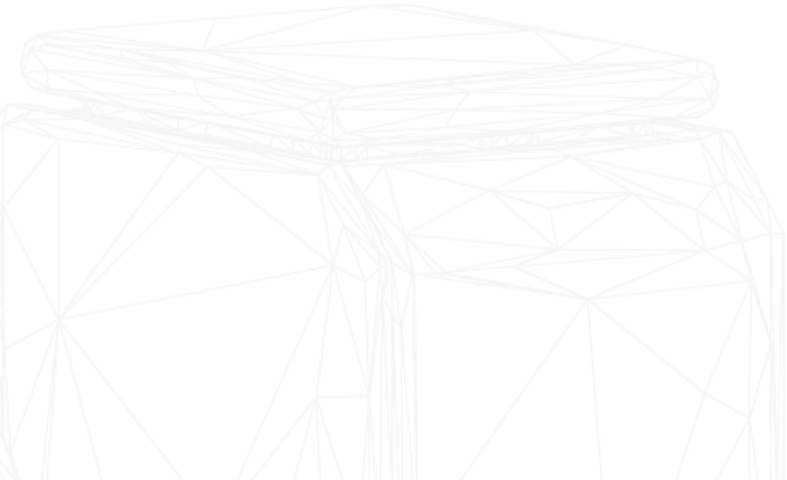
With regard to robot control, the literature shows that no single control modality is sufficient across all construction scenarios. Voice control is efficient when reliable, while gestures become useful in noisy conditions but can interrupt workflow. Adaptive control approaches, such as Sliding Scale Autonomy and virtual force fields, allow shared control where the robot assists or constrains user input based on context. These insights support developing a flexible control strategy that keeps the painter engaged while ensuring safety and efficiency.

Together, these insights inform the design of the behavioural repertoire of the robot for painters by providing inspiration and guidelines for the development of a flexible control approach combined with a transparent behavioural repertoire for the robot.

Takeaways

The following takeaways summarize the most relevant findings and their implications for the development of the robot's interaction and behavioural repertoire.

- 1 Robots should be designed as functional tools, not social partners**
Research shows that anthropomorphic design can reduce reliability and distract users, supporting a clear, tool-like robot identity.
- 2 Safety and transparency are essential in construction HRI**
Dynamic work environments require robots to clearly communicate intent, state, and limitations, while always allowing safe human override.
- 3 Usability must follow established design frameworks**
Standards like ISO and Nielsen's heuristics provide the foundation for consistent and error-resistant interaction design.
- 4 Attention must remain on the primary task**
Feedback should be minimal and peripheral by default, becoming more direct only when safety or action is required.
- 5 Multimodal feedback improves understanding but must stay simple**
Sound, light, and motion can support transparency, but overly abstract signals risk confusion and should be avoided.
- 6 Control must be flexible across modalities and contexts**
Voice, gesture, and tangible interaction each have situational strengths, supporting a multimodal rather than single-input control strategy.
- 7 Shared control and sliding autonomy are most suitable**
Autonomy should be dynamic, blending human and robot control while keeping the user engaged and in control at all times.
- 8 Readable motion is key for transparency**
The robot should communicate intent through movement itself to reduce cognitive load and improve predictability.
- 9 Regulation requires explicit supervision and clear control states**
EU machinery rules enforce transparent behaviour, mode clarity, emergency stop access, and continuous human oversight.



Chapter 3

State of the art

Benchmark

Autonomy

Interaction design

Benchmark

Autonomy

To figure out how the painter robot should behave and be controlled, it is important to look at existing solutions. Therefore, a benchmark was conducted of various robots across different industries. The goal of this benchmark is to analyse how current robots balance autonomy with human control, and to see which input and output methods they use. This helps define the right level of automation for the robot cart and provides practical inspiration for the interaction design. To structure this analysis, the robots are ranked and analysed based on Beer et al.'s adaptation of Endsley's levels of automation [1, 9], mentioned in the literature review.

Low Automation and Direct Control

(Levels 1–3)

Robots at the lowest levels of automation rely entirely on the human for cognitive tasks and decision-making. The system purely acts as physical power assistance.

Makita DCU180Z (Level 2)

The Makita DCU180Z is a motorized wheelbarrow that provides basic propulsion assistance [36]. The human is fully responsible for steering, navigation, and load control, while the system only amplifies physical movement. The input device consists of a dual-hand handlebar with integrated throttle controls, designed for manual operation. Output is entirely implicit and embodied in system behaviour, primarily through motor vibration, resistance changes, and drivetrain noise, which inform the user about load and terrain conditions.



Figure 8: Makita DCU180Z [36].

Brokk 200 (Level 3)

At Level 3, the robot executes complex physical actions, but all decision-making and spatial control remain fully with the human operator. The Brokk 200 is a teleoperated demolition robot controlled remotely via a wearable belly-box interface with dual joysticks and industrial-grade switches [37]. The input enables full manual control of navigation and tool operation from a distance. The output is primarily implicit and visually interpreted through the robot's behaviour but additional feedback is provided through basic machine state indicator lights.



Figure 9: Brokk 200 [37].

Batch Processing and Decision Support

(Levels 4–5)

At intermediate levels, robots begin to support environmental sensing and partial task preparation. However, the human remains responsible for defining objectives and approving or initiating system actions. Autonomy is therefore limited to execution support rather than independent operation.

HP SitePrint (Level 4)

At Level 4, the human defines the complete task structure in advance, while the robot autonomously executes the physical implementation. HP SitePrint operates through a batch-based workflow where the human defines a layout using a digital model [38]. The system then autonomously executes the physical marking of construction layouts. Input is provided through a tablet-based CAD interface, where the operator uploads and positions design data. Output is expressed through ink markings printed directly onto the floor surface, which function as a construction reference.



Figure 10: HP SitePrint [38].

Canvas 1200CX (Level 4)

The Canvas 1200CX provides automated surface processing such as spraying and sanding [39]. The human configures the system before execution by defining spatial boundaries and operational zones. Input is handled through a combination of a handheld joystick controller and a tablet interface, used to position the robot and define wall segments. The joystick allows for ground positioning, while the tablet provides positioning on the wall. Output is communicated through progress visualisation on the tablet interface and status light bars positioned on each corner of the robot, allowing the operator to monitor execution from a distance.



Figure 11: Canvas 1200CX [39].

Hilti Jaibot (Level 5)

At Level 5, both the human and robot contribute to task planning, but the human ultimately reviews and approves system-generated plans before execution. Hilti Jaibot generates drilling plans based on BIM data, which are then reviewed and confirmed by a human operator through a tablet interface [27]. Only after approval does the robot execute drilling operations autonomously. The output uses laser projection systems to display intended drilling positions on ceilings before execution, providing automation transparency and allowing the operator to validate system intent.



Figure 12: Hilti Jaibot [27].

Shared control

(Levels 6–8)

At higher levels of automation, robots operate autonomously within shared environments, while human involvement shifts toward activation, mode selection, or supervisory intervention. The key distinction lies in whether autonomy is command-driven, mode-based, or adaptive.

Burro (Level 7)

The Burro operates as an agricultural logistics cart driven by multiple operational modes [40]. The operator selects a specific behaviour such as 'follow-me', 'route navigation', or 'row-based traversal' via a rugged remote control or on the screen on the robot, with additional physical start/stop buttons on the chassis for direct physical control. Once a mode is engaged, the robot autonomously handles all sensing, planning, and acting to transport materials within that specific behavioural framework. The output is expressed through LED and auditory signals to indicate its system state. It is classed as level 7 because the human provides a high-level goal through mode selection, and the robot executes the task autonomously, only prompting the user for assistance if it encounters an environment it cannot navigate.



Figure 13: Burro [40].

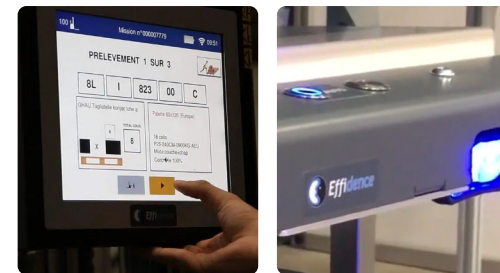
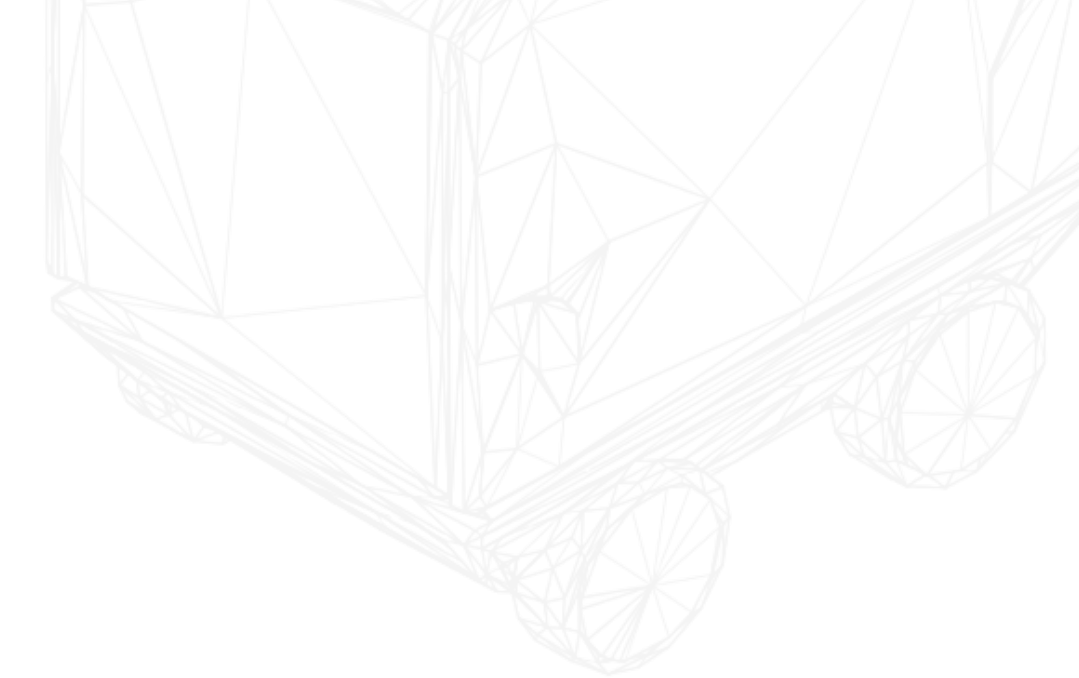


Figure 14: Effidence EffiBOT [41].

Effidence EffiBOT (Level 8)

At Level 8, the robot continuously performs sensing, planning, and acting during task execution, while the human primarily supervises and intervenes only when necessary. The EffiBOT is an industrial logistics cart where the user initiates a follow-me mode through a simple touch-screen interface on the robot [41]. Once active, the robot autonomously tracks the user and generates collision-free paths in real time using onboard sensors. Human input is limited to activation, mode selection, or emergency intervention rather than continuous control. The output is communicated through colour-changing LED status indicators integrated into the robot body, which signal states such as active following, standby, or error conditions. It is classed as Level 8 because the robot independently adapts its behaviour during operation while the human remains in a supervisory role, intervening only when the system encounters situations it cannot resolve autonomously.

Supervisory Control and Full Autonomy

(Levels 9–10)

At the highest tiers of the taxonomy, the robot takes over continuous real-time execution. The human either steps back into a high-level monitoring role with manual override capabilities or is removed from the operational loop entirely.

Lionsbot R3 (Level 9)

The Lionsbot R3 is an industrial cleaning robot where the user manually positions it using a physical push bar [34]. Once brought to an RFID tag on the wall, the robot autonomously performs all sensing, planning, and acting to execute its cleaning route. The human supervises via an app, while the robot communicates its status through an onboard screen and expressive LED "eyes". It is classified as Level 9 because the robot independently performs sensing, planning, and execution throughout the cleaning task while continuously adapting to its environment. The human remains outside the operational control loop and supervises only overall task progress.



Figure 15: Lionsbot R3 [34].

OKIBO (Level 10)

The OKIBO is a painting robot where the system operates entirely autonomously [42]. The user initiates commands via a touchscreen interface on the robot itself and physical buttons, after which the robot independently scans the room, maps the plan, and acts to apply the paint without any local human intervention. It communicates its status through an indicator light on the corner, while the painted wall serves as the functional output. It is classified as Level 10 because the robot performs all sensing, planning, and acting autonomously, requiring absolutely zero human interaction during the active execution phase.



Figure 16: OKIBO [42].

GO AGV (Level 10)

The GO AGV is an industrial warehouse robot that handles all routing and execution based strictly on centralized fleet software commands [43]. While it features an onboard touchscreen, this is used solely for monitoring errors rather than active control. Operating with full autonomy in shared spaces, it relies on outputs like a blue signal light, alongside audible chimes to signal its presence. It is classified as Level 10 because the system manages all sensing, planning, and acting completely independently, with zero direct human input required during active operation.



Figure 17: GO AGV [43].

Conclusion

A trend can be seen from the benchmark: As autonomy increases, direct control inputs become less important, while explicit feedback becomes increasingly necessary to communicate system intent and status. Interaction shifts from continuous manual control toward high-level task specification and supervisory control.

Because the robot cart for painters is envisioned as an autonomous tool carrier, traditional manual controls and implicit feedback are no longer sufficient. To function effectively on a busy construction site, the robot requires intuitive, high-level inputs to direct its autonomous tasks, combined with clear output to communicate its intent. These insights provide a good starting point for defining the robot's behavioural repertoire and interface in the next phase of this project.

Interaction design

Building on the benchmark of autonomy levels, the selected robots were further analysed to understand how their autonomy is translated into practical interaction design. This analysis focuses on the specific input and output methods used by existing autonomous robots, including visual interfaces, physical controls, feedback mechanisms, and safety features.

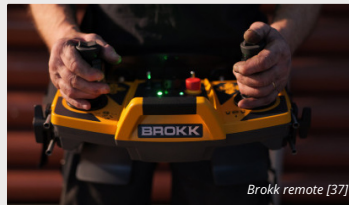
By comparing these design solutions across the benchmark examples, relevant interaction principles and design opportunities were identified. The analysis provides inspiration for the design of the remote control, dashboard, behaviour modes, and safety feedback.

Physical inputs and manual control

The mapping reveals that robots operating in heavy-duty or manual contexts rely heavily on robust, tactile input devices designed for continuous engagement.

Wearable interfaces

The Brokk 200 uses a fully tactile belly controller [37]. To support the operator during use, this interface includes physical straps, handgrips, and robust hand holds. The primary input is a joystick, paired with a dedicated safety button and physical instructions printed directly on the controller.



Tactile remotes

For simpler tasks, the Kewazo Liftbot uses a rugged remote control featuring tactile buttons with height separators to separate them, allowing the user to operate it without looking down [44].



Physical state toggles

Transitioning a robot between manual and autonomous states is frequently tied to distinct physical actions. For example, the Lionsbot R3 requires the user to explicitly push a handle down for autonomy mode [34]. The Burro has a dedicated hardware turn switch on the remote to toggle autonomy on and off, preventing accidental mode switches [40].



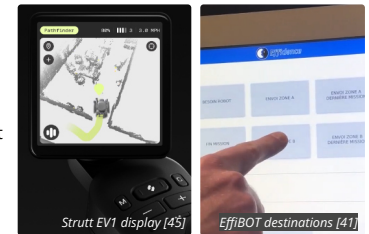
Across these examples, physical controls are primarily used for frequent, safety-critical, or repetitive interactions. Their tactile nature allows operation while wearing gloves and minimizes the need to divert visual attention away from the primary task.

Digital interfaces

When directing autonomous tasks, the precedent mapping shows a heavy reliance on digital interfaces and screens to handle complex environmental data and goal setting.

Screen-based wayfinding

The autonomous wheelchair Strutt EV1 uses a display to show a mapped environment that allows the user to select destinations directly on the screen [45]. This feature also allows transparency, because it shows what the robot sees on the display. The EffiBOT robot allows the users to set specific autonomy waypoints or choose from multiple destinations to where the robot should go [41].



Mobile and accessible inputs

The Lionsbot R3 can be driven via an app on a smartphone, allowing the operator to manage the robot from a distance [34]. The Hilti Jaiobot has a dedicated screen in the remote above the buttons, which can be operated via a pen on a touch screen, ensuring it can be used even if the operator is wearing gloves [27].



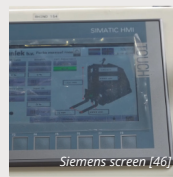
These examples suggest that digital interfaces are most valuable for configuring autonomous behaviour, selecting destinations, and visualizing information that changes dynamically. In contrast, they are rarely used for interaction during physical work activities.

Hybrid interface

Many industrial robots avoid relying entirely on a touchscreen by blending digital information on a screen with physical tactile controls.

Integrated panels

Controllers like the Siemens SIMATIC HMI [46] and KUKA controllers [47] place physical buttons alongside the screen. This allows the digital screen to show complex, changing information while keeping tactile buttons for critical or repetitive actions.



Hardware Integration

The Hilti Jaibot has a dedicated controller space inside the robot to house its controller, protecting the controller within the machine when not in use [27].



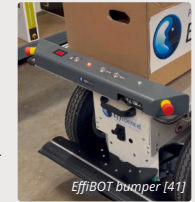
The combination of physical and digital controls appears to be a recurring design strategy in industrial environments. Hybrid interfaces leverage the strengths of both modalities. Physical controls support quick and reliable interaction, while screens provide flexibility and access to complex information.

Safety features

Safety and transparent feedback are deeply integrated into both the physical hardware and the digital software of these precedents.

Physical safety

To physically prevent collisions, systems like the EffiBOT [41] and Burro [40] are equipped with front and back safe-stop bumper bars. Other physical safety measures include plexiglass protection screens and placing control interfaces directly on the front bumper for immediate access.

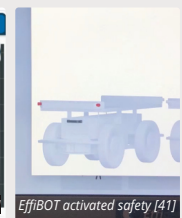
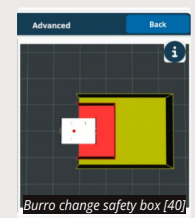


Visual safety

To communicate status and movement intent to bystanders in shared spaces, robots utilize distinct visual cues such as brake lights on every side and a blue safety spot light projected onto the floor.

Software safety

On the software side, the interface of Burro and EffiBOT allow users to visually change the size of the safety zone or adjust the safety box to accommodate external objects attached to the device. Furthermore, the UI of EffiBOT explicitly highlights activated safety elements on the screen so the operator knows exactly which safety elements are currently engaged.



The analysed robots apply multiple layers of safety simultaneously. Rather than relying on a single mechanism, physical safeguards, visual communication, and software controls are combined to ensure both safe operation and user trust.

Autonomy behaviour

Lastly, the mapping highlights established navigational behaviours for autonomy.

Follow Me mode

Systems like the EffiBOT, Burro, and Strutt EV1 all utilize a dedicated Follow Me mode. The specific behaviour of this mode requires the robot to first wait for a person to be recognized before it initiates to follow behind the user.



Waypoint navigation

Several systems, including EffiBOT and Strutt EV1, allow users to specify destinations or waypoints, after which the robot autonomously plans and executes a route.



These examples demonstrate that successful autonomous systems rarely remove the human entirely from the process. Instead, they shift interaction toward setting goals such as selecting a destination or choosing a behavioural mode, while leaving planning like navigation and obstacle avoidance to the robot.

Conclusion

The key findings and resulting design implications are summarized in Figure 17. The analysis of interaction design across existing autonomous work robots reveals a consistent pattern across autonomous work robots. Physical controls are retained for frequent and safety-critical interactions, while digital interfaces are primarily used for configuration, planning, and status monitoring. Furthermore, safety is communicated through multiple complementary channels, combining physical safeguards, visual indicators, and clear feedback.

Taken together, the analysed systems indicate that successful autonomous work robots do not replace user interaction, but rather shift it from continuous control toward supervision and higher-level task specification.

Because the robot for painters is intended to operate alongside active workers, complex touchscreen interactions such as the Hilti Jaibot's stylus-based interface may be unsuitable during active work. Instead, the precedent mapping suggests a hybrid interaction approach that combines tactile physical controls with explicit visual feedback. Particularly relevant precedents include the wearable and tactile controls of the Brokk 200 and Kewazo Liftbot, the adjustable safety systems of Burro and EffiBOT, and the Follow-Me behaviour found across multiple robots.

These insights provide design directions for the development of the painter robot's interface, safety systems, and behavioural repertoire in the subsequent concept generation phase.

Observation from existing robots	Design takeaways
Physical controls dominate in rugged environments	Use tactile controls for core functions
Touchscreens are used for setup rather than continuous control	Avoid screen dependence during active work
Autonomous robots require explicit status communication	Integrate clear visual feedback (LEDs/lights)
Mode switching is often a physical action	Use a dedicated autonomy activation mechanism
Follow-me behaviour is common in logistics robots	Investigate follow-me as primary navigation mode
Hybrid interfaces are common in industrial robots	Combine tactile controls for operation with digital interfaces for setup and configuration

Figure 17: Observations from existing robots.

Chapter 4

Interaction exploration

Stakeholder and user feedback

Functionality cards

Stakeholder and user feedback

To gather early feedback and connect with the industry, van Zoest organized a presentation to showcase the hardware prototype, see Figure 18. I attended this session to note down stakeholder feedback and collect insights relevant to the development of the robot's behavioural repertoire and interface design. Attendees included key stakeholders and potential users from organizations such as OnderhoudNL, SUSAG, Elk, Bilfinger, Hoedemakers and more. For this project, the session served two purposes: Establishing contacts for future user tests and collecting practical insights to shape the robot's behavioural repertoire and interface design. The feedback gathered from the attendees provided interesting directions across several key themes.

Control and interface preferences

The stakeholders provided concrete input on how the robot should be controlled. There was a strong consensus that a smartphone application is a highly viable, cost-effective, and accessible controller. Users explicitly requested the ability to create personal profiles and customize the interface buttons based on their specific preferences or daily tasks. The interface must also allow for dynamic inputs. For instance, if a worker attaches a large box or ladder to the cart, they need a way to input these new dimensions so the robot can safely adjust its obstacle avoidance behaviour.

Autonomous behaviour and workflow

The discussion highlighted that the robot must function as a true "buddy" to be accepted on the worksite. Because strict safety regulations (such as the 3-point contact rule when climbing scaffolds) prevent painters from carrying equipment, the robot's ability to autonomously bring materials to the worker is highly valued. The stakeholders envisioned the robot navigating long distances independently, such as driving from a distant storage area to the worksite, or using Building Information Modelling (BIM) to position itself at the site before the painters even arrive.

During close-quarters collaboration, the robot's following behaviour needs careful tuning. For example, if the robot is following a painter, it should not immediately back away when the painter turns around to grab a tool. It must also handle multi-user scenarios, such as seamlessly passing tools between two painters working in the same room.

Safety, communication, and job satisfaction

Safety and clear communication are critical in the dynamic construction environment. Stakeholders suggested adding blinking indicator lights on the sides to communicate the robot's movement intentions. There was also strong interest in remote supervision via a camera and an SOS emergency button. However, stakeholders also noted that if an admin is watching remotely, a specific indicator light must turn on to inform the workers on site. Furthermore, the attendees saw potential in utilizing the robot outside of working hours. By equipping the cart with a spotlight and using its camera, it could function as a mobile surveillance system (similar to a 'Bauwatch') to guard the construction site at night.

Finally, the attendees emphasized that the robot should actively improve job satisfaction. Suggestions like an integrated radio, a "coffee alarm," carrying a first-aid kit (AED), or monitoring the humidity and weather were brought up as valuable secondary features to make the physically demanding job of painting more enjoyable and safe.

Key insights can be seen on the next page in Figure 19.

Next steps

Beyond the design insights, this session also successfully gave opportunities for upcoming user tests. The practical insights gathered from this session will directly feed into the Define phase to generate the initial interaction concepts.



Figure 18: Prototype presentation held by van Zoest with stakeholders.

Key insights from stakeholders

Theme	Key insight	Design implication
Control & Interface	Users strongly prefer a smartphone app as the controller because it is familiar, accessible, and cost-effective.	Use a mobile app as a control interface.
Personalisation	Users want multiple user profiles and customisable buttons based on personal preferences and tasks.	Allow profile-based settings and configurable interface layouts.
Dynamic Configuration	Workers may attach ladders, boxes, or scaffolding components to the robot.	Enable users to input additional dimensions so obstacle avoidance can adapt accordingly.
Autonomous following	Workers cannot carry tools while climbing scaffolding due to safety regulations (3-point contact rule).	Allow autonomous following to carry tools and materials to workers.
Long-Distance Navigation	Significant time is lost walking between storage areas and work locations.	Enable autonomous navigation over long distances and between work zones.
BIM Integration	Stakeholders envision the robot arriving at the correct location before workers start.	Investigate BIM integration for task planning and positioning.
Following Behaviour	The robot should understand normal work movements and not react unnecessarily.	Design context-aware following behaviour that supports painting workflows.
Multi-User Collaboration	Construction work is often performed in pairs or teams.	Support interactions involving multiple users.
Safety Communication	Workers need to understand what the robot is doing and where it is moving.	Use visual cues such as indicator lights to communicate intentions.
Remote Assistance	Stakeholders want remote supervision and emergency support capabilities.	Include camera functionality, remote monitoring, and an SOS button.
Privacy & Transparency	Workers want to know when remote monitoring is active.	Display a clear indicator when a remote operator is viewing the camera feed.
Environmental Monitoring	Humidity and weather conditions are important for painting activities.	Integrate environmental sensing and weather information.
Lighting Support	Construction work often begins in low-light conditions.	Equip the robot with work lights and visibility lighting.
Site Security	The robot could provide value outside working hours.	Investigate surveillance functionality using cameras and lighting.
Safety Equipment	Stakeholders suggested carrying emergency resources.	Consider integrating an AED, first-aid kit, or emergency supplies.
Job Satisfaction	The robot should improve not only productivity but also the work experience.	Include features that reduce workload and increase user enjoyment.

Figure 19: Key insights from stakeholders.

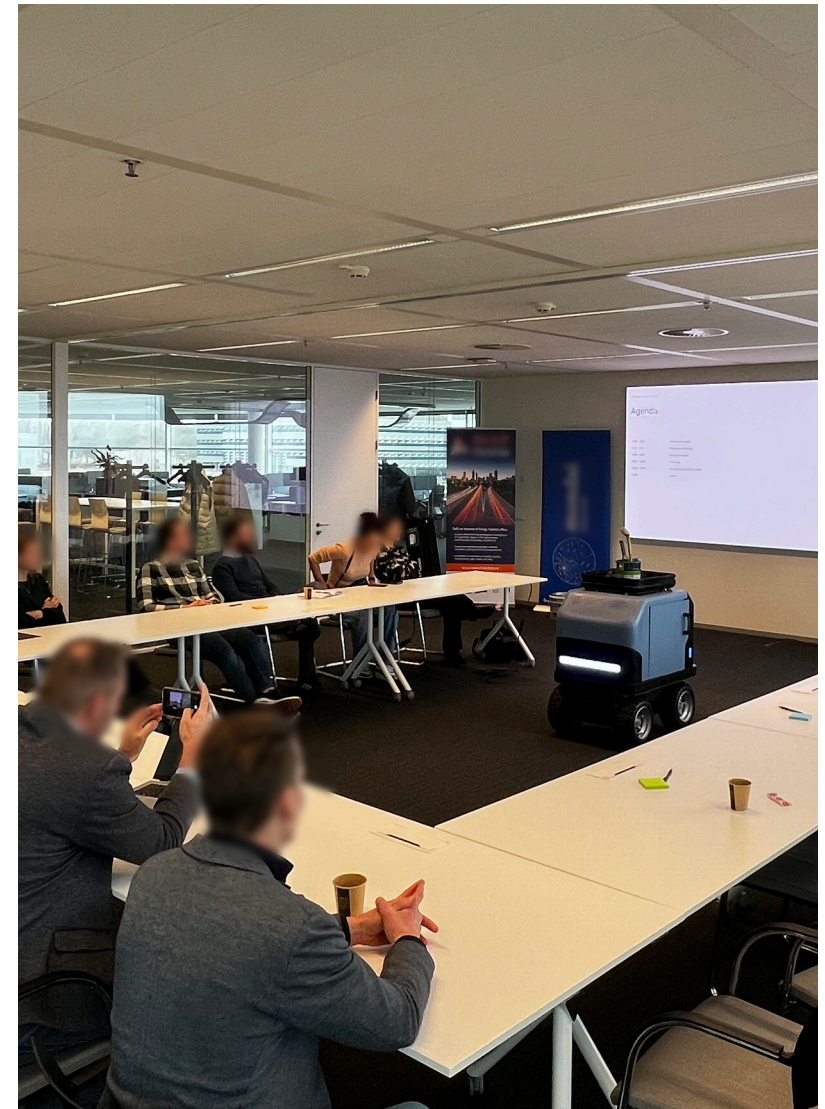


Figure 20: Stakeholders sitting around the prototype providing feedback.

Functionality cards

Following the benchmark and stakeholder feedback, the next step was to explore how the identified requirements could be translated into explorative interaction concepts. Rather than immediately selecting a single solution, a broad range of interaction possibilities was generated to explore different balances between human control and robot autonomy.

The concepts were derived from the findings of the previous phase. The benchmark revealed common input and output modalities used at different levels of automation, while the stakeholder session highlighted practical requirements such as hands-free operation, clear status communication, flexible autonomy, and minimal workflow disruption. These insights were translated into a set of functionality cards that represent possible interaction mechanisms and behaviours, see Figure 21. The cards were created to span a spectrum from direct manual control to highly autonomous operation, enabling comparison and discussion with professional painters to highly autonomous operation, enabling comparison and discussion with professional painters during later user evaluations. All cards can be seen in Figure 22 on the next page.

Moving the cart

For moving the cart around the construction site, the cards explore a sliding scale of autonomy. On the manual side, interactions include pushing or pulling the cart with a physical handle, which could be enhanced with motor assistance to reduce physical strain. Another direct control option is using a manual joystick, potentially assisted by autonomous collision prevention to keep the cart safe. On the highly autonomous side, the cards suggest picking a destination point on a screen, using voice commands, or having the robot follow a physical line. Other concepts involve setting waypoints using buttons on the cart, using a "smart wireless leash", or having the robot autonomously follow the user step by step.

Proximity during work

When the painter is actively working (such as painting or sanding), the robot needs to stay nearby without obstructing the workflow. The cards explore spatial relationships, such as whether the cart should drive in front of or behind the painter. To control when the robot moves, the interaction ideas range from explicit commands, like pressing a button or using a waving gesture to call the cart closer, to more autonomous behaviours. For example, the cart could constantly maintain a set distance or autonomously move closer only when the gap between the user and the cart exceeds a certain threshold. The cards also include a function where the user presses a button to explicitly set the working distance between the cart and the wall.

Controlling the hardware

Finally, the functionality cards explore how the painter will control the robot's features, specifically the height-adjustable platform. Basic interaction ideas include setting the desired height on a digital screen or using simple physical up and down buttons. More advanced, sensor-driven concepts include pressing a button to automatically match the platform's height to the height of the user's remote, or having the system autonomously recognize and match the user's hip height.

These functionality cards serve as a practical toolkit of interaction mechanisms. These cards will be tested with professional painters to see which interactions work best in the field.

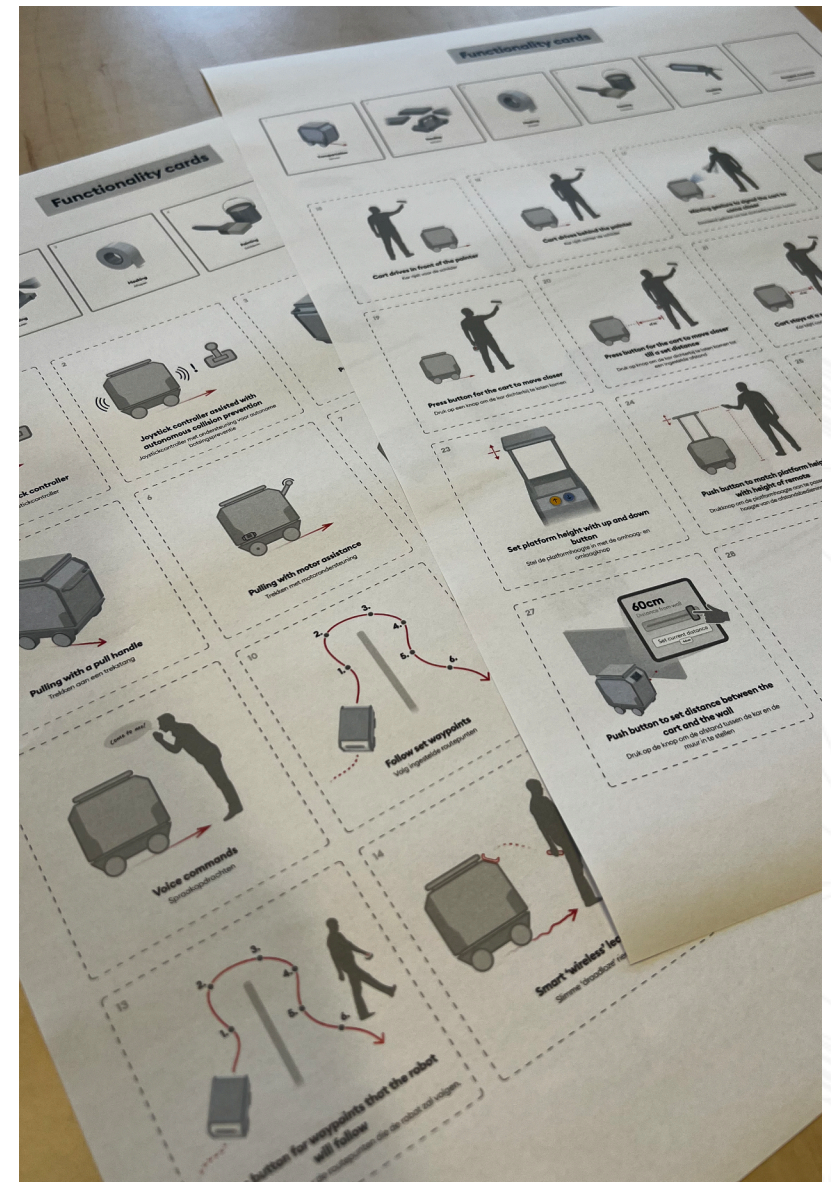


Figure 21: Functionality cards printed out.

Functionality cards

<p>1</p> <p>Manually with a joystick controller</p>	<p>2</p> <p>Joystick controller assisted with autonomous collision prevention</p>	<p>3</p> <p>Pushing with a push handle</p>	<p>4</p> <p>Pushing with motor assistance</p>	<p>5</p> <p>Press button for waypoints that the robot will follow</p>	<p>6</p> <p>Cart drives in front of the painter</p>	<p>7</p> <p>Cart drives behind the painter</p>
<p>8</p> <p>Waving gesture to signal the cart to come closer</p>	<p>9</p> <p>Cart moves closer only when the gap exceeds a set distance</p>	<p>10</p> <p>Pulling with a pull handle</p>	<p>11</p> <p>Pulling with motor assistance</p>	<p>12</p> <p>Follow user step by step autonomously</p>	<p>13</p> <p>Pick a point on a screen where to go to</p>	<p>16</p> <p>Push button to set distance between the cart and the wall</p>
<p>14</p> <p>Press button for the cart to move closer</p>	<p>15</p> <p>Press button for the cart to move closer till a set distance</p>	<p>16</p> <p>Cart stays at a set distance constantly</p>	<p>17</p> <p>Set height platform on screen</p>	<p>18</p> <p>Voice commands</p>	<p>19</p> <p>Follow set waypoints</p>	<p>20</p> <p>Following a line</p>
<p>21</p> <p>Press button on cart to set waypoints</p>	<p>22</p> <p>Push button to set distance between the cart and the wall</p>	<p>23</p> <p>Set platform height with up and down button</p>	<p>24</p> <p>Push button to match platform height with height of remote</p>	<p>25</p> <p>Platform recognizes and matches height according to hip height</p>	<p>26</p> <p>Set height of platform with your hands</p>	<p>27</p> <p>Smart 'wireless' leash</p>

Figure 22: Functionality cards of explorative interaction ideas

Chapter 5

Field test

Explorative user field test

Explorative user field test

It is essential to understand how professional painters actually want to work with it in practice. Therefore, an explorative user field test is conducted. The goal of this test is to move beyond theoretical ideas and physically test interaction concepts on an active job site. By observing painters working alongside a physical prototype, this test aims to answer three core questions that will define the robot's behavioural repertoire.

First, the test investigates the ideal movement of the robot. It explores how the cart should navigate the construction site and position itself during active tasks without obstructing the painter's physical workflow. Second, it examines the practical human-robot relationship. The test will determine whether painters prefer to treat the cart as a direct tool or a collaborative co-worker. Finally, the test evaluates the role of autonomy. It clarifies exactly which functions the robot should handle independently and how the painter can intuitively oversee and take back manual control of these features on the job.

Methodology

Test objectives & scope

The primary objective of this exploratory field test is to evaluate the user experience and preferred behavioural repertoire of the robot cart within the dynamic context of a painting job site. This test will be physically enacting various interaction concepts, to determine what is required to support professional painters across different transportation and active work scenarios. Grounding this evaluation in physical enactment ensures the test focuses on how the robot should behave to function as a helpful, non-disruptive tool, rather than an unpredictable machine.

Materials

- Prototype of the robot cart
- Mock-up of interaction inputs
- Printed out functionality cards
- Camera
- Audio recorder
- Printed consent forms
- Clipboard, notepad, and pens

Participants & context

- **Target participants:** Professional painters with at least 3 years of experience.
- **Sample Size:** 4-8 participants. 2 at a time, as painters usually work in duo's.
- **Location:** The test will take place on a job site where professional painters are working

Setup

The physical prototype

To conduct the user tests on-site, the physical hardware prototype developed by van Zoest will be used. Because the robot needs to be easily maneuvered and transported during these field tests, the prototype body is temporarily removed from its autonomous platform and placed on a manual cart (see Figure 23 & 24). This ensures the physical dimensions, footprint, and moving platform accurately represent the real concept in a practical setting. To evaluate the new behavioural repertoire, several mockups of interaction elements have been added to the cart (see Figure 25 & 26). These include a push button, an up-and-down button, a microphone, a camera, and a display. By combining the realistic hardware with these interaction mock-ups, the evaluation of the interaction points remains valid and realistic for the painters.

Manual enactment

Because the prototype lacks motor control, the movements will be simulated through manual enactment. The researcher acts as the system's control unit, physically pushing and positioning the cart to simulate intended autonomous behaviours, such as following, moving out of the way, or presenting a tool. This transparent, interactive setup allows for fast iterations based on the painter's real-time feedback without the constraints of operating a complex robot.



Figure 23: Prototype on manual cart.



Figure 24: Prototype on manual cart.



Figure 25: Mockup push button, microphone and display.



Figure 26: Mockup camera on the front of the prototype.

Test procedure and scenarios

The user test takes approximately 60 to 75 minutes and is structured into four phases.

Phase A:

Introduction and consent (10 mins)

The session begins with a briefing that explains the overarching goal of the project and the specific purpose of the test. To help the participant bridge the gap between the test setup and the final design, they are shown images and videos of the high-fidelity prototype. These visuals are used to establish a clear mental model of the robot's intended appearance, motorized movement, and autonomous capabilities.

After this, the manual enactment process is explicitly explained to the participant. The painter is instructed to treat the prototype cart as a fully functioning, motorized autonomous robot, acknowledging that the researcher will physically move it to simulate its behaviour. Subsequently, the participant signs the required informed consent forms (see Appendix C).

Phase B:

Baseline physical familiarisation (5 mins)

Before introducing complex tasks, the painter is allowed to interact with the static prototype. This establishes a baseline impression

regarding the size, positioning and platform accessibility, ensuring the user is comfortable moving around the cart and speculate how to use it.

Phase C:

Scenario enactment (40 mins)

This phase forms the core of the test, wherein the participant works through five specific scenarios. For each scenario, a two-step loop will be done:

First, an unprompted natural exploration takes place. The scenario begins without external prompts, allowing the painter to act out their task naturally while the researcher anticipates and manually enacts the cart's movement. The interaction is verbally negotiated to capture the user's baseline mental model.

Second, prompted exploration is conducted using the functionality cards. Cards relevant to the specific scenario are introduced to prompt new interaction modalities. The painter selects the most appealing concepts, and the scenario is physically re-enacted utilizing these new interaction rules.

The test evaluates the robot's behavioural repertoire across six scenarios (see Figure 27):

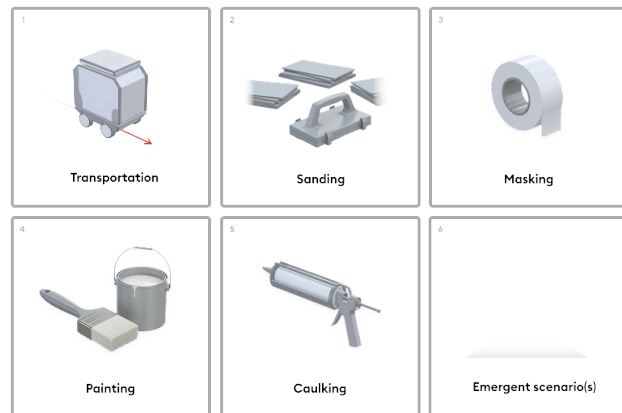


Figure 27: Six scenarios to play out during the field test

1. Transportation: Moving the cart from a storage area to the active work area.

2. Sanding: A dynamic, high-dust preparation task requiring constant movement along a wall.

3. Masking: A precision task requiring work near the floor or tight edges.

4. Painting: The primary task requiring continuous access to the cart while maintaining visual focus on the wall.

5. Caulking: A finishing task requiring smooth, continuous movement.

6. Emergent Scenario: An open scenario where the participant can add an additional task that would benefit from using the cart, allowing for spontaneous co-creation of a new robot behaviour.

