MIXED REALITY FOR PRESERVING CRAFTMANSHIP EXPERIENCES IN HUMAN ROBOT INTERACTOIN

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ABSTRACT

This project investigates how Mixed Reality (MR) can enhance the experience of Human-Robot Interaction (HRI) for crafting tasks, aiming to preserve the positive aspects of user experience and feeling of craftsmanship.

Initiated with an interest in the growth of MR and robotic automation, the research examines how MR might bridge the gap between user satisfaction and the increasing robot implementation in automating tasks execution. While automation streamlines repetitive or labour-intensive tasks, it often removes aspects that contribute to user engagement and job satisfaction. MR, as an immersive and interactive tool, offers a promising solution to enabling users to control and collaborate with robots in a more intuitive and meaningful way.

The project is built around the research question: "How can a unilateral vision-based control system, implemented through a Mixed Reality headset, enable telemanipulation of a robotic arm for crafting purposes, without disrupting the user's experience and performance?"

The study defines MR's unique potential for HRI by leveraging vision-based hand-tracking to control a robotic arm, specifically in a crafting task. A prototype was developed to explore the interaction dynamics, using, due to technical constraints, virtual reality to simulate the MR interaction and the robot The primary goal was to design an interaction system that offers full control of spatial navigation and force application, allowing the direct and real-time adjustments essential to a crafting task.

The iterative design process involved testing multiple prototypes with users, identifying challenges and the experience in relation to craftsmanship. Key issues identified included difficulty in manipulating the robot precisely, due to the absence of haptic feedback, limited visual depth awareness, and a reliance on visual-only feedback, which, while informative, have a low robustness and clutters the user interface. These findings lead to the design of three revised prototypes with various constraint levels, one with full user autonomy, one with low constraints and a one highly constrained, to test the impact on user experience and task effectiveness and find the right balance between user control and ease of manipulation.

The results indicate that the low-constraint system provided the most positive user experience, finding the right balance between user control and guidance while maintaining the essential qualities of craftsmanship. Although MR offers a viable framework for enhancing user experience in HRI, the research highlights limitations in replicating the experience of real-world crafting. The study concludes by recommending that future MR applications should leverage MR's unique qualities, rather than simply mimicking traditional crafting qualities, to foster novel, user-centred interactions.

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INTRODUCTION

The rapid advancement of technology has brought extended reality (XR) technologies and robotic automation to the forefront of both professional and personal environments. This project originates from examining these advancements and their implications, particularly in professional settings, where automation is transforming the workers' experience by making production processes more autonomous and efficient.

Automation, driven by innovations in robotics, artificial intelligence, and related fields, has brought undeniable benefits in terms of precision, productivity, and safety across sectors. However, this shift has also introduced a considerable downside: as tasks are increasingly automated, the worker's role becomes more passive, and the enjoyment and satisfaction that traditional hands-on involvement delivers can diminish. In many cases, robots are not only taking over repetitive or hazardous tasks but also removing parts of the work that contribute meaningfully to a sense of purpose, skill, and craftsmanship. This loss risks creating environments where workers become disengaged to the task, leading to decreased job satisfaction.

Maintaining human satisfaction within automated workflows is an important challenge for designers of modern systems. Workers report a sense of fulfilment from tasks that allow them to engage their skills and experience firsthand the results of their labour, which automation alone may not provide. Craftsmanship, for instance, is deeply associated with a tactile, immersive experience—qualities often missing in fully automated systems. Therefore, it is crucial to consider ways in which robots can integrate into professional environments without eliminating these essential aspects of user experience.