Phase D:

Post-test debrief (20 mins)

The session concludes with a short, semi-structured interview, giving the participant time to reflect on their physical experience with the robot cart, the questions can be found in Appendix B. Through open-ended questions, the painter is asked to share their overall impressions, brainstorm about possible functionalities and answer any unanswered questions that the researcher has.

Data collection

Given the exploratory nature of this test, the data collection will be looking at qualitative insights and not quantitative measurements. The goal is to capture natural workflows and interaction preferences without imposing artificial constraints or time pressure on the participants.

Metrics

The focus during the enactment phases is observing how the painter naturally integrates the cart into their physical workspace. Key metrics include:

- **Spatial preferences:** Noting the preferred physical distance between the user and the cart during different tasks, such as how close they want the cart during painting versus how far trailing it should be during transportation).

- **Interaction behaviours:** Observing spontaneous or emergent physical interactions, such as how the user approaches the cart, where they attempt to grab it, or if there is any hesitation.

- **Friction and utility:** Identifying moments of good collaboration versus visible indicators of frustration, confusion, or task interruption.

Recording methods

- **Observational notes:** Live observations, spatial setups, and immediate insights will be documented manually on paper during the physical enactment.

- **Photography and video:** Pictures will be taken to document the physical setup, robot-human relationships, and specific actions. Ad-hoc video recording will be utilized to capture highly notable or complex physical interactions that require deeper movement analysis.

- **Audio Recording:** The whole manual enactment and post interview will be audio-recorded to ensure accurate transcription of what is said during the enactment and the interview.

Roles & responsibilities

- **Cart-operator:** Manoeuvres the cart around by hand, acting out specific movement that the participants suggest or from the functionality card and asks questions.

- **Facilitator:** Walks with the painter, asks questions, takes notes and pictures.

Results explorative field test

Following the earlier stakeholder feedback session, an industry contact provided the opportunity to conduct the field test at an active work site. The location was managed by a renovation and maintenance company that employs various trades professionals, including painters.

Test execution and circumstances

The test took place on an active renovation site in a suburban street in The Hague. The location was a large housing block surrounded by scaffolds, with 15 to 20 professionals of various trades working simultaneously (see Figure 29).

The session began in the site's temporary canteen, where bringing in the physical prototype immediately attracted a lot of curiosity and attention from the crew. Initially, around ten workers gathered to evaluate the cart, with a lot of curiosity but some also questioning if the machine was designed to replace them. While the goal was to isolate a duo of painters to execute the manual

enactment, the broader group was quite interested and followed along when we moved outside for the transportation scenarios, see Figure 28. After the first enactments on the ground floor about the movement to the workplace, the whole group moved to a narrow first-floor gallery corridor, accessed via a small elevator, to simulate active work tasks like painting, masking, and caulking. After an hour, the crew needed to return to their own tasks, so the formal post-test interview had to be skipped, though much of the necessary interaction data had already been gathered during the scenarios.



Figure 28: Prototype on cart being used in the field test



Figure 29: Representation of the test location in The Hague.

Contextual and interpersonal reflexivity

This section reflects on how the field-test context and researcher involvement may have influenced the observations and feedback collected, following the reflexivity guidelines of Olmos-Vega et al. [21]. Here, contextual reflexivity concerns the influence of the worksite, group size, time constraints, and testing conditions. Interpersonal reflexivity concerns how the researcher's presence and actions may have influenced participants.

Contextual Reflexivity

Testing on an active construction site provided a realistic setting, but the larger-than-planned group changed the session from an observation of a small group of painters into a broader discussion. This generated valuable feedback, but made it more difficult to collect structured individual responses. Limited time, the narrow gallery corridor, and the group size also restricted documentation. Data collection therefore relied mainly on written notes and audio recordings, and the planned post-test interview could not take place.

Interpersonal reflexivity

The researcher's role may also have influenced the results. During movement scenarios, the cart was operated through a Wizard of Oz approach, which may have made participants feel safer because they knew a person was controlling its movement and stopping distance. Reported trust in the following behaviour should therefore be interpreted cautiously. Finally, the researcher's explanations and the physical mock-ups may have directed attention towards particular ideas, including interface controls and physical features of the cart.

Analytical lens and filtering

Because the group was so engaged, they provided a wealth of simultaneous feedback. Naturally, much of this initial feedback focused on the physical build quality of the prototype.

Such as requests for specific hardware: "*It should have tracks instead of wheels*", built-in heating elements: "*A heating element for epoxy and caulk inside the cart would be ideal*", and adjustments to the platform size.

While valuable for the overall product design, this hardware-focused feedback requires filtering to maintain alignment with the core research questions of this project regarding the robot's behavioural repertoire, interface preferences, and autonomy.

Movement and proximity insights

During transportation to the work area, the painters reacted quite positively to the autonomous following behaviour.

They stated that having the robot follow them was a significant improvement over manually pushing or pulling a heavy cart, noting, "*I trust the following, I wouldn't push it.*"

Regarding the specific navigation and proximity of the robot, they strongly preferred the robot to follow behind them rather than alongside them, saying: "*It should follow behind me, not next to me.*"

For a safe distance they preferred that the robot maintains a gap of 1 to 1.5 meters. They emphasized the need for personal space so they can turn around without fear of collision. On the gallery at the work area, the cart should not constantly mirror their every step. Instead, it needs a delayed following behaviour.

As one participant noted, "*If you move while painting, it should wait till a certain distance, wait a bit,*"

Another painter mentioned: "*It should be a meter behind you... if I turn, then it shouldn't hit you, I don't want to be scared of it.*"

Furthermore, the robot must be able to recognize narrow environments and be able to move out of the way (Figure 30), as multiple users pointed out that "*People should be able to pass it on a gallery.*"



Figure 30: Enactments on the first-floor gallery.



Figure 31: Participant explaining their work.

Interface and autonomy preferences

The physical mock-ups revealed a clear preference for minimalist, wearable controls over complex interfaces.

The painters dismissed the joystick and explicitly stated that a screen is unnecessary, noting that "Constantly looking at a display only makes me lose time." (Figure 32).

Similarly, they pointed out that voice commands would be useless on a loud construction site. Instead, the concept of a tangible remote worn directly on the body emerged as a highly viable option that the painters genuinely liked.

As one participant stated: "A button is not always the best option, but being able to clip it to your belt is ideal, you could press it to come closer."

Regarding any physical buttons placed directly on the robot cart itself, they noted these must be recessed and protected rather than protruding, warning that "The button should be put away on the outside, so you can't break it when it hits something."

When evaluating autonomy, the painters strongly favoured a responsive, on-demand system over one that proactively anticipates their needs. They do not want an intelligent collaborator that tries to anticipate their work or closely participate in delicate tasks. Instead, they view the robot as an autonomous transportation device for materials.

The cart proved especially useful for caulking and epoxy scenarios because these tasks require carrying a large amount of various items.

As they noted: "It is primarily useful while doing epoxy, you carry a lot of stuff," and "With caulking you have a lot of stuff, caulking gun, caulk knives, mixing epoxy."

By contrast, they clarified that a constantly following, autonomous robot is invasive during precise work.

Noting that: "While painting you just hold your small can of paint.", "If you would ask me I would just use it as a transportation device for your tools."

Researcher reflection

Hearing the painters immediately dismiss the screen and voice controls forced me to let go of some of the more high-tech interface assumptions I had going into the project. It reinforced that in this nonsense environment, physical controls like a belt clip are far superior to advanced digital inputs. Furthermore, it grounded my perspective on how 'smart' the robot needs to be. The painters want a reliable, autonomous tool carrier that stays out of their way until called.

Methodological improvements

Overall, the approach of bringing a physical prototype on an active construction site proved highly valuable. Conducting the test on-site generated good engagement from the workers and provided a realistic, dynamic context that a lab setting could not replicate. The Wizard of Oz technique, combined with scenario-based enactments for transporting, masking, and caulking, successfully resulted in practical insights into the painters' actual workflows and spatial needs.

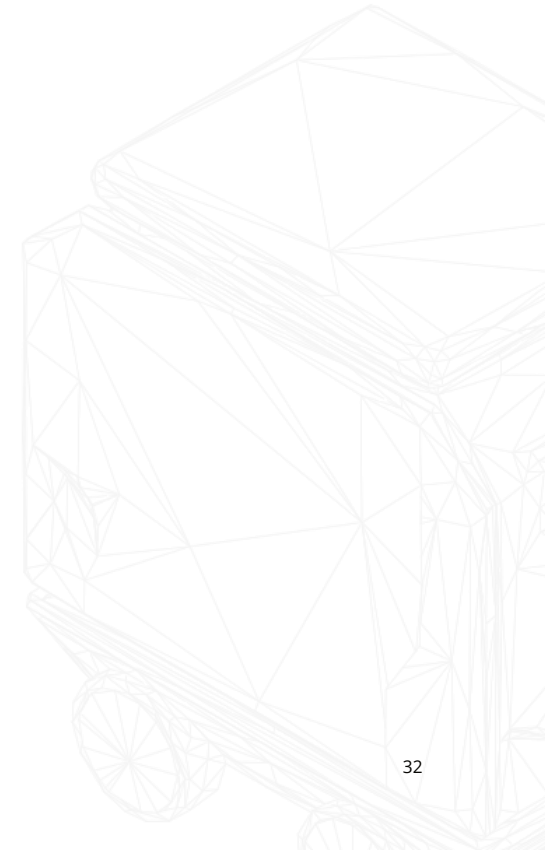
However, the field test setup also highlighted the need for a more controlled testing environment to capture higher-quality qualitative, but also quantitative data. Specifically, a structured and less crowded session would guarantee time for proper scenario enactment and post-test interviews, which had to be skipped during this test, allowing for a deeper, more focused reflection on the users' experiences. If this field test were to be done again, the number of participants should be limited to prevent the session from turning into a big simultaneous group discussion, ensuring proper time for interviews and better documentation. Finally, while the mandatory Informed Consent Form cannot be changed, bringing a simplified introduction to explain it more effectively, would help a lot.

Implications for design requirements

The exploratory field test fundamentally narrows the scope of this project. By rejecting complex interfaces and invasive autonomy behaviour, the painters clearly defined the robot's ideal role as an autonomous tool carrier that can be controlled with ease. Consequently, the research focus must pivot away from broad interaction exploration and focus on developing the specific, accepted control method: a wearable remote controlling the various follow behaviours that the autonomous cart should have.



Figure 32: Mockup interaction buttons and screen.



Key findings

To translate the observations and reflexive insights from the field test into a concrete foundation for the next prototyping phase, the overarching takeaways have been summarized in the following key findings (see Figure 33). The complete transcripts and notes from the field test can be found in Appendix D.

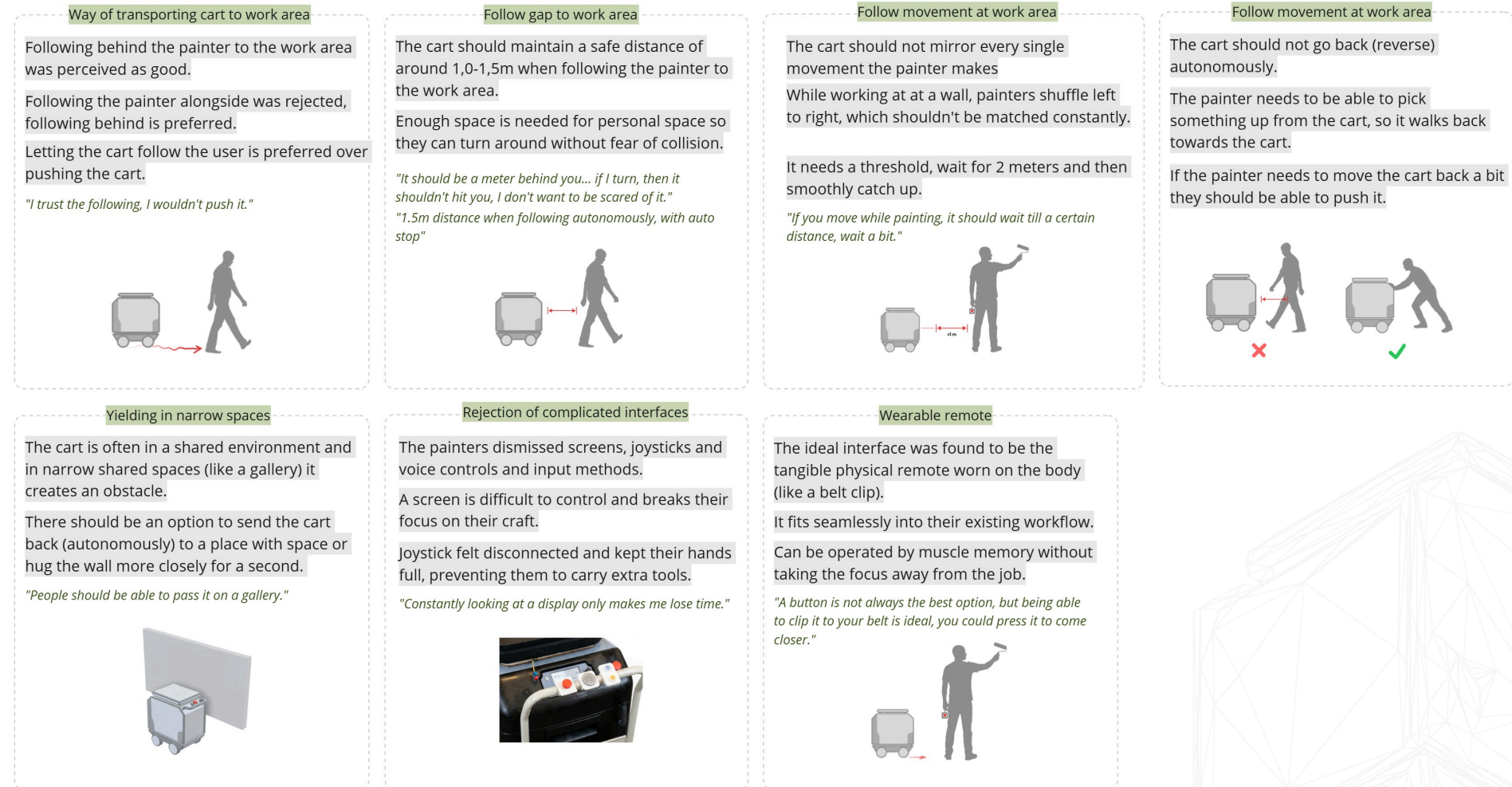


Figure 33: Key findings explorative field test.

Chapter 6

Narrowed scope

Narrowed scope

Determining autonomy level

Findings from talks with experts

Workflow scenario

Narrowed scope

The functionality cards developed during the interaction exploration phase already categorized the robot's behaviour into distinct two scenarios, distinguishing between transporting the cart to the workspace and operating the cart at the workspace itself. The explorative field test reinforced this distinction, demonstrating how fundamentally different the painter's needs and interaction preferences are in each context.

Focussing on the 1D-workspace

The findings indicated that the most significant uncertainties did not come from transportation between locations, but rather the interaction between the painter and robot during active work.

Moving forward, the next phase of this project will focus on the cart at the workspace scenario. Bringing the cart to the workspace is less relevant for the next phase of this research. The field test showed that painters already approve of a basic following behaviour, as it frees their hands and relieves the physical strain of pushing a heavy cart. Recreating this specific interaction for a functional prototype is technically demanding, highlighted by Nikdel et al. [20], simply getting a robot to smoothly follow a human requires an intricate orchestration of hardware and software. Furthermore, testing this transportation scenario would primarily lead to optimizing pathfinding and navigation, rather than providing valuable insights into new interaction methods or distinct behavioural modes in a more dynamically complex scenario.

In contrast, the behaviour of the cart while the painter is actively performing their job at a wall presents a richer human-robot interaction

challenge. The dynamic between the cart and the painter in this scenario is considerably more complex. It raises questions regarding proximity and movement: when should the cart be near the painter, when should it stop, and how can the painter intuitively control this while their hands and focus are occupied by their craft? These questions directly relate to the project's objective of designing appropriate autonomous behaviour and interaction modalities for the robot cart.

Focussing on this active work scenario comes with a significant advantage. Creating a prototype of the cart's movement for this task is relatively simple. Because the painter works along a wall, the robot essentially only needs to move in one dimension. This eliminates the need for complex steering mechanisms and algorithms to navigate cluttered construction sites. By restricting the research to this 1-dimensional (1D) workspace, the prototyping and testing can focus on the core interaction: the movement of the cart along the wall and its relationship to the painter. This makes the scenario not only far more interesting to evaluate from a HRI perspective, but also much more feasible to recreate for a functional prototype.

Steps for the next phase

Now that the foundational interaction guidelines have been defined, the project moves into the Develop phase. This requires transitioning from Wizard-of-Oz enactments toward a functional prototype capable of reproducing the interaction dynamics identified during the field test. The objective is to create a working motorized platform that can evaluate the relationship between the painter and the robot while work is being performed at a wall. For this development cycle, the next steps are:

Determining autonomy levels

1. Establish the level of autonomy required for the cart by applying the Robot Autonomy Framework, providing guidelines for the robot to be able to effectively assist the painter without becoming intrusive or unpredictable.

Talk with experts

2. Meet with professionals from the robot/high-tech industry to get advice on how to take on designing the robot cart's autonomy and controls.

Motorized platform prototyping

3. Build a functional motorized platform to physically test the robot's movement and interaction dynamics within a 1D-workspace.

Remote prototyping

4. Develop a physical, wearable remote that allows the painter to intuitively control the cart's proximity and behaviour without interrupting their manual workflow.

Display UI prototyping

5. Design a digital user interface for the cart's control display to facilitate initial setup and communicate system status.

Setting up the next user test

6. Setup and execute a user test to evaluate the user experience and preferred control methods of a motorized robot cart, with autonomy, within a one-dimensional workspace alongside a wall.

Determining autonomy level

Robot autonomy framework

To define the autonomy direction of the painter's cart, the Robot Autonomy Framework by Beer et al. is used as an analytical framework providing guidelines for structuring autonomy in HRI [1]. Because an autonomous robot does not occupy a single, static level of autonomy, the framework is applied here to identify a suitable autonomy range and derive implications for the interaction design. The framework consists of five guidelines and can be seen in Figure 34.

Guideline 1: Task and Environment Variables

The required autonomy level is determined by what task the robot should perform and in which environment.

• Task criticality (Medium-High):

Errors in positioning or movement may disrupt workflow and introduce safety risks in narrow, shared workspaces. The system must therefore prioritise predictable motion, safe stopping, and yielding behaviours.

• Task accountability (Medium):

The painter remains ultimately responsible for task execution and workspace safety. This requires the system to remain fully overridable at all times.

• Environmental complexity (High):

Construction environments are dynamic and unpredictable, requiring continuous perception and real-time adaptation to human movement and obstacles.

Guideline 2: Subcomponents of task

Each task can be divided up in different aspects, sensing, planning and acting. The level of what the robot should perform is different.

• **Sense (High):** The cart utilizes its onboard ultrasonic sensors, LiDAR, and cameras to continuously monitor the environment, measure the gap to the painter, and detect approaching bystanders.

• **Plan (Medium):** The human defines the high-level intent such as following distance, behaviour mode, while the robot translates this into navigation decisions.

• **Act (High):** The robot autonomously executes movement, including speed regulation, obstacle avoidance, and yielding. It is entirely managed by the cart's drivetrain.

Guideline 3: Measuring Autonomy

For the painter's cart, effective autonomy is defined as the robot operating during work of the painter with minimal interruption. Not interrupting during painting activities is considered the baseline, while human intervention is expected only in specific situations, such as:

- Resolving safety or proximity conflicts.

- Adapting to changes in workspace conditions.

- Intentional overrides or operational mode changes.

Guideline 4: Categorizing robot autonomy

Rather than occupying a single fixed level of autonomy, the system operates within a context-dependent autonomy range:

• Level 7 – Shared Control with Robot Initiative (Primary Mode):

The robot executes user-defined behaviour goals such as maintaining a set following distance), and requests assistance only when necessary.

• Level 6 – Shared Control with Human Initiative (Override Mode):

Used when the user actively adjusts the robot's behaviour or directly commands repositioning.

• Level 1 – Manual Control (Manual Mode):

A requirement derived from the exploratory field test is the ability to physically push the robot away without digital input, allowing an immediate drop to manual control.

Guideline 5: HRI Implications

• **Transparency (Robot-Related):** As autonomy increases, the system must clearly communicate its intent and motion to maintain predictability and safety in shared spaces.

• Role definition (Social Variables):

The robot is deliberately positioned as a supportive tool rather than an autonomous collaborator, ensuring the user retains authority over task execution.

• Workload and trust (Human-Related):

Higher autonomy reduces physical strain during operation, but the interface must preserve simple, immediate override pathways to maintain user trust in dynamic environments and keep cognitive load increase minimal.

Conclusion

The combined application of the Beer et al. framework, benchmark analysis and stakeholder input converges on a shared-control autonomy range (Levels 6–7) for the painter's cart. Within this range, the robot performs continuous sensing and motion execution, the human defines high-level behavioural intent, and control remains interruptible and supervisory.

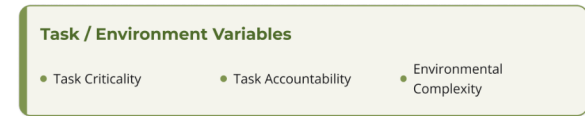
This autonomy framing identifies two key design constraints for prototype development:

1. Interaction must support supervisory control: Inputs should enable, high-level adjustments rather than direct control.
2. The interface must remain usable during work: Interaction methods should avoid disrupting the painter's primary task or requiring continuous visual attention.

This autonomy framework defines a coherent prototype scope. Autonomy should be expressed through adaptive following behaviour, human input should be supervisory and intermittent, and interaction should be embedded in a wearable remote control.

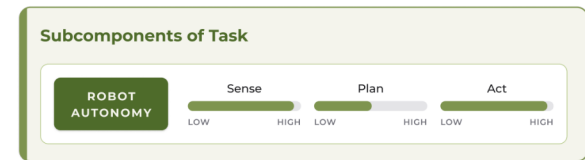
GUIDELINE 1

What task is the robot to perform?



GUIDELINE 2

What aspects of the task should the robot perform?



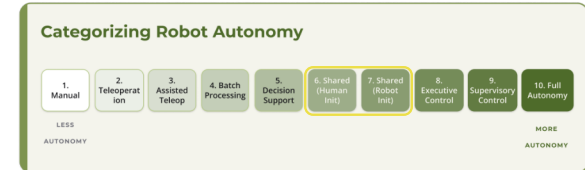
GUIDELINE 3

To what extent can the robot perform those aspects of the task?



GUIDELINE 4

What level can the robot's autonomy be categorized?



GUIDELINE 5

How might autonomy influence HRI variables?

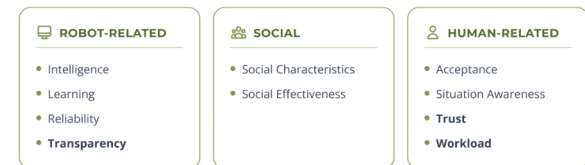


Figure 34: Robot Autonomy Framework adapted from Beer et al. [1].

Findings from talks with experts

While the literature provided a theoretical foundation for how to design the robot and its interface, practical considerations regarding interaction, communication, and usability required additional industry expertise. Therefore, expert consultations were conducted with two design agencies experienced in high-tech product development and robotics. The sessions provided practical insights into tactile interaction, robot communication, user testing methodologies, and the mental model of a user.

Ko:work

Ko:work, an Amsterdam-based design bureau specializing in the high-tech industry, provided advice on approaching the wearable remote and how to test the design of the remote.

• Designing for blind use:

Because users need to keep their focus on the painting job, the remote must be designed for blind use. The user must be able to use muscle memory to reach for the controller without looking. Therefore, tactile feedback is important.

• Physical differences:

To enable this blind operation, buttons must have distinct, easily recognizable physical characteristics, such as varying sizes, shapes, or textures, allowing the user to confidently navigate the controls through touch alone.

• Low-fidelity prototyping:

Start simple. Before moving to complex materials, use basic materials like MDF and foamboard to quickly try out different shapes and sizes for the remote.

• The designer's role in testing:

A key piece of advice for the upcoming user tests is to ask people about their specific expertise, but not to let them design the solution for you. Gathering their practical insights is essential, but translating those insights into a working design remains the task of the designer. Participants should therefore not be asked to propose design solutions. Instead, user testing should focus on getting insights from their professional expertise.



Figure 35: Studio of Ko:work in Amsterdam (image from Google Streetview [48]).



Figure 36: Studio of Spark Design & Innovation in Rotterdam.

Spark Design & Innovation

The second company, Spark Design & Innovation in Rotterdam, an expert on smart systems & robotics gave advice on the robot's communication, its movement, and how to keep the user's mental model clear.

• Communicating state:

For robots without a face, intentions and states can still be clearly conveyed through visual and auditory cues. Dynamic lighting, such as soft pulses or directional indicators, can signal motion or upcoming actions. Additionally, non-verbal audio cues like gentle chimes or beeps can signal start, stop, or waiting states, and should be pleasant [12].

• Motion design:

A robot's movement shapes how it is perceived by the user. Fluid, natural motions feel intuitive and reduce anxiety, while abrupt or clunky movements can seem mechanical and unsettling [12]. The robot's movement characteristics should align with its intended role as a reliable and efficient tool carrier.

• Working with modes:

The robot's operational state should be transparent at all times. Dividing its behaviour into explicit modes helps users develop an accurate understanding of the robot's capabilities and limitations. Each mode should communicate a distinct set of capabilities and constraints, reducing uncertainty about the robot's behaviour.

• Deliberate engagement:

Activating a mode should be a deliberate action. For example, when arriving at a wall, the user should actively engage 'work mode,'

perhaps through a physical twist system. If a situation arises where the robot can no longer do its job, it should automatically disengage. This ensures the user always knows what is happening and stays in control. Based on this a concept remote was made, where there is a ring on the outside that should be twisted to activate 'work mode', see Figure 37.

• Interface simplicity:

Do not put too much functionality on the remote; keep it simple and clear. The main output of the robot should be communicated on a screen using symbols that are easy to understand and can be read from a distance. These symbols should use different colours that directly match the current output or mode of the machine.



Figure 37: Remote concept with a twist ring.

Workflow scenario

Building on the recommendation to use explicit operational modes to support the user's mental model, a practical workflow scenario was developed. During the discussion with Spark Design & Innovation, a use workflow was mapped, covering arrival at the work area, task execution, interruption, and task resumption. This scenario informed the definition of the robot's operational modes and their transitions, as illustrated in Figure 38.

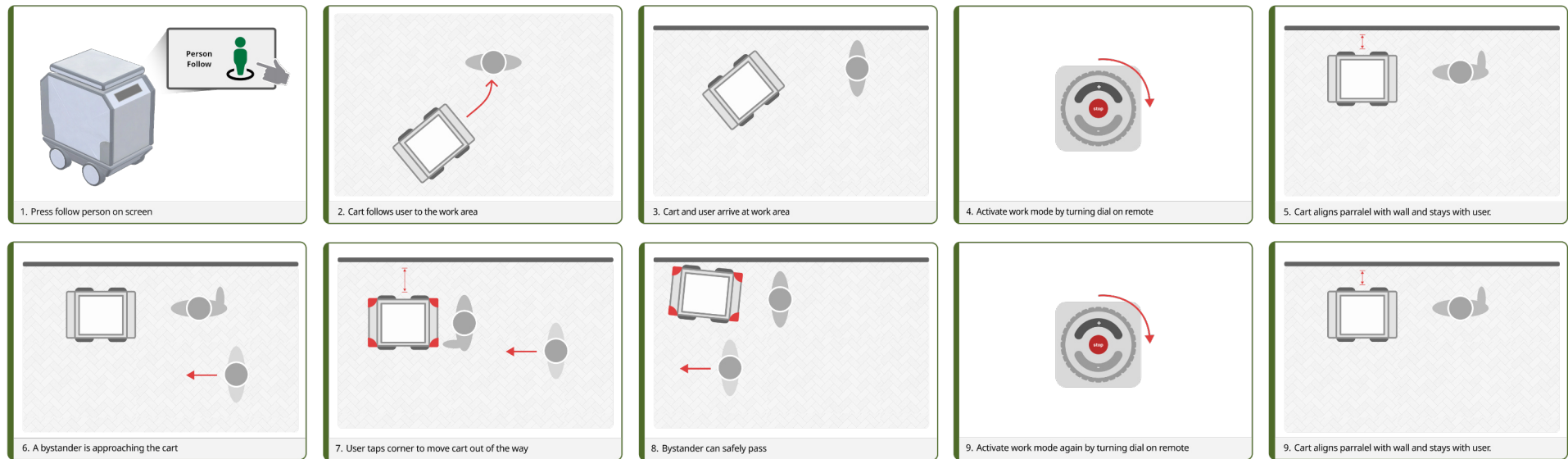


Figure 38: Workflow scenario with a bystander approaching.

Design implications

The expert consultations largely reinforced themes that emerged from the literature review, benchmark, and stakeholder session. Across these activities, maintaining a clear user mental model consistently appeared as a requirement for successful human-robot collaboration. As a result, the robot should communicate its state and intentions transparently through clear visual, auditory, and physical feedback. Furthermore, robot behaviour should be structured around operational modes with clearly defined

capabilities and limitations, enabling users to understand what the robot is doing and what can be expected from it at any given moment.

For the wearable remote, the advice from experts emphasized the importance of interaction without visual attention. Since painters must remain focused on their work surface, the controller should support operation through touch and muscle memory, requiring distinct tactile characteristics and a limited set of essential controls.

Chapter 7

Building the platform

Platform base

Sensing and control

Prototype assembly

Behaviour modes

Wearable remote

Dashboard interface

Overview of system

Platform base



Figure 39: Comparison of mobile prototype with the high-fidelity prototype.

To simulate a cart moving alongside a wall, a mobile platform was developed that can drive forwards and backwards. The dimensions of the platform were matched to those of the high-fidelity prototype to ensure that the physical footprint during user testing was representative of the intended robot. The resulting platform measures 580mm x 520 mm x 800 mm. Figure 39 compares the original high-fidelity prototype with the lightweight prototype platform developed for this project.

To keep the platform lightweight, it was constructed from seven foamboard panels connected through a frame made from wooden rods and 3D-printed corner connectors, see Figure 40. This construction method allowed for rapid prototyping while maintaining sufficient structural rigidity for testing. The interior of the platform provides space for the battery, electronics, and wiring.

On both sides of the cart, push bars were integrated into the design. These bars afford manual repositioning of the robot and signify that the cart can be physically pushed when required. This supports the requirement for immediate user override identified during the autonomy analysis.

The platform uses two independently driven 180 mm wheels at the front and a caster wheel at the rear for stability, see Figure 41. This setup allows the platform to move smoothly and drive forwards and backwards along a wall.

To increase resemblance to the intended product concept, the exterior panels were finished with black graphic elements based on the design language of the high-fidelity prototype, see Figure 39.

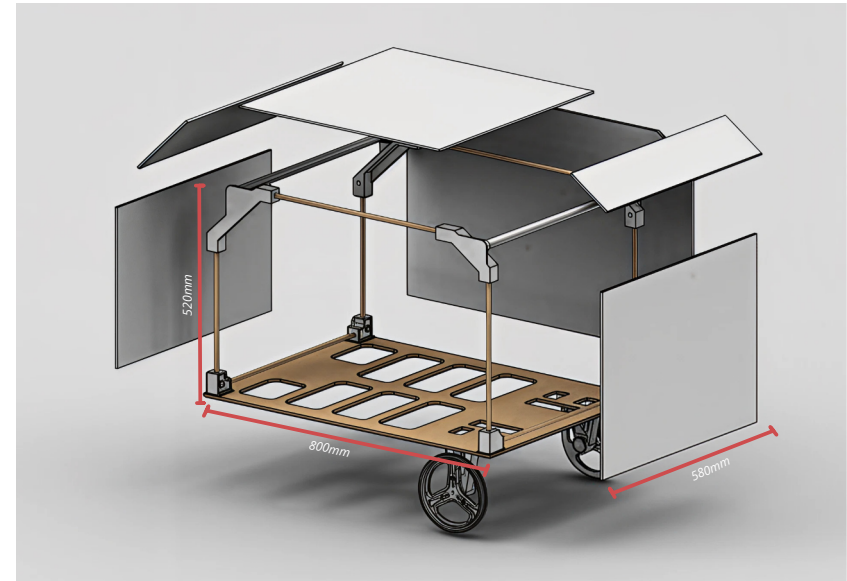


Figure 40: Exploded view of prototype frame.

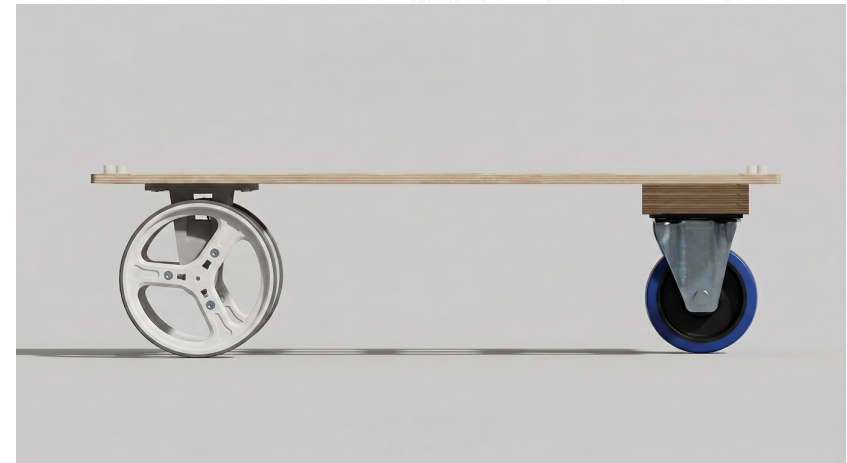


Figure 41: Wheel assembly of prototype cart.

Sensing and control

The platform measures the distance to the user and uses this information to regulate its movement along the wall. The system is implemented on a Seeed XIAO ESP32-C6 microcontroller, which handles sensor processing and control logic, and communicates with a motor driver shield that drives the DC motors, see Figure 42.

The system uses a VL53L5CX Time-of-Flight (ToF) sensor mounted at the front of the cart. The sensor measures infrared reflection time to estimate depth and is capable of capturing a spatial depth map of up to 8x8 zones with a wide field of view of approximately 63°, enabling depth perception in front of the platform.

In this implementation, the sensor operates in a reduced 4x4 configuration at approximately 10 Hz, balancing spatial resolution with the performance constraints of the microcontroller, see Figure 43.

To obtain a stable estimate of user distance, the raw sensor data is processed through a filtering pipeline. First, only the central region of the grid is used, while the top and bottom rows are excluded to remove irrelevant

measurements outside the human interaction zone. This ensures that only measurements at the height of a human contribute to the estimation.

Next, each zone is evaluated based on spatial consistency. A confidence score is computed by comparing each reading with its neighbouring zones within a ±300 mm threshold. This allows the system to distinguish coherent human-shaped clusters from noise and reflections. The remaining valid zones are then combined into a single distance estimate using a weighted average, where more consistent regions contribute more strongly to the final value.

Finally, the resulting signal is smoothed using a rolling average filter to reduce noise and improve stability during movement. If no valid detection is received for a short period (500 ms), the system transitions into a safe stop state.

Together, this processing pipeline produces a stable estimate of the distance between the platform and the user, allowing for a smooth following behaviour.

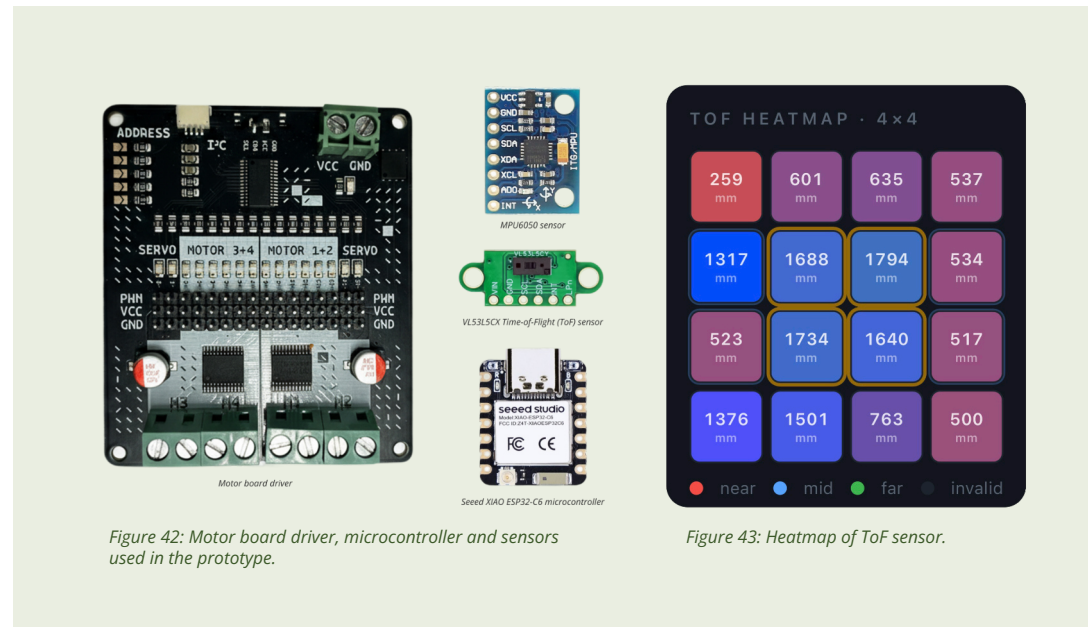


Figure 42: Motor board driver, microcontroller and sensors used in the prototype.



Figure 43: Heatmap of ToF sensor.

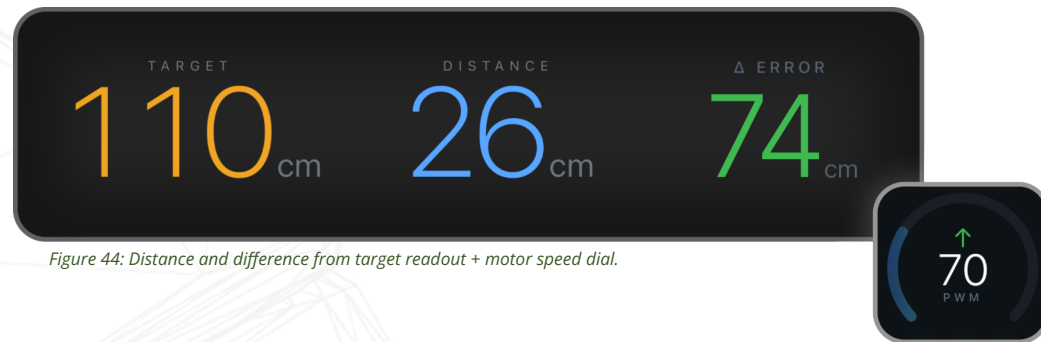


Figure 44: Distance and difference from target readout + motor speed dial.

Motion control

The distance value is used to control a differential drive system with two DC motors. The system uses speed control and steering correction with a motor board driver to move the platform along the wall in a straight line.

The distance to the user is compared to a target distance, see Figure 44. The difference between these values determines the base speed of the platform: it moves faster when the user is further away and slows down or reverses when the user is too close. This is the main logic for following the user.

To keep the platform driving in a straight line, a MPU6050 sensor is used. This is a 6-axis sensor combining a 3-axis gyroscope and a 3-axis accelerometer and detects rotations of

the platform while driving. When a drift is detected, the system corrects it by adjusting the motor speeds.

Motor commands are not applied instantly but ramp up and down. This results in gradual acceleration and deceleration, improving stability and making the robot approach people in a smoother and more natural manner. The system also uses a short start-up boost to help the motors start moving from a standstill with low speed, since low motor power is not always enough to overcome friction to move the platform.

Together, this results in a system where distance influences the speed and the gyroscope keeps the platform driving straight.

Prototype assembly

The assembled prototype combines the mobile platform base with the sensing and control architecture to create a functional autonomous cart for user evaluation, see Figure 45. The platform base houses the battery, electronics, motor drivers, and sensors (see Figure 46),

while the foamboard shell can be mounted on top of the platform to replicate the appearance and dimensions of the high-fidelity design concept (see Figure 46).

The resulting prototype is capable of autonomous forward and backward movement and user-distance

sensing, while being light, safe and maintaining a physical appearance representative of the envisioned product. This enables the evaluation of both the autonomous behaviour and the user interaction concept with a realistic full-scale prototype.



Figure 45: Assembled prototype.

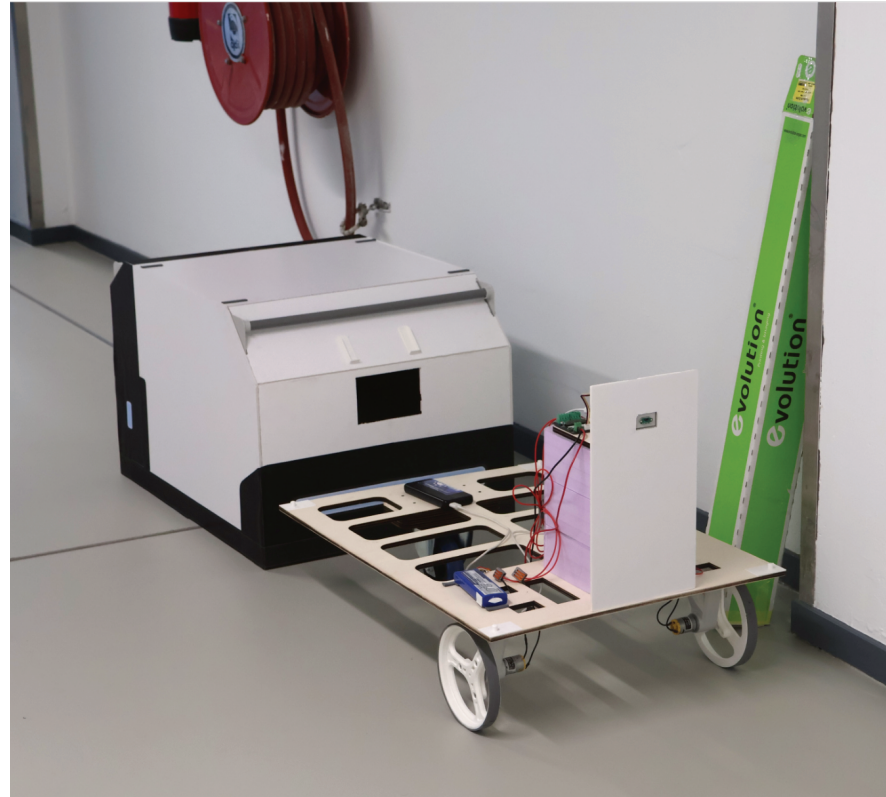


Figure 46: Foamboard shell and platform with electronics.

Behaviour modes

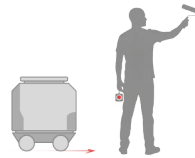
The prototype can be operated with three behaviour modes that were derived from the autonomy direction established from the Autonomy Framework and the preferences identified during the exploratory field test. Together, these modes allow users to choose between direct control and varying levels of autonomous assistance while working along the wall.

Regardless of the selected mode, the cart can always be repositioned manually by pushing or pulling with the handlebars. This overrides the autonomy and ensures that users keep control over the system at all times.



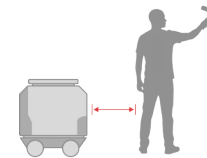
Manual Mode

In manual mode, the platform is fully controlled through the wearable remote. The user can drive forward and backward with the buttons on the remote, while all autonomous following behaviour is disabled. This mode gives the user complete control over the cart's movement.



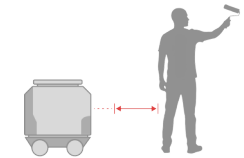
Continuous Mode

In continuous follow mode, the platform automatically maintains a user-defined distance to the user. As the user moves along the workspace, the cart smoothly follows the user continuously as they move to stay near the selected target distance.



Segmented Mode

In segmented follow mode, movement happens in steps rather than continuously. The platform stays still until the user moves beyond a set threshold away from the target distance. It then drives forward to restore the distance and stops again. This creates a stop-and-go behaviour that reduces continuous motion of the platform.



Physical override

Regardless of the selected mode, the cart can always be repositioned manually using the handlebars. This ensures that users retain immediate physical control over the system at all times.



Wearable remote

The wearable remote and the dashboard together form the main interaction loop between the user and the platform. The remote is used to control movement and behaviour, while the dashboard provides feedback on the system state, see Figure 48. Together, they allow the user to both influence and understand the behaviour of the robot during operation, see Figure 49.

The cart is controlled through a remote that allows the user to influence both movement and behavioural mode during operation. It can be clipped to a belt or a pocket with a clip on the back, allowing the user to wear the remote on their body. The remote is implemented using a Seeed XIAO ESP32-C3 microcontroller, which handles user input processing and wireless communication with the platform. It forms the primary interface between the user and the system. Figure 47 shows the electronics of the remote, consisting of the Seeed XIAO ESP32-C3 microcontroller, a potentiometer and two push-buttons mounted on a small PCB.

The remote communicates wirelessly with the cart using ESP-NOW [33], a low-latency peer-to-peer protocol that enables real-time control without requiring an external network.



Figure 47: Exploded view of the remote control.



Figure 48: Front view of the remote control.



Figure 49: Remote control in use, worn in a jean's pocket.

How to use the remote

The wearable belt remote has three main controls that allow you to manage the cart's behaviour during your work. In manual mode, the input mapping changes. The buttons control forward and reverse motion directly, while the potentiometer is used for speed control, see Figure 50.



Adjustment Dial

- 1 This turnable dial changes its function depending on which mode the cart is in.

Autonomous Mode: The dial adjusts your preferred following distance. Turn it to bring the cart as close as 50cm or push it as far back as 250cm.

Manual Mode: The dial acts as a throttle, to increase or decrease the driving speed of the cart.

Reverse Button

- 2 This is your manual override, it always drive the cart backwards, no matter the mode.

Press and hold this button to manually drive the cart backward. This is useful if the cart gets too close and the cart should reverse a bit.

Tracking Button

- 3 This button activates or deactivates the cart's autonomous following mode.

Autonomous Mode: Press it for the cart to start tracking the movement of user, and press it again when you want to park the cart in place.

Manual Mode: Press and hold it to drive the cart forwards.

Hold both Buttons

- 4 When you press and hold both buttons, the cart will switch to the next mode.

Press and hold both buttons, this will switch the mode that the cart is in to the next one. Useful if not nearby the cart to switch to another mode on the display.

Figure 50: Explanation of the remote control.

Design iterations

The remote was developed through several iterations, moving from a breadboard test setup to a finished working device. Each step improved usability, robustness, and the ability to use it without looking at it, see Figure 51.

The first version was built on a breadboard to test the interaction logic between the potentiometer, buttons, and the control system. At this stage, the focus was on validating how inputs map to mode switching, distance control, and manual driving, rather than on physical design.

Once the interaction logic was stable, the circuit was soldered onto a small PCB. This reduced loose wiring and improved reliability, while also fixing the input layout for the final design. A first enclosure was then built to house the PCB, consisting of a simple box with cut-outs for the potentiometer and buttons. While this made the system usable, the form factor was not yet optimised for handheld use and had to be widened to properly fit the internal components.

Further iterations focused on improving handling and tactile control. Side grips were added so the remote can be held more

securely, and the buttons were enlarged and given surface ridges to make them easier to locate by touch. Raised edges above and below the buttons provide additional tactile guidance, allowing the user to position their fingers without looking. The potentiometer knob was also modified to improve grip and control precision.

In the final version, the enclosure was refined into a compact handheld form with a fixed input layout and integrated grips, allowing one-handed use during operation. Finally, graphics were added to the surface to indicate the function of each input, see Figure 52.



Figure 52: Final iteration of the wearable remote.



Figure 51: Iterations of the remote casing.

Dashboard interface

The dashboard provides feedback to the user during operation. It displays the active behavioural mode, the target distance set by the user, and the distance measured by the ToF sensor, see Figure 54. By presenting this information on the front of the platform, below the push/pull handle, the user can see how the robot is interpreting and responding to their inputs while working, see Figure 53.

For this prototype, the dashboard runs on the platform itself and is accessed through a WiFi access point hosted by the microcontroller on the platform. By connecting a smartphone to this network, the interface can be opened in a browser without needing any external setup. In this setup, the phone is just a practical way to show the interface during development, not part of the final design.



Figure 53: Smartphone with dashboard on the robot.



Target distance

- 1 This is the target distance from the robot to the user.

Current mode

- 2 Shows which mode the cart is in. Swipe on the icon to change modes or use the remote.

Distance & target distance

- 2 This bar shows the distance and target distance at a quick glance.

Actual distance

- 4 The actual distance from the robot to the user.

Information icons

- 5 Indicates if all systems are ready to go.
 - Shows if the distance sensor is providing data or not
 - Shows if the safety button on the cart is activated or not
 - Indicates if the remote is connected or not

Motor speed

- 6 This dial shows the motor speed and direction in PWM (Pulse-Width Modulation).

Figure 54: Explanation of the dashboard.

Mode switching

Because the small mode icon on the dashboard may not be visible when the user is working away from the cart, every mode change initiated through the remote is accompanied by a temporary full-screen mode display, see Figure 55. This allows users to verify the selected mode from a distance without needing to approach the cart.



Figure 55: Full-screen view of switching modes.

Dashboard iterations

The dashboard underwent several iterations throughout the development process, moving from an initial design concept to the final testing interface.

The first iteration was design concept that explored the intended user experience, focussing on clear presentation of distance information, behaviour modes, and system status, see Figure 56. Once communication between the robot and dashboard was established, a second iteration was developed for technical testing and debugging, displaying sensor data, motor states, and other system variables required for development, see Figure 57.

The third iteration returned to the original design vision by removing unnecessary technical information and focussing on the values most relevant to the user: behaviour mode, target distance, and measured distance, see Figure 58. Readability from a distance was also improved.

The final iteration further simplified the interface and transformed it into a user-focused control dashboard, see Figure 59. Users could monitor system status, change behaviour modes, and receive feedback on mode changes, all with large typography and clear visual indicators.

During user testing, the dashboard was displayed on a smartphone placed on the cart platform. In the final product concept, this temporary solution would be replaced by an integrated display mounted on the cart itself.

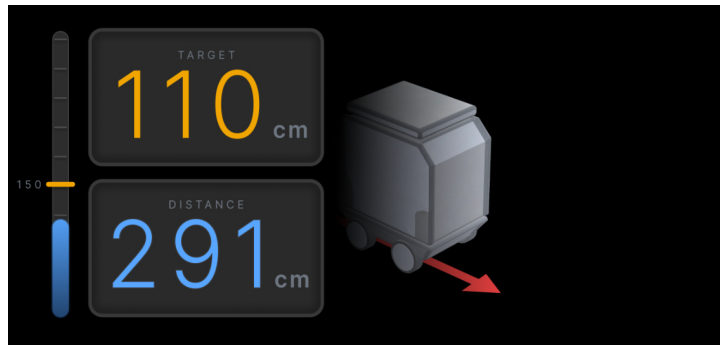


Figure 56: Design concept of dashboard.

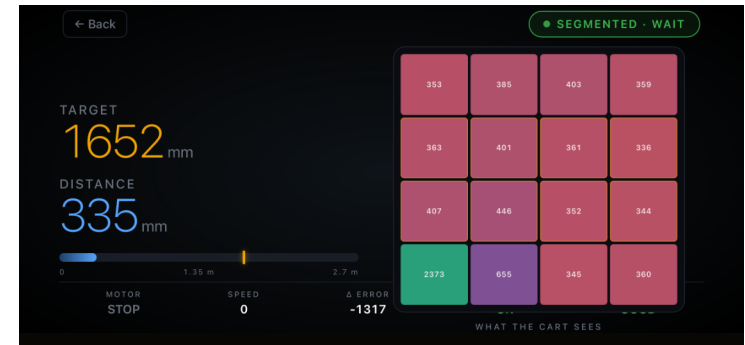


Figure 57: Technical validation dashboard.

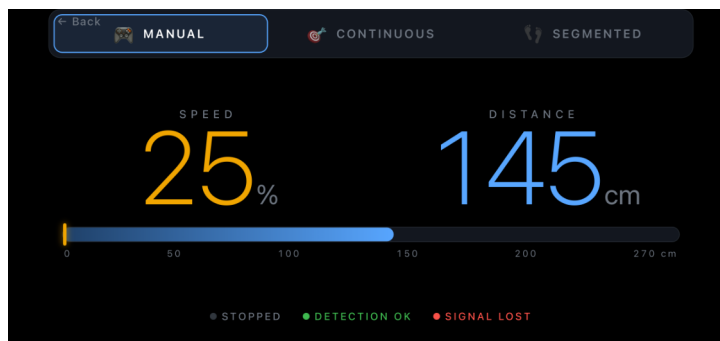


Figure 58: Combination of concept and functional dashboard.



Figure 59: Final iteration of dashboard.

Overview of the system

Together, the platform, sensors, motion control system, wearable remote, and dashboard forms a functional prototype capable of reproducing the interaction behaviours identified in the earlier stages of the project and able to replicate them for a validation study. While the prototype does not represent the final product, it provides a safe and flexible platform for evaluating the proposed autonomy concepts and interaction modalities.



Figure 60: Functional prototype front.



Figure 61: Functional prototype back.



Figure 62: Wearable remote being used.



Figure 63: Dashboard UI.



Figure 64: Dashboard and sensor on prototype.

Chapter 8

Validation test

Validation in a one-dimensional workspace

Results

Takeaways

Limitations

Validation in a one-dimensional workspace

The previous field test identified a promising direction for the behavioural repertoire for an autonomous painter's cart. Based on these findings, a functional prototype was developed that implements autonomous following behaviours, a wearable remote, and multiple behaviour modes.

This chapter evaluates these concepts through a user study in a controlled one-dimensional workspace, see Figure 65. The objective is to investigate how users experience the implemented behaviours during tasks at a wall and to determine when autonomous assistance is preferred over manual control.

In addition, the study examines the value of autonomy itself. While a traditional manual cart is a simple and familiar solution, an autonomous cart introduces additional complexity. Comparing both approaches helps identify when autonomous behaviour provides a meaningful benefit to the user and when a manual cart is more than sufficient.

Rather than replicating complete painting activities, the study uses abstract tasks that reproduce different movement patterns and workload characteristics commonly encountered during work of painters. This controlled setup makes it possible to compare interaction preferences, perceived workload, and autonomy use across participants while maintaining consistent test conditions.

The study aims to answer three questions:

1. How do different behavioural modes influence the user experience and perceived workload?

2. What value does autonomous assistance provide compared to a traditional manual cart?

3. How should control be shared between the user and the robot during operation?

Methodology

Test objective & scope

This study evaluates how users interact with a motorized cart in a controlled one-dimensional workspace, focussing on the effects of different control strategies during wall-based tasks.

The evaluation focuses on three aspects: differences between manual and autonomous operation, the impact of three behavioural modes (manual, continuous follow, segmented follow), and how these influence perceived workload during use. The perceived workload is assessed using the NASA-TLX, a standardized tool for subjective workload assessment in human-machine interaction tasks [11]. It captures how demanding a task feels across mental, physical, and temporal demand, as well as effort, frustration, and perceived performance. It is used here to compare workload between manual and autonomous cart operation under identical task conditions.

The setup compares a manual cart baseline with the autonomous prototype under consistent task conditions, allowing direct comparison of interaction behaviour and workload across both systems.

Rather than observing general use in a real painting context, the study isolates movement and control as the primary variables, in order to analyse how autonomy changes the interaction itself.

Materials

- Functional prototype of the robot cart
- Remote prototype
- Unpowered manual cart
- Wall of at least 5 meters
- Testing tools: four physical wooden stencils, coloured felt pens (black, green, and red), tape, and a number sheet
- Digital NASA-TLX form
- Data collection tools: audio recorder, camera, and clipboard for observational notes

Participants & location

Target participants: People from StudioLab / IDE faculty

Sample size: 10 participants, tested individually

Location: Controlled indoor setup in the basement and ground floor of the IDE faculty, see Figure 66 & 67.

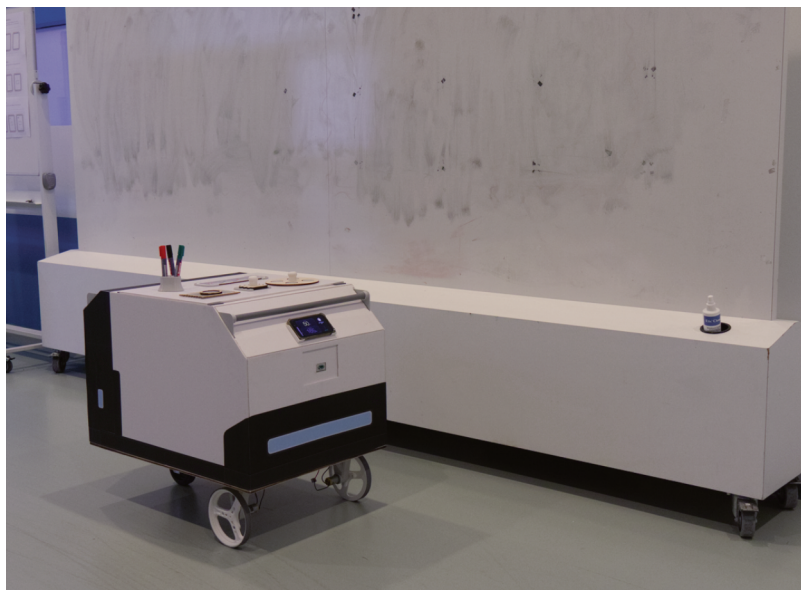


Figure 65: Controlled setup for the validation user test.



Figure 66: Location in the basement.

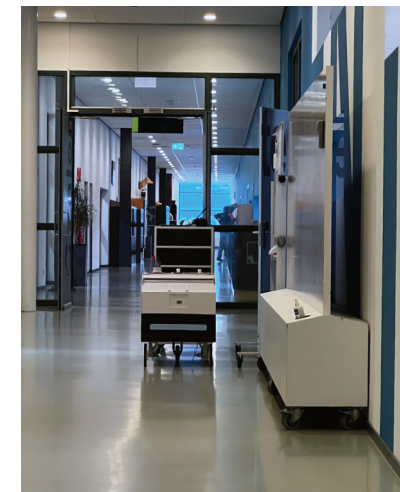


Figure 67: Location on the ground floor.

Test setup

The study is conducted along a straight wall forming a one-dimensional workspace where all tasks are performed, see Figure 68 & 69.

The setup is carried out in two equivalent configurations depending on space availability, a 7 meter wall covered with paper (Figure 68), and a 5 meter whiteboard on wheels (Figure 69). Both configurations serve the same purpose and are treated as functionally identical workspaces.

Two carts are used, a manual cart (Figure 70) and a motorized autonomous cart (Figure 71). Both have a similar footprint. The manual cart already has some weight to simulate a fully loaded painting cart. It is unpowered and is

moved by the participant through pushing and pulling. The autonomous cart is motorized and can operate either through remote input or automatic following behaviour depending on the selected mode. It can also be manually repositioned by pushing or pulling if the participants prefers.

Both carts carry the same set of tools on the platform, including coloured pens, wooden stencils for shape tracing, and a number sheet for the tasks, see Figure 72.

This setup allows for a direct comparison between manual and autonomous assistance under identical task conditions.



Figure 70: Manual cart



Figure 71: Autonomous cart



Figure 68: Controlled setup for the validation user test in the basement.

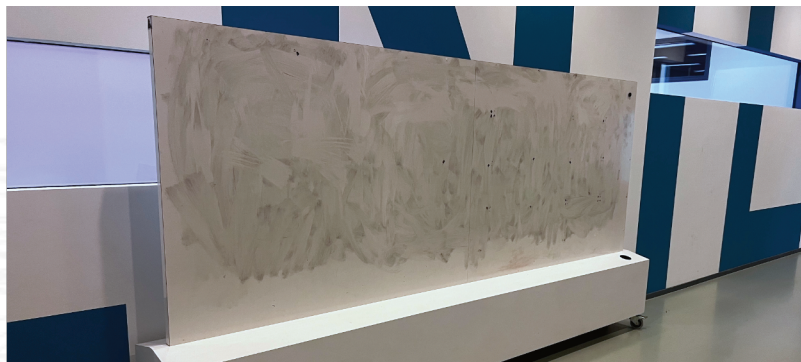


Figure 69: Controlled setup for the validation user test on the ground floor.

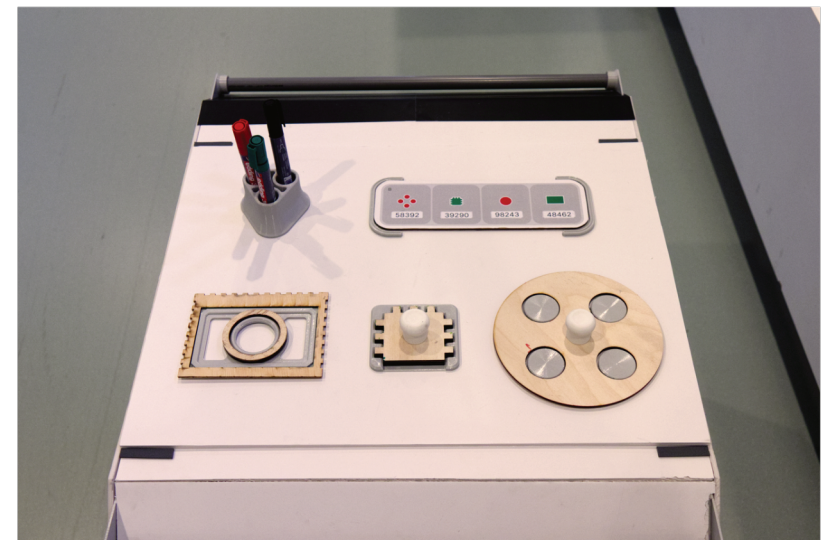


Figure 72: Tools for simulation of painting tasks.

The three simulation tasks

Participants perform three tasks along a wall, which is their workspace, see Figure 76. The tasks are designed to simulate different movement, coordination, and cognitive demands similar to those encountered in professional painting work. Each task is intended to elicit specific workload characteristics defined by NASA-TLX. In addition, the tasks are designed to loosely reflect activities in painting workflows, such as painting, sanding, caulking, and masking, by varying precision, tool handling, and movement patterns. The three tasks:

Task 1: Window framing

Participants create four large windows on the wall, see Figure 73. Each window consists of:

- a **black** outer outline
- a **green** inner outline
- a squiggly **red** outer border

Only one pen may be held at a time, to reflect the constraint that painters typically cannot hold multiple tools, such as wet brushes, simultaneously.

This task primarily targets physical demand and temporal demand due to continuous movement and frequent tool switching.

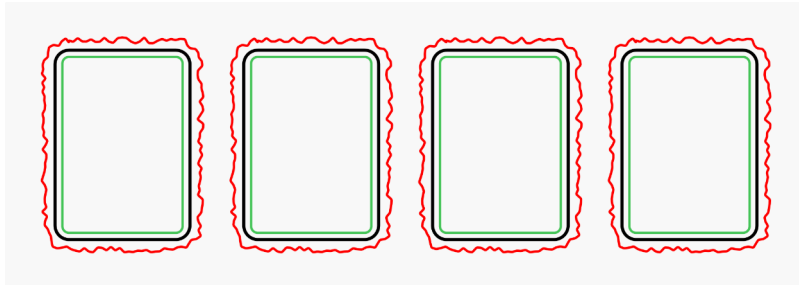


Figure 73: Task 1

Task 2: Trace stencil

Participants use wooden stencils to draw shapes inside each window, see Figure 74. Circles must be traced in red, and squares in green. Only one pen and one stencil may be held at a time.

This task increases physical demand and effort due to the added coordination required between stencil positioning and drawing.

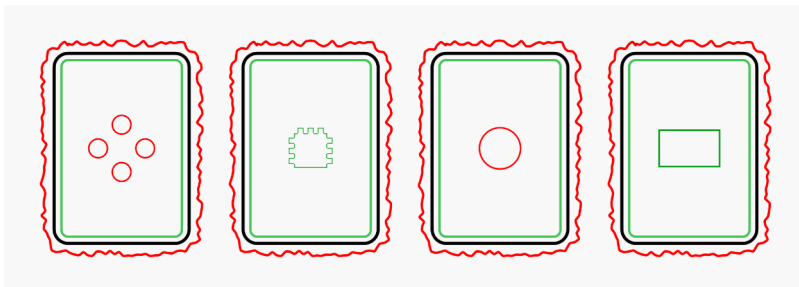


Figure 74: Task 2

Task 3: Window numbering

Participants assign a number to each window by referring to a number sheet placed on the cart platform, see Figure 75. The sheet cannot be removed from the cart, requiring repeated movement between the wall and the cart.

This task primarily targets mental demand and frustration due to memory load and task switching.

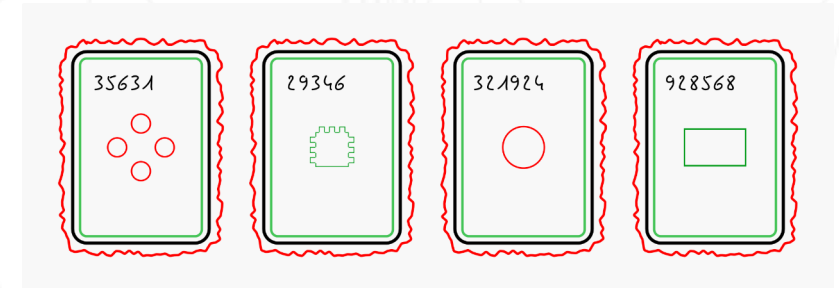


Figure 75: Task 3



Figure 76: Participant executing one of the tasks.

Test procedure

The user test takes approximately 45 minutes and is structured into four phases.

Phase A:

Introduction and consent (5 min)

The session begins with a briefing that explains the overall goal of the study and the specific purpose of the test. The participant then signs the required informed consent forms, which can be found in Appendix C.

After this, a briefing on the motorized prototype is given. The researcher explicitly demonstrates the wearable belt remote, explaining that the participant can control the cart using the remote or by physically pushing it. The participant is given a few minutes to explore the controls and observe the robot's responses in order to build a basic understanding of its behaviour, see Figure 77.

Phase B:

Task training (5 min)

Before using the robot, the participant can practice the three tasks with guidance. This ensures they understand the rules and expected output of each task before interaction with the carts begins.

Phase C:

Performing tasks with manual and autonomous cart (20 min)

The participant carries out the tasks twice, using both a manual cart and the autonomous prototype. The order of the carts is

randomised across participants to reduce ordering effects. Participants are instructed to focus on how they experience and use each system, rather than on speed or accuracy.

1. Manual cart baseline (10 min):

The participant completes the three tasks using the unpowered manual cart to establish a baseline experience.

2. Autonomous cart (10 min):

The participant performs the same tasks using the motorised cart, with access to all behavioural modes. They are free to use the system in whichever way feels most appropriate for each task.

Phase D:

Post-test debrief & discussion (15 min)

The session concludes with a NASA-TLX workload assessment followed by a semi-structured interview.

1. Workload assessment:

After completing both conditions, the participant fills in the NASA-TLX questionnaire, which can be found in Appendix B. They rate perceived workload across the six dimensions for both the manual and autonomous cart conditions.

2. Semi-structured interview:

The researcher conducts a semi-structured interview based on participant behaviour and comments during the tasks.

Data collection

Given the explorative, qualitative nature of this test, data collection focuses on observing natural workflows, friction, what the user says, and the post-task discussion.

Metrics:

• **Subjective workload assessment tool (NASA-TLX):** While the NASA-TLX provides numerical data, in this context the scores are used to map the participant's subjective workload profile. It provides a structured way to describe what kind of workload the robot reduces or introduces.

• **Spatial preferences:** Documenting where participants prefer the cart to be positioned during different tasks.

• **Interaction flow & friction:** Noting moments where the participant has to break their working rhythm to interact with the remote, or conversely, where the robot integrates smoothly into the workflow.

Recording methods:

• **NASA-TLX:** A questionnaire filled in after the participant has completed both the manual and autonomous cart conditions, see Figure 78.

• **Observational notes:** Live observations and immediate insights documented during the test.

• **Photography:** Images used to document interaction patterns, spatial relationships, and task execution.

• **Audio recording:** The full session and post-test interview are audio-recorded to ensure accurate transcription.

Roles and responsibilities

• Participant:

Operates the wearable remote, performs the drawing tasks, completes the NASA-TLX questionnaire, and provides feedback during and after the tasks.

• Facilitator:

Guides the participant through the procedure, asks clarifying questions during task execution, takes observational notes, manages the prototype setup, and conducts the post-test discussion.

NASA TASK LOAD INDEX
Autonomous Cart
Participant ID: P56/80778

Move each slider to indicate your perceived workload for the Autonomous Cart. All six dimensions must be rated.

1. MENTAL DEMAND
How mentally demanding was the task?
Very Low 1 2 3 4 5 Very High
10
+ Add comment

2. PHYSICAL DEMAND
How physically demanding was the task?
Very Low 1 2 3 4 5 Very High
10
+ Add comment

3. TEMPORAL DEMAND
How hurried or rushed was the pace of the task?
Very Low 1 2 3 4 5 Very High
10

Figure 78: NASA-TLX questionnaire



Figure 77: Participant getting familiar with the controls.



Results validation test

A total of 10 participants (n = 10) completed the study. All participants completed the three simulation tasks using both the manual cart and the autonomous prototype (in a random order), followed by a NASA-TLX assessment and semi-structured interview. Due to restrictions on the original testing location, data collection was conducted across two almost equivalent workspace configurations. No notable differences in participant behaviour were observed between the two environments.

Reflexivity

To ensure that the personal, interpersonal, and contextual factors influencing the validation study are explicitly accounted for, the reflexivity analysis is structured according to the framework proposed by Olmos-Vega et al. [21]. This framework is used as a guiding structure to critically reflect on how study conditions and researcher involvement may have shaped participant behaviour and the interpretation of results.

- Contextual reflexivity considers how the test setting, task design, participant group, and practical study constraints may have shaped the observed interaction.
- Interpersonal reflexivity considers how the researcher's presence, explanations, and interview questions may have influenced participants' behaviour and responses.

Contextual reflexivity

Unlike the previous field study, this experiment was conducted in a controlled environment using participants from the university rather than professional painters. This introduces an important contextual difference. Participants did not have extensive experience with painting work and therefore approached the tasks from a more general perspective. While this limits transferability to professional workflows, it provides a controlled setting in which the human-robot interaction can be more directly observed.

The simulation tasks were intentionally abstract rather than realistic painting activities. This allowed workload-related aspects of the interaction with the cart to be

isolated and compared across participants. However, it also means that the observed behaviours may differ from those longer in real-world use. Participants occasionally focused on completing the tasks themselves rather than optimizing the workflow with the cart, despite instructions that speed and accuracy were not being evaluated.

Another important contextual factor is novelty. For many participants, this was their first experience interacting with a mobile autonomous system. Several participants explicitly commented that they needed time to understand the robot's behaviour and controls. As a result, part of the observed workload is likely influenced by initial learning effects.

An additional contextual constraint was the limited time available for participants to learn the system. The number of behavioural modes and interaction options required an initial cognitive effort to understand the cart's behaviour. This resulted in an increased cognitive load during early interaction phases, particularly when switching between or interpreting different cart behaviours.

The physical test environment also influenced interaction patterns. The relatively short wall length allowed participants to quickly return walk back to the beginning, reducing the relative advantage of autonomous following behaviour. In a longer workspace, the benefits of reduced manually repositioning a cart in the autonomous condition may have been more pronounced.

Furthermore, the tasks, while designed to represent different workload dimensions such as physical, temporal, and cognitive demand, do not fully replicate the complexity of real-world painting activities. Combined with the fact that participants were primarily university students rather than professional painters, this limits the ecological validity of the findings. However, this setup was intentional to isolate interaction effects between user and system under controlled conditions

Interpersonal reflexivity

The presence of the researcher during the test may have influenced participant behaviour and responses. As the facilitator explained the system and demonstrated the wearable remote, participants may have formed implicit expectations about how the robot should behave or how the interface was intended to be used.

During the task execution phase, participants were aware that they were being observed, which may have influenced how they interacted with the system, potentially making them more cautious in their task execution than they would be in a natural work setting.

Furthermore, the phrasing of questions during the semi-structured interviews may have subtly shaped how participants articulated their experiences, particularly when discussing differences between manual and autonomous operation.



Figure 79: Participant executing one of the tasks.

Workload comparison

To complement the qualitative observations, perceived workload was measured using the NASA Task Load Index (NASA-TLX) after participants completed both conditions. All data can be found in Appendix D. The autonomous cart produced a lower overall mean workload score (32.2/100) than the manual cart (37.8/100). However, the individual workload data reveals a more nuanced picture, see Figure 80.

The largest differences were found in physical demand and effort. Physical demand decreased from an average score of 48.0 for the manual cart to 23.0 for the autonomous cart, while effort decreased from 46.5 to 23.5. This corresponds to lower physical interaction with the autonomous cart.

In contrast, mental demand increased from 28.0 for the manual cart to 40.0 for the autonomous cart. Participants frequently reported needing to think about the robot's behaviour, monitor its movement, and understand the control system.

One participant noted that they: *"needed to think about what the robot was doing and had an additional cognitive load in my head,"* and *"You are busy with where I want the cart to be and how it follows me, it feels like you are thinking about it more."*

While another explained that the autonomous cart *"took some time to understand"* because there were multiple options available.

Temporal demand and frustration showed only minor differences between conditions. However, interview responses revealed that the source of frustration differed considerably. In the manual condition, frustration was mainly associated with physically moving the cart and repeatedly walking back and forth, see Figure 81. In the autonomous condition, frustration was more often linked to uncertainty regarding the robot's behaviour, such as not knowing which mode was active or when the platform would begin or stop moving.

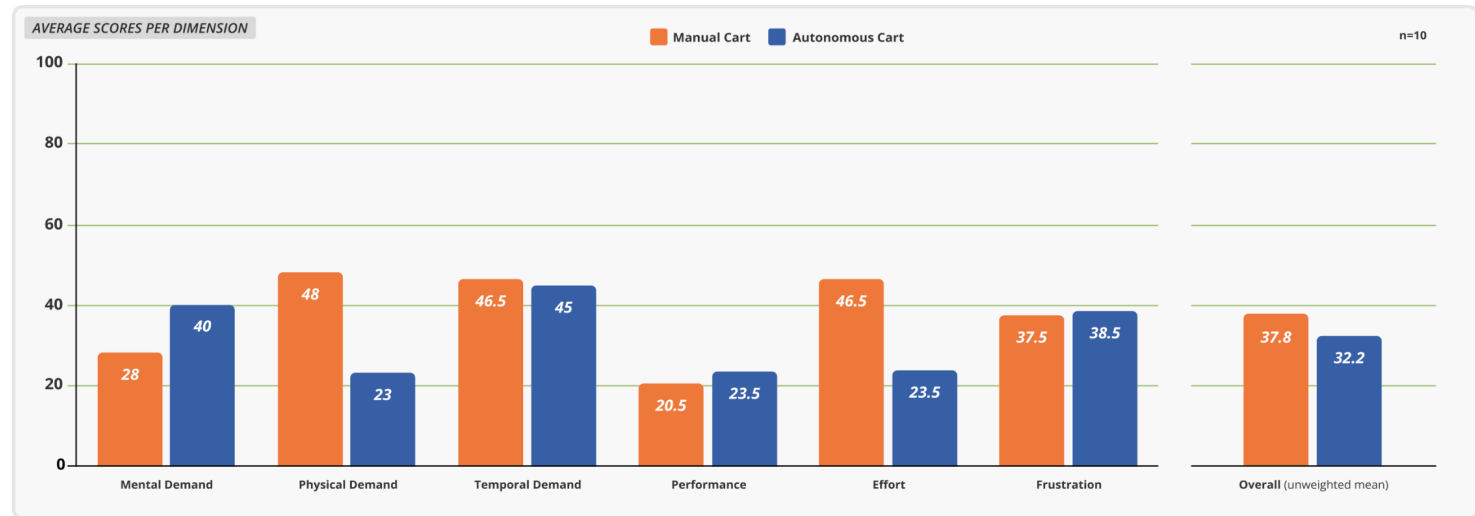


Figure 80: Graph of average scores per dimension from the NASA-Task load index form.



Figure 81: Participant pushing the manual cart.

Autonomy and workload

A central objective of this study was to investigate whether autonomy provides sufficient value to justify the additional complexity introduced by an autonomous system.

The primary advantage of the autonomous cart was that it reduced the need to repeatedly reposition the platform while working. Several participants reported that tools remaining nearby reduced physical effort during work.

One participant stated: *"With the autonomous cart there is less walking so I can get more done in one workflow."*

This was reflected in the lower physical demand and effort scores reported in the NASA-TLX assessment.

However, participants also experienced additional cognitive demands.

As one participant summarized: *"With the autonomous cart I was still quite busy operating it, it sometimes cost more effort than it gave me."* Rather than simply using the cart as an object that remains where it is placed, participants had to monitor the robot's actions and predict its behaviour.

Several participants expressed a desire to understand what the robot was planning to do before it moved. *"I was confused sometimes because it felt like a black box,"*

Others indicated that they initially spent time watching the platform move to ensure that it behaved as expected: *"I would like to know when it is going to start moving."*

Some participants reported that the manual cart felt more predictable, as all movement decisions were only controlled by the user. Others noted that they felt more in control over task execution with the manual cart.

These observations indicate that manual control provides better predictability, while autonomous operation reduces physical interaction requirements but introduces additional cognitive monitoring demands.



Figure 82: Participant working with cart.

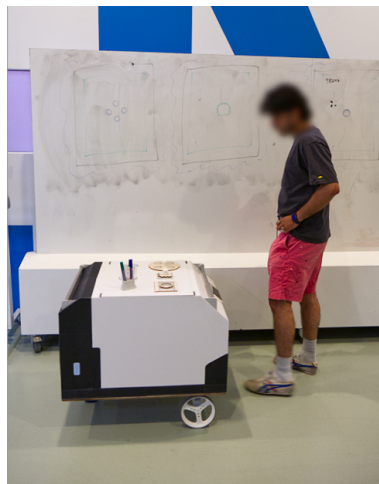


Figure 83: Participant confused with the cart.



Figure 84: Participant doing the tasks by section.



Figure 85: Participant doing the tasks by colour.

Workflow

One of the most notable findings was that the autonomous cart did not simply support existing behaviour but actively changed how participants approached the tasks. With the manual cart, participants typically worked in a sequential manner. They completed work at one window, moved the cart, and then continued to the next location. Others left the cart stationary and repeatedly walked back and forth to retrieve tools.

With the autonomous cart, participants frequently adopted a different strategy. Rather than completing one window at a time, many switched to processing the entire wall by tool or colour. For example, participants would first complete all black outlines, then all green outlines, before moving on to the next step. This reduced the number of interactions with the cart and created a smoother workflow.

One participant explained: *"With the manual cart I went from A to B and back, but with the robot I already had everything with me so I could just go back and forth in one flow."*

Several participants described the autonomous cart as functioning similarly to a toolbelt or assistant that continuously kept the required materials nearby. Rather than thinking about retrieving tools, they were able to focus more directly on the task itself. This behavioural shift indicates that autonomy influences not only workload but also the workflow.

Proximity preferences

A consistent finding across participants was the preferred distance to the robot. The majority of participants (6 out of 10) actively selected the minimum available following distance of 50 cm and explicitly left this setting unchanged for the remainder of the session.

Furthermore, 4 out of 10 participants explicitly stated during the interviews that even the 50 cm minimum felt too far away. Distances of 20–30 cm were frequently suggested because users wanted immediate access to tools without taking an additional step towards the platform.

One participant noted: *"50 cm is still a bit too far away, I would prefer 20–30 cm so I don't need to step back to reach things."* At the same time, some participants acknowledged a boundary where proximity becomes uncomfortable: *"If it gets closer than 50 cm it might hit my arm."*

Participants rarely adjusted the distance once a comfortable setting had been found. This behaviour was consistent across participants and conditions involving autonomous follow behaviour.

This indicates a strong preference of having the cart nearby. Users preferred the platform to remain as close as possible while still avoiding interference with their movement.

Behaviour mode preferences

Participants were encouraged to freely experiment with all three behaviour modes while using the autonomous cart. While all modes were used at some point during the tasks, clear preferences emerged.

Continuous mode

Continuous follow mode was preferred by most participants because it kept the cart nearby with minimal interaction. Users appreciated that tools remained accessible while they worked and generally described the behaviour as predictable and easy to understand.

One participant noted: *"It's nice that it just follows you, like a little assistant."*

The behaviour was generally described as predictable once familiarised, with one participant stating: *"After a while I just knew what it would do, so I didn't really think about it anymore."*

Segmented mode

Segmented follow mode received more mixed reactions. Some participants appreciated that the cart remained stationary for longer periods, reducing continuous movement in the workspace. However, many participants reported that the mode was harder to predict because the cart only moved after a threshold had been exceeded.

One participant said: *"I sometimes didn't know when it would start moving, and then it felt a bit unexpected."*

This uncertainty increased the need for monitoring and reduced trust in some cases, with participants indicating they needed additional cues: *"I would like to know when it is going to start moving."*

Manual mode

Manual mode was used primarily as an override mechanism rather than as a preferred operating mode.

One participant described it as more reliable in certain situations: *"With manual mode I know exactly where the cart is and what it will do."*

Participants valued the ability to reposition the cart when necessary, but few preferred continuous manual control over autonomous following. Instead, manual mode was typically used when participants wanted immediate control over the cart's position when not nearby the cart.

Overall, the results suggest that participants preferred behaviours that kept the cart close and predictable while requiring minimal interaction. Continuous follow mode most closely matched these preferences, whereas segmented follow mode highlighted the importance of transparency and predictability in autonomous movement.



Figure 86: Participant reaching for item.



Figure 87: Cart following participant.



Figure 88: Participant confused with cart.

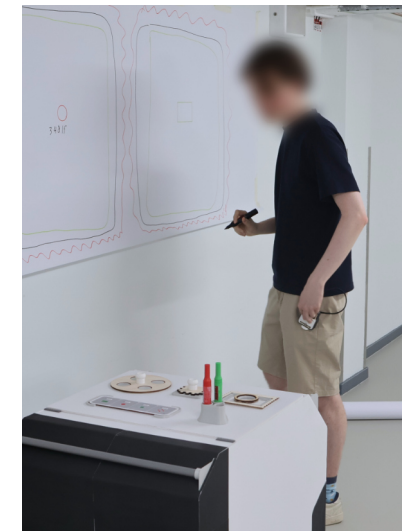


Figure 89: Participant controlling the cart manually.

Control, trust and predictability

Trust in the autonomous platform was strongly linked to predictability. Participants generally felt comfortable allowing the robot to follow them when they understood how it would behave.

Many participants relied heavily on auditory feedback rather than visual feedback.

One participant explained: *"The sound of the motors made it clear where the robot was, so I trusted it more."*

The sound of the motors provided information about the robot's movement, allowing participants to determine whether the platform was approaching, stopping, or remaining stationary without turning around.

Several participants reported increased confidence because the platform followed a straight trajectory, participants quickly developed confidence in its movement behaviour. Several users reported feeling comfortable turning their back to the robot because they trusted that it would remain behind them.

However, trust decreased whenever behaviour became less predictable.

One participant said: *"I sometimes didn't know when it would start moving, so I kept checking if it was going to hit me."*

This was particularly evident in segmented follow mode, where delayed movements occasionally surprised participants. This suggests that predictability plays a key role in perceived safety and usability of the autonomous system.

Participants preferred systems that matched their mental model of control: *"When I control it manually I know exactly where it is, with the autonomous mode it feels more like a black box."*

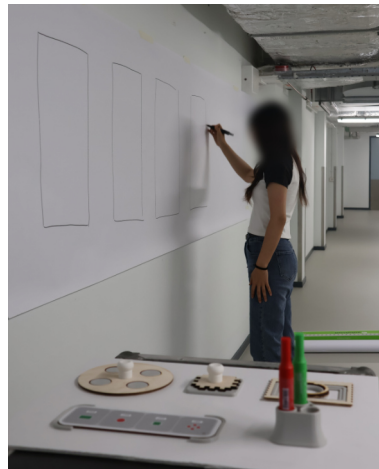


Figure 90: Participant executing task 1.

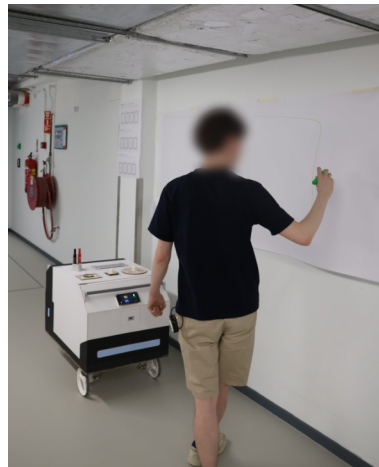


Figure 91: Participant focussing on the wall.



Figure 92: Participant checking when the cart is going to move.



Figure 93: Participant checking when the cart is going to move.

Remote and dashboard

The wearable remote and dashboard successfully enabled users to control and understand the robot's behaviour, but both interfaces revealed opportunities for improvement.

The wearable form factor itself was generally appreciated because it allowed participants to control the robot without returning to the platform. However, several usability issues emerged during testing.

Participants frequently confused the two primary buttons because they were visually and tactually identical: *"I often pressed the wrong button because they look too similar."*

One participant explained that the buttons should be easier to distinguish without looking, suggesting that *"one button should feel different from the other" so the remote can be operated by touch alone.*

Several participants found the control scheme unintuitive at first due to overlapping functions: *"There are too many options in too little time, it feels like a whole tree of functions."*

Mode switching proved particularly problematic. The current interaction requires users to hold both buttons simultaneously to cycle through the modes. Participants described this as unintuitive and disconnected from the action they were trying to perform.

One participant said: *"Switching modes with the same buttons that also handle controls feels a bit scary to me"* and another stated that a dedicated physical switch would make more sense because *"then you immediately know what mode you're in."*

However, after short use participants reported rapid learning: *"After about 30 seconds it becomes intuitive and you don't need to think about it anymore."*

When the robot obstructed their task or moved too close, 6 out of 10 participants instinctively pushed the platform away rather than using the remote.

One participant explained this preference directly: *"If it's in my way, I'll just push it."* Another suggested that the robot should include a grab handle or touch-sensitive ring around the whole platform so that it can be repositioned from any side.

The dashboard was primarily used during setup and experimentation rather than during the task: *"I only looked at it to check if the mode or distance was correct."*

Participants appreciated that it provided insight into the robot's behaviour and helped them understand the relationship between the selected mode, target distance, and measured distance. The colour coding and graphical indicators were frequently mentioned as useful because they could be interpreted quickly.

However, participants varied in how much of the displayed information they used. Several reported focussing only on a few specific elements, such as mode and distance, while ignoring others. The speed indicator in particular was often mentioned as less relevant to task execution.

One participant noted that *"the speed value doesn't really tell me anything,"* and others described continuously changing numerical values as distracting during active use.

This suggests that while the dashboard was effective for confirming the system state, not all displayed parameters were considered equally useful during interaction.



Figure 94: Participant pushing the manual cart.

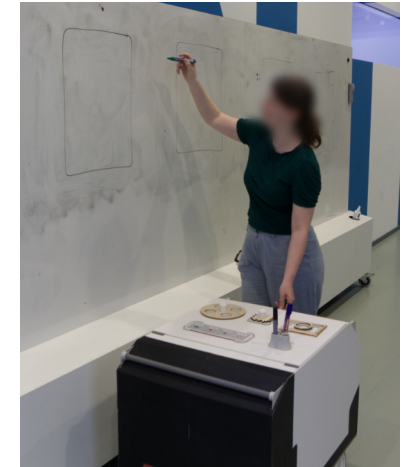


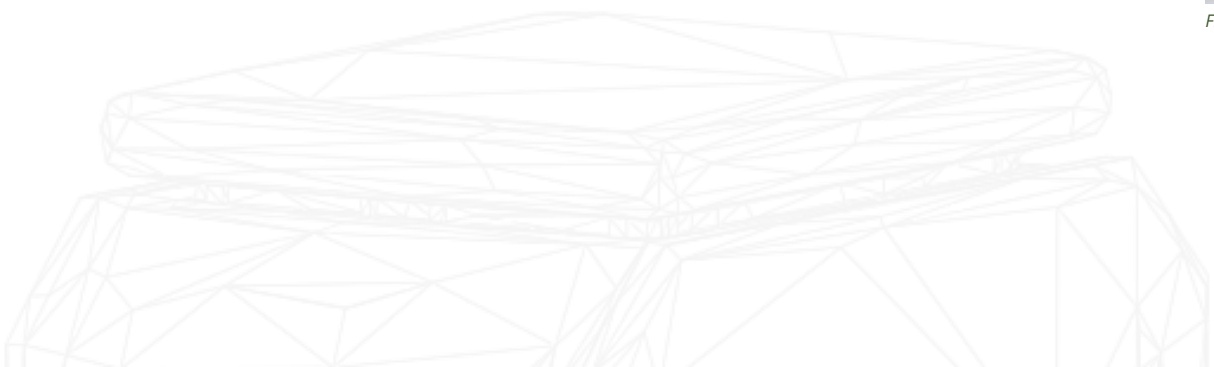
Figure 95: Participant pushing and drawing.



Figure 96: Participant using the remote.



Figure 97: Participant confused with options.



Takeaways

The validation study answers its three research questions based on observed workload, behaviour, and interaction patterns.

1. Influence of behavioural modes on user experience and workload

Behavioural modes mainly changed how workload was distributed rather than the total workload. The autonomous mode reduced physical demand by removing repeated repositioning of the cart, while increasing mental demand due to monitoring robot behaviour and interpreting system state. Overall, participants reported lower total workload in the autonomous condition. Manual control was experienced as more predictable, while autonomous behaviour required more attention, especially when mode state or robot actions were less clear.

2. Value of autonomous assistance compared to a manual cart

Autonomous assistance provided value by reducing physical effort and supporting more continuous workflows. Participants were able to keep tools nearby, reduce walking, and work more continuously across the wall. The main change was in task workflow. With the manual cart, participants typically worked in a location-based sequence, while with the autonomous cart they more often organised work around tools or colours. However, this benefit depended on the predictability of the robot behaviour. When the behaviour was clear, autonomy was useful. When uncertainty increased, the added cognitive effort reduced its perceived benefit.

3. Control sharing between user and robot

Control worked as a shared setup where the robot handled movement and the user maintained final authority. Physical override by pushing the cart was frequently used and seen as a normal part of interaction. The remote was mainly used for setting mode and distance rather than for continuous control during the task execution. Confusion mainly occurred when inputs combined multiple functions or required holding button combinations, which sometimes led to incorrect actions. Once the controls and cart behaviour was understood, interaction became easier, but uncertainty about robot state led to increased checking and reduced ease of use.

Limitations

1. Participant demographics and ecological validity

This study involved university participants rather than professional painters, so the findings cannot be directly transferred to professional painting practice. Professional painters may have different workflows, movement patterns, and expectations of how a cart should support their work.

The tasks were also simplified simulations rather than real painting activities. This made it easier to compare interaction and workload, but may not fully represent how the cart would be used during longer, real-world painting work.

2. Novelty effect and cognitive load

A significant contextual factor was the novelty of the autonomous cart. For many participants, this was their first experience with a mobile autonomous system. Participants therefore needed time to understand the robot's behaviour, behavioural modes, and control interface. Because the available familiarisation period was limited, interpreting the different modes and interaction options may have created an initial cognitive burden.

Consequently, part of the higher mental demand reported for the autonomous condition may reflect an early learning effect rather than the cognitive workload of continued use.

3. Environmental constraints

The physical dimensions of the test environment also constrained the observed interaction patterns. The relatively short test wall allowed participants to return to the manual cart quickly and with limited effort. This reduced the relative physical advantage of autonomous following behaviour.

In a longer workspace, where repeatedly returning to a stationary cart would require more walking and repositioning, the physical benefits of autonomous assistance may be greater. However, this should be validated in a more representative work environment.

Chapter 9

Updates from feedback

Updated remote control design

Updated dashboard design

Update remote control design

Based on the validation study, the remote control was redesigned to make its functions easier to distinguish, reduce uncertainty about the active behaviour mode, and support faster intervention during work (see Figure 98). The previous remote was generally considered intuitive after a short learning period, but participants reported that the two main buttons were difficult to distinguish by touch and that switching modes through a simultaneous button press was slow and unclear. Participants also wanted clearer feedback about the current mode and a more direct way to regain control when the cart was in an inconvenient position.

The updated remote separates movement, mode selection, and safety functions more clearly (see Figure 99). The forward and backward controls are arranged vertically (3), reflecting the direction of cart movement. Each one has different surface relief so that they can be recognised without looking at the remote. This supports use while painting or handling tools, when visual attention should remain on the work surface.

Mode selection is moved to a dedicated physical slider (2). This allows the user to switch directly between the three behaviour modes rather than cycling through them by pressing two buttons simultaneously. The slider position also provides a physical indication of the currently selected mode. This makes the robot state easier to understand at a glance and reduces the need to consult the dashboard.

A dedicated home button (6) was added to send the cart back to a predefined home position. This provides a quick way to clear the workspace or return the cart to the beginning of the wall without manually reversing it over a longer distance.

The remote also includes an independent emergency stop button (5). This button is separated from the normal controls so that users can immediately stop the cart if necessary, regardless of the selected mode. This maintains clear user authority over the autonomous system.

Haptic feedback (7) was added to improve awareness of robot state without requiring users to look at the remote or dashboard. The remote gives one, two, or three short vibration bursts when the selected mode changes, corresponding to the three behaviour modes. It also provides a short confirmation vibration when the remote is switched on. In addition, the remote vibrates when the cart moves autonomously, for example when it starts moving towards the selected target distance. It will not vibrate when the user directly presses the forward or backward controls, since the movement is then already initiated intentionally by the user.

Together, these changes aim to make the remote more legible, more tactile, and easier to use during active work. The revised design reduces reliance on the dashboard for basic state awareness while preserving direct user control over the cart.



Figure 98: New remote in use.

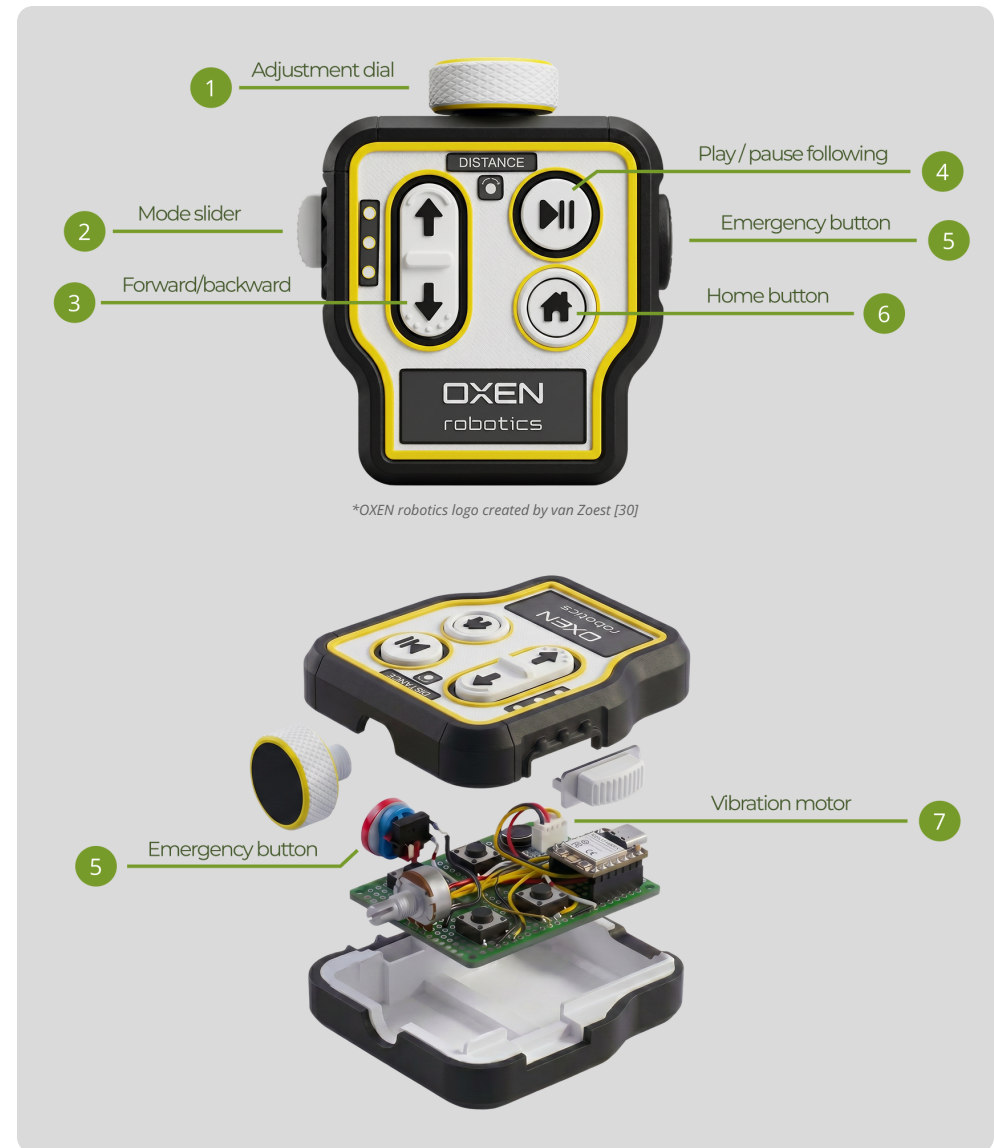


Figure 99: Explanation of new remote.

Update dashboard design

The dashboard was updated based on feedback from the validation study. Although participants generally found the dashboard useful for checking the robot's state, they mainly used it as a quick status monitor rather than a detailed control interface. They reported that the screen could be difficult to interpret from a distance and that frequent updates could feel overwhelming during active work, see Figure 100. In particular, the behaviour mode needed to be more visible, while the speed indicator was considered less relevant.

The revised dashboard therefore prioritises clear state awareness over detailed information, see Figure 101. The speedometer was reduced in size, creating more space for the behaviour mode icon, which was enlarged and made more prominent to improve readability at a distance.

In addition, a home function was introduced, allowing the user to set a home point (Figure 107) and clearly initiating a return-to-home behaviour. A dedicated home screen communicates when the cart is returning or has reached this position (Figure 106), making this state distinct from normal operation.

The dashboard also uses colour-coded borders to communicate system states. Each behaviour mode is assigned a colour shown as a border around the screen, providing immediate visual feedback without requiring detailed reading, see Figure 102/103/105. Home-related actions are indicated with a blue border, distinguishing them from standard operation, see Figure 107.

When the emergency stop is activated, a dedicated emergency screen appears with a red border, clearly indicating that all motors are disabled, see Figure 104.

Together, these changes improve readability at a distance and reduce the need for detailed interpretation during work. The dashboard now focuses on the most relevant information: behaviour mode, target distance, current distance, home status, and emergency state.



Figure 100: Previous dashboard design.



Figure 101: Updated dashboard design with enlarged mode icon.



Figure 102: Colour-coded borders of manual mode.



Figure 103: Colour-coded borders of continuous mode.

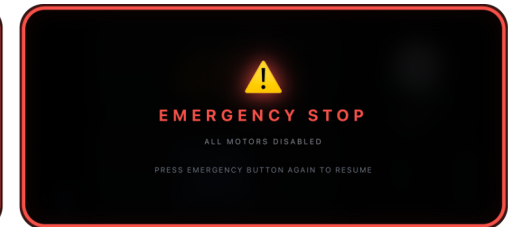


Figure 104: Emergency stop screen.



Figure 105: Colour-coded borders of segmented mode.

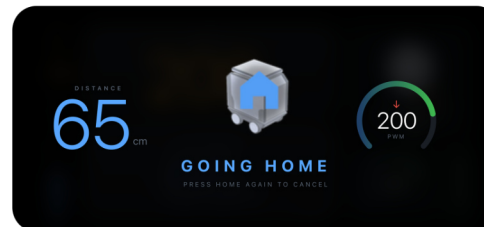


Figure 106: Going home screen.



Figure 107: Home point set when holding home button.

Chapter 10

Familiarisation study

Investigating familiarisation effects

Results

Takeaways

Limitations

Investigating familiarisation effects

The previous validation study showed that the autonomous cart reduced physical demand and effort compared with a manual cart, but also resulted in higher perceived mental demand. Participants had to understand the different behaviour modes, interpret the robot's movement, and monitor its position while completing the wall-based tasks. As participants only had a limited time to familiarise themselves with the system, it remained unclear whether this increased mental demand was caused by the autonomous interaction itself or by the initial learning required to understand a new robot and control interface.

This follow-up study therefore investigates how interaction with the autonomous cart (Figure 108) changes over a longer period of use. Rather than comparing the autonomous cart with a manual baseline, the study focuses on repeated use of the autonomous system. By allowing participants to perform the same tasks multiple times, it examines whether

perceived mental workload decreases as the cart's behaviour and controls become more familiar.

The study also investigates how users adapt their workflow over time. This includes whether they develop preferred behaviour modes, distance settings, control strategies, or ways of coordinating their task with the robot's movement. The updated remote control and dashboard are included in the study to evaluate whether their clearer feedback and simplified controls support this familiarisation process.

The study aims to answer two questions:

1. How does perceived mental workload change during prolonged use of the autonomous cart?

2. What interaction patterns and control behaviours emerge as users become more familiar with the autonomous cart?



Figure 108: Autonomous cart prototype

Methodology

Test objective & scope

The primary objective of this test is to investigate how user experience, perceived mental workload, and interaction behaviour evolve during prolonged use of an autonomous robot cart within a one-dimensional workspace alongside a wall.

The participant will repeatedly perform a series of wall-based simulation tasks while using the autonomous cart. Unlike the previous validation study, which focused on comparing manual and autonomous operation, this study focuses exclusively on extended interaction with the autonomous system. By repeating the same tasks multiple times, the study aims to investigate whether the elevated mental demand observed during the validation study decreases as users become more familiar with the robot's behaviour and controls.

In addition, the study seeks to identify how users adapt their workflow over time, including the emergence of self-developed interaction strategies, preferred behaviour modes, cart positioning preferences, and methods of coordinating task execution with robot control. The participant is free to use the autonomous cart in any way they consider effective, allowing natural optimisation strategies to emerge.

Finally, the study aims to evaluate whether prolonged exposure changes the perceived balance between the physical benefits of autonomy and the cognitive effort required to understand and supervise robot behaviour.

Rather than observing general use in a real painting context, the study isolates movement and control as the primary variables, in order to analyse how autonomy changes the interaction itself.

Materials

- Motorized, functional prototype of the robot cart.
- Second iteration of wearable belt-clip remote control.
- Wall setup (5-to-10 meter length with whiteboard).
- Testing tools: Four physical wooden stencils, coloured felt pens (black, green and red), tape, and a number sheet.
- Timer
- Mental demand scale sheet
- Data collection: Audio recorder, camera, and clipboard for observational notes.

Participants & location

Target participants: People from StudioLab, fellow students, preferably participants who have participated before so the initial learning effects have already happened.

Sample Size: 1 participant.

Location: Wall in the basement of the IDE faculty, see Figure 109.



Figure 109: Location in the basement.

The tasks

The participant performs a sequence of wall-based tasks using only the autonomous cart.

The tasks are identical to those used during the validation study (window framing, stencil placement, and window numbering), see Figure 110. However, unlike the previous study, the participant repeats the complete task sequence four consecutive times.

For each iteration, both completion time and task accuracy are recorded. The participant is instructed to achieve the highest possible score, balancing speed and accuracy throughout the session. Introducing a performance goal encourages the participant to actively optimize their workflow and interaction with the cart rather than merely completing the tasks.

Repeating the same task sequence allows the participant to gradually develop familiarity with the robot's behaviour and controls. This creates an opportunity to observe learning effects over time, including changes in perceived mental workload, interaction patterns, mode usage, cart positioning preferences, and the emergence of self-developed strategies for working with the autonomous cart.

The participant is free to use any available behaviour mode, adjust following distance and speed, reposition the cart physically, or use the remote control as desired throughout the session. No instructions are given regarding the preferred way of operating the robot, allowing natural interaction strategies to emerge.

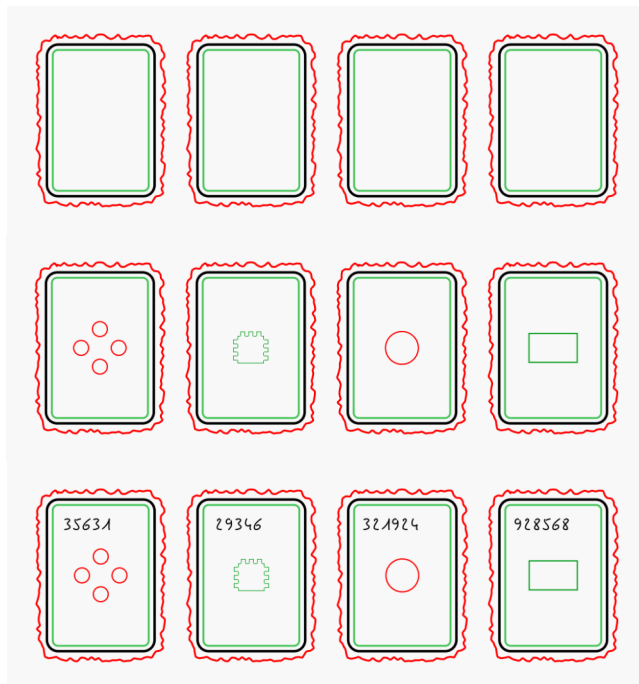


Figure 110: Same tasks as validation study, but repeated 4 times.

Test procedure

The study is designed as a single-participant controlled evaluation lasting approximately 45–60 minutes. The participant repeatedly performs the same wall-based tasks using only the autonomous cart. This repeated exposure allows investigation of whether mental workload decreases as familiarity with the system increases.

Phase A: Introduction and familiarisation (10 min)

The session begins with a brief explanation of the project, its goals, and the purpose of the study. The participant is informed that the study investigates interaction with an autonomous cart during repeated task execution, with a focus on workload, behaviour, and learning effects over time. This is followed by a brief safety briefing covering safe interaction with the cart, including how to stop or physically reposition the cart if necessary. The participant then reads and signs the informed consent form before the experiment continues.

After consent, the autonomous cart, wearable remote, and dashboard are introduced. The participant is informed that performance will be measured based on both task completion time and accuracy.

They are then given time to freely explore the system, including switching behaviour modes, adjusting following distance, and testing the controls until they feel comfortable operating the robot, see Figure 111.

Phase B: Repeated task execution (30–40 min)

The participant completes the same three wall-based tasks used in the previous validation study. The full task sequence is repeated four times. For each repetition, task completion time and accuracy are recorded. The participant is instructed to achieve the highest possible score, introducing a performance element that encourages workflow optimisation and experimentation with the cart.

After each repetition, the participant rates their perceived mental workload on a scale from 0 to 100. During the tasks, the participant is free to use any behaviour mode, adjust

following distance, operate the remote, or physically reposition the cart.

The autonomous cart automatically logs interaction data, including behaviour modes, target distances, measured distances, and button presses. Observational notes are taken to document emerging interaction strategies, workflow changes, and moments of confusion or adaptation.

Phase C: Post-test interview (10–15 min)

After completing the final repetition, the participant provides a final mental workload rating and participates in a semi-structured interview.

The interview focuses on changes in mental effort over time, confidence in predicting robot behaviour, preferred interaction methods, and any strategies developed to improve performance or reduce workload. Particular attention is given to whether the participant felt that using the robot became easier as familiarity increased.

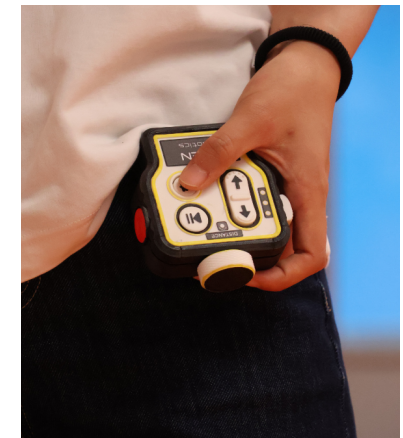


Figure 111: Getting familiar with the controls.

Data collection

This study is designed as a controlled evaluation of whether the elevated mental workload observed in the previous validation study decreases as users become more familiar with the autonomous cart. The focus is on identifying learning effects in mental workload and interaction behaviour over repeated use of the system.

Metrics

- **Perceived mental workload** (0–100 scale): After each task repetition, the participant provides a subjective mental workload rating. This provides a simple but measure of perceived cognitive effort over time, see Figure 112.

- **Task performance metrics:** For each repetition, task completion time and accuracy are recorded. Accuracy is based on correctness of drawn elements and adherence to task rules. These metrics provide a performance-based complement to subjective workload ratings.

- **System logs:** The autonomous cart can record data, including selected behaviour modes, target distance settings, measured distance values, and button interactions, see Figure 113.

- **Interaction behaviour and workflow:** Observations are made of how the participant approaches the tasks, including mode usage, frequency of manual overrides, physical repositioning of the cart, and changes in task organisation across the trials.

Recording methods

- **Workload ratings:** After each trial, the participant reports perceived mental workload on a 0–100 scale on a form, see Figure 112.

- **System logging:** All robot control inputs and sensor-related outputs are stored on the microcontroller during the experiment and downloaded right after, see Figure 113.

- **Observational notes:** The researcher documents live observations focussing on interaction patterns, friction points, and strategy changes over time.

- **Audio recording:** The post-test interview is audio-recorded for a complete transcript.

TIME: ACCURACY:

MENTAL DEMAND
How mentally demanding was the task?

Very Low Very High

0 5 10 15 20

Comments:

Figure 112: Score card time, accuracy and mental demand.

	A	B	C	D	E	F	G
1	timestamp,mode, followActive, segActive,targetMm,actualMm,speed,motors						
2	13:52:54,1,1,0,600,599,0,STOP,0,0,0,0,0,1,0,0						
3	13:52:55,1,1,0,600,594,0,STOP,0,0,0,0,0,1,0,0						
4	13:52:56,1,1,0,600,587,0,STOP,0,0,0,0,0,1,0,0						
5	13:52:57,1,1,0,600,588,0,STOP,0,0,0,0,0,1,0,0						
6	13:52:58,1,1,0,600,588,0,STOP,0,0,0,0,0,1,0,0						
7	13:52:59,1,1,0,600,579,0,STOP,0,0,0,0,0,1,0,0						
8	13:53:00,1,1,0,600,460,0,STOP,0,0,0,0,0,1,0,0						
9	13:53:01,1,1,0,600,324,0,STOP,0,0,0,0,0,1,0,0						
10	13:53:02,1,1,0,600,262,0,STOP,0,0,0,0,0,1,0,0						
11	13:53:03,1,1,0,600,269,0,STOP,0,0,0,0,0,1,0,0						
12	13:53:04,1,1,0,600,314,0,STOP,0,0,0,0,0,1,0,0						
13	13:53:05,1,1,0,600,328,0,STOP,0,0,0,0,0,1,0,0						
14	13:53:06,1,1,0,600,479,0,STOP,0,0,0,0,0,1,0,0						
15	13:53:07,1,1,0,600,564,0,STOP,0,0,0,0,0,1,0,0						
16	13:53:08,1,1,0,600,826.34,FORWARD,0,0,0,0,0,1,0,0						
17	13:53:09,1,1,0,600,882.50,FORWARD,0,0,0,0,0,1,0,0						
18	13:53:10,1,1,0,600,661.28,FORWARD,0,0,0,0,0,1,0,0						
19	13:53:11,1,1,0,600,603,0,STOP,0,0,0,0,0,1,0,0						
20	13:53:12,1,1,0,600,606,0,STOP,0,0,0,0,0,1,0,0						
21	13:53:13,1,1,0,600,640,0,STOP,0,0,0,0,0,1,0,0						
22	13:53:14,1,1,0,600,642,0,STOP,0,0,0,0,0,1,0,0						
23	13:53:15,1,1,0,600,640,0,STOP,0,0,0,0,0,1,0,0						
24	13:53:16,1,1,0,600,873.49,FORWARD,0,0,0,0,0,1,0,0						
25	13:53:17,1,1,0,600,1080.86,FORWARD,0,0,0,0,0,1,0,0						
26	13:53:18,1,1,0,600,907.55,FORWARD,0,0,0,0,0,1,0,0						

Figure 113: Example cart log data.

Roles and responsibilities

Participant: Operates the autonomous cart and wearable remote, see Figure 114, performs the wall-based tasks, reports perceived mental workload after each task repetition, and reflects on their interaction experience during the post-test interview.

Facilitator: Explains the project and safety procedures, obtains informed consent, introduces the cart and its controls, sets up and monitors the test environment, records task time and accuracy, documents observations, manages data recording, and conducts the post-test interview.



Figure 114: Participant with the autonomous cart.

Results familiarisation study

This section presents the results of the familiarisation user study in which a single participant completed four consecutive repetitions of the same wall-based task sequence using the autonomous cart. The study aimed to examine whether perceived mental workload decreases with familiarity, and how interaction behaviour, workflow strategies, and performance evolve over time.

Across the four trials, clear changes were observed in perceived workload, task performance, and interaction strategies. The participant moved from an exploratory mode of interaction in the first trial toward more efficient, confident, and autonomous use of the system in later trials.

Mental workload over time

Perceived mental workload decreased across the four trials, see graph in Figure 116. In Trial 1, the participant reported a mental demand of 75/100, reflecting the cognitive effort required to understand system behaviour, switch between modes, and coordinate robot control with task execution.

By Trial 2, workload decreased to 45/100 and remained stable in Trial 3 (45/100), before dropping further to 25/100 in Trial 4, see graph in Figure 116.

This pattern suggests that the initial workload is largely associated with unfamiliarity with the system, with cognitive effort decreasing as the participant becomes more experienced in operating the cart. The participant supported this transition, stating:

“And for controlling the robot, yeah it became easier, I got totally familiar with all the button positions so in the last run I tried to control it without looking at the controller.”

By Trial 2, workload had already decreased substantially, accompanied by perceived improvements in interaction fluency and cooperation with the system:

“I think I cooperated with the robot pretty well. Felt more free and easy to paint.”

Although workload remained stable between Trials 2 and 3, qualitative data indicates a shift in the nature of cognitive effort, from learning basic controls to experimenting with interaction strategies, such as using the home function to influence robot movement.

In Trial 4, workload decreased further to 25/100. The participant reported increased fluency in controlling the system, including the ability to operate the remote without visual attention while continuing the drawing task.

Performance improvements

Task performance improved consistently over time, see graph in Figure 116. Completion time decreased from 6:08 in Trial 1 to 3:57 in Trial 4, nearly halving total execution time while maintaining or improving accuracy, see graph in Figure 116.

Accuracy improved from 7/10 in Trial 1 to 8.5/10 in Trial 4, indicating that increased speed did not come at the expense of task quality.

While Trials 2 and 3 showed small fluctuations in time, the overall trend indicates faster and more efficient task execution over time.

Interestingly, the participant reported that they intentionally slowed down in the final trial to improve precision, yet still achieved the fastest completion time:

“I wanted to do my best this time, I feel like I drew everything carefully and slower this time but it turned out to be faster.”

This suggests that improved familiarity with the system reduced cognitive overhead, allowing more attention to be allocated to task execution rather than robot control.



Figure 115: Participant collaborating with the cart.

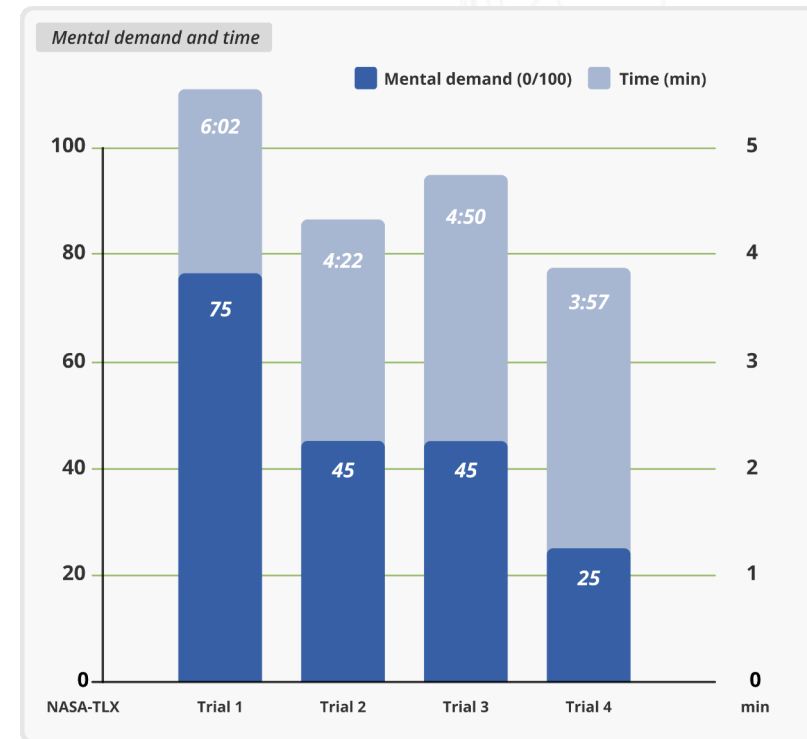


Figure 116: Graph of mental demand and time per trial.

Distance control and home behaviour

The distance and motor-speed timeline graph in Figure 117 provides further insight into how the participant used the cart's autonomous movement functions throughout the study.

The target following distance was adjusted only once, from 60 cm to 50 cm during Trial 1. As shown by Annotation 1, the participant retained this 50 cm target distance for the remainder of the study. This suggests that the participant quickly established a preferred working distance and did not need to repeatedly adjust this setting.

The participant made repeated use of the home function. Annotation 2 shows an instance where the participant activated the home function and allowed the cart to return fully to its home position. This can be identified by the sustained reverse motor movement and the increasing distance between the participant and cart until the cart reached the start of the workspace.

In contrast, Annotation 3 shows an instance where the participant activated the home function but walked backwards alongside the cart. By moving with the platform, the participant kept the cart in reverse motion while continuing to progress through the workspace. This demonstrates how the home function was adapted from a simple return-to-start command into an active movement strategy, see Figure 118.

At several points, the measured distance drops below the selected target distance. As shown in Annotation 4, these moments occurred when the participant approached the cart to retrieve tools or materials, see Figure 119.

Finally, Annotation 5 shows that the participant used the home function at the end of each trial to return the cart to the beginning of the workspace. This repeated pattern indicates that the home function became an established part of the workflow, both as a practical repositioning method during the task and as a consistent way to conclude each trial.

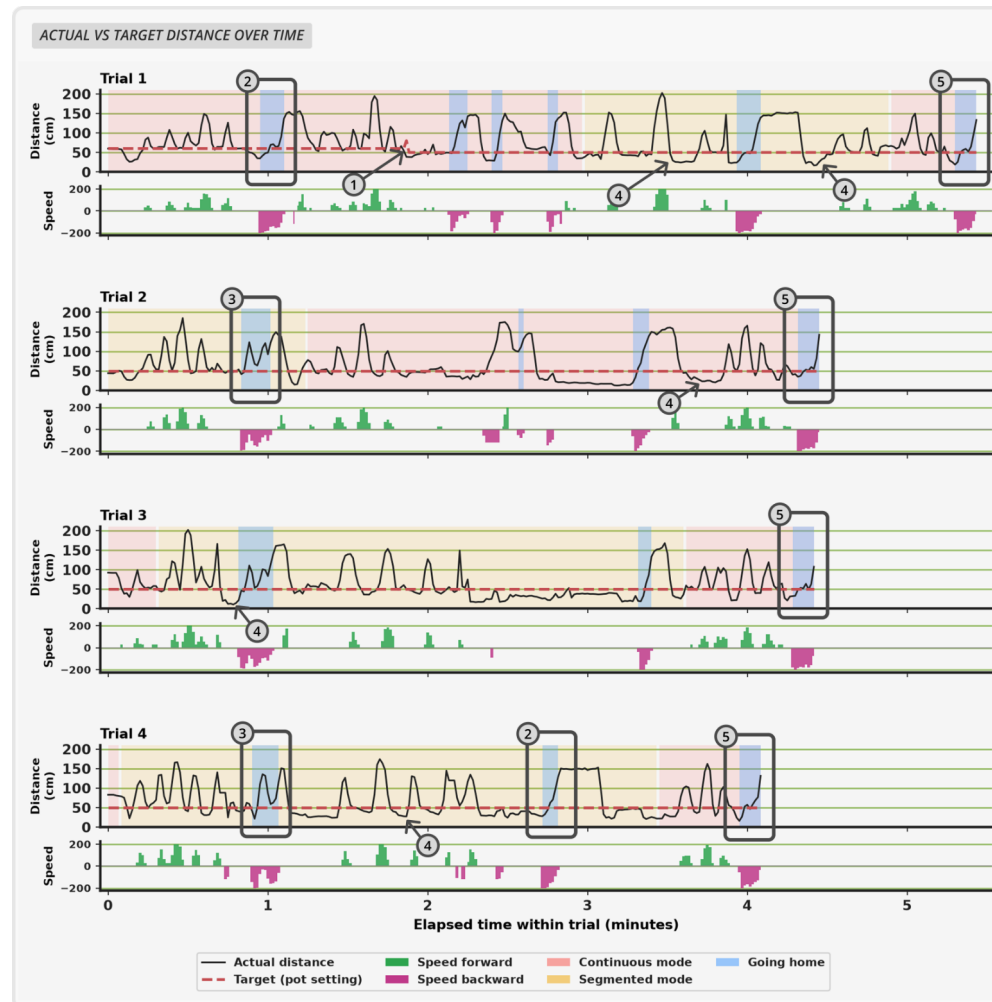


Figure 117: Annotated graph of actual distance vs target distance and below that motor speed.



Figure 118: Participant pressing the home button.

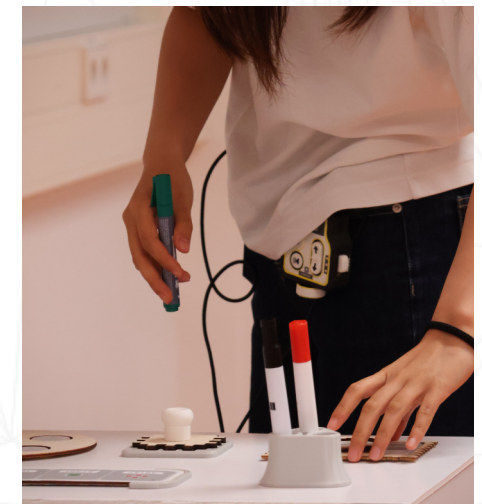


Figure 119: Participant grabbing something from the cart.

Interaction frequency

A reduction in interaction effort was observed across the four trials. The total number of button presses decreased from 18 presses in Trial 1 to 12 in Trial 2, 11 in Trial 3, and 9 in Trial 4 (see graph in Figure 120). This decline indicates a transition from exploratory use of the controls towards more intentional and efficient interaction with the autonomous system.

The cart state and control-event timeline on the next page in Figure 123, further illustrates this change. In Trial 1, the timeline shows frequent control events and switching between continuous and segmented follow behaviour. This corresponds with the relatively high number of button presses (18), as the participant explored which functions and modes worked best.

Across the later trials, the number of control events becomes lower and mode selection becomes more structured. In Trial 2, the participant first used segmented follow behaviour and then switched to continuous follow behaviour. In Trial 3, the participant used segmented, continuous, and segmented follow behaviour in sequence. In Trial 4, the interaction was primarily structured around segmented follow behaviour, followed by continuous follow behaviour for faster movement over longer distances.

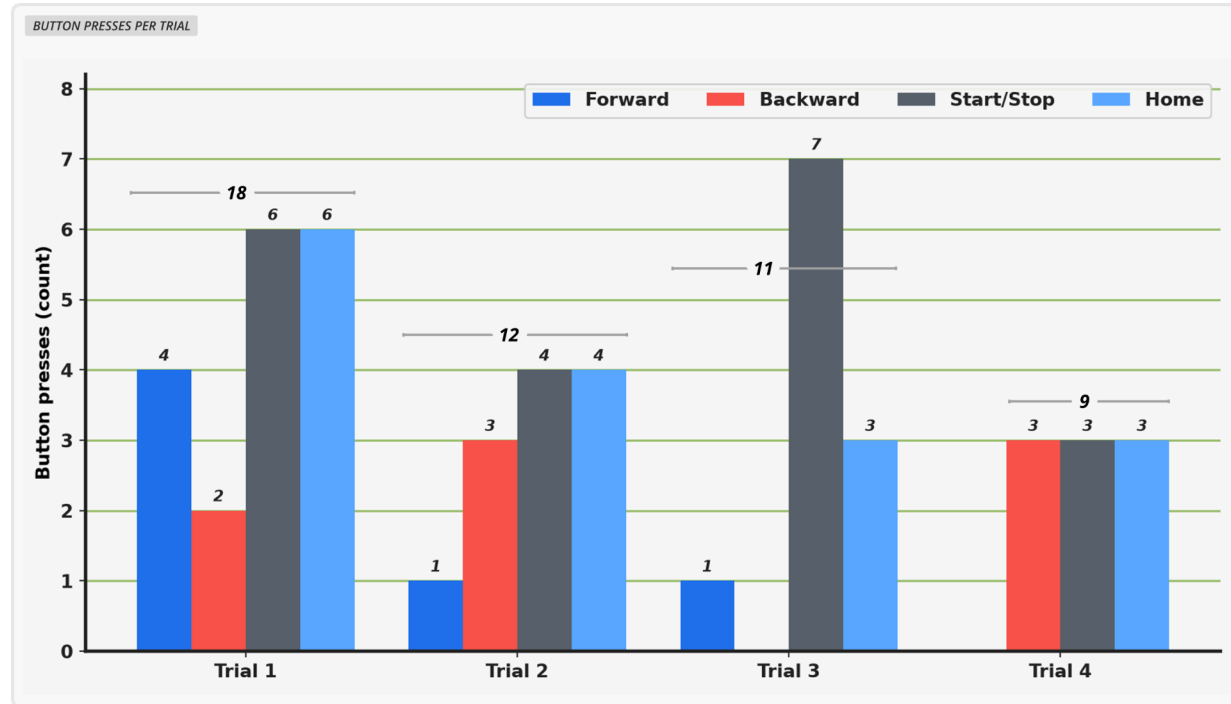


Figure 120: Graph of amount of buttons presses per trial.



Figure 121: Participant pushing the backward button.



Figure 122: Participant looking at which button to press.

Emergence of interaction strategies

One of the most notable findings was the emergence of new interaction strategies over time, which can be seen in the graph in Figure 123.

In the early trials, the participant explored all available modes and controls (1). By Trials 3 and 4 (2), behaviour became more selective and optimised. A key strategy involved the use of the home function as a movement shortcut (3), rather than only fully going home option.

The participant described this adaptation explicitly:

"I used the home mode to go back... and then I tried to do my task really quick to keep it moving."

Later, this evolved into a more refined strategy where the home function was used even for short-distance adjustments (3):

- Sending the robot slightly backwards
- Cancelling the command mid-way
- Avoiding manual forward/backward buttons

This indicates that users quickly reinterpret system functions when given time for exploration, transforming them into flexible workflow tools rather than fixed controls.

The participant also developed clear preferences for behaviour modes:

- Continuous mode: preferred for long distances and fast movement
- Segmented mode: preferred for short, controlled movements

A key reason for this distinction was the perceived pacing of the system. Continuous mode was sometimes experienced as too fast or "rushed" according to the participant, particularly in situations with short-distance adjustments, because the cart continuously made small movements to maintain the target

distance. In contrast, segmented mode felt more deliberate and controllable because the cart did not constantly move a little bit, but instead waited briefly between movements.

The participant described this distinction as a balance between speed and control:

"For short distances I prefer segmented mode... for long distances I want it to follow me quickly."

This pattern is also visible in the control-event timeline (Figure 123), where later trials show longer and more deliberate periods of a mode (4), rather than frequent switching between modes (1).

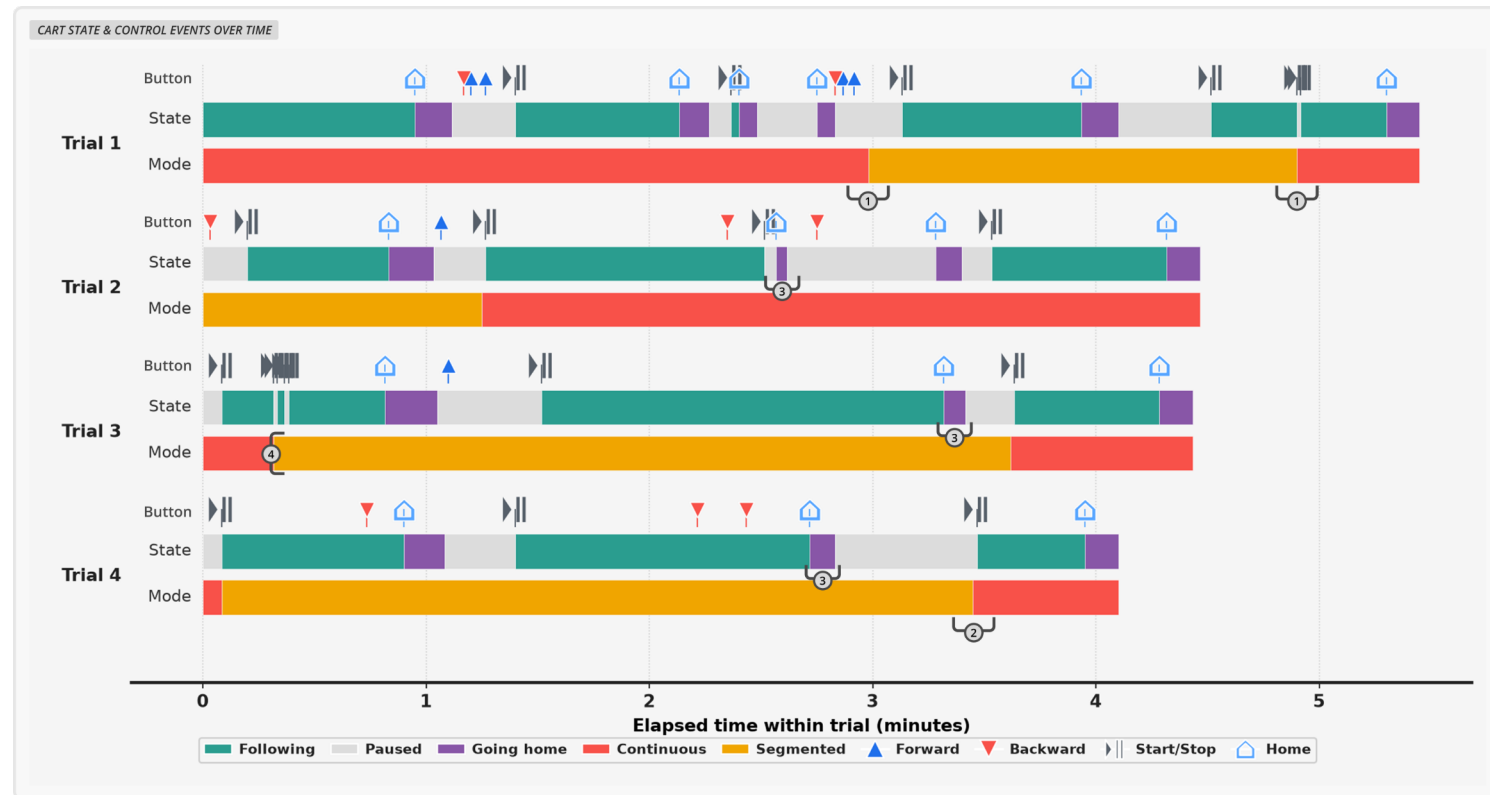


Figure 123: Cart state & control events over time.



Figure 124: Home button on the remote.



Figure 125: Switching modes on the remote.

Trust in the system

Trust in the system increased over time and was strongly linked to predictability and feedback.

The participant reported that they did not need to constantly monitor the robot visually because they started to trust its movement.

"I don't think I watched it a lot, only when I walked a long distance and it moves really fast towards me, then I will check if it will really stop in front of me."

However, high-speed movement from the cart still triggered occasional safety checks, particularly during longer travel distances where the participant described the behaviour as slightly "scary."

Overall, trust increased as the participant learned that the robot reliably maintained distance and followed expected movement patterns.



Figure 126: Participant checking cart.

Workflow changes

A clear shift in workflow structure occurred over the four trials.

In Trial 1, the participant followed a more structured and sequential approach, frequently checking instructions and switching between modes. By Trial 3 and 4, the workflow became more fluid and integrated with the robot's behaviour.

The participant began to synchronise drawing with robot movement, allowing the cart to support during the task rather than acting as a separate system requiring management.

This change is reflected in their reflection on system cooperation:

"It feels like good cooperation with the cart."

The improved coordination between movement and drawing contributed to both increased speed and reduced perceived effort.



Figure 127: Participant cooperating with the cart.

Interface experience

A notable behavioural change occurred in the participant's ability to split attention between drawing and robot control. By Trial 4, the participant began operating the remote without visual attention:

"I tried to switch the mode with my left hand while drawing with my right hand, a little hard but I did it."

This indicates a transition from conscious control to embodied interaction, where operation with the robot become part of the workflow.

However, some usability issues persisted, particularly confusion between forward and backward buttons, which the participant described as:

"I feel like if it was flipped it is better, because the remote is upside down."

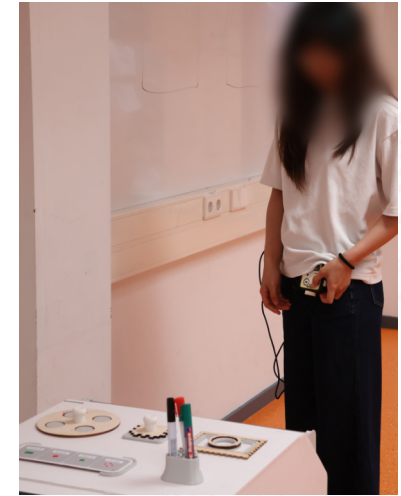


Figure 128: Participant confused about buttons.

Experience contrast

Although the participant could physically push the cart manually at any point during the study, they increasingly preferred using its autonomous movement functions. The participant described autonomous operation as enabling and engaging, while manual pushing was experienced as more physically demanding and less motivating.

"It was more labour... with pushing the cart I feel like I am just a sad worker."

In contrast, autonomous following supported a more creative and less physically burdensome experience:

"When it is autonomously following you I feel like more of a drawer or artist."

This contrast highlights that the cart's autonomy influenced not only workload and performance, but also how the participant experienced their role during task execution. Rather than feeling responsible for moving both themselves and the cart, autonomous movement allowed them to focus more directly on the drawing task.

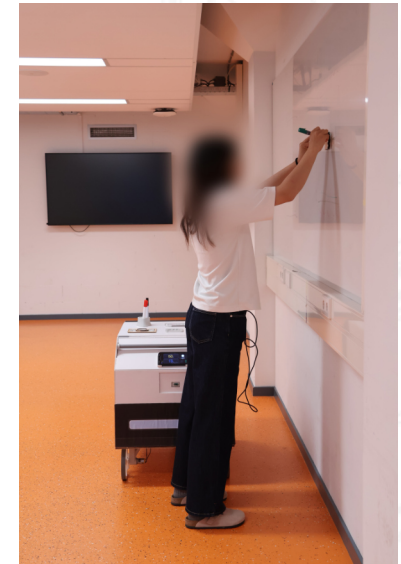


Figure 129: Participant focussing on their task.

Takeaways

This study examined whether the higher mental demand observed in the previous validation study was related to autonomous interaction itself or to the initial learning required to understand the cart's controls and behaviour. It also explored how repeated use influenced control strategies and workflow methods.

1. Familiarity reduced workload and improved performance

Mental demand decreased from 75/100 in Trial 1 to 25/100 in Trial 4. At the same time, completion time decreased from 6:08 minutes to 3:57 minutes, while accuracy improved from 7/10 to 8.5/10. This suggests that the initial workload was largely related to learning the cart's behaviour and controls.

2. Interaction became more efficient and deliberate

Button presses decreased from 18 in Trial 1 to 9 in Trial 4. Over time, the participant moved from exploring multiple controls and modes towards more structured use of autonomous behaviour, particularly the home function and selected follow modes.

3. The participant developed context-dependent strategies

Segmented mode was preferred for short, controlled movements, while continuous mode was preferred for longer movements where speed was more useful. The home function was also adapted from a return-to-start command into a flexible tool for repositioning the cart during the task.

4. Autonomy supported trust and workflow integration

The participant increasingly relied on the cart's autonomous movement, monitored it less visually, and was eventually able to control the remote while drawing. Although the forward and backward buttons occasionally caused confusion, autonomous movement was preferred over manually pushing the cart because it allowed the participant to focus more directly on the drawing task.

Limitations

This follow-up study had only one participant, so it should be seen as a detailed example of a possible familiarisation effect rather than something that can be generalised. The reduction in perceived mental workload, improvement in task performance, and emergence of interaction strategies may be influenced by this participant's individual learning style, prior experience, motivation, and comfort with the prototype.

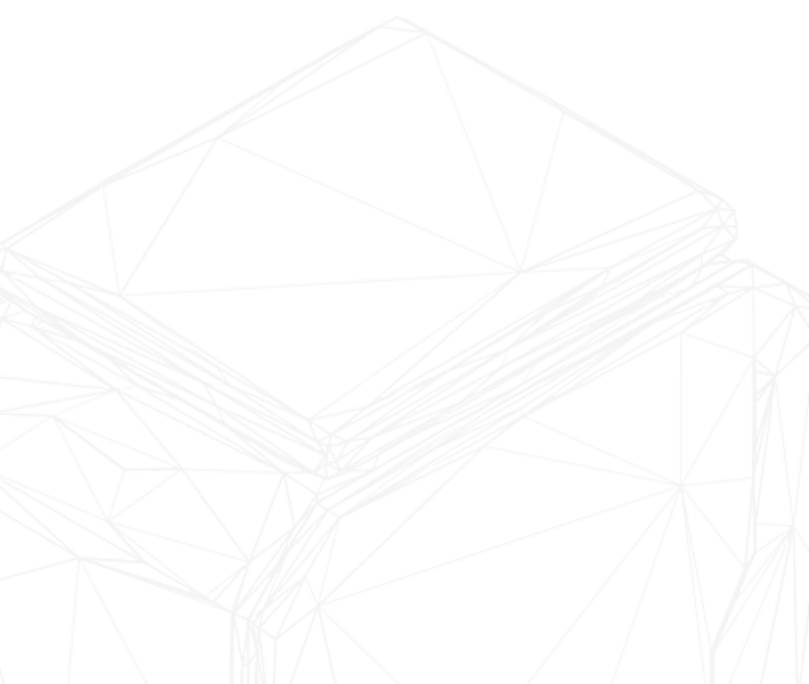
In addition, the participant repeated the same task sequence four times. Some of the observed performance improvement may

therefore be related not only to learning how to use the autonomous cart, but also to becoming familiar with the drawing tasks themselves.

The study was conducted in a controlled indoor setting with simplified tasks and a relatively short workspace. This limits how directly the findings can be transferred to professional painting work or longer real-world environments. Finally, the researcher was present throughout the study, which may have influenced how the participant used the cart or described their experience.

Conclusion

Despite these limitations, the study provides initial evidence that the elevated mental workload observed during first-time interaction may be strongly related to familiarisation rather than to autonomous interaction alone. With repeated tries, the participant developed more efficient control strategies, used the cart's autonomous functions more deliberately, and integrated the cart into the task workflow with less effort. Further studies with more participants and more realistic work settings are needed to determine whether these familiarisation effects occur consistently across users and professional painting contexts.



Chapter 11

Concluding

Discussion

Conclusion

Limitations

Future work

Discussion

The objective of this thesis was to develop the behavioural repertoire and interaction modalities for an autonomous robot cart designed to assist professional painters. Through field testing and controlled validation, the research demonstrated that introducing an autonomous robot into a highly physical craft does not only solve a physical strain and transportation, but it can reshape the relationship between the worker, their tools, and their environment. The findings indicate shifts in physicality, workflow approach, and the learning process required to integrate a robot into an active workspace.

Physicality shift

The integration of the autonomous cart addressed its primary objective by reducing the physical strain associated with manually repositioning a heavy cart. However, the initial validation study revealed that this reduction in physical effort was accompanied by an increase in cognitive demand. The nature of the painter's workload shifted from physical strain to mental demand, as users actively monitored the robot's state, predicted its movements, and navigated the control interfaces.

However, the familiarisation study demonstrated that this cognitive burden may not be a permanent trade-off of autonomy, but can partly reflect an initial learning effect. Over repeated trials, the participant's perceived mental demand decreased substantially, and interaction shifted from consciously supervising a machine towards more seamless use of the robot as a tool. The emotional impact of this physicality shift was also notable. The participant noted that pushing a manual cart felt like hard work, whereas autonomous tracking made them feel free and more like an artist. These observations suggest that appropriately designed robotic assistance can reduce perceived physical effort while supporting a more positive experience of the craft.

Approach shift

A key emergent finding was that the autonomous cart did not simply automate an existing task, but it reshaped the painters' workflow. In manual operations, participants naturally adopted a location-based, sequential approach, completing all steps at a single window before dealing with the friction of moving the cart to the next location.

With the autonomous cart continuously maintaining a close distance, this spatial friction was reduced. Consequently, users transitioned towards a shift toward grouping tasks by tool, completing tasks by tool or colour across the entire wall before switching. The robot effectively functioned as an extension of the user's personal workspace, a "wearable toolbelt", allowing painters to reorganise their approach around the task itself rather than the logistical constraints of their materials.

This finding suggests that the value of the robot lies not only in reducing manual transport, but also in enabling alternative ways of organising work. Future research should examine whether this workflow change results in measurable improvements in productivity, quality, or fatigue during real painting tasks.

Control shift

The literature review highlighted a tension in industrial robotics regarding whether a robot should be framed as a "co-worker" or a "tool." The exploratory field test provided a strong indication that painters preferred a responsive, predictable tool carrier over proactive, intelligent collaboration that could interfere with their work. They wanted the cart to stay out of the way until needed, rather than independently interpreting or initiating work-related actions.

This led to a shared-control autonomy model, made possible through a set of clear, mode-based behaviours. Rather than requiring painters to understand a continuously changing and vague autonomous system, each mode communicates an understandable relationship between the user and robot, what the robot will do and what level of user involvement is expected. The robot handles low-level sensing and movement within the selected mode, while the user retains final authority over goals, mode selection, and intervention.

The modes therefore function not only as technical settings that defines the robot's behaviour, but also as a structure for how users understand and anticipate the system. Each mode corresponds to an understandable interaction state, which allows users to form a simpler mental model of what the robot is doing and how it will respond. This separation of behaviour into distinct states reduces the need for continuous interpretation of the robot's actions and supports more predictable and confident interaction.

A refinement across the three studies was found in the segmented follow behaviour. The field test first indicated that painters preferred the robot not to continuously mirror their movement, but instead to follow with a delay or intermittent response, particularly in constrained spaces. However, in the validation

study, segmented mode was less well received, as participants found it less predictable and harder to interpret compared to continuous follow.

The familiarisation study helped resolve this contradiction. With repeated use, the participant developed a clearer understanding of the mode, distinguishing between continuous follow for longer distances and segmented follow for short distances where continuous behaviour felt too "rushed." This suggests that segmented follow is an important feature, but requires time to learn and becomes more meaningful once its behavioural logic is understood.

Manual override was explicitly requested by painters in the field study as an important feature too, particularly for situations where the cart would obstruct their work. In the validation study, this was reflected in practice through both physical pushing of the cart and the use of the manual remote control, which were seen as good and intuitive options to move the cart backwards.

In the familiarisation study, however, the role of manual override changed. While still available, physical pushing became less desirable due to its effort and disruption of workflow. Instead, the participant increasingly relied on remote control and autonomous behaviour, especially the home function, which reduced the need for manual repositioning.

The final design therefore focusses on autonomy but still includes physical override, ensuring direct control remains available when needed but is not required for routine interaction. Allowing the cart to be physically pushed also contributes to a strong sense of control, even if rarely used, the possibility of direct intervention reassures users that the system is always manageable and safe.

Process of learning with a robot

The familiarisation study provided a detailed look at how one participant learned to interact with an autonomous system in a physical workspace. The learning process showed a pattern of moving from initial exploration of the robot towards more integrated use within the workflow.

- **Exploration and high friction:** Initial interactions were characterised by frequent mode switching and visual monitoring, resulting in a high cognitive load and frequent manual button presses.
- **Strategy emergence:** As the participant developed a mental model of the system, they began to creatively adapt its features to their needs. For example, the Home function was reinterpreted from a simple return-to-start command into a workflow tool for short-distance reversing.
- **Trust and embodied interaction:** By the final trials, predictable movement and feedback reduced the need for constant visual checking. The participant even achieved to operate the remote without looking while continuing to paint with the other hand.

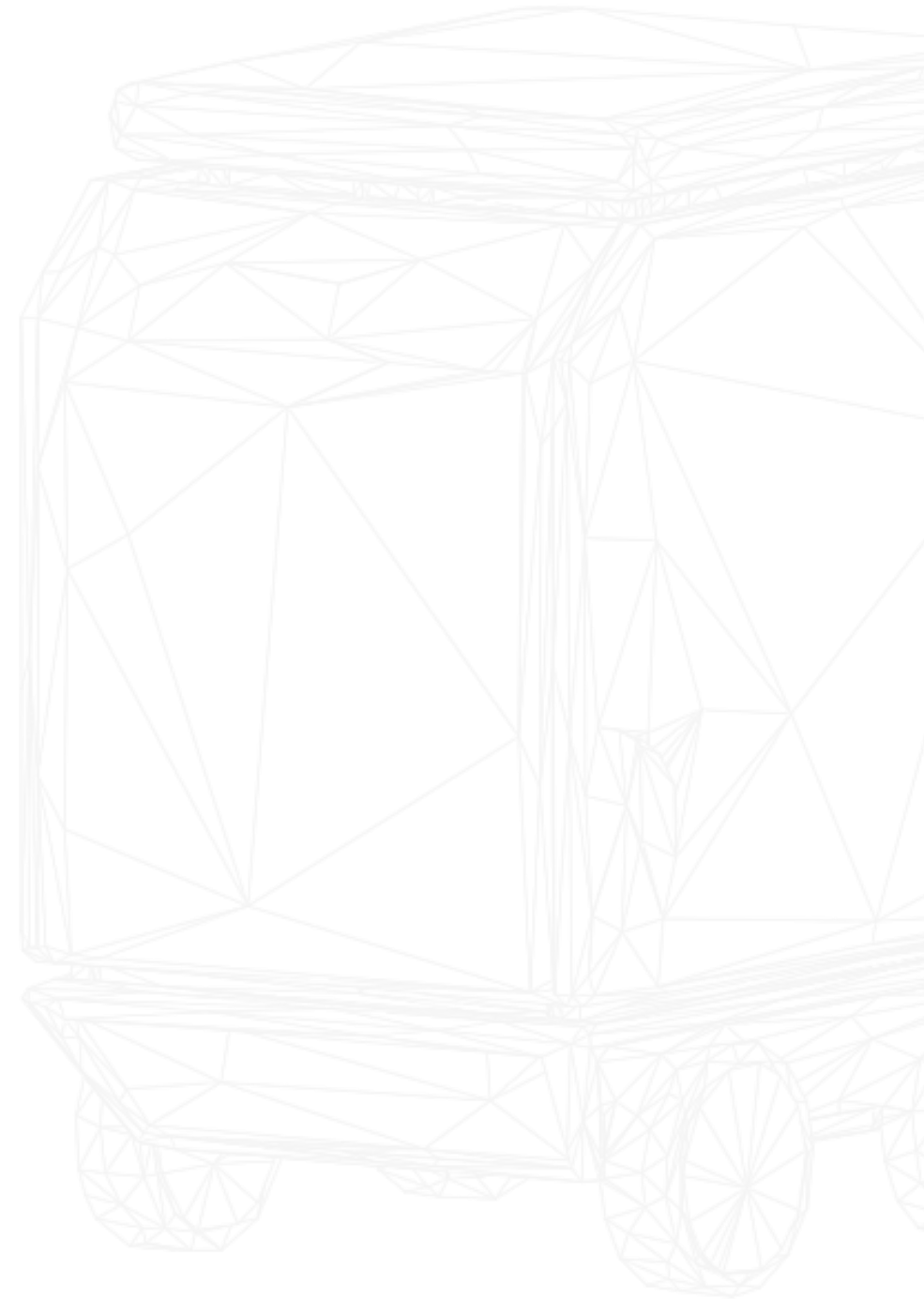
Although this pattern of learning cannot be generalised from a single participant, it indicates that learning should be treated as a design consideration in construction robotics. Interfaces should support early-stage exploration and transparency, while allowing the interaction to become increasingly an embodied experience.

Interfaces for construction environments

The progression of the interface design underscores a valid reality for construction robotics. Complex digital interfaces are poorly suited for visually demanding, hands-on work. The limited suitability of touchscreens and voice controls during the field test suggested the use of a wearable, tactile remote. The final iteration of the remote, featuring distinct buttons, dedicated physical mode slider, and haptic feedback, demonstrates that effective human-robot interaction in this domain can rely on muscle memory and peripheral awareness rather than continuous focus on the controls.

The dashboard screen ultimately served its most effective purpose not as a control panel, but as a transparency tool for confirming the system's internal state. An important distinction is that physical controls supported frequent, time-sensitive actions during painting, whereas the screen supported occasional checking, configuration, and understanding of the robot's behaviour.

Overall, the findings suggest that successful autonomy for professional painters should not attempt to act as an intelligent co-worker, but as a predictable and interruptible tool. Instead, it should reduce logistical and physical friction while preserving the painter's control over the task and attention on the work. The behavioural repertoire developed in this thesis therefore positions autonomy as a background capability: active enough to support the workflow, but predictable and interruptible enough to remain a tool under the user's control.



Conclusion

This thesis set out to develop a behavioural repertoire for an autonomous robot assistant for professional painters. By evolving from a high-fidelity prototype with limited control modalities into a transparent, collaborative tool, this research addressed the gap between technical capability and effective integration in real-world work environments. Through exploratory field observations, iterative prototyping, and controlled validation, the study answers the research questions formulated at the project's beginning

1. How can multimodal interaction enable intuitive control of an (semi-)autonomous robot in the complex operational environment of painting job sites?

Intuitive control is not achieved through complex digital interfaces, but through simple, grounded physical interaction. The research demonstrates that for professional painters, who must maintain visual attention on their work, the most effective modality is a wearable, tactile remote enabling one-handed operation based on muscle memory rather than visual input. Digital interfaces are suitable for configuration and setup, but are poorly suited for active use in the field. Physical controls, supported by clear buttons, haptic feedback, and direct manual override, are therefore essential for unobtrusive and reliable integration into the workflow.

2. How can multimodal feedback and expressive behaviours enable a robot cart to communicate intentions, capabilities, and operational state without demanding continuous visual attention from painters?

Effective transparency in construction robotics must be ambient rather than intrusive. Trust and spatial awareness are primarily supported through auditory feedback from the cart and haptic feedback from the wearable remote, which communicate movement and mode changes without drawing attention away from the task. The dashboard functions as a verification tool, using simple visual structure, colour coding, and clear state indicators to support quick checks rather than continuous monitoring or cognitive interruption during work.

3. How can a robot cart's autonomy be structured along a sliding scale to provide appropriate assistance while preserving intuitive human oversight and intervention?

For this robot cart, autonomy is most effective when structured on the "shared-control" level, positioning the robot as a responsive tool carrier rather than an autonomous co-worker. By structuring behaviour into predictable modes such as Manual, Continuous Follow, and Segmented Follow, the system allows the user to define high-level intent while the robot manages low-level movement execution. Importantly, preserving user authority through immediate physical override by being able to physically push the robot, provides a sense of agency and safety that digital controls cannot replicate, reinforcing the robot's role as a manageable tool rather than an independent agent.

Work flow and learning over time

The user tests show that the robot not only changes how work is organised, but also how tasks are approached spatially and operationally. Once spatial constraints are reduced, users shift from location-based sequences toward more flexible, tool-centred grouping of tasks, as tools remain continuously accessible during work. Within this restructured workflow, different control modes support distinct types of activity. Continuous follow is most effective during longer movements, where it reduces interruption and allows work to continue with less friction. Segmented follow becomes valuable in short-range, where continuous behaviour feels too responsive or imprecise, enabling better control over the robots driving.

Manual override remains an important part of this reconfigured workflow. Although autonomous modes reduce the need for direct intervention, physical control is still used when the robot interferes with the task. This ensures that users can immediately regain control, maintaining both practical flexibility and confidence in how the system behaves.

Concluding remarks

Overall, the findings show that the autonomous cart reduces the physical demand of the job, while introducing an initial increase in cognitive load related to learning the system. With familiarity, this cognitive load decreases, and interaction shifts from conscious supervision toward more fluid and embodied use. At the same time, the robot's contribution extends beyond reducing physical effort, as it also reshapes workflow by enabling more flexible, tool-based organisation of tasks.

The study concludes that an effective autonomous assistant for painters should not attempt to behave as an intelligent co-worker, but rather as a predictable, interruptible, and highly controllable tool. By prioritizing clarity in behaviour, tactile interaction, and user agency, this thesis establishes a validated foundation for designing autonomous systems in physically demanding professional workflows.

Limitations

While this research provides a validated foundation for the interaction design of an autonomous painter's cart, the findings should be interpreted within the following limitations.

Single-participant familiarisation study

The familiarisation study involved only one participant. As a result, the observed reduction in mental workload and the emergence of interaction strategies should be interpreted as a detailed case study rather than a generalisable outcome. While it provides insight into a likely learning process, further research is required to assess whether these adaptation patterns are consistent across a larger and more diverse user group.

Participant demographics

The validation study was conducted with students and university staff, rather than professional painters. While this allowed for a controlled and consistent testing environment, participants did not possess the experience, established workflows, and movement habits characteristic of professional construction workers. Their feedback and interaction strategies may therefore differ significantly from those of the intended end-user group.

Tasks and spatial constraints

The study relied on simulated tasks, such as tracing shapes on a wall with a marker, to simulate different painting-related movements and interaction needs. Although these tasks enabled controlled analysis of specific interaction variables, they do not fully replicate the environmental and operational complexity of real construction sites, such as dust, uneven terrain, time pressure, and interference from other workers. In addition, the evaluated tasks primarily took place along a straight wall, meaning more complex conditions, such as corners, occlusions, narrow passages, and multi-directional movement, were not fully represented. This limits the generalisability of findings regarding navigation behaviour and follow strategies in more complex environments.

Prototype maturity

The system was evaluated as a functional prototype rather than a fully production-ready robotic system. Consequently, limitations in robustness, sensing reliability, and long-term autonomy behaviour may have influenced user interaction and perception during testing.

Researcher influence

The presence of the researcher during all stages of testing may have influenced participant behaviour. Across the validation, field, and familiarisation studies, participants were aware of being observed and interacting with a research prototype, which may have led to more cautious, reflective, or structured behaviour than would occur in real-world use. In particular, the use of Wizard-of-Oz control during the field study may have further shaped participants' perception of system autonomy and safety, potentially affecting their reported trust.

Future work

This thesis provides a foundation for further research into shared-control autonomous systems for professional construction work, particularly in skilled manual tasks such as painting. The findings are relevant to SUSAG to see how robotic assistance can be introduced into professional painting workflows. However, further research is needed to understand how the proposed interaction principles perform during sustained use in real work environments.

A key next step is the transition from prototype evaluation to longer tests on site. Future research should investigate how autonomous tools behave when embedded in daily work routines, where variability in environment, time pressure, and collaboration with other workers becomes central. This is essential to move beyond controlled studies towards understanding real-world adoption.

In addition, further studies should explore how interaction with shared-control systems evolves across different users and levels of expertise. The findings of this thesis suggest that familiarity plays an important role in reducing cognitive load and shaping effective use of autonomy. This indicates that interaction design should be evaluated as a longer process rather than a single-test outcome.

More broadly, this work highlights the need for continued research into how autonomy should be structured in physically demanding work contexts. Rather than treating autonomy as a fixed level, future research should further develop it as a configurable relationship between human control, system behaviour, and feedback design. This includes investigating how different modes of control and transparency affect trust, workload, and workflow integration over time.

Chapter 12

References

AI disclosure

References

AI disclosure

AI tools like Google Gemini and ChatGPT were used to improve the clarity and readability of parts of this report. The tools assisted in refining the wording and structure of existing text and in adapting selected images to improve their clarity and readability while preserving their original content and meaning. Claude Code was used to assist with writing and refining code used in this project.

All core ideas, analyses, interpretations, and conclusions are the author's own. The AI-generated suggestions were reviewed and edited before being incorporated into the final document.

References

[1] Jenay M. Beer, Arthur D. Fisk, and Wendy A. Rogers. 2014. Toward a framework for levels of robot autonomy in human-robot interaction. *J. Hum.-Robot Interact.* 3, 2 (July 2014), 74–99. <https://doi.org/10.5898/JHRI.3.2.Beer>

[2] Bohkyung Chun and Heather Knight. 2020. The Robot Makers: An Ethnography of Anthropomorphism at a Robotics Company. *J. Hum.-Robot Interact.* 9, 3 (June 2020), 16:1-16:36. <https://doi.org/10.1145/3377343>

[3] Nazli Cila. 2024. Designing Human–Robot Ecologies: Beyond Utilitarian Relations. In *Designing Interactions with Robots*. Chapman and Hall/CRC.

[4] Andre Cleaver, Darren Vincent Tang, Victoria Chen, Elaine Schaertl Short, and Jivko Sinapov. 2021. Dynamic Path Visualization for Human-Robot Collaboration. In *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction (HRI '21 Companion)*, maart 2021. Association for Computing Machinery, New York, NY, USA, 339–343. <https://doi.org/10.1145/3434074.3447188>

[5] Christian Colceriu, Sabine Theis, Sigrid Brell-Cokcan, and Verena Nitsch. 2023. User-centered design in mobile human-robot cooperation: consideration of usability and situation awareness in GUI design for mobile robots at assembly workplaces. *i-com* 22, 3 (December 2023), 193–213. <https://doi.org/10.1515/icom-2023-0016>

[6] Jacob Crandall and Michael Goodrich. 2001. Experiments in adjustable autonomy. <https://doi.org/10.1109/ICSMC.2001.973517>

[7] Carla Dei, Matteo Meregalli Falerni, Turgut Cilsal, Davide Felice Redaelli, Matteo Lavit Nicora, Mattia Chiappini, Fabio Alexander Storm, and Matteo Malosio. 2025. Design and testing of (A)MICO: a multimodal feedback system to facilitate the interaction between cobot and human operator. *J Multimodal User Interfaces* 19, 1 (March 2025), 21–36. <https://doi.org/10.1007/s12193-024-00444-x>

[8] M. Desai and H.A. Yanco. 2005. Blending human and robot inputs for sliding scale autonomy. *ROMAN* 2005. IEEE International Workshop on Robot and Human Interactive Communication, 2005. (2005), 537–542. <https://doi.org/10.1109/ROMAN.2005.1513835>

[9] Mica R. Endsley. 2017. From Here to Autonomy: Lessons Learned From Human–Automation Research. *Hum Factors* 59, 1 (February 2017), 5–27. <https://doi.org/10.1177/0018720816681350>

[10] Michael A. Goodrich and Alan C. Schultz. 2008. Human–Robot Interaction: A Survey. *Foundations and Trends in Human-Computer Interaction* 1, 3 (January 2008), 203–275. <https://doi.org/10.1561/1100000005>

[11] Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Advances in Psychology*. North-Holland, 139–183. [https://doi.org/10.1016/S0166-4115\(08\)62386-9](https://doi.org/10.1016/S0166-4115(08)62386-9)

[12] Hugo Honijk. Robot (interaction) design principles. Retrieved June 1, 2026 from <https://www.sparkdesign.nl/insights/from-aesthetics-to-acceptance>

[13] Fabian Hoogendijk. 2023. Portfolio Fabian Hoogendijk - PaintPal. Retrieved March 6, 2026 from <https://fabianhdbdesign.nl/paintpal>

[14] Fleur Jansen. 2025. Designing a Robot Assistant for Professional Painters through User-Centered Design. (2025). Retrieved November 27, 2025 from <https://repository.tudelft.nl/record/uuid:79205af9-5f1f-475b-aabe-3876040fe371>

[15] Daeguk Lee, Donghun Lee, Jae Hyun Jung, and Taezoon Park. 2025. Control Modality and Accuracy on the Trust and Acceptance of Construction Robots. *Applied Sciences* 15, 21 (January 2025), 11827. <https://doi.org/10.3390/app152111827>

[16] Chaomin Ma, Chenqi Wang, and Feng Zou. 2024. Proposing a tangible interaction framework for the design of industrial robot teaching systems: Enhancing user efficiency in learning operations. June 23, 2024. . <https://doi.org/10.21606/drs.2024.823>

[17] Abdullah Al Masri, Bruno Barzellay F. da Costa, Diego Vasco, Dieter Boer, Assed N. Haddad, and Mohammad K. Najjar. 2024. Roles of robotics in architectural and engineering construction industries: review and future trends. *Journal of Building Design and Environment* 2, 1 (April 2024), 28029–28029. <https://doi.org/10.37155/2811-0730-0302-9>

[18] Muzus. 2024. Ontwerp van slimme hulpmiddelen geeft boost aan schildersbranche. TU Delft. Retrieved March 26, 2026 from <https://www.tudelft.nl/2024/io/juni/ontwerp-van-slimme-hulpmiddelen-geeft-boost-aan-schildersbranche>

[19] Jakob Nielsen. 1994. Enhancing the explanatory power of usability heuristics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '94)*, April 24, 1994. Association for Computing Machinery, New York, NY, USA, 152–158. <https://doi.org/10.1145/191666.191729>

[20] Payam Nikdel, Rakesh Shrestha, and Richard Vaughan. 2018. The Hands-Free Push-Cart: Autonomous Following in Front by Predicting User Trajectory Around Obstacles. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*, May 2018. 4548–4554. <https://doi.org/10.1109/ICRA.2018.8461181>

[21] Francisco M. Olmos-Vega, Renée E. Stalmeijer, Lara Varpio, and Renate Kahlke. 2023. A practical guide to reflexivity in qualitative research: AMEE Guide No. 149. *Medical Teacher* 45, 3 (March 2023), 241–251. <https://doi.org/10.1080/0142159X.2022.2057287>

[22] Linda Onnasch and Clara Laudine Hildebrandt. 2021. Impact of Anthropomorphic Robot Design on Trust and Attention in Industrial Human-Robot Interaction. *J. Hum.-Robot Interact.* 11, 1 (oktober 2021), 2:1-2:24. <https://doi.org/10.1145/3472224>

[23] Gert Pasman. 2003. Designing with precedents. (2003). Retrieved February 26, 2026 from <https://repository.tudelft.nl/record/uuid:f615038e-95b4-4ce9-82f0-8803caf44c1a>

[24] Jing Qi, Li Ma, Zhenchao Cui, and Yushu Yu. 2024. Computer vision-based hand gesture recognition for human-robot interaction: a review. *Complex Intell. Syst.* 10, 1 (February 2024), 1581–1606. <https://doi.org/10.1007/s40747-023-01173-6>

[25] Svenja Y. Schött, Rifat Mehreen Amin, and Andreas Butz. 2023. A Literature Survey of How to Convey Transparency in Co-Located Human–Robot Interaction. *Multimodal Technologies and Interaction* 7, 3 (March 2023), 25. <https://doi.org/10.3390/mti7030025>

[26] Leila Takayama and Doug Dooley. 2011. Expressing thought: Improving robot readability with animation principles. <https://doi.org/10.1145/1957656.1957674>

[27] Hilti USA. Jaibot Drilling Robot. Retrieved June 1, 2026 from <https://www.hilti.com/content/hilti/W1/US/en/business/business/trends/jaibot.html>

[28] H.A. Yanco and J. Drury. 2004. Classifying human-robot interaction: an updated taxonomy. In *2004 IEEE International Conference on Systems, Man and Cybernetics*, October 2004. 2841–2846 vol.3. <https://doi.org/10.1109/ICSMC.2004.1400763>

[29] Ming Zhang, Rui Xu, Haitao Wu, Jia Pan, and Xiaowei Luo. 2023. Human-robot collaboration for on-site construction. *Automation in Construction* 150, (June 2023), 104812. <https://doi.org/10.1016/j.autcon.2023.104812>

[30] Jesper van Zoest. 2026. Developing a Robot Assistant for Professional Painters. (2026). <https://doi.org/https://resolver.tudelft.nl/uuid:bc6a4b8d-83d1-41a4-82d1-8a8882126d3c>

[31] 2006. Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast) (Text with EEA relevance). Retrieved March 26, 2026 from <http://data.europa.eu/eli/dir/2006/42/oj>

[32] 2020. ISO 9241-110:2020. ISO. Retrieved December 10, 2025 from <https://www.iso.org/standard/75258.html>

[33] 2023. ESP-NOW Wireless Communication Protocol. Espressif Systems. Retrieved June 3, 2026 from <https://www.espressif.com/en/solutions/low-power-solutions/esp-now>

[34] 2023. R3 Scrub Pro - Compact Robotic Floor Scrubber. Retrieved June 1, 2026 from <https://www.lionsbot.com/r3-scrub-pro-compact-robotic-floor-scrubber/>

[35] 2023. Regulation (EU) 2023/1230 of the European Parliament and of the Council of 14 June 2023 on machinery and repealing Directive 2006/42/EC of the European Parliament and of the Council and Council Directive 73/361/EEC (Text with EEA relevance). Retrieved February 25, 2026 from <http://data.europa.eu/eli/reg/2023/1230/oj>

[36] DCU180Z - LXT 18 V Kruiwagen met nul tilbelasting. Retrieved June 1, 2026 from <https://www.makita.nl/artikel/makita-dcu180z-lxt-18-v-kruiwagen-met-nul-tilbelasting.html>

[37] Brokk 200. Brokk Global. Retrieved June 1, 2026 from <https://www.brokk.com/product/brokk-200/>

[38] HP SitePrint - Robotic Layout Solution. Retrieved June 1, 2026 from <https://www.hp.com/us-en/printers/site-print/layout-robot.html>

[39] Canvas 1200CX Drywall Robot. Retrieved June 1, 2026 from <https://www.jlg.com/en/canvas/1200cx>

[40] Burro. Burro. Retrieved June 1, 2026 from <https://burro.ai/burro/>

[41] EffiBOT, (AGV / AMR) - EFFIDENCE ROBOTICS robot autonome de manutention. EFFIDENCE ROBOTICS. Retrieved June 1, 2026 from <https://www.efdidence.com/en/effibot-2-2/>

[42] OKIBO-Smart Robots For Construction Sites. OKIBO. Retrieved June 1, 2026 from <https://okibo.com/>

[43] Betrouwbare Automatisch Geleide Voertuigen (AGV's). GO. Retrieved June 1, 2026 from <https://www.go-agv.nl/>

[44] KEWAZO LIFTBOT. Retrieved June 1, 2026 from <https://www.kewazo.com/product>

[45] strutt-ev1. Strutt NL. Retrieved June 2, 2026 from <https://eu.strutt.inc/pages/strutt-ev1>

[46] SIMATIC HMI Panels. Siemens. Retrieved June 2, 2026 from <https://www.siemens.com/nl-nl/products/simatic-hmi/panels/>

[47] iiQKA.OS2: flexibly customizable operating system for robots. KUKA Germany. Retrieved June 2, 2026 from <https://www.kuka.com/en-de/products/robot-systems/software/system-software/iiqkaos2-operating-system-industrial-robots>

[48] Google Maps. Google Maps. Retrieved June 6, 2026 from https://www.google.nl/maps/place/Ko:work/@52.3692449,4.9128175,3a,75y,25.08h,90t/data=!3m7!1e1!3m5!1srqfRwleTmnxL6aE_2rvYQ!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv_tactile%26w%3D900%26h%3D600%26pitch%3D0%26panoid%3DrqfRwleTmnxL6aE_2rvYQ%26yaw%3D25.078686!7i16384!8i8192!4m1!1m7!3m6!1s0x47c609a3b75a7395:0xb391cbe8907ee5d1!2sKo:work!8m2!3d52.369333!4d4.9128864!16s%2Fg%2F1thp75sb!3m5!1s0x47c609a3b75a7395:0xb391cbe8907ee5d1!8m2!3d52.369333!4d4.9128864!16s%2Fg%2F1thp75sb?entry=ttu&g_ep=EgoyMDI2MDYwMS4wKXMDSoASAFQAw%3D%3D

Chapter 13

Appendix

Appendix A: ISO design principles

Appendix B: Interview questions

Appendix C: HREC

Appendix D: Data

Appendix E: Project Proposal form

Appendix A - ISO principles

ISO design principles (ISO 9241-110, 9241-112 and 9241-113)

Principle	Application	Code
Suitability for the task	Robot button not visible if robot is not available	110-Ta-1
	Information about component only on request	110-Ta-2
	Remaining time and number of tasks is displayed	110-Ta-3
Self-descriptiveness	Current task is marked blue in the task bar and always visible	110-Se-1
	Completed tasks are colored black	110-Se-2
	User is guided by red markers	110-Se-3
Conformity with user expectations	Familiar vocabulary in checklist (e.g. lubricant, dosage etc.)	110-Ex-1
	Generally accepted conventions through play button like in video player and back and forward buttons like in media galleries	110-Ex-2
	Internal consistency of information presentation through elements that are always in the same place, e.g. servo motor	110-Ex-3
	System teaches user, as button on top left can be pressed or not	110-Le-1
Controllability	System guides through application, by explanation in checklist	110-Le-2
	System allows user to retry dialog steps by deselecting checklist buttons	110-Le-3
	User controls how dialog continues, since switching between tasks is always possible	110-Co-1
Error tolerance	User controls speed by pausing the robot	110-Co-2
	Dialogue windows can be closed and reopened	110-Co-3
	System prevents user from errors, as inactive elements cannot be pressed, e.g. play/pause button	110-Er-1
Suitability for individualization	Error management by indication of wrong action in checklist	110-Er-2
	Activation can be undone by confirmation of check in checklist; error correction	110-Er-3
	Possibility to select level by hint, which can be viewed, but doesn't have to be	110-In-1
	Possibility to choose between different dialog techniques by clicking Next button or directly clicking on task	110-In-2

Design principles of ISO 9241-110 related to the GUI [4].

Principle	Application	Code
Detectability	Red markings at components	112-De-1
	Blue border at current task	112-De-2
	Flashing of the next button	112-De-3
Freedom from distraction	Task-related information is distinguishable from the background	112-Fr-1
	Structuring of information by grouping the list elements	112-Di-1
	Checklist with red and green buttons for better differentiation	112-Di-2
Discriminability	Round and angular shape of buttons when displaying remaining tasks and time	112-Di-3
	Familiar vocabulary in checklist	112-Un-1
Unambiguous interpretability	Clear representation of parts through 3-dimensional view	112-Un-2
	Simple representation without unnecessary colors	112-Conc-1
Conciseness	Possible actions	112-Conc-2
	Compact alternative by possibility to click on tasks directly	112-Conc-3
	Known elements pause button and back and forward button as external consistency	112-Cons-1
Consistency (internal and external)	Position and layout of different groups always the same as inner consistency	112-Cons-2

Design principles of ISO 9241-112 related to the GUI [4].

Principle	Application	Code
Common guidance recommendations	Window can be closed and reopened on demand	13-Co-1
	Terms like <i>lubricant</i> and <i>dosage</i> are typically used by workers	13-Co-2
Prompts	Click the button that flashes, as explicit input	13-Pr-1
	Specific input prompt, as limited number of input possibilities	13-Pr-2
Feedback	Window opens after click	13-Fe-1
	Pause button becomes Play button when clicked	13-Fe-2
	Task page and button change after click	13-Fe-3
Status information	Progress of tasks	13-St-1
	Number of remaining tasks and time left	13-St-2
	Progress of the robot	13-St-3
Error management	Hint appears when checkbox is clicked	13-Er-1
	Error handling by user, clicking can be undone	13-Er-2
On-line help	Hint appears in checklist	13-On-1

Design principles of ISO 9241-113 related to the GUI [4].

Appendix B - Interview questions

Semi-structured interview questions explorative field test

General impressions:

1. Now that we have finished the tasks, what was your overall impression of working alongside the cart today?
2. During which of the tasks (transportation, sanding, painting, etc.) did you feel the cart was the most helpful, and during which was it the least helpful?
 - o Why do you think it struggled with that specific task?

Robot control & input:

3. We tried a few different ways to tell the cart where to go and what to do today. Which method felt the most natural to you while you were working?
4. Did you ever feel like you had to completely stop doing your actual job (like painting) just to manage or control the cart?
5. If the cart is moving autonomously and you need it to stop immediately, what is your first instinct on how to do that?

Robot feedback & transparency:

6. If the cart intends to move to a new spot, how should it communicate to you before it starts driving?
7. Imagine the cart gets stuck and cannot reach you. How should it communicate that error to you without being annoying?

Autonomous behaviour & mode switching:

8. How much control would you like to keep on the movement of the cart?
9. Would you trust the robot to autonomously follow you to your destination?
10. For which scenarios would autonomous behaviour help the most?

Closing

11. If could add a feature to this cart that we didn't test today, what would it be?
12. Is there anything else you want to share about your experience today that I haven't asked about?

Semi-structured interview investigation familiarisation effects with the autonomous cart

Mental workload

- Did working with the robot become easier over time?
- At what point did the controls become familiar?
- What aspects still required attention?
- Did you stop consciously thinking about the robot at any point?

Trust and predictability

- Did your trust in the robot change during the session?
- Did you feel comfortable turning your attention away from the robot?
- Did the robot become more predictable over time?


Emerging strategies

- Did you develop any tricks or shortcuts?
- Did your preferred behaviour mode change?
- Did your preferred distance change?
- Did you discover a better workflow?

Comparison with initial use

- If you compare the beginning and end of the session, what changed most?
 - What became easier?
 - What remained difficult?

NASA-TLX Questionnaire Interactive autonomy preferences user test



NASA Task Load Index (NASA-TLX) Evaluation

Cart System Workload Comparison

A previous session was found (ID: P56F8D770).
You completed 1 of 2 conditions.

Resume session
Start new session

STUDY INFORMATION

Study Title
Developing the behavioural repertoire of a robot assistant for professional painters: Interactions and autonomy preferences in a 1D workspace

Institution
Delft University of Technology (TU Delft) — Human-Robot Interaction Lab

Corresponding Researcher
Geert Hansma [REDACTED]

Responsible Researchers
Marco Rozendaal [REDACTED] & Jordan Boyle [REDACTED]

ABOUT THIS STUDY

You will be asked to rate the physical and mental workload of operating two different cart systems — a **Manual Cart** and a motorized **Autonomous Cart** — using the NASA Task Load Index (NASA-TLX). This is a standardized tool used widely in human factors research.

- ✓ Takes approximately 5–10 minutes to complete.
- ✓ You will rate 6 dimensions for each cart condition.
- ✓ The order of conditions is randomized.

PRIVACY & ETHICS

Anonymity
You will be assigned a random anonymous participant ID. No personal identifying information (PII) such as names or email addresses will be collected within this tool.

Data Storage
All data is saved locally on the researcher's computer, is never transmitted to any external server, and will be used solely for academic research purposes.

Data Deletion
All identifiable data associated with this project will be permanently deleted by August 1, 2026, in accordance with the Data Management Plan (DMP).

Voluntary Participation
Your participation is entirely voluntary. You may withdraw at any time during the test without providing a reason.

NASA Task Load Index — Hart & Staveland, 1988

Progress 1 of 2

Autonomous Cart
Manual Cart

NASA TASK LOAD INDEX
Participant ID: P56F8D770

Autonomous Cart

Move each slider to indicate your perceived workload for the **Autonomous Cart**. All six dimensions must be rated.

1 MENTAL DEMAND
How mentally demanding was the task?

Very Low Very High

+ Add comment

2 PHYSICAL DEMAND
How physically demanding was the task?

Very Low Very High

+ Add comment

3 TEMPORAL DEMAND
How hurried or rushed was the pace of the task?

Very Low Very High

+ Add comment

4 PERFORMANCE
How successful were you in accomplishing what you were asked to do?

Perfect Failure

+ Add comment

5 EFFORT
How hard did you have to work to accomplish your level of performance?

Very Low Very High

+ Add comment

6 FRUSTRATION
How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low Very High

+ Add comment

General comments (optional)

Any overall observations about this condition...

● ● ● ● ● ● 0 / 6 dimensions rated

Please move all six sliders before submitting.

Submit & Continue to Manual Cart

Progress 2 of 2

Autonomous Cart
Manual Cart

NASA TASK LOAD INDEX
Participant ID: P56F8D770

Manual Cart

Move each slider to indicate your perceived workload for the **Manual Cart**. All six dimensions must be rated.

1 MENTAL DEMAND
How mentally demanding was the task?

Very Low Very High

+ Add comment

2 PHYSICAL DEMAND
How physically demanding was the task?

Very Low Very High

+ Add comment

3 TEMPORAL DEMAND
How hurried or rushed was the pace of the task?

Very Low Very High

+ Add comment

4 PERFORMANCE
How successful were you in accomplishing what you were asked to do?

Perfect Failure

+ Add comment

5 EFFORT
How hard did you have to work to accomplish your level of performance?

Very Low Very High

+ Add comment

6 FRUSTRATION
How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low Very High

+ Add comment

General comments (optional)

Any overall observations about this condition...

● ● ● ● ● ● 0 / 6 dimensions rated

Please move all six sliders before submitting.

Submit & Finish Study

Appendix C - HREC

Informed consent forms

Informed Consent Form Field test revised 2.0

Deft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT FORM
(English Version: January 2022)

Introduction

You are being invited to participate in a Master's thesis research study titled *Developing the behavioural repertoire of a robot assistant for professional partners*. This study is being done by Gerrit Huisman from the TU Delft and is part of a project connected to the Human Robot Interaction (HRI) Lab, aimed at enhancing the pairing strategy by exploring the design of a robot assistant for professional partners.

The purpose of this research study is to explore interaction possibilities with a robot cart that assists professional partners during their work, and will take you approximately 60 minutes to complete. The data will be used for academic publications, where future robotic applications are possible for the researcher. We will be asking you to answer open and closed questions regarding how to work with the robot and act out your work actions to simulate working with the robot.

What to expect

By participating, you agree to:

- Allow the researcher to observe and document your interactions with the prototype.
- Actively engage with the prototype to evaluate its features, usability, and interactions.

Privacy & Data Handling

- Data collected may include transcripts, researcher notes, audio recordings, and, where applicable, video recordings.
- All personal data will be anonymized and stored securely in accordance with applicable data protection regulations.
- The collected data will be used solely for academic research purposes and may be included in academic publications or presentations in anonymized form.
- Access to identifiable data will be restricted to the research team. All identifiable data will be permanently deleted when the study is finished.
- Physically informed consent forms will be scanned and securely stored on the TU Delft OTC Project Drive, after which the original physical copies will be immediately destroyed.
- You have the right to request access to, correction of, or deletion of your personal data until 1 August 2026.

Risks & Safeguards

- There is a small risk of physical harm to the usability event of misuse of the prototype. However, this risk will be reduced through a clear safety briefing and supervised interaction with the prototype.

Voluntary Participation & Withdrawal

- Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to end any situation.

Reimbursement

- No financial compensation will be provided, but travel expenses may be reimbursed if applicable.

For any further information or questions, please feel free to reach out to the Corresponding Researcher: Gerrit Huisman. g.huisman@tudelft.nl or contact the Researcher: marco.konrad@tudelft.nl or contact the Researcher: marco.konrad@tudelft.nl

Explicit Consent points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated _____ or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="checkbox"/>	<input type="checkbox"/>
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="checkbox"/>	<input type="checkbox"/>
3. I understand that taking part in the study involves: <ul style="list-style-type: none"> Participating in an interactive session exploring possible ways of interacting with a robot cart. Engaging in discussions and activities guided by the researcher to evaluate and reflect on different interaction possibilities. During the session, the researcher may record audio and take notes on paper or on a laptop. Photos or videos of the interaction may also be captured for research analysis purposes. The recordings and notes will be used only for academic research purposes, including transcription and analysis of the interaction sessions. Audio, photo, and video recordings will be securely stored, transcribed or analysed where relevant, and deleted after the project is completed in accordance with the Data Management Plan (DMP). 	<input type="checkbox"/>	<input type="checkbox"/>
4. I understand that I will not receive payment for participating, but I will receive travel reimbursement if there is any travel involved.	<input type="checkbox"/>	<input type="checkbox"/>
5. I understand that the study will end by the 1 st of August 2026.	<input type="checkbox"/>	<input type="checkbox"/>
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the risks of interacting with an unknown prototype. I understand that these will be mitigated by listening to an explanation of the prototype before interacting with it.	<input type="checkbox"/>	<input type="checkbox"/>
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) about occupational role and experience, and associated personally identifiable research data (PIRD) such as personal views/beliefs with the potential risk of my identity being revealed.	<input type="checkbox"/>	<input type="checkbox"/>
8. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: Anonymous data collection, (pseudo-) anonymization, secure data storage with limited access, transcription, blurring of faces.	<input type="checkbox"/>	<input type="checkbox"/>
9. I understand that personal information collected about me that can identify me, such as e.g. my name or email address, will not be shared beyond the study team.	<input type="checkbox"/>	<input type="checkbox"/>
10. I understand that the (identifiable) personal data I provide will be destroyed after this research project is finished.	<input type="checkbox"/>	<input type="checkbox"/>

Informed Consent Form interactive cart

Deft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT FORM
(English Version: January 2022)

Introduction

You are being invited to participate in a Master's thesis research study titled *Developing the behavioural repertoire of a robot assistant for professional partners: interaction and autonomy performance in a 3D environment*. This study is being done by Gerrit Huisman from the TU Delft and is part of a project connected to the Human Robot Interaction Lab from TU Delft, aimed at enhancing the pairing strategy by exploring the design of a robot assistant for professional partners.

The purpose of this research study is to evaluate the user experience and performance control measures of a robotized robot cart within a 3D environment with digital reality. The research will take approximately 60-70 minutes to complete. The data will be used for academic publications and to inform future robotic applications or products on the market. We will ask you to participate in a series of tasks that simulate the research of pairing, using both a manual cart and a robotized cart. However, you will be asked to complete a NASA TLX workload questionnaire and answer questions during a reflective discussion.

What to expect

By participating, you agree to:

- Allow the researcher to observe and document your interactions with the prototype.
- Actively perform drawing and control tasks using a well-spaced using both a manual cart and the robotized prototype.
- Complete a NASA TLX workload questionnaire to rate your physical and mental effort.
- Participate in a short audio-recorded interview about your experience.

Privacy & Data Handling

- Data collected may include transcripts, researcher observational notes, audio recordings, photographs of your interaction with the robot, and completed NASA TLX questionnaires.
- All personal data will be anonymized and stored securely in accordance with applicable data protection regulations.
- The collected data will be used solely for academic research purposes and may be included in academic publications or presentations in anonymized form.
- Access to identifiable data will be restricted to the research team. All identifiable data will be permanently deleted when the study is finished.
- Physically informed consent forms will be scanned and securely stored on the TU Delft OTC Project Drive, after which the original physical copies will be immediately destroyed.
- You have the right to request access to, correction of, or deletion of your personal data until 1 August 2026.

Risks & Safeguards

- There is a small risk of physical harm to the usability event of misuse of the prototype. However, this risk will be reduced through a clear safety briefing and supervised interaction with the prototype.

Voluntary Participation & Withdrawal

- Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to end any situation.

Reimbursement

- No financial compensation will be provided.

For any further information or questions, please feel free to reach out to the Corresponding Researcher: Gerrit Huisman. g.huisman@tudelft.nl or contact the Researcher: marco.konrad@tudelft.nl or contact the Researcher: marco.konrad@tudelft.nl

Explicit Consent points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated _____ or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="checkbox"/>	<input type="checkbox"/>
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="checkbox"/>	<input type="checkbox"/>
3. I understand that taking part in the study involves: <ul style="list-style-type: none"> Participating in a 60-70 minute session performing abstract drawing tasks (like drawing complex and using stretch) using a well-to simulate pairing workforces. Interacting with both an unpowered manual cart and a motorized prototype. Completing a NASA TLX workload questionnaire to rate my physical and mental effort. Participating in an audio-recorded interview about my experience and control preferences. The researcher will take photographs and researcher observational notes for analysis. The recordings and notes will be used only for academic research purposes, including transcription and analysis of the interaction sessions. Audio recordings, photos will be securely stored, transcribed or analysed where relevant, and deleted after the project is completed in accordance with the Data Management Plan (DMP). 	<input type="checkbox"/>	<input type="checkbox"/>
4. I understand that I will not receive payment for participating.	<input type="checkbox"/>	<input type="checkbox"/>
5. I understand that the study will end by the 1 st of August 2026.	<input type="checkbox"/>	<input type="checkbox"/>
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the risks of interacting with and physically pushing a motorized prototype. I understand that these will be mitigated by a clear safety briefing, an explanation of the prototype's behaviour, and continuous researcher supervision during the study.	<input type="checkbox"/>	<input type="checkbox"/>
7. I understand that taking part in the study involves collecting specific personally identifiable information (PII) such as my name on this consent form, and associated personally identifiable research data (PIRD) such as my personal views and preferences on the robot's autonomy, with the potential risk of my identity being revealed.	<input type="checkbox"/>	<input type="checkbox"/>
8. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: Anonymous data collection, (pseudo-) anonymization, secure data storage with limited access, transcription, blurring of faces.	<input type="checkbox"/>	<input type="checkbox"/>
9. I understand that personal information collected about me that can identify me, such as e.g. my name or email address, will not be shared beyond the study team.	<input type="checkbox"/>	<input type="checkbox"/>
10. I understand that the (identifiable) personal data I provide will be destroyed after this research project is finished.	<input type="checkbox"/>	<input type="checkbox"/>

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the de-identified information I provide will be used for reports, academic publications, websites, or video channels related to this project. The data could contribute to product development for a robot assistant for professional partners. This information may also be shared with collaborating organizations for further research purposes.	<input type="checkbox"/>	<input type="checkbox"/>
12. I agree that my responses, views or other input can be quoted anonymously in research outputs.	<input type="checkbox"/>	<input type="checkbox"/>
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
13. I give permission for the de-identified transcripts, quotes, pictures that I provide to be archived in the TU Delft repository so it can be used for future research and learning.	<input type="checkbox"/>	<input type="checkbox"/>
14. I understand that access to this repository is open to public access.	<input type="checkbox"/>	<input type="checkbox"/>

Signatures

Name of participant [printed] Signature _____ Date _____

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name [printed] Signature _____ Date _____

Study contact details for further information:
Gerrit Huisman
g.huisman@tudelft.nl

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the de-identified information I provide will be used for reports, academic publications, websites, or video channels related to this project. The data could contribute to product development for a robot assistant for professional partners. The information may also be shared with collaborating organizations for further research purposes.	<input type="checkbox"/>	<input type="checkbox"/>
12. I agree that my responses, views or other input can be quoted anonymously in research outputs.	<input type="checkbox"/>	<input type="checkbox"/>
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
13. I give permission for the de-identified transcripts, quotes, pictures that I provide to be archived in the TU Delft repository so it can be used for future research and learning.	<input type="checkbox"/>	<input type="checkbox"/>
14. I understand that access to this repository is open to public access.	<input type="checkbox"/>	<input type="checkbox"/>

Signatures

Name of participant [printed] Signature _____ Date _____

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name [printed] Signature _____ Date _____

Study contact details for further information:
Gerrit Huisman
g.huisman@tudelft.nl

HRX checklist

I. Applicant Information

PROJECT TITLE:	Developing the behavioural repertoire of a robot assistant for professional painters
Research period: <small>(Over what period of time will this specific part of the research take place?)</small>	February 2025 – August 2025
Faculty:	ICE
Department:	Human Centered Design
Type of the research project:	Master's thesis
Funder of research: <small>(Who is funding your research? Please provide name and contact information.)</small>	N/A
Name of Corresponding Researcher: <small>(Please provide full contact details for the corresponding researcher.)</small>	Geert Havens
E-mail of Corresponding Researcher:	[REDACTED]
Position of Corresponding Researcher: <small>(Please provide the title of the corresponding researcher.)</small>	Master
Name of Responsible Researcher: <small>(Please provide full contact details for the responsible researcher.)</small>	Marco Rozendaal, Jordan Boyle
E-mail of Responsible Researcher:	[REDACTED]
Position of Responsible Researcher: <small>(Please provide the title of the responsible researcher.)</small>	Associate Professor, Assistant Professor

II. Research Overview

NOTE: You can find more guidance on completing this checklist [here](#).

a) Please summarise your research very briefly (100-200 words). What are you looking into, who is involved, how many participants there will be, how they will be recruited and what are they expected to do?

The research will look into the interaction between professional painters and a robot cart that assesses the painters with carrying their tools while working.

I will visit the workplace of the painters possibly three times. First, interviews and acting out interaction with a simple manual cart to explore interaction possibilities for the robot. For the second time, I would like to bring a functioning prototype of the interaction possibilities for the painters to interact with and interview them during/afterwards. For the last time, I would like to evaluate the final concept with the painters.

The recruitment of the painters will be done through SUSAG, who is a client company for this project. Each visit will take around 1-2 hours with a maximum of 4 painters involved at a time.

b) If your application is an additional project related to an existing approved HREC submission, please provide a brief explanation including the existing relevant HREC submission number(s).

Use your own text - please avoid plagiarism!

c) If your application is a simple extension of, or amendment to, an existing approved HREC submission, you can simply submit an [HREC Amendment form](#) as a submission through LabServer.

Area	Requirement	Compliance	Notes
1.1	Project title	Yes	
1.2	Research period	Yes	
1.3	Faculty	Yes	
1.4	Department	Yes	
1.5	Type of the research project	Yes	
1.6	Funder of research	Yes	
1.7	Name of Corresponding Researcher	Yes	
1.8	E-mail of Corresponding Researcher	Yes	
1.9	Position of Corresponding Researcher	Yes	
1.10	Name of Responsible Researcher	Yes	
1.11	E-mail of Responsible Researcher	Yes	
1.12	Position of Responsible Researcher	Yes	

Area	Requirement	Compliance	Notes
2.1	Research overview	Yes	
2.2	Additional project	Yes	
2.3	Extension/amendment	Yes	

Area	Requirement	Compliance	Notes
3.1	Risk assessment and mitigation plan	Yes	

III. Risk Assessment and Mitigation Plan

Please provide a table with a risk assessment and mitigation plan. The table should be completed by the researcher and the responsible researcher. The table should be completed by the researcher and the responsible researcher. The table should be completed by the researcher and the responsible researcher.

Risk	Impact	Probability	Mitigation
1.1	Low	Low	None
1.2	Low	Low	None
1.3	Low	Low	None
1.4	Low	Low	None
1.5	Low	Low	None
1.6	Low	Low	None
1.7	Low	Low	None
1.8	Low	Low	None
1.9	Low	Low	None
1.10	Low	Low	None
1.11	Low	Low	None
1.12	Low	Low	None

Risk	Impact	Probability	Mitigation
2.1	Low	Low	None
2.2	Low	Low	None
2.3	Low	Low	None

Risk	Impact	Probability	Mitigation
3.1	Low	Low	None

H: More on Informed Consent and Data Management

NOTE: You can find guidance and templates for preparing your Informed Consent form [here](#).

Your research involves human participants as Research Subjects if you are recruiting them or actively involving or influencing, manipulating or directing them in any way in your research activities. This means you must seek informed consent and agree/ implement appropriate safeguards regardless of whether you are collecting any PII.

Where you are also collecting PII, and using Informed Consent as the legal basis for your research, you need to also make sure that your IC materials are clear on any related risks and the mitigating measures you will take – including through responsible data management.

Get a comment on this checklist or the HREC process? You can leave your comments [here](#).

IV. Signature/s

Please note that by signing this checklist list as the sole, or Responsible, researcher you are providing approval of the completeness and quality of the submission, as well as confirming alignment between GDPR, Data Management and Informed Consent requirements.

Name of Corresponding Researcher:	Geert Havens
Signature of Corresponding Researcher:	[REDACTED]
Date:	18-05-2025
Name of Responsible Researcher:	Marco Rozendaal
Signature (for upload consent by mail) Responsible Researcher:	[REDACTED]
Date:	09-05-2025

V. Completing your HREC application

Please use the following list to check that you have provided all relevant documentation

- Required:**
- Always: This completed HREC checklist
 - Always: A data management plan (reviewed, where necessary, by a data steward)
 - Always: A complete Informed Consent form (including Participant Information and/or Opening Statement (for online consent))

Device report

Delft University of Technology INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies¹.

The first part of the report has to be completed by the researcher and/or a responsible technician.

Then, the safety officer (Health, Security and Environment advisor) of the faculty responsible for the device has to inspect the device and fill in the second part of this form. An actual list of safety-officers is provided on this [website](#).

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. Information on ethics topics, including the application process, is provided on the [HREC website](#).

Device identification (name, location): Painter assistant motorized cart, TU Delft

Configurations inspected²: NA

Type of experiment to be conducted on the device³: Driving cart that carries tools during experiment

Name(s) of applicant(s): Geert Hanisma

Job title(s) of applicant(s): MSc student

(Please note that the inspection report should be filled in by a TU Delft employee. In case of a BSc/MSc thesis project, the responsible supervisor has to fill in and sign the inspection report.)

Date:

Signature(s):

- Modified, altered, used for a purpose not reasonably foreseen in the CE certification
- If the devices can be used in multiple configurations, otherwise insert NA
- e.g. driving, flying, VR navigation, physical exercise, ...

1

2

3

4

Device inspection

(to be filled in by the AMA advisor of the corresponding faculty)

Name: Martin Haverkamp

Faculty: IDE

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical fitting, measurements for electrical safety etc.))

Date: 5-jun-2026

Signature:

Inspection valid until:

5-jun-2029

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

¹ Indicate validity of the inspection, with a maximum of 3 years.

6

Setup summary

The experimental device is a low-fidelity, motorized robot cart prototype made out of foamboard designed to assist professional painters by carrying tools and dynamically adjusting its position.

Operating strictly within a 1D linear workspace, the cart has two motors, a proximity sensor, and a wearable belt-clip remote. Participants can switch between three drive modes: continuous follow, segmented follow, and manual control (via the remote or by physically pushing the cart). The experimental setup consists of a 5 to 10-meter paper-covered wall in the IDE basement, where users will perform abstract drawing tasks to simulate painting workflows. For a comprehensive description of the device's components, interaction modes, and photos of the setup, please refer to Appendix.

Risk checklist

Please fill in the following checklist and consider those hazards that are typically present in many research setups. If a hazard is present, please describe how it is dealt with.

Also, mention any other hazards that are present.

Hazard type	Present	Hazard source	Mitigation measures
Mechanical (Sharp edges, moving equipment, etc.)			
Electrical	x	The prototype contains a microcontroller, power bank, DC motor, and sensors.	All electrical components are enclosed within the prototype housing and are not accessible to participants during operation.
Structural failure	x	The prototype consists of a foamboard enclosure, 3D printed supports, and a wooden base.	The structure is sufficiently rigid for the intended use. In the event of a failure, components remain attached to the internal frame, minimizing the risk of loose parts.
Touch Temperature			
Electromagnetic radiation			
Ionizing radiation			
Ultraviolet radiation (Lasers, IR, UV, bright visible light sources)			
Noise exposure			
Materials (Flammability, off-gassing, etc.)			
Chemical processes			
Fall risk			
Other:			
Other:			

Appendices

1. General description and context: The experimental device is a low-fidelity, functional prototype of a motorized robot cart designed to assist professional painters. For the scope of this study, it operates strictly within a one-dimensional linear workspace alongside a wall. The device is designed to carry tools and materials (e.g. stencils, pans, and reference sheets) while dynamically adjusting its position relative to the user to reduce physical and cognitive strain during painting workflows.

2. Key components: The prototype consists of two primary hardware elements: the motorized cart and the user interface (wearable remote).

• **The motorized cart:** A wheeled platform equipped with two motors made out of foamboard with a wooden base, allowing it to be moved motorized or pushed manually.

• **Sensor array:** Onboard sensors (e.g. a Time of Flight sensor (ToF)) that tracks the physical distance between the cart and the user.



Motorized cart with sensor on the front

- **Wearable belt-clip remote:** A physical control interface worn by the participant, featuring:
 - **Button A:** Triggers autonomous tracking (On/Off).
 - **Button B:** Commands the cart to drive in reverse.
 - **Rotatable dial (positionnement):** Adjusts the desired following distance (ranging from 50cm to 250cm) when in autonomous mode, or controls the driving speed when in manual mode.



Wearable remote with a clip on the back

3. Functions and interaction modes: The device operates using three distinct drive modes, which the user can freely switch between during the test:

- **Continuous follow:** The cart's sensors actively track the user and mirror their movements to maintain a constant distance.
- **Segmented follow:** The cart remains stationary until the user exceeds a specific distance threshold (e.g., 1 meter), at which point it drives forward to catch up.
- **Manual control:** The user manually drives the cart using the remote, or physically push/pull the cart along the wall with their hands.

4. Experimental setup: The test setup simulates a safe, controlled construction environment. It consists of a 5 to 10-meter stretch of flat wall located in the basement of the IDE facility. The wall is covered in paper where participants will execute abstract drawing tasks (drawing windows, tracing stencils) to simulate the physical ergonomics of painting. The robot cart operates only laterally (left to right) parallel to this wall space.



5

Data management plan

Plan Overview

A Data Management Plan created using DMPonline

Title: Developing the behavioural repertoire of a robot assistant for professional painters

Creator:Geert Hansma

Project Administrator: Jordan Boyle, Marco Rozendaal

Affiliation: Delft University of Technology

Template: TU Delft Data Management Plan template (2025)

Project abstract:

Currently an assistive robot for professional painters has been developed, but it still lacks a behavioural repertoire. In short, the robot itself is not able to be controlled yet by the painters and how it should move on the construction site. It lacks the interaction and is not able yet to communicate what it will do. I will address this challenge by developing the robot's behavioural repertoire, specifically defining its movement and multimodal communication aligned with a graphical user interface.

ID: 198104

Start date: 10-02-2026

End date: 01-08-2026

Last modified: 18-05-2026

Created using DMPonline. Last modified 18 May 2026

1 of 7

Developing the behavioural repertoire of a robot assistant for professional painters

0. Administrative questions

1. Provide the name of the data management support staff consulted during the preparation of this plan and the date of consultation. Please also mention if you consulted any other support staff.

Matty Nieten, Data Steward at the Faculty of Industrial Design Engineering, has reviewed this DMP on (date of review).

2. Is TU Delft the lead institution for this project?

- Yes, the only institution involved

I. Data/code description and collection or re-use

3. Provide a general description of the types of data/code you will be working with, including any re-used data/code.

Type of data/code	File format(s)	How will data/code be collected/generated (or re-used data/code what are the sources and terms of use)?	Purpose of processing	Storage location	Who will have access to the data/code?
Audio recordings	WAV, mp3	Recording interviews	To transcribe interviews done with participants in my study.	U Drive	The project team
Video recordings	mov, mp4	Recording of observations and interactions of the participants with a prototype.	To analyse the human-robot interaction.	U Drive	As above
Pictures	HEIC, jpg, png	Taking photos at the workplace and participants interacting with the prototype.	Photos will be used to capture the interaction between the participant and the prototype, to capture the environment of the website.	U Drive	As above
Informed consent forms	PDF	Informed consent forms signed on printed out paper.	To obtain and document informed consent.	U Drive	As above

Created using DMPonline. Last modified 18 May 2026

2 of 7

II. Storage and backup during the research process

4. How much data/code storage will you require during the project lifetime?

- < 250 GB

5. Where will the data/code be stored and backed-up during the project lifetime? (Select all that apply.)

- Project Data Storage (U:) drive at TU Delft

III. Data/code documentation

6. What documentation will accompany data/code? (Select all that apply.)

- Data - Methodology of data collection
- Data - README file or other documentation explaining how data are organised

My graduation report will include a methodology section about data collection.

IV. Legal and ethical requirements, code of conducts

7. Does your research involve human subjects or third-party datasets collected from human participants?

If you are working with a human subjects, you will need to obtain the HREC approval for your research project.

- Yes - please provide details in the additional information box below

I intend to apply for ethical approval from the Human Research Ethics Committee, but have not yet done so.

Created using DMPonline. Last modified 18 May 2026

3 of 7

8. Will you work with personal data? (This is information about an identified or identifiable natural person, either for research or project administration purposes.)

- Yes

9. Will you work with any other types of confidential or classified data or code as listed below? (Select all that apply and provide additional details below.)

If you are not sure which option to select, ask your Faculty Data Steward for advice.

- No, I will not work with any other types of confidential or classified data/code

10. How will ownership of the data and intellectual property rights to the data be managed?

For projects involving commercially-sensitive research or research involving third parties, seek advice of your Faculty Contract Manager when answering this question.

This is an internal TUD MSc thesis project.

11. Which personal data or data from human participants do you work with? (Select all that apply.)

- Proof of consent (such as signed consent materials which contain name and signature)
- Audio recordings
- Video material
- Photographs
- Job title and/or employer
- Names as contact details for administrative purposes

12. Please list the categories of data subjects and their geographical location.

Professional painters working in the Netherlands.

13. Will you be receiving personal data from or transferring personal data to third parties (groups of individuals or organisations)?

- No

Created using DMPonline. Last modified 18 May 2026

4 of 7

16. What are the legal grounds for personal data processing?

- Informed consent

17. Please describe the informed consent procedure you will follow below.

The researcher will inform the potential participants about the goals and procedures of the research project. The researcher will also inform them about the personal data that are being processed and for what purpose. All participants will be asked for their consent for taking part in the study and for data processing by signing an adapted for of the informed consent form provided by the TU Delft before the start of the interview/segment.

18. Where will you store the physical/digital signed consent forms or other types of proof of consent (such as recording of verbal consent)?

The proof of consent (digital copy of signed document) will be preserved on the TU Delft Project Data Storage (U:) drive. The original physical copies will be permanently destroyed immediately after they are scanned.

19. Does the processing of the personal data result in a high risk to the data subjects? (Select all that apply.)

If the processing of the personal data results in a high risk to the data subjects, it is required to perform a Data Protection Impact Assessment (DPIA). In order to determine if there is a high risk for the data subjects, please check if any of the options below that are applicable to the processing of the personal data in your research project.

If any category applies, please provide additional information in the box below. Likewise, if you collect other type of potentially sensitive data, or if you have any additional comments, include these in the box below.

If one or more options listed below apply, your project might need a DPIA. Please get in touch with the Privacy team (privacy@tudelft.nl) to get advice as to whether DPIA is necessary.

- None of the above apply

23. What will happen with the personal data used in the research after the end of the research project?

- Other - please explain below

Personal research data will be destroyed after the end of the research project (01-08-2026).

24. For how long will personal research data (including pseudonymised data) be stored?

- Personal data will be deleted at the end of the research project

The end of the research project will be 01-08-2026.

25. How will your study participants be asked for their consent for data sharing?

- In the informed consent form, participants are informed that their personal data will be anonymised and that the anonymised dataset is shared publicly

V. Data sharing and long term preservation

27. Apart from personal data mentioned in question 23, will any other data be publicly shared?

Please provide a list of data/code you are going to share under 'Additional Information'.

- All other non-personal data/code produced in the project

In my graduation project, the following data will be shared:

- Interview insights
- Results and insights of co-creation sessions with students and painters
- User study insights about interaction possibilities between a robot and a painter

29. How will you share research data/code, including those mentioned in question 23? Select all that apply and provide additional details below.

- I am a Bachelor's/Master's student at TU Delft and I will share the data/code in the body and/or appendices of my thesis/report in the TU Delft Repository

Created using DMPonline. Last modified 18 May 2026

6 of 7

- < 100 GB

31. When will the data/code be shared?

- At the end of the research project

32. Under what licence(s) will the data/code be released?

- CC BY

VI. Data management responsibilities and resources

33. If you leave TU Delft (or are unavailable), who is going to be responsible for the data/code resulting from this project?

M: My co-creators are: Marco Rozendaal [redacted] and Jordan Boyle

34. What resources (for example financial and time) will be dedicated to data management and ensuring that data will be FAIR (Findable, Accessible, Interoperable, Reusable)?

None, I will handle the data myself using resources provided by TU Delft.

35. Which faculty do you belong to?

- Faculty of Industrial Design Engineering (IDE)

Created using DMPonline. Last modified 18 May 2026

7 of 7

Appendix D - Data

Data explorative field test

Notes:

Screen is not necessary Didn't use joystick Following a person is useful It should be able to move away when another person is walking on the gallery Platform should be as big as the top area of the robot Platform shorter ledge Button clip on your belt is really useful There should be space inside the cart that heats up your epoxy at the right temperature Being able to charge your batteries inside the cart Behind or in front of you while painting is not important It should be less wide, someone should be able to pass it on a gallery A construction lamp would be really useful Talking to it wouldn't work on a loud construction site A remote you can hold and keep with you to control follow and stop would be ideal. When arriving people immediately asked if it was going to replace them or that they won't live to see it anyway

Transcript:

"Push cart as a fallback if it breaks"

"1.5m distance when following autonomously, with auto stop"

"Send it to another person"

"I trust the following, I wouldn't push it"

"It should follow behind me, not next to me"

"It is too wide, people cant walk past it"

"It should have tracks instead of wheels"

"That would solve the shaking"

"Useful to put putty bucket on the plateau when doing the ceiling"

"Only for the ceiling thats useful"

"Being able to put your batteries in it would be useful"

"Also lamps for when its dark"

"All the blue area is not necessary for a painter"

"As a moveable power source it would be great"

"The moving plateau is not necessary"

"It is primarily useful while doing epoxy, you carry a lot of stuff"

"With painting it is not so useful, you can just hold a small can of paint"

"If you move while painting, it should wait till a certain distance, wait a bit"

"I see it more like a transportation cart for tools, not for paint"

"You cut put a big paint bucket on it, but then it would topple"

"With sanding and masking the cart following you would be nice, you got everything with you"

"While painting you just hold your small can of paint"

"For carpenters it would be way more useful, they have a lot of stuff"

"If you would ask me I would just use it as a transportation device for your tools"

"You could charge your batteries for your sanding machine"

"The plugs on the back are a plus"

"Putting your caulk on it would save a lot of time, if would follow behind me, that's ideal"

"You do need some space, so constantly following you it is not needed"

"It should not be constantly next to you, when you step to the side it should wait a bit"

"A button is not always the best option, but being able to clip it to your belt is ideal, you could press it to come closer"

"It should be a meter behind you, it need to get something and I turn, then it shouldn't hit you, I don't want to be scared of it"

"Constantly looking at it only makes me lose time"

"The moving plateau is definitely useful"

"The space inside should be bigger, with one big paint bucket it is full already, should be way more efficiently designed"

"A heating element for epoxy and caulk inside the cart would be ideal"

"Now the door of the hinge, it shouldn't even have a name"

"The inside should be insulated"

"The platform should be as big as the cart surface area, bigger"

"With caulking you have a lot of stuff, caulking gun, caulknives, mixing epoxy"

"The edge of the plateau is too high, a small ledge is good enough"

"Repairs with epoxy are often down low, but sometimes it is also high up so then the plateau raising would be useful"

"With masking you could also raise the platform, so you can get your stuff more easily"

"It should carry all your tools, small stuff useful when filling in holes"

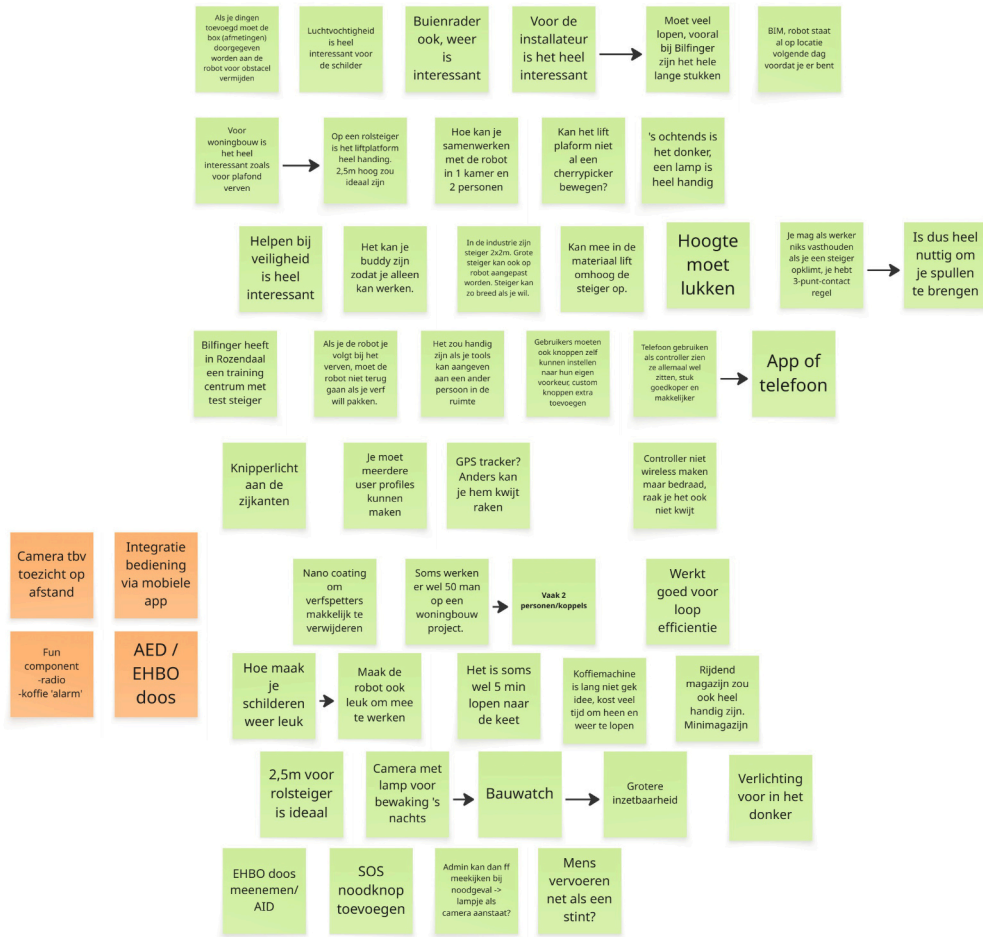
"The heating element is really a good idea for when its colder, that would really be ingenious"

"It is too wide, it also could be a bit longer, keep it within 60-70cm"

"People should be able to pass it on a gallery"

"The button should be put away on the outside, so you can't break it when it hits something"

Data stakeholder and user feedback session



Data Interactive autonomy prefereces user test

Participant ID: PE65299FC

Audio: Test 1

Date: 26-05-2026

Notes:

I have trust that it won't ram me.

It nice that there is sound, not like a silent electric car that you can't here approaching. With the sound that it makes you know where it is.

Busier cognitively to get it to reverse.

Transcript:

Wat vond je er van?

Ik merkte wel verschil tussen de twee en ik merkte dat ik ook mn aanpak kon aanpassen gebaseerd dat er een robot achter me aanzit. Want die met de manual ik doe het per raam de opdrachten, en met de autonomus zit ik toch al in de flow om het sneller te doen omdat ie toch achter me aan gaat. Was wel, misschien omdat ie nieuw is was het cognitief wel drukker om hem achteruit te krijgen was ik daar wel meer over na aan het denken, dat was wel wat meer moeite, voor de rest ging de autonomus wel iets gemakkelijker.

Had je gevoel dat je er controle over had?

Ja! Ik had wel echt vertrouwen in, ik hoorde op de achtergrond de robot achter me aan rijden, en dat werkte wel echt heel goed. Dus in dat was wel een hoop vertrouwen. In een rechte lijn natuurlijk.

Wat was je tactiek?

Bij de automatische heb ik eerst alle kleuren gedaan in volgorde en dan weer terug met de vormpjes en dan weer heen met de cijfers. Bij de manual ging ik het per raampje doen, ik merkte dat dat iets langzamer was.

Had je het gevoel dat het ook minder zwaar was?

De handmatige kar staat nu op een oppervlakte die makkelijk rolt, dus kost het niet veel moeite, maar ik kan me voorstellen als je op een grindpad ofzo staat is dat veel zwaarder en dan ben ik blij dat ik geen kar hoeft te sjouwen, maar deze testopstelling is natuurlijk de perfecte ondergrond voor rollende kar, dus dan kost het rollen van de handmatige kar evenveel moeite als de automatische kar.

Had je ook het gevoel dat je meer de tijd had om te kijken naar wat je aan het doen was, meer focus op je opdracht?

Ja, met de automatische kar had ik meer aandacht over voor de opdracht dan met de handmatige kar. Bij de handmatige moest je steeds een extra stap uitvoeren, en bij de automatische hoefde ik niet steeds naar links te kijken van oh waar is die kar en nu moet ik die nu weer meetrekken, bij de automatische was dat niet het geval.

Had je het gevoel dat je steeds naar de knopjes van de afstandsbediening moest kijken?

Nee, op een gegeven moment snapte ik wel waar welke knop was. Maar dat kwam ook omdat we een test run hadden gedaan. De knopjes snappen was geen probleem. Groot genoeg en op een prima locatie ook.

Wat voor dingen had je ingesteld, wat vond je fijn?

Ik had de continuous mode aangezet, en dan de kleinste afstand (50cm) want ik heb niet hele lange armen. Eigenlijk had ik nog liever gehad dat de afstand nog kleiner had kunnen zijn, maar misschien door veiligheids redenen kan dat niet korter? Ik had liever nog 20cm qua afstand willen hebben, dan had ik geen stap terug meer hoeven doen om iets te pakken.

Heb je de modus van de robot ook aangepast tussendoor?

Ik heb het niet aangepast, de hele tijd op de kortste afstand gezet, dat werkte goed.

Had je niet de neiging om de robot zelf terug te duwen, ipv steeds de knop te gebruiken?

Nee niet gedaan, ik dacht als die coole functie er is ga ik die ook gebruiken.

En werkte dat ook wel goed?

Ja dat werkte wel goed. Het duwen is zwaarder dus dan gebruik ik liever de knop op de afstandbediening. En ik kon het op gevoel automatisch doen, dan ging ik met mn linkerhand de knop indrukken en met mn rechterhand op hetzelfde moment nog ff verder met de opdracht.

Kon je dat wel doen mentaal, die twee dingen tegelijk?

Ik denk dat je dat heel vaak doet, dan kan dat heel makkelijk ja. En nu ging het eigenlijk ook best wel simpel.

En kon je dan ook daardoor meer focussen op de muur?

Ja ik kon wel meer focussen op mn vormpjes tekenen, dat helpt wel.

Wat vind je van de controller?

De controller heeft een aantal dingen die ik heel verwarrend vindt. Bijvoorbeeld de labels bovenin, die zijn heel erg perfect gealigned met de knoppen eronder, ik dacht dat de knoppen speed en distance deden, terwijl het de draaiknop ervoben is. De rechterknop is pauzeren, maar dat is alleen pauzeren voor de laatste twee modussen en dat heb je opzich daaronder op het label staan. Maar ook als ik hier zo sta kijkend richting de muur en de robot links of rechts van mij, dan zegt zo'n pijltje onder de knop mij echt totaal niks, want het gaat de compleet andere kant op, dat is een beetje verwarrend. De pijlen kloppen in de meeste gevallen niet met de oriëntatie waarin ik sta. De pijlen zijn een beetje verwarrend.

Werkte de modus veranderen door de twee knoppen inhouden wel goed?

Ja! Dat was best nice. En opzich zijn het niet zoveel modussen dat je daar helemaal doorheen moet scrollen, en ik vind als de afstandbediening zo hing aan mn broek, zijn de knoppen groot genoeg om zo te voelen, qua grote is het wel heel nice. De draaiknop zit misschien zo een beetje onhandig, maar ik snap het ook anders gaan mensen het misschien aanstoten.

Wat vind je van het dashboard op het scherm?

Het scherm is wel echt goed, dat is echt heel duidelijk. Daar heb ik geen op of aanmerkingen over.

Zou je ook modus wisselen door op het scherm te swipen?

Ja, als ie dichtbij is wel ja, als ik al ga multitasken heeft dat geen nut.

Keek je wel eens naar het scherm, was het goed te zien?

Bijna niet, want ik dacht ik ga zo snel mogelijk mn taak uitvoeren maar toen ik het aan het begin aan het instellen was was het wel een heel goed duidelijk overzicht voor wat ik nodig had. Het is niet te klein en het is ook niet teveel informatie dus het is gewoon heel overzichtelijk. Bijvoorbeeld die snelheid meter, zou ik er bijna geeneens meer opzetten, want dat boeit me niet.

Je had niet het gevoel dat je andere modussen had.

Nee, ik heb eigenlijk alleen maar gebruik gemaakt van die continuous omdat dat soort van ja dat waren alle functies in een, ik kan hem nog steeds naar achter doen. Ik vind het eigenlijk heel chill dat er een korte afstand zit tussen mij en dat ding, het mag zelfs nog wel wat kortere afstand.

Je had er ook wel vertrouwen dat ie je volgde?

Nee, dat kwam ook wel door dat geluidje (van de motors) want ik wist daardoor waar de robot dan ongeveer in de ruimte was, dat was wel nice.

Participant ID: PD9C23AB1

Audio: Test 2

Date: 26-05-2026

Notes:

Je doet als schilder wel verf dopen in iets natuurlijk. Dus dan loop je vaker terug om te dopen. Ipv de stift die het oneindig doet.

Ik vind het fijn om de controller helemaal zelf te houden

Het volgen is best chill eigenlijk

Met vieze handen hoeft je dan niet aan de kar te zitten

Met segmented mode zit er veel onverwachtheid in.

Er zou reliëf in de knop moeten zitten zodat je het verschil kan voelen.

Feedback op de controller zou fijn zijn, schermpje of schuifknop slider om de modussen te switchen. Er zou ook een emergency knop op moeten zitten, zodat je weet dat je altijd kan stoppen. Er zijn wel teveel opties.

Er moet meer feedback op de controller.

NASA-TLX comments:

Manual Cart - Frustration - De kar is een sta in de weg en de wielen draaien waardoor de kar uit koers raakt.

Autonomous Cart - Frustration - Het gebruiken van de verkeerde knop, dat de kar achteruig ging in plaats van vooruit.

Autonomous Cart - Mental Demand - Het gebruik van de afstandsbediening vereist wat oefening/ervaring. Ik denk dat als je dit gewend bent de mental demand lager zal zijn.

Autonomous Cart - General - Ik houd graag de controle in het proces, of wil weten wat de kar van plan is om te gaan doen. Ik wil bijvoorbeeld weten wanneer hij gaat rijden.

Transcript:

Wat vond je ervan, was het een beetje te doen?

Ja, ik vond het goed te doen inderdaad. Ik vond de autonome kar wel een stuk fijner omdat je dan niet de hele tijd belast bent omdat je steeds de

handmatige kar moet verrijden. Minder fysieke belasting. De mentale belasting ligt wel wat hoger. Dat komt omdat je hebt drie modussen, en dan moet je zeker aan het begin er goed over nadenken over welke je gaat gebruiken en dan voelt de manual modus het veiligste waarin niks echt mis in kan gaan. Dan is het alleen vooruit achteruit, dat had ik dan ook een paar keer fout dat ik het verkeerde knopje indrukte, ik zat al te denken misschien omdat die knopjes heel erg op elkaar lijken. Misschien zou je het uiterlijk van de knopjes iets kunnen aanpassen. Dat de knop het reliëf van een pijltje heeft, zodat het kan voelen, of dat de knop de vorm van een pijl heeft, ik zeg maar wat. Of dat ze misschien net anders van kleur zijn. Dat je ze soort van, als je dus ook andersom aan je broek hangt dat je niet bezig bent met wat was links en rechts, maar dat je weet ohja groen vooruit, rood achteruit. Ik miste ook een feedback in welke modus die zit op de afstandsbediening. Ik kan me voorstellen dat als de kar ver weg is dat je het scherm niet meer kan zien dat dat ook lastig is. Feedback op de controller over de modus zou fijn zijn. Ik vond het indrukken van beide knoppen en dat je dan door zo'n menu heen gaat wat omslachtig, ik denk dat het mijn voorkeur zou hebben als er gewoon een heel simpel schuifknopje zou zitten dat ik gewoon met mn vinger zo kan sliden 1 2 3 op de afstandsbediening zelf en dan heb je meteen feedback van oh hij staat helemaal links of in het midden of rechts dat je dat dan ook nog kan voelen als bevestiging.

Qua feedback op de controller, wat zou je fijn vinden?

Qua feedback zou ik vooral willen weten in welke modus die zit, met zo'n schuifje of met een klein schermje. Waar ik ook nog over na zat te denken. Om dit moment heb ik nu dat segmented modus niet heb gebruikt omdat ik het gevoel had dat ie dan vrij plotseling ging rijden. Ik vind het wel fijn als ik weet wanneer die kar iets gaat doen.

Je vond het dus vrij onverwacht wat de kar ging doen in segmented mode?

Ja! Ik kan me zo voorstellen als die kar eerst bijvoorbeeld eerst een klein signaal afgeeft of de afstandsbediening een trilling geeft, iets van feedback, dat je weet van oh nu gaat er iets gebeuren. Dan weet je wat ie gaat doen en waar die mee bezig is. Want nu kun je het eigenlijk alleen aan dat scherm zien en het is wel fijn dat je weet van oh hij gaat nu beginnen met rijden. Een klein geluidje en dan komt ie.

Op het laatst ging je toch de volg modus testen, wat vond je daarvan, had je het gevoel dat je er controle over had?

Ja, ja vond ik wel het ging opzich best prima.

Had je ook het gevoel dat je meer focus op de muur kon houden met de autonome kar ipv de handmatige kar?

Ik dat dat bijna hetzelfde was, want ik was wel de hele tijd aan het checken waar is de robot nu. Maar is denk dat er ook een stukje gewenning in zit. Dat op het moment dat je het al een aantal keer gedaan hebt dan weet je van wat ie doet enzo en nu was het nog wel even testen

Had je het gevoel dat je controle had over de robot?

De autonome robot gaat opens rijden, dat je in het begin denkt van gaat ie niet ineens tegen mij aan ofzo of iets dergelijks. In mn hoofd denk ik dan misschien rijdt ie dan opens een stellage af. Ik denk dat, misschien heb ik dan ook iets van een stopknop nodig. Op een gegeven moment stond ik niet meer helemaal goed in het bereik van de sensor, en ik kan me wel voorstellen op het moment kan zijn dat er iets niet goed is of dat er verf over de sensor zit en dan rijdt dat ding mij voorbij, dan moet ie gewoon stoppen en dan heb je de pauze knop, maar misschien moet er een emergency knop op, wat nog wel beter zou zijn, niet geïntigreerd in de basis functies maar gewoon een eigen knop. Bijvoorbeeld hier, dit is nu de draaiknop, maar stel je voor dat je hierop ook nog een klein drukknopje hebt waardoor die altijd stop, waardoor je als mens altijd autoriteit heb over de robot. Je wil weten wat ie doet, en op het moment dat het niet zo gaat als ik wil, druk ik op een knop en stop.

Wat vond je van het dashboard scherm?

De plaatjes van de modussen vond ik goed gekozen. Tussen de target en de distance getallen zou ik soms te twifelen van waar moet ik nou naar kijken. Ze zijn allebei in centimeters. Maar ja, je zag dan wel wat er veranderde als je aan de draaiknop draaide.

Was het wel duidelijk te lezen en keek je er wel een paar keer na?

Ja ik heb er wel naar gekeken. Zeker met het afstand regelen keek ik er wel naar, want dat was de enige feedback die je krijgt. De snelheid regelen is een beetje onduidelijk.

Heb je ook naar de verticale bar aan de linkerkant van het scherm gekeken?

Ik heb daar niet naar gekeken. En hier heb ik ook niet naar gekeken (de snelheid meter van de robot).

Voelde het een beetje natuurlijk werken met de robot?

Ik vond wel dat ik heel veel moest nadenken ja. Omdat ik het gevoel heb voor iets relatiefs simpels, namelijk een karretje met spullen ineens wel heel erg veel opties had. Het zou iets eenvoudiger mogen denk ik. En als er meer feedback in de afstandsbediening zit dat mist nog het meest, daar zou ik nog even naar kijken.

Nog andere laatste dingen?

De handmatige kar ging steeds uit koers door die draaiende wieljes, en dan moet je weer kracht gebruiken om dat ding weer recht te laten rijden, omdat ie steeds uit koers raakt. Het is veel meer gehannes de handmatige kar. En dan is het wel fijner dat die autonome kar dat wel gewoon goed doet.

Participant ID: PB7F9F506

Audio: Test 3

Date: 26-05-2026

Notes:

Distance should be shorter.

Especially with the numbers task the autonomous cart is easier. With the manual it is more of a burden.

NASA-TLX comments:

Manual Cart General - I did feel more tired walking around.

Autonomous Cart - General - Good to have it following me like a companion, also I felt cool to paint by one hand and control the card by the other.

Transcript:

What do you think of it?

I do feel like after doing the manual one, if I feel more out of breath, more tired than the autonomous one. Also, like for the task 2 (scribing the shapes on the wall) I wanted to put the cart in the middle. I feel that that is also troublesome to walk around it. I wanted to put the manual cart in the middle of the space, so I could just walk around it and walk less from side to side, instead of walking back to the beginning all the time. Then I thought I would walk less. I walked way more with the manual cart

What was the difference then with the autonomous cart?

It follows me there, and then I can directly take another pen and walk the same way back with the cart and with the manual cart I need to walk back first to get a pen. I tried to move the manual cart with one hand but it is heavy to be honest.

What was the burden of the autonomous cart?

It did not take a lot of effort. With one hand I press the buttons and with the other I could hold the pen. I feel like that it does not cost much energy and I feel cool to put my hand here on the remote and press it and controlling things.

Did you feel like you could pay more attention to the wall with the autonomous robot?

To be honest, I think more focus on the wall, because once I am familiar with how to control the cart I don't have to look at it, I can just feel the button and I know left is backwards and right is forwards so. So yeah I can focus more on the drawing, after some time when I get familiar with the remote.

How do you feel about the remote? What did you think of it, did you understand it?

It was pretty clear. Sometimes with holding the two buttons it would trigger something else first, but it is not a big deal. Overall it is pretty clear.

Did you feel in control of the autonomous cart?

Yeah, but one thing is the speed. When I hold the reverse button it should go a bit faster

Are you comfortable with the distance?

I think the distance is fine.

Did you change the distance a lot?

I changed it once, when I noticed that one of the pens on the robot was a little bit far from me I changed it from 60cm to 50cm distance. I think it can even be more closer.

Did you use different modes?

Yeah at first I used the manual mode. With the manual mode I can just let it come to me and directly change the pen.

Did you like the following mode more than the manual mode?

Yeah I think so. Well its because I feel like I don't need to walk as much and it makes me feel something is accompanying me to finish my work, but the only issue is that I need to press a button to make it go backwards. It does not go back on it self.

And the workflow you used with one hand on the remote and one hand painting?

Yeah that was good, its interesting. I don't need to much effort to do that.

And with the manual cart?

With that one I feel like I always need to take care with it, first I feel like I hold the pen in my hand and the other hand on the cart trying to drag it with me but it is heavy and inconvenient so I just let it go and let it stay there. So I am walking more.

What did you think of the dashboard screen?

Not really, only to check if the following mode is on or off. It was pretty clear. Also reading the target distance. I did not switch modes on the screen.

Do you have any other comments?

I just feel like one hand presses the button and the other hand painting is really cool! I think that's cool.

Participant ID: P507BEB28

Audio: Test 4

Date: 26-05-2026

Notes:

Knoppen lijken teveel op elkaar

Ik wou graag sturen

Beide knoppen indrukken is eng omdat je daar ook andere dingen mee bediend.

Geluid van de motors was heel fijn, want dan wist je wanneer de kar er aan kwam.

NASA-TLX comments:

-

Transcript:

Wat vond je er van?

Ik weet niet, bij die automatische kar wat ik wel fijn vond is dat ie de hele tijd bij je bleef. Na een tijdje deed ik hem wel op manual mode zo dat ik hem zelf een beetje heen en weer kon rijden.

Had je er wel een beetje controle over?

Ja eerst wel, en ook met dat geluid dat je dan hoort van hij is nu naar me toe aan het rijden dat gaat goed. Ik vond het ook fijn dat ie gewoon recht reed en niet zoals de handmatige kar die moest je echt recht houden, die bleef niet in een rechte lijn rijden daar moest je echt wat meer over na denken. Dat ging bij de autonome een stuk makkelijker om hem echt bij je te houden. Ipv de handmatige die je steeds vast moest houden.

Had je ook het idee dat je meer kon focussen op je taken?

Ehm, ik denk wel dat ik bezig was met bijhouden dat de autonome kar niet iets raar deed met het geluid enzo en ik had de controller dus dan dacht ik is dit nog wel de handigste mode waarin ik zit terwijl bij die handmatige kar daar weet je gewoon die gaat niet tegen je aan rijden of iets raar doen. Dus ik denk in dat opzicht dat ik er wel daar wel mee bezig was tijdens mn taken en bij de handmatige kar was ik er veel meer mee bezig tijdens het lopen. Ik vond het wel fijn dat de autonome automatisch met je mee reed. Dat had ik met de handmatige kar ook gedaan, ik dacht dat is makkelijk maar had misschien niet altijd gehoeven. Ik heb het gevoel dat ik qua afstand wel ongeveer hetzelfde heb gelopen.

Welke workflow heb je gebruikt?

Mn idee was eerst een kleur dan ga ik daar mee tekenen en daarna de andere kleur, dan hoef je niet de hele tijd te switchen, of dat goed werkte mwaah. Ik had hem eerst in automatisch volgen mode en toen weer in manual en deed ik hem gewoon heen en weer laten rijden. Dat werkte opzich wel. Maar het had opzich fijner geweest als ik dat niet had hoeven doen.

Wat vind je van de controller zelf?

Ik moest er wel even aan gewend raken, vooral omdat er dus twee knopjes zijn die best wel veel functionaliteiten hebben. Ik wou ook heel graag sturen maar dat kan niet. En ook ik moest er even aan wennen dat ie alleen maar naar voren en naar achteren kon. Ik vond het niet zo fijn dat je modussen kon switchen door ze in te houden terwijl die ook de besturing doen, dat voelt voor mij een beetje eng. Het is niet alsof je het stuur van je auto moet draaien om je radio op een andere zender te krijgen, dat voelt eng. Maar toen ik het wat beter had gelezen en jij ook wat tips gaf snapte ik het ongeveer wel. Nee ik vond het wel logisch dat er twee knopjes zijn van naar voren en naar achteren, maar dan zou ik die verticaal onder elkaar zetten van naar voren en naar achteren. Ik vond het ongemakkelijk om die mode te switchen. De draaiknop, moest ik wel ff nadenken.

Ik zag je ook een paar keer de kar gewoon duwen?

Dat was wel intuïtief opzich, maar dat was dan ook opzich dat ik eigenlijk wou dat ie ook naar achteren reed. Maar dat is natuurlijk onhandig want dan kan je er niks van afpakken. En dan voel het terugduwen toch wel intuïtiever dan op het knopje drukken om de kar even naar achteren te laten gaan.

Was het ook handig dat de afstandsbediening in je broekzak zat en blind kon besturen?

Ik denk dat ik dat wel deed na een tijdje. Ik wist na dat ik op een knopje had gedrukt wat die deed en daar hield ik mn vinger dan zodat ik wist wat die deed. Het is vooral ook fijn dat ie recht rijdt. Ik hoefde me geen zorgen te maken van oh hij gaat nu tegen een muur aanrijden ofzo. En je hoeft natuurlijk alleen naar voren en naar achteren met twee knopjes dat is vrij simpel. En die snelheid heb ik volgensmij ook nooit aangepast, ik had hem gewoon op het hoogste gezet. De afstand heb ik wel een paar keer aangepast maar ik vond het eigenlijk het fijnst dat ie zo dichtbij mogelijk bij me bleef.

Was het dichtbij genoeg?

Ja ik denk dat als je het nog dichterbij gaat doen dat je er tegenaan gaat lopen. Want ik had hem volgensmij op 50cm gezet, dat was het laagste. Ik snap dat dat misschien nog te kort is maar voor mij zou nog dichterbij irritant zijn, dat ie dan tegen je arm aan komt etc. Ik had hem de hele tijd op 50cm afstand gezet en ook een keertje groter maar dat vond ik niet fijn.

Wat vond je van het scherm zelf?

Ik keek ernaar als bevestiging of ik de instelling goed had gezet. En een paar keer om de afstand aan te passen omdat ik daar ook een beetje mee aan het spelen was. En ook om te checken om te kijken of ie wel deed wat ik wil door op de knopjes te drukken.

Was het duidelijk wat er gebeurde op het scherm?

In het begin denk ik niet helemaal. De modus switchen op het scherm was uiteindelijk wel duidelijk toen ik eenmaal door had wat het deed. Het is

fijn als ie naar je toe rijdt en ziet dat ie ook echt stopt bij 50cm met de target en distance getalle op het scherm, en toen vertrouwde ik dat en dacht ik okay nu gaat het gewoon goed en toen keek ik er niet meer zoveel naar. Het was als een bevestiging of dat de instellingen die ik probeerde in te stellen ook goed werkte.

Je zei ook dat het geluid fijn was?

Ja dan wist ik van okay, nu is die aan het rijden. Het geeft je een soort van bevestiging van nu is ie achter me aan aan het rijden. Zonder geluid had ik er wel steeds naar gekeken. Toen ie even wat vreemds deed keek ik ook naar het scherm van wat ben je aan het doen.

Wat vond je van het de opdrachten doen met de normale kar?

Ik vond het echt heel irritant ik wou er zo aan trekken, zoals ik ook de autonome kar steeds bij me had, maar dan rolt ie de verkeerde kant op dus je moet hem wel echt netjes op een pad houden, vrij irritant. Terwijl bij de autonome hoefde dat niet, die ging gewoon vooruit en dan bleef ie op de goede plek. Dat was wel fijn. Tijdens het verplaatsen was de handmatige heel irritant, maar toen ik hem niet verplaatste was dat wel prima.

Participant ID: PBCB09F4B

Audio: Test 5

Date: 27-05-2026

Notes:

Eigenlijk altijd dichtbij, ingesteld op 50cm, niet meer dan dat.

Terugduwen werkt goed.

Zou fijn zijn dat die ook zelf naar achter kan gaan.

Dr zou een thuis knop op moeten zitten. Als je daar op drukt gaat ie terug naar zn begin punt. De reverse knop inhouden duurt lang.

Het fysiek duwen van de kar is chill

Met de manual kar wissel je veel vaker van tools.

Het geluid is chill.

Er zou een terug naar thuis knop moeten zijn.

Icoonjes po de knoppen zou fijn zijn. Matchend met het scherm.

Er moeten eigenlijk maar drie knoppen zijn: Kom naar me toe, ga weg of blijf staan

Op de draaiknop kunnen drukken om iets aan te geven zou ook chill zijn.

NASA-TLX comments:

Manual Cart - Mental Demand - second time, and I did not need to learn the controls of the robot

Manual Cart - Physical Demand - Moving the cart myself well it was heavier as the robot

Manual Cart - Frustration - I did knew better what to expect then for the robot

Autonomous Cart - Mental Demand - Had to learn how the robot works

Autonomous Cart - Physical Demand only - when moving it back, and it was lighter

Autonomous Cart - Frustration - moved to me but not back, which was what I hoped

Transcript:

Wat vond je ervan?

Bij de robot vond ik het fijn dat ie de hele tijd achter me aan ging en dat ik steeds een tafel had waar ik bij kon, dat was met de handmatige kar niet zo, ik merkte dat ik daardoor me niet gelimiteerd voelde van laat ik nu deze dingen doen hier en ik kon wat vrijer rondlopen. Ik was wat vrijer in mn taken. Ik dacht van ik heb geen zin om de handmatige kar steeds mee te sleuren dus dan doe ik wel eerst hier alles en dan de volgende doe ik daar alles. En bij de automatische kar dacht ik van ik heb nu deze pen vast dus laat ik alles met deze pen doen en dan daarna de rest, zo kon ik iets meer taak voor taak werken, ipv alles op een plek volledig doen eerst en dan weer naar de volgende. Ik was wat vrijer in mn beweging. Met de robot moest ik wel iets meer nadenken over de controls. Bij de handmatige kar weet je hoe het werkt, er is niet heel veel onverwachts, dus daardoor was dat wel makkelijker.

Vertrouwde je de automatische robot/kar?

Het volgen vertrouwde ik wel! De eerste dacht ik wel, hij komt wel redelijk snel op me af, maar daarna merkte ik wel dat ie stopte dan geloof ik het wel. Het tempo was ook wel goed, niet te snel, het piepje van de motors was fijn, van wanneer je hem niet ziet dan weet je dat ie stopt. En voor de rest, de controller snapte ik pas toen het werd uitgelegd. Maar van nature denk ik niet. En ook je hebt de controller hangt natuurlijk naast je en de iconnetjes maken duidelijk wat ie doet maar die zie je dan niet. Dus ik moest ff denken wat was het ook alweer en dan deed ik ff de controller omhoog om te kijken, je zou eigenlijk willend dat dat niet nodig is. Dat er een visuele hint is. Of dat de ene een knop is en de andere een andere manier van interactie zodat je het verschil wat beter weet. Dat je ze makkelijker uit elkaar haalt. Bijvoorbeeld, dit was pauze en dit is voor achtervolgen, je zou bijvoorbeeld eenje kunnen hebben dat je het kan duwen, een verschillende beweging van de andere knop.

Miste je ook wat op de controller?

Dat je een soort van thuis knop hebt, een zero punt, dat de robot weer terug naar z'n thuis/beginpunt gaat. Ik miste dat als ik de afstand groter maakte terwijl ik dichtbij was, dat de robot dan stil bleef staan ipv achteruit ging om die afstand te houden. Het voelde voor mij een logische manier om hem weer terug te banen. De eerste keer deed ik de afstand groter maken en toen bleef ie stil staan, hij ging niet naar achteren om die afstand tussen mij te maken. Ik zou eigenlijk willen dat ie luistert als ik de afstand groter maken dat ie dan ook weer wat afstand van mij neemt. Wat ik heel fijn vond, ik merkte dat ik de robot dichtbij me wou hebben om steeds dingen te pakken, maar dat ik ook soms terug moest lopen en dat ik dan hoopte dat de robot dan automatisch ook terug ging. En dan zou ie op een wat verdere afstand moeten zijn dan wat ie normaal is. Je wil eigenlijk als ik terugloop die ie eigenlijk een sprongetje naar achteren doet en daarna op mijn tempo terug rijdt.

Het enige probleem is dan, wanneer blijft de kar staan om spullen te kunnen pakken en wanneer rijdt de kar terug?

Ja dat is een lastige. Misschien een losse knop toevoegen van nu blijf je ff staan, een park knop zou ook fijn zijn.

Welke modus vond je het fijnst?

Ik heb vooral de continuous mode gebruikt op het dichtste bij, 50cm.

Was dat dichtbij genoeg?

Ja dat was precies goed. De afstand was fijn. Maar het is inderdaad lastig van wanneer mag ik dan wel terug ipv stil blijven staan.

Wat vond je van het dashboard op het scherm?

Ik keek vooral naar de target afstand en de slider aan de linkerkant vond ik ook nice.

Was dat intuïtief?

Ja dat vond ik wel, met die lijn zo. Ik vond het ook fijn dat het logootje oplichtte als het volgen aan stond.

Keek je ook tijdens het schilderen naar het scherm?

Ik keek ernaar als ik de afstand goed wou zetten en voor de rest alleen de eerste keer toen ik op me afkwam, van okay wanneer ga je stoppen. Eigenlijk keek ik er alleen naar toen ik instellingen veranderde. Dan ga je er naar kijken.

Voelde het logisch dat het scherm op de robot zat?

Ja dat voelde als een goede locatie

Had je het gevoel dat je meer op de muur kon focussen met de volg robot?

Nee niet perse. Ik was juist iets meer bezig met de volg robot dan de handmatige kar, maar dat komt ook omdat het iets nieuws was. Ik was nieuwsgierig naar de robot, de handmatige kar ken ik wel. Ik was benieuwd hoe de robot ging reageren op dingen, daar was ik op gefocust. Maar na een kwestie van tijd zou dat wel anders zijn, maar voor focus denk ik niet dat het veel verandering brengt want er is juist een andere variabele in de ruimte waardoor dat minder is. Maar het heeft vooral voordeel in efficiëntie en vrijheid van keuze. Bijvoorbeeld als je twee dingen in je hand hebt is een handmatige kar heel vervelend.

Wat is het grootste verschil tussen de handmatige en de automatische kar?

De handmatige kar was bekender en wist ik meer waar ik aan toe was, ik wist wat ik kon verwachten. Bij de automatische kar was het volgen heel fijn en kan ik veel efficiënter werken, alleen was het een extra factor in de ruimte die bewoog waardoor mn aandacht ook daar naar toe ging. En ik ging spelen met de knopjes, maar ja dat is allemaal omdat het nieuw is. En ik vond deze controller nog niet helemaal intuïtief. De controller op je riem is net wat te dichtbij, je hebt langere armen, in je broekzak is het beter. Ik heb dan wel in mn hoofd het voordeel, van deze robot is dat je je handen vrij hebt, maar als je dan vervolgens je handen op de knoppen moet doen dan verlies je dat een beetje. Misschien kun je iets met ringen aan je vingers doen als controller waardoor je je handen wat vrijer houdt.

Nog andere opmerkingen?

Nou ik zou zo'n ding meteen willen hebben. Voor klussen dat ie achter je aan gaat zou heel nice zijn.

Participant ID: P94D1E1AA

Audio: Test 6

Date: 27-05-2026

Notes:

Just lets the manual cart stand in the same place for the whole test.

Used the continuous mode and the manual mode.

Pushed the cart back physically a bunch.

NASA-TLX comments:

Autonomous Cart - Mental Demand - needed to think about what the robot was doing and had an additional cognitive load in my head

Autonomous Cart - Frustration - A little bit because I didn't know when the speed went to 0. or what the mode was sometimes

Manual Cart - Frustration - A little bit while pushing the cart itself.

Transcript:

What did you think of it?

I think it was fun, it felt like a little assistant for you. And I did feel like when I was pushing the manual cart like why am I putting in this much effort and it was okay if you do this repeatedly you get physical strain and the manual cart was kind of hard to control. It was spinning a way for second, the manual cart. Initially I thought I will push and pull the manual cart around because I do like all my tools with me within reach all the time, but then I tried keeping the manual cart with me, pushing it up and down that was not it. It is better if I just leave the cart there and come back for it. Too much effort to constantly pull the manual cart with me.

Was the autonomous cart easier?

Yeah it was easier. For the first task, I felt that it was nice, I was kinda following me around. I was a little scared I was going to hit me or I would hit it, and I was scared of touching it. One thing was that switching between modes, I kind of forgot which one I was in and forgot to look at the dashboard. I did switch modes. First continuous and it was following me, and then I was okay I want to control it myself, the pace of it. Because it was coming closer to me but never knew when it was going to reach me and then I was like it is better to control in manually and I switched to manual mode. Manually suited me more, more control of where the cart is. And it didn't feel like that much effort to control it, in my mind I knew this is where I am at and this is where the cart is at, it was easy to control. Then it reduced the cognitive load in my mind, because when it was following me I was like is it going to hit me or how long is it going to take and then when I was in manual mode I stopped thinking about it at all. If I felt that it was to close I would just drive it back and when it was too far away I would drive it closer to me.

You had kind of a synergy of pushing the buttons on the remote with your left hand and painting with your right hand?

Yeah! I felt in control of the cart. When the cart is in continuous following mode you are not really in control, kind of like a black box, even though I know how it should work I was like confused sometimes because when I walked towards it, it didn't go away from me.

Did you push the autonomous cart physically to get it to move away from you?

That's when I switched to manual mode, I was like okay I want a certain distance. I want to be able to control it. This felt better than pushing the cart, why would I need to push it when I am in manual mode. That's the only thing I thought. I kind of forgot that I could always press the reverse button no matter in what mode I am in, when its in continuous I was thinking something else, it just follows you

What did you think of the remote?

I think it was very intuitive. One thing when I switched from follow mode to manual the speed went to 0% and I didn't realise that. Once I got used to it, it was pretty intuitive, reverse forwards. I felt like controlling like a remote controlled car. To control the speed was also intuitive, I did not even look at it after the first try.

What about looking at the remote on first sight?

I did have trouble understanding it. I did not understand the graphics, it makes sense, but I could not understand it. When you explained it, it was okay and when I tried it out. Initially reading the explanation poster it was too much at once. I just wanted to use it and try, and when I did that it was really intuitive. Once you try it with the robot, you just get it instantly in my opinion.

What did you think of the dashboard on the screen?

I did have to look at when I wanted to check the state of the robot, like what mode is it in and the speed. It did not really look at the distance

Did you look at this bar on the left side of the screen?

No I did not look at it. I looked mainly at the target distance and the mode. That's it. Target distance and speed.

And did you switch modes on the screen or only with the remote?

Only with the remote. One thing was when I switch with the remote it goes from continuous to segmented to manual, so I have to switch twice, that was quite slow. It would have been better to use the dashboard maybe. But the remote worked fine with switching modes. Otherwise the dashboard looks pretty clean. I did not use the speed thingy. I mainly used the speed/target distance and the mode, that's it. That's all I looked at. It is like status monitor, to see okay this is what it is doing. Felt like a screen that is there, I don't need to interact with it.

Did you feel like you could focus more on the painting / your tasks?

Yeah I think so, because like not pushing the cart was good enough for me, that kinda resulted in having all the stuff with me, not having to walk around so much. The manual cart I had to drag and stuff. The stencil task was a bit difficult with the robot because I had to look there in the beginning but the robot was in the way. I need to go back to the beginning anyway, so letting the cart follow me did not make sense. The manual cart I just left it for the task with the stencils. I loved the manual mode on the robot cart.

What do you think was more effort, the manual cart or the autonomous cart?

The manual cart for sure. Because you have to push it around and the extra walking added to much time and walking for the sake of competing the task. With the autonomous cart there is less walking so I can get more done in one workflow then I could with the manual cart.

Did you have a different workflow with the manual cart vs the autonomous cart?

Yeah I think so, because with the manual cart there was more walking back, walking back, walking back, then for the autonomous cart where everything is in reach. With the manual cart you are constantly walking to the end and coming back to the beginning etc and that's all time that you have lost and I don't like that. The autonomous cart was easier. And if you are doing it for the whole day, these minutes and seconds can add up and something that takes 20min with the autonomous cart takes like 30min with the manual cart. If I had the option I would do the tasks with the autonomous cart. Then you are not doing the unnecessary walking around.

Did you feel in control of the robot cart?

100%, 100% fully in control. I never felt that I was not in control, so I was not scared of it.

Any final remarks?

I love the intuitiveness of the remote. I just needed like 30sec in the beginning to understand it. I loved the manual mode, I was like having a personal assistant, but you don't need to say anything, you can just control it with your fingers, there is no gap in communication. It always does what I want it to do. That was nice. Yeah if there is a small buddy following you with tools when you have to do stuff it looks good.

Participant ID: P2A354B97

Audio: Test 7

Date: 27-05-2026

Notes:

Poster links met instructies is moeilijk want je moet steeds terug

De handmatige kar helemaal niet bewogen

Duwen van de autonome kar voelt natuurlijk

Segmented mode gebruikt, 50+80cm

Snelheid op het dashboard zou een andere kleur moeten krijgen.

50cm is zelfs nog iets te ver weg.

NASA-TLX comments:

-

Transcript:

Wat vond je ervan?

Ik vond het een leuke opdracht. Leuk om te doen. Het was ook heel leuk om de robot te kunnen testen.

Wat vond je het grootste verschil tussen de handmatige en de autonome kar?

Met de handmatige kar was het heel makkelijk je weet precies waar die is, je loop gewoon heen en weer, het een statisch object. De robot is wel fijn want die volgt je, maar je bent ook meer bezig met hij volgt je en hoe moet ie achteruit. Je bent er mentaal iets meer mee bezig. Je bent bezig met waar wil ik waar die is. Het was op twee verschillende manieren makkelijk, zelfde hoeveelheid makkelijk, verschillende manieren.

Bij de normale kar was je veel aan het lopen?

Ja deze kar is veel te zwaar om heen en weer te gaan trekken

Wat vond je van het gebruik van de autonome kar?

Makkelijk, ik koos ook om hem steeds weg te duwen, bij het trekken wou ik juist dat ie me volgde maar bij het achteruit gaan duwde ik hem gewoon ff weg ipv met de remote.

Voelde dat ook natuurlijk om te doen?

Ja, want je had die staaf en dat maakte het makkelijk om gewoon even een duwtje te geven en dat was mentaal dan makkelijker dan ohja de knop indrukken voor achteruit hoe doe ik dat ook alweer. Dat is ook een beetje wennen aan de controls, als je dat eenmaal in je vingers hebt dan gaat het ook makkelijker.

Had je ook een andere workflow bij de verschillende karren?

Ik had twee verschillende workflows. Bij de handmatige ging ik van A naar B en dan ging ik weer terug naar A om nieuwe tools te pakken en dan weer van A naar B. Met de robot ging ik meer van A naar B en dan van B naar A en dan weer van A naar B, want ik had alles al bij me dan hoefde ik niet meer heen en weer te lopen

Voelde dat ook sneller?

Ja ik denk het wel, het spaart je een keer heen en weer lopen.

Was het goed te bedienen met de controller?

Ja, zoals ik zei, moet ik deze twee knopjes (de labels onder de knoppen) in drukken om de modus te veranderen. Ik denk dat dat is deze knoppen zijn gevoelig voor heen en weer rijden dus die wil je niet teveel aanraken als je het niet nodig hebt.

Als je wil wisselen van modus wil je dus een andere knop daarvoor hebben?

Ja, je wil niet dat de robot perongeluk tegen je aanrijdt omdat je de twee knoppen indrukt maar perongeluk eentje niet goed indrukt, bijvoorbeeld.

Was het draaien met de draaiknop ook duidelijk?

Ja! Misschien mentaal, want eerst is het de snelheid en dan daarna de afstand. Dat is lastig te onderscheiden. Omdat ze dezelfde kleur zijn zie ik ze

als hetzelfde getal, maar als ze visueel anders zijn dan kan je makkelijker in je hoofd denken van ohja ik zie nu een ander dashboard feature. Het is fijn om de afstand ook te zien die de robot ziet, van dan weet je dat hij mij heeft geregistreerd, hij weet waar die is, dat is een beetje transparant, dat is fijn.

Gebruikte je ook andere modussen?

Ik gebruikte volgensmij alleen maar de segmented modus.

Vond je het fijn dat ie dan soms ff wachte en dan pas naar je toe kwam?

Ja hij hoefde eigenlijk niet op mij te wachten van mij, hij had gewoon in een keer kunnen komen en 50cm is iets te ver weg nog, want dan moet je nog steeds wel die stap nemen om dingen te pakken. Hij zou voor mij nog wel op 30cm afstand mogen zijn, nog dichterbij en dat is echt naast me staat, want dat is het voordeel dat je iets naast je hebt, dat je niet een stap terug hoeft te doen.

Had je het gevoel dat je er controle over had?

Ja, ja ik wist soort van wat ik ermee moest doen. Op het einde toen ik wou dat ie dichterbij kwam ging ik nog een stapje opzij en dan kwam die wel. Hij reageerde wel op wat ik wou. Bij segmented had ik graag gewild dat ie ook achteruit ging als ik naar hem toe liep, maar ik snap ook als ik iets wil pakken dat dat niet werkt. Misschien kun je als ie stil staat een klein duwtje geven en dan gaat ie naar achteren als je met hem mee loopt en als jij stop stopt ie zelf ook weer. Ik vond het cool dat je de afstandsbediening in je broekzak kon hangen.

Ja was dat handig?

Ja dat was een handige plek. Het had misschien slimmer geweest als ik de remote in de linkerbroekzak deed en dan met rechts kon schilderen. In mijn hoofd dacht ik, ik ben rechtshandig dus hij moet aan de rechterkant, maar dan ben je ook steeds met je rechterhand aan het schilderen, dat klopt niet. Maar het was wel goed te bedienen. Ik moest nog ff veel kijken maar daar raak je aan gewend. Uiteindelijk weet je waar de knoppen zitten.

Wat koste meer moeite, met de handmatige of met de autonome kar?

De handmatige kar koste meer moeite.

Nog een laatste opmerking?

Het schermje zou groter kunnen, soms was het een beetje ver weg. Ik heb er alleen maar naar gekeken toen ik modus aan het wisselen was en de target distance aan het veranderen was. De target is groot genoeg.

Kon je ook meer focussen op de muur?

Nee ik denk niet dat daar een verschil in zat. Ik voel me ook gewoon cool dat ik met een robot bezig mocht, dat was leuk. Het werkt ook beter op een grote afstand, als ik zeg maar deze hele muur af moest, dan zie ik echt wel de waarde, misschien is deze test muur van 5m niet lang genoeg, maar 50m zeker.

Participant ID: P8125A7EE

Audio: Test 8

Date: 27-05-2026

Notes:

Eerst manual mode steeds gebruikt

Volgen op 100cm gebruikt

Terug met knop veel gebruikt

De handmatige kar helemaal niet bewogen.

NASA-TLX comments:

Autonomous Cart - Mental Demand - sometimes selecting the right color or shape for the window needed some mental load, and the numbers, but the rest was basically on autopilot.

Autonomous Cart - Temporal Demand - i wanted to rush to recreate a painters work effort.

Autonomous Cart - Performance - i did what was asked, though its maybe not the most beautiful

Manual Cart - Temporal Demand - the same as before

Manual Cart - Mental Demand - actually, here i let the car be which reduced the cognitive load since i didnt have to control it

Manual Cart - Performance same same

Manual Cart - Frustration - i could not read the numbers at one point and had to grab the cart

Transcript:

Hoe vond je het gaan?

Goed, het was niet zo heel ingewikkeld. Ik hoop dat het niet ging om hoe mooi het was hahah.

Wat vond je het grootste verschil?

Met de autonome kar was ik nog relatief veel bezig met het bedienen. Op deze schaal koste het me meer moeite om de kar te bedienen dan het me opleverde. De handmatige kar heb ik gewoon laten staan en heb ik iets meer gelopen. Het was makkelijker om te lopen dan de handmatige kar steeds mee te slepen.

Deed de autonome kar je goed helpen?

Als je op volgen stond hoefde ik niet met de autonome kar te dealen, behalve als ik weer terug wou gaan naar het begin. Hij zat me in de weg als ik weer terug wilde. Maar dan kon ik met het knopje hem weer terug sturen naar het begin, dat ging goed.

Voelde je een beetje in controle over de autonome kar?

Ja, ja! Ik vond het ook wel heel leuk om zo'n ding te gebruiken. Dat is natuurlijk ook de novelty, ja maar ik vond het wel leuk.

Had je niet het idee dat de autonome kar gekke dingen ging doen?

Nee, omdat je liet zien hoe het werkte. Had ik vertrouwen in dat ik kon voorspellen wat ie ging doen. Het was misschien nog wel ff wennen hoe het precies te controleren is. Ik heb de manual mode en de segmented mode niet gebruikt. Misschien had de segmented mode ook wel handig geweest, achteraf gezien.

Gebruikte je ook een andere workflow voor de autonome en de handmatige kar?

Ja ik ben van volgorde veranderd omdat ik bij de autonome van links naar rechts werkte kon ik steeds van keur veranderen en bij de handmatige ben ik steeds terug gaan lopen.

Was de controller duidelijk te gebruiken?

Ja, het was heel fijn dat ie maar 3 knopjes heeft.

Snapte je de controller op eerste opzicht ook?

Nee, voor de uitleg niet. Maar na de uitleg was het wel duidelijk.

En tijdens het schilderen?

Niet bewust opgelet, maar ik liep er ook niet tegenaan.

Heb je de autonome kar ook een keer fysiek teruggeduwd?

Nee dat heb ik ik niet gedaan. Dat deed ik met de terug knop steeds. Het was voor mij goed genoeg omdat met de controller te doen.

Ik zag je ook een paar keer de afstand veranderen?

Vooral om hem naar me toe te laten komen, als ik een pen nodig had had ik hem graag dichtbij en als ik bezig was had ik hem liever op een afstandje zodat ik er niet tegenaan liep. Dan deed ik de afstand omhoog als ik dichtbij stond en dan bleef ik wat langer staan. Misschien was de segmented mode dan toch wel handig geweest.

Je zei ook dat je met de draaiknop de robot dichterbij je wil laten komen?

Ja dat lijkt me nog steeds handig. Eigenlijk als je dan draait aan de draaiknop komt ie dichterbij en als je dan terugdraait gaat ie van je weg. Eigenlijk dat je de positie op de lengte as bepaald met de draaiknop.

Wat vond je van het dashboard op het scherm?

Het was duidelijk maar heb er niet echt naar gekeken, behalve de snelheids meter. Die is niet echt duidelijk. Het is heel fijn dat de target afstand en de echte afstand een andere kleur heeft, want toen kon ik heel makkelijk zien dit is het ene en dat is het andere.

Keek je ook naar de afstand, wat de echt afstand was?

Nee niet naar gekeken, ik keek vooral naar de target afstand.

Keek je ook naar de bar aan de linkerkant van het scherm?

Nee, niet echt.

Keek je wel eens naar het scherm?

Ja ik keek wel eens naar het scherm, vooral als ik de afstand wou veranderen van het volgen. Verder niet echt.

Had je ook het gevoel dat je meer tijd en focus voor de muur had?

Ik denk dat ik wel. Het was makkelijker om de getallen af te lezen van de kar en welk vormpje bij welke frame hoorde, omdat bij de handmatige kar het steeds verder weg was ik meer afgeleid. Over een hele dag zou de autonome kar veel fijner zijn. Ook als de afstanden groter worden, 10-15m dan wil je niet steeds teruglopen.

Zat de autonome kar je niet in de weg?

Als ik weer terug wou gaan naar het begin zou het handig zijn geweest dat ie al voor me uitliep.

Koste het ook meer moeite?

Het besturen van de autonome kar koste iets meer moeite. Maar het kijken wat ik precies moest doen was wel makkelijker.

Had je ook het gevoel dat het een leercurve had?

Ik vond het heel fijn dat het twee knoppen en een draaiknop had omdat je dat heel makkelijk op gevoel kon doen. Nu moest ik nog wel eens kijken maar ik kan me voorstellen dat je als je hier een week mee werkt dat je dat heel makkelijk kan.

Participant ID: P4E80467E

Audio: Test 9

Date: 27-05-2026

Notes:

Van rechts naar links van de muur de automatische kar helemaal terug geduwd met de hand.

Output mist nu, zou chill zijn, geluidje als ie gaat bewegen.

Er waren teveel opties.

Manual mode moet je snel naar toe kunnen switchen, nu duurde dat lang.

NASA-TLX comments:

Manual Cart - General - I did like the walking back and forth, made me more energised.

Autonomous Cart - General - The autonomous cart took some time to understand. There were quite a few options.

Transcript:

Wat vond je er van?

Ik vond het best wel goed gaan, ik vond het leuk. De autonomous cart was echt wel grappig. Hij is een beetje dikking en voelt een beetje aan als een soort droid. Hij had wel echt veel opties. Teveel opties in een kleine tijd. Zo'n schermpje is dan gelijk wel zo van wow. De knopjes waren wel nice, de remote. Ook wel een klein beetje ingewikkeld, de labels onder de knoppen snapte ik niet helemaal.

Had je het gevoel dat je controle had?

Ik wist niet dat je de speed kon aanpassen ook, dat was een beetje onduidelijk. Je krijgt een soort boom van wat je kan met de knopjes, dat is wel lastig. Ik denk omdat de knopjes allebei hetzelfde zijn, is het makkelijk door elkaar te halen. De vormen zijn symmetrisch, je kan niet zonder te kijken snel zien wat het verschil is. Over tijd zal dat wel gaan denk ik. De vorm moet niet symmetrisch zijn. De draaiknop is wel heel nice, dat gaf wel gevoel van controle.

Heb je die ook veel gebruikt?

Nee dat niet. Ik moet zeggen ik had geen behoefte om de afstand aan te passen, ook omdat ie niet dichterbij kon dan 50cm. Dat vond ik al best ver. Ik zou hem dichterbij willen hebben, misschien wel op 10cm.

Had je het gevoel dat je controle of dacht je dat er dingen konden gebeuren wat je niet had verwacht?

Dat niet perse, maar ik had wel het gevoel dat dat kon gebeuren. Bij de handmatige ging dat sowieso niet gebeuren, dat is een makkelijker interactie. En aan de autonome moet je echt even wennen. En het zou ook wel nice zijn als je het zelf zou kunnen programmeren. Ik zou zelf zeggen van ik wil hem zo min mogelijk adjustments geven. Voor mijn gevoel had ie teveel opties. Als ik hem echt zou gebruiken zou ik het veel simpeler willen. Afstand moet er sowieso op. Alleen zou ik de afstand niet zo vaak veranderen. Allen dichtbij is goed. Ik zou hem wel willen stoppen, dat vind ik wel nice. Dat je kan switchen naar manual mode is fijn, maar dat moet wel makkelijker gemaakt worden. Dat zou ik vaker willen switchen, tussen manual en volgen. Dat je het heel snel kan wisselen. Maar ik zou het ook grappiger vinden dat ie soms ff een beetje onvoorspelbaar is, als ik denk wat ik leuk zou vinden. Iets meer levend is. Iets meer geluidjes. Stel je voor dat je R2D2 uit zou kunnen zetten, dat is wel heel verdrietig. Ik vond het geluidje van de motors van dat je weet dat ie eraan komt heel chill. Verder zou ik zeggen ik kon de tekst wel goed lezen en de symbooltjes wel goed zien.

Merkte je ook een verschil in aanpak bij de twee karren?

De handmatige kar liet ik gewoon staan, Hij is net wat te zwaar om te bewegen. Ik zou het wel chill vinden dat je de autonome kar gewoon een beetje kan wegduwen, net als de handmatige kar. Ik zou bijna willen zeggen dat er een soort ring om de kar heen zit waar je hem overal kan vastpakken, in plaats van de twee buizen nu. Dat je hem overal kan vastpakken en aan de kant kan doen. Dat je hem altijd overrude als je hem vastpakt. Hij is een beetje laag moet ik toegeven.

De echte kar heeft wel een instelbaarplatform voor de hoogte, zou je dat gebruiken?

Ja, maar ik zou dat niet instelbaar willen hebben met een scherm of knoppen, dat wil ik gewoon met mn handen omhoog en omlaag doen. Ik zou dat niet zo vaak willen aanpassen, dat kan ik gewoon handmatig doen.

Vond je de controller handig?

Ik vond het wel nice, alsof je het bestuurd en ik had er wel controle over, net als een vorkheftruck.

Heb je ook veel naar het schermje gekeken?

Niet heel veel, ik vond dit te moeilijk, kijken in welke modus je zit. Je kan niet echt lezen wat er staat op afstand en het is net ook je zou iets meer met kleur werken. Grote stukken kleur dat je het makkelijk op afstand kan lezen. Hij geeft teveel feedback op het scherm, teveel informatie. Als ik dit schermpje zie is het overweldigend. Werk met kleur dat je makkelijk vanaf een afstandje kon kijken. Het veranderde nu de hele tijd, alle getallen, was een beetje overweldigend. Je ging de hele tijd controleren van doet ie het wel.

Nog andere opmerkingen?

Soms dacht ik, misschien met moeilijke vloeren is het lastig. Ik heb ook wel geschilderd en dan moet je je in moeilijke bochten wringen en dan heb je je emmer verfvast en je kwast en dan ook nog je hand willen vast houden aan de trap werkt niet. Als je dan je emmer op de kar kan zetten zou wel heel handig zijn.

Participant ID: P97C3B246

Audio: Test 10

Date: 27-05-2026

Notes:

Duwde steeds de autonome kar fysiek terug.

NASA-TLX comments:

Autonomous Cart - Performance - I made some mistakes in painting, so I wont fully blame the cart

Autonomous Cart - Temporal Demand - I felt a bit rushed with the cart following behind me

Autonomous Cart - General - I sometimes would move and then the cart wouldnt immediately follow me, I was also first watching the cart move (maybe to make sure it wouldn't run into me)

Manual Cart - Temporal Demand - I feel like I could take my time

Manual Cart - General - Maybe because I was the only one in control and I felt good about my work

Transcript:

Wat vond je er van?

Ik had het idee dat ik een paar stappen zette, en dat ik dan keek komt de kar wel achter mij aan. Dan kijk ik dus of de (autonome) kar wel naar me toe komt. Ik merkte ook dat ik het fijn vond om dingen anders aan te pakken.

Had je een andere aanpak?

Ja ik had wel degelijk een andere aanpak tussen de handmatige en de autonome kar. Iets in mn hoofd dacht bij de handmatige kan ik eerst alles bij plek 1 doen, dan 2, dan 3, dan 4. Dat zou chiller zijn. Ik merkte dat met de autonome kar, dat het niet boeit waar die kar staat en dat ik per kleur alle taken kon doen, dat was fijner, en ik vond de automatische modus best fijn.

Welke modus vond je fijn?

Ik heb eigenlijk alleen de continuous mode ingesteld en dan zo dichtbij mogelijk, 50cm. Dat ik er voor kon staan en er bij kon bij alles wat erop lag. Ik merkte wel, ik vond het opzich wel fijn om een afstandsbediening te hebben, maar ik merkte wel dat ik het fijner om de kar fysiek terug te duwen dan het knopje te gebruiken dat ie terug beweegt. Dat voelde voor mij intuïtiever. Ik denk wel dat het fijn is om de keuze te hebben dat je ook de afstandsbediening kan gebruiken. Ik denk dat daar wel een use case voor is, maar niet voor tijdens het schilderen. Als ik naast de kar sta, ben ik wel meer geneigd om de kar te duwen. In automatische modus heb ik liever toch het gevoel dat die kar gewoon naast me staat en in principe het gevoel heb alsof ik al mn tools in mn eigen broekzak heb. Zo kon ik ook steeds van kleur pen wisselen zonder moeite. Het probeerde het zo te gebruiken, alsof ik alles bij me had in mn eigen broekzak, maar dan dus op de kar. Dus ik wou hem ook dichtbij me hebben.

Wat vond je van de controls?

Ja, ik moest eerst wel ff puzzelen. Er was ook een derde modus die ik niet gebruikt heb (segmented). Maar dat was ff puzzelen, want op het scherm had je eerst in de layout bij manual hier de speed. En dan in de volg modus staat daar de afstand. Dat vond ik raar. Want hier dacht ik dat je nog steeds in percentages moest denken, een percentage van deze afstand. Meer verschil daarin zou handig zou voor een volgende iteratie.

Kon je het wel goed lezen, het scherm?

Dit vond ik fijn, de verticale bar aan de zijkant van het scherm. Dan kon ik zegmaar zien wat de afstand was, zonder naar het getal te kijken, want dat boeit me niet zo. Wat het precieze nummer is dat boeit me niet echt, maar minder of meer afstand kan ik goed aflezen van de bar. Dat vond ik fijn om te kunnen zien. Qua controls, ik had wel gevoel dat ik controle erover had.

Heb je nog opmerkingen over de controller?

Ik had hem in mn broekzak gedaan, ik ben ook niet geneigd om hem eruit te halen. Er valt niet heel veel over te zeggen want ik heb hem vooral op automatisch gedaan. Nadat ik de robot had ingesteld heb ik de controller ook niet echt meer gebruikt. Ik duwde hem ook fysiek terug om terug te gaan in plaats van met de controller.

Wat was het grootste verschil met de handmatige kar en de autonome kar?

De handmatige kar is hoger, dus dat was fijner, de autonome kar was iets te laag waardoor je er meer naar moest grijpen. Bij de handmatige kar gebruikte ik steeds wel mn beide handen om hem te verplaatsen. Ik zou niet met een hand aan de kar en dan met mn andere hand bezig met schilderen. Ik deed steeds met twee handen verplaatsen en dan ff schilderen. Met de autonome kar die me volgde kon ik makkelijker met iets met mn hand rond bewegen. En dan kon ik snel ff wat dingen in mn hand wisselen.

Nog andere opmerkingen?

Het zou fijn zijn als de tools iets hoger hadden gelegen op de robot kar.

Raw data from NASA-TLX form.

Participant ID	Condition	Order	Mental	Phys.	Temp.	Perf.	Effort	Frust.	Overall	Submitted
PE65299FC	Manual	1st	25	35	25	65	50	25	37.5	26/05/2026
PE65299FC	Autonomous	2nd	35	15	55	20	10	15	25	26/05/2026
PD9C23AB1	Manual	1st	25	75	25	25	75	100	54.2	26/05/2026
PD9C23AB1	Autonomous	2nd	75	25	25	75	25	75	50	26/05/2026
PB7F9F506	Manual	1st	40	75	60	25	75	35	51.7	26/05/2026
PB7F9F506	Autonomous	2nd	35	25	25	25	40	20	28.3	26/05/2026
P507BEB28	Manual	1st	10	60	90	10	15	75	43.3	26/05/2026
P507BEB28	Autonomous	2nd	10	10	70	10	10	80	31.7	26/05/2026
PBCB09F4B	Manual	1st	35	60	50	10	60	40	42.5	27/05/2026
PBCB09F4B	Autonomous	2nd	60	30	55	50	40	55	48.3	27/05/2026
P94D1E1AA	Autonomous	1st	35	15	40	10	25	40	27.5	27/05/2026
P94D1E1AA	Manual	2nd	55	75	35	25	55	55	50	27/05/2026
P2A354B97	Manual	1st	5	20	0	0	20	0	7.5	27/05/2026
P2A354B97	Autonomous	2nd	10	10	15	0	10	0	7.5	27/05/2026
P8125A7EE	Autonomous	1st	25	15	80	5	15	0	23.3	27/05/2026
P8125A7EE	Manual	2nd	15	15	75	5	20	10	23.3	27/05/2026
P4E80467E	Manual	1st	55	25	70	35	65	25	45.8	27/05/2026
P4E80467E	Autonomous	2nd	80	40	30	30	35	60	45.8	27/05/2026
P97C3B246	Autonomous	1st	35	45	55	10	25	40	35	27/05/2026
P97C3B246	Manual	2nd	15	40	35	5	30	10	22.5	27/05/2026

Manual Cart Autonomous Cart

Condition	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall	n
Manual Cart	28	48	46.5	20.5	46.5	37.5	37.8	10
Autonomous Cart	40	23	45	23.5	23.5	38.5	32.3	10

Data investigation familiarisation effects with the autonomous cart

TRIAL 1

Time: 6:08

Accuracy: 7/10

Mental demand: 75/100

Comments:

Need sometime to practice switching between modes and getting used to the speed & sound of the cart. Spend some time to walk back to check the explanation of the tasks.

Notes: A to B, B to A with the home button. For task 2 with the stencils did the circles from left to right first and then from right to left the squares. Did not push the cart physically.

TRIAL 2

Time: 4:22

Accuracy: 8/10

Mental demand: 45/100

Comments:

I think I cooperate with the robot pretty well. Feel more free and easy to paint. Even want to play its moving but this time I don't have enough attention to do. Just one thing also happened before, I mixed up the forward/backwards button sometimes with each other.

Notes: Used the manual buttons to go back but changed to the home button because that was quicker. Home button is used a lot. The forwards and backwards buttons were mixed up with each other. Moved from A to B, B to A, A to B.

TRIAL 3

Time: 4:50

Accuracy: 8/10

Mental demand: 45/100

Comments:

This time when I walk back to draw the green outline, I use the home mode. Because of this I drew the 3rd & 2nd faster because I want the mode keep moving until I get to the first one. So I feel I drew the 3rd and 2nd roughly, not very well. Also tried manually pushing the cart, feels so boring and start hating the painting work because of it.

Notes: Did the outlines of task 1 from A to B, from B to A and the from A to B. So per colour. Pushed the cart when using the stencils physically. Switched to continuous mode for the third task.

TRIAL 4

Time: 3:57

Accuracy: 8.5/10

Mental demand: 25/100

Comments:

I wanted to do my best this time, I feel I drew everything carefully and slower this time but it turned out to be faster. Also I tried to switch the mode with my left hand while drawing with the right hand, a little hard but I did it.

Notes: Segmented mode for the black border of task 1 going from A to B. Home button for the green button going from B to A. Segmented mode again for the red border going from A to B.

Manual button to go back, but follow was still active so after reversing it went to the set distance again, this was confusing for the participant.

Target distance was always 50cm.

TRANSCRIPT OF POST INTERVIEW

What did you think of it?

Yeah it was interesting. After a while it was getting boring, especially the third time when I tried to push the cart physically I did feel like a job. It was more labour, because with it autonomously moving I feel better and it is easier too because I can focus on the drawing, but with pushing the cart manually I feel like I am just a labourer/worker. When it is autonomously following you I feel like more of a drawer/artist or something but with pushing the cart I feel like I am just a sad worker.

So, the cart did support you?

Yeah!

Did it become easier over time?

Yeah, of course! I tried to use the home button to go back because it went autonomously back. When I wanted the cart to go back, I used the going home mode and then I tried to do my task really quick to try to walk with it to keep it going reverse, but then noticed that you do not have to do that and the home mode is still on if I draw slower, it will keep going

And you can just continue without looking at it?

Yes, that right.

Did you have different approaches for each trial?

First time I didn't have a fixed mode, I tried to use all the modes to see if there are any differences. For the continuous one, I mainly used it for walking from the left to the right and for the task where you needed to write the numbers, that was where the continuous mode was useful and for the segmented mode, I did use that one. For longer distances the continuous mode and segmented mode don't have much difference, but for short distances I do feel the difference.

When do you prefer the segmented mode?

I just feel its moderate/not that rushed in segmented mode. For short distances I prefer the segmented mode, when you are taking small steps. Because you do not need to be that rushed in a short distance. But for a long distance I want it to follow me quickly. But also the speed, when I walk for a long distance, the speed is pretty fast and I can't help myself to check it, whether it will hit me but it's fine.

Did you have the feeling that you needed to constantly watch it?

No, I don't think I watched it all, only when I walked a long distance and it moves really fast towards me, then I will check if it will really stop in front of me.

Did somethings change over time?

Yes, the last trial I even tried to draw with my right hand and use the controller with my left hand. It is still a little bit hard for me, but I did it! I feel like when I am more familiar with it that I would be more free to do that. And also I feel in the last trial I did not even use the forward and backward button. Only the autonomous movement.

Did you use the forwards and backwards button?

Yes I did use it. I mainly used the backward button to reverse it for really short distances.

I saw that sometimes when you used the backwards button it also directly come back too?

Yeah haha, the follow mode was still one.

Where you comfortable with the robot following you?

Yes, I felt pretty comfortable, just for the long distances the speed is a little bit high. Then it is a little bit scary and I need to look at the robot to make sure I am safe.

Did sometime become easier of time?

Yeah, I could remember what the tasks where, where to draw what kind of shape.

And for controller the robot?

Yeah it became easier, I got totally familiar with all the button positions so in the last run I tried to control it without

looking at the controller.

Was that possible or did you have a mix up sometimes?

I can feel the differences of the buttons. But it did sometimes mess up the forward and backwards button. I feel like if it was flipped it is better, because the remote is upside down.

Did you any accidental button presses?

No, I didn't mix that up. I could feel the buttons pretty good and the icons where clear.

Did you notice the difference in relief on the forwards and backwards buttons?

Only now that you point it out.

Did the mode switching work well with the slider?

Yes it works well, I can remember the position of the switch to know which mode I am in.

Did you look at the screen during the tasks?

At the first trial, I did look at the screen to see when I switched modes to check if I pressed the follow me button. I do check the screen sometimes, to check whether the following is on or off. But then I didn't really look at the screen.

Did you change the follow distance?

I changed it to 50cm from 60cm, I feel like 50cm is pretty good, although it is still a little bit far for me to grab the marker. But I feel like that is the safe distance. Maybe closer when it moves really slow, but when it moves fast I don't want it to go that close to me

You did not want it further away?

If it was possible that it could go backwards to create a bigger distance between the cart and me, because I only need to turn the knob instead of clicking the home button. So you can send it backwards more by increasing the target distance, setting the distance between the cart and me. Then you can also get it to go forward more by decreasing the distance, that would be easier then pressing the forward and backward button.

Did you like to going home button?

Yeah I liked that, I used it a lot. I think I used a little trick, even when I did not want it to go all the way home, I used it to walk back a bit and then cancel it. But also it can just go back to the beginning while I finish a task. Also when I am finishing my work, sending it back home, feel pretty cute and feels like ah I finished the work and it goes back home and I can go home.

Was the cart in your way at any point?

The home button completely solved that, I did not need to push it. It just goes all the way back.

Was it in your way when doing your tasks?

I don't thing it was in my way, I just went away with the going home mode.

What things required attention still, from a mental demand point of view?

I feel like switching modes, after you switch a mode you need to press the start button, so that is like one extra step. After that, because I don't have good memory remembering the instructions of the tasks. Also moving backwards, need more time to get familiar with that because that is not autonomous, you need to learn how to use the home button, when I used the home button at first I felt rushed because I don't want it to stop and walk with it, but then I noticed that was not necessary.

Anything you want to add?

I just feel like pushing the cart manually makes me feel so sad and tired.

So it makes a big difference?

Yes it makes a huge difference

Where you also more focussed on your tasks?

Yes of course. And also for the last round, I tried to do my best, I felt like a drew slower and more carefully but it turned out that it was the quickest trial. I think that happened because there was good cooperation with the cart.

Mental demand sheet filled in by participant

TIME: 6:08 ACCURACY: 7/10

MENTAL DEMAND
How mentally demanding was the task?
Very Low Very High

Comments:
Need practice to practice the switching between modes and get used to the speed & how the use cart.
Spent some time to walk back to check the steps.

TIME: 4:22 ACCURACY: 8/10

MENTAL DEMAND
How mentally demanding was the task?
Very Low Very High

Comments:
I think I cooperate with the robot pretty well. Feel more free and easy to push. Even need to play with its buggy but this time I don't have enough attention to do. Just one thing also happen before I missed of the forward/backward button switches.

TIME: 4:50 ACCURACY: 8/10

MENTAL DEMAND
How mentally demanding was the task?
Very Low Very High

Comments:
This time when I walk back to draw green outline, I use the home mode. Because of this I draw the first & 2nd faster because I use the mode automatically until I get to the first one. so I feel I draw the first & 2nd roughly, not very neat. Also need manually push the cart. feels so heavy and about hitting this parking mark.

TIME: 3:57 ACCURACY: 8.5/10

MENTAL DEMAND
How mentally demanding was the task?
Very Low Very High

Comments:
I want to do by best this time, I feel I draw everything carefully and slower this time but then not slow time is slower. Also I tried to pushed the mode with left hand while drawing with right hand, a little hard but I did it.

Appendix E - Project Proposal form

Project Proposal form IDE Master Graduation Project

In this proposal the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document needs to be prepared for the Kick-off meeting and should be submitted in MyCase.

Name student: Student number:

Project title:

Please state the site of your graduation project (above). Keep the site compact and simple. Do not use abbreviations. The extension of this document allows you to define and clarify your graduation project.

MSc programme: Design for Interaction Integrated Product Design Strategic Product Design

Other (in case of a double degree outside IDE):

Introduction

Describe the context of your project in the box below. What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

My graduation project will focus on developing the behavioural repertoire of a robot assistant for professional painters. Professional painting is a physically demanding job, where workers frequently face long-term health issues due to repetitive strain and heavy lifting. The domain of the project is Robotics in Construction, specifically focusing on a collaborative robot assistant designed to support, rather than replace, professional painters. The primary stakeholders are the painters themselves, who face health and career longevity risks at stake, alongside industry partners BUNAC and Corderhouse.nl, who aim to preserve craftsmanship while modernizing working conditions.

While robotics offers the opportunity to alleviate physical burdens, the construction environment presents significant limitations. It is dynamic and complex, making full autonomy difficult. This project will build on work from previous students that have already worked on the robot concept, explored user-centred design options, and realized the physical robot design (see Figure 1). A team of students have also worked out a base platform at RoboHouse to be used as a prototype (see Figure 2). I will continue this development by specifically defining the robot's behavioural repertoire. By developing lighter movements and multimodal communication capabilities aligned with a graphical user interface, the project aims to transform the physical prototype into a concept that intuitively understands and supports the professional painting workflow.

→ space available for images / figures on next page

Introduction (continued): space for images

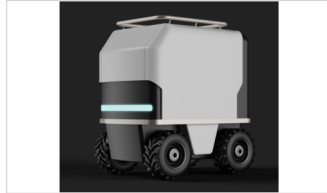


Figure 1. Previous work by Jasper van Zoest, working on the physical design of the robot.



Figure 2. Base platform prototype developed by a team of students at RoboHouse (Picture by Jasper van Zoest)

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 150 working days? In Master Graduation Project of 30 ECTS, what opportunities do you see to create added value for the described stakeholders? Substantiate your choice. (max 200 words)

Currently, a supportive robot for professional painters has been developed, but it still lacks a behavioural repertoire. In short, the robot itself is not able to be controlled yet by the painters and how it should move on the construction site. It lacks the interaction and is not able yet to communicate what it will do. Within the 150-day timeframe, I will address this challenge by developing the robot's behavioural repertoire, specifically defining its movement and multimodal communication aligned with a graphical user interface.

The opportunity lies in transforming the robot from a static machine into a transparent tool. By implementing an interface for the robot, this project creates added value by taking the next step in the project of reducing the painter's health issues due to repetitive strain with a robot assistant. For the industry partners BUNAC and Corderhouse.nl, providing a convincing prototype of the behavioural repertoire of the robot is the goal to be able to show how the robot could work with professional painters, so they can look for ways to develop the robot for real.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to journal regarding what you expect to deliver as result at the end of your project (1 sentence). As you graduate as an industrial design engineer, your assignment will start with a verb (Investigate/Design/Validate/Create), and you may use the format: (Investigate/Design/Validate/Create) a (what) for (the) beneficiary → prototype/ready-to-produce/intervention. Approach guideline strategy: 'I' to 'what' should I do → 'how' to understand/evaluate/validate/represent/analyze → 'the' objective → 'experience/validate/produce/process' → 'for whom' → 'target group/context'. 'I' as (what context)

Design a behavioural repertoire and multimodal interface prototype to enable and validate intuitive human-robot collaboration for professional painters in dynamic construction environments. The aim is exploring the expressive capabilities of the robot, including motion, sound, and light, alongside interaction modalities that may involve human guidance, physical control, and verbal communication.

Explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

I will work on this project at the IDE faculty's StudioLab, following an iterative, user-centred design process. The project starts with an orientation and research phase, benchmarking existing robotic solutions by their interaction styles and conducting a context analysis based on key interaction requirements, prior studies work, and human-robot interaction literature. Based on these insights, the project will move into an ideation and concept development phase, where multiple interaction and behavioural concepts will be explored and evaluated through the Wizard of Oz method and speculative enactment techniques. The most promising concept is then developed through iterative prototyping into a high-fidelity prototype of the robot's multimodal interface and behavioural repertoire. In the final phase, the focus will be on integration and validation. The behavioural repertoire and interface will be evaluated using user feedback and usability principles. The final behavioural repertoire will be more rigorously tested and validated. The project concludes with analysis and reporting, resulting in a validated prototype that demonstrates how the robot should function and be controlled.

Project planning

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 150 working days. Your planning should include the Kick-off, Midterm Evaluation, Green Light, and Finalisation (concretely). Please indicate periods of part-time activities and/or periods of not working time on your graduation project, if any (for instance because of holidays or parallel course activities). Add an image of the planning in the box below. If it is not readable, you can send the planning as an attachment to MyCase along with this Proposal.

Evaluation project planning

Week	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Week 1	Task 1.1	Task 1.2	Task 1.3	Task 1.4	Task 1.5
Week 2	Task 2.1	Task 2.2	Task 2.3	Task 2.4	Task 2.5
Week 3	Task 3.1	Task 3.2	Task 3.3	Task 3.4	Task 3.5
Week 4	Task 4.1	Task 4.2	Task 4.3	Task 4.4	Task 4.5
Week 5	Task 5.1	Task 5.2	Task 5.3	Task 5.4	Task 5.5
Week 6	Task 6.1	Task 6.2	Task 6.3	Task 6.4	Task 6.5
Week 7	Task 7.1	Task 7.2	Task 7.3	Task 7.4	Task 7.5
Week 8	Task 8.1	Task 8.2	Task 8.3	Task 8.4	Task 8.5
Week 9	Task 9.1	Task 9.2	Task 9.3	Task 9.4	Task 9.5
Week 10	Task 10.1	Task 10.2	Task 10.3	Task 10.4	Task 10.5
Week 11	Task 11.1	Task 11.2	Task 11.3	Task 11.4	Task 11.5
Week 12	Task 12.1	Task 12.2	Task 12.3	Task 12.4	Task 12.5
Week 13	Task 13.1	Task 13.2	Task 13.3	Task 13.4	Task 13.5
Week 14	Task 14.1	Task 14.2	Task 14.3	Task 14.4	Task 14.5
Week 15	Task 15.1	Task 15.2	Task 15.3	Task 15.4	Task 15.5
Week 16	Task 16.1	Task 16.2	Task 16.3	Task 16.4	Task 16.5
Week 17	Task 17.1	Task 17.2	Task 17.3	Task 17.4	Task 17.5
Week 18	Task 18.1	Task 18.2	Task 18.3	Task 18.4	Task 18.5
Week 19	Task 19.1	Task 19.2	Task 19.3	Task 19.4	Task 19.5
Week 20	Task 20.1	Task 20.2	Task 20.3	Task 20.4	Task 20.5
Week 21	Task 21.1	Task 21.2	Task 21.3	Task 21.4	Task 21.5
Week 22	Task 22.1	Task 22.2	Task 22.3	Task 22.4	Task 22.5
Week 23	Task 23.1	Task 23.2	Task 23.3	Task 23.4	Task 23.5
Week 24	Task 24.1	Task 24.2	Task 24.3	Task 24.4	Task 24.5
Week 25	Task 25.1	Task 25.2	Task 25.3	Task 25.4	Task 25.5
Week 26	Task 26.1	Task 26.2	Task 26.3	Task 26.4	Task 26.5
Week 27	Task 27.1	Task 27.2	Task 27.3	Task 27.4	Task 27.5
Week 28	Task 28.1	Task 28.2	Task 28.3	Task 28.4	Task 28.5
Week 29	Task 29.1	Task 29.2	Task 29.3	Task 29.4	Task 29.5
Week 30	Task 30.1	Task 30.2	Task 30.3	Task 30.4	Task 30.5

Motivation and personal ambitions

Explain why you wish to start this project, what competences you want to prove or develop (e.g. competences acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some (max 3) personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. This might consist of a goal acquiring in-depth knowledge on a specific subject, broadening your competences or experimenting with a specific tool or methodology (200 words max).

For this project, I am highly motivated to start because I have always had an interest in the interaction between humans and machines. Robots present a particularly interesting challenge, as they are often difficult for humans to understand and therefore difficult to interact with. With this project, I want to better understand how humans can naturally control robots and understand their behaviour.

The construction domain makes this challenge even more interesting. It is a non-monotonic environment where solutions must work reliably, without unnecessary complexity. I am drawn to this project because the robot is designed to support professional painters rather than replace them. It builds on their craftsmanship and aims to work alongside them instead of replacing an innovative solution.

This project allows me to apply competencies from my BSc Industrial Design and MSc Integrated Product Design, including human-machine interface design, physical and digital prototyping, CAD modelling, and user testing. Through this graduation project, I want to further develop my skills in human-robot interaction design.

My learning ambitions are to gain knowledge of human-robot interaction in construction, develop a workflow for prototyping combined physical-digital interfaces, and explore innovative ways of integrating sensors for intuitive robot control.