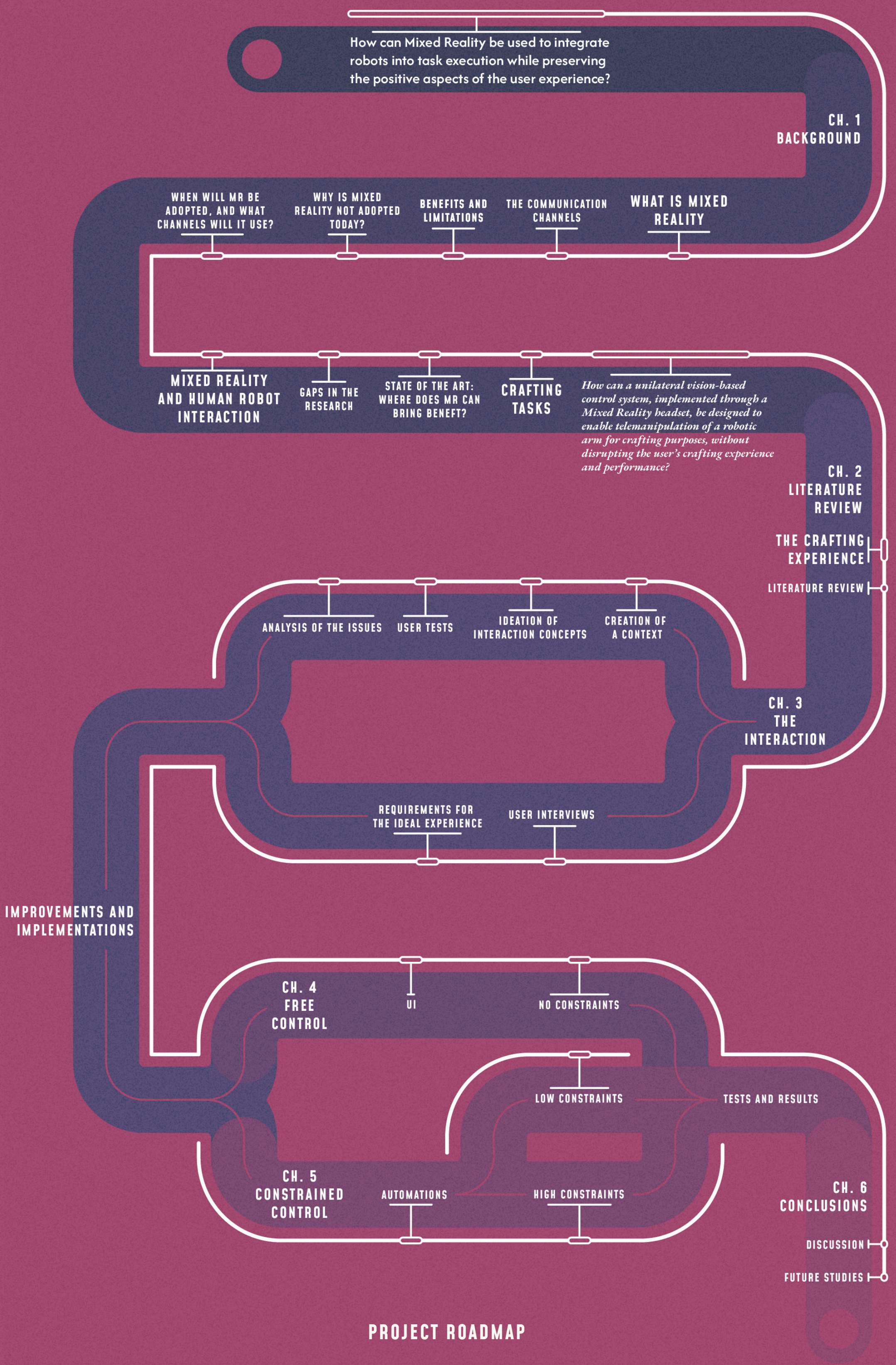
Ensuring human satisfaction within the workflows presents an important challenge in the designing of modern systems that implement robotic automations. Workers find a sense of fulfilment in tasks that allow them to apply their skills and see firsthand the results of their efforts. Therefore, it is essential to consider ways in which robots can integrate into professional environments without eliminating these aspects that are so integral to user experience.

One promising approach to this challenge is through mixed reality. MR technology, by bridging the physical and digital realms, allows users to interact with digital content in a far more immersive and intuitive way than traditional screens or interfaces. In recent years, MR has evolved from simple augmented overlays to systems that support complex, interactive experiences with digital content. This capability positions MR as a valuable tool for enhancing communication between users and robots, potentially enabling a more natural and engaging mode of operation which could allow users to maintain control, sense of involvement, and other positive aspects of the traditional crafting experience,without sacrificing the efficiency benefits of robot implementations.

This context leads to the central research question of this thesis:

"HOW CAN MIXED REALITY BE USED TO INTEGRATE ROBOTS INTO TASK EXECUTION WHILE PRESERVING THE POSITIVE ASPECTS OF THE USER EXPERIENCE?"

In answering this question, this project explores how MR could serve as a tool to facilitate human-robot interaction in a way that respects the experiential qualities of crafting valued by craft makers.
By focusing on the crafting process as a case study, this research examines how MR can provide the means for a human robot interaction that preserves the feeling of craftsmanship while balancing the capabilities of robotic automation.
Through both theoretical analysis and practical prototyping, this work aims to identify methods of interaction that, even as automation increases, allow for desirable and meaningful human experiences within the workflow.



PROJECT ROADMAP

1 CHAPTER BACKGROUND

SECTION 1.1

WHAT IS MIXED REALITY?

Before delving into implementing Mixed Reality (MR) in Human-Robot Interaction (HRI), it is necessary to first understand what mixed reality is exactly. This is necessary to understand the full capabilities of this device and what type of interaction it can enable, for today and tomorrow.

MR DEFINITION

From the literature it emerged how the use of the word mixed reality blurs in different definitions.
Mixed Reality is a technology that is going through many innovations and transformations, because of this it is important to define it not by using a specific model, but rather understand what Mixed Reality is in the general terms and aspects that define it.
Mixed reality is an aggregation of different technologies that together define the product. By understanding what are the functions of these technologies it is possible to define what is the type of interaction that the MR can offer.
The blur in the definition is probably due to the rapid development of technologies related to the MR field that constantly modify or provide new functions. Moreover, with the recent relative spread of Extended Reality (XR) technologies into the mainstream, the definitions used are often mixed up and it is not clear anymore to which technology one word refers to.
Although the word Mixed Reality seems to not have an official definition, in this project the definition of MR is referred to as one of the three parts of the Extended Reality:

- ***Augmented Reality*** (AR) AR generates the illusion, in real-time, of 3D virtual objects appearing to exist in the real world around the user, either supplementing or modifying how users see their surroundings. AR does not allow the user to interact directly with the digital content.
- ***Mixed Reality*** (MR) MR, like AR, integrates digital content into the real environment, but, in addition, MR allows the user to experience and interact with the digital objects as if they were present in the physical space. All while not decreasing the experience of the real world.
- ***Virtual Reality*** (VR) VR completely replaces what a user sees with a purely virtual 3D environment, AR retains the user's view of the real world and modifies or supplements that with 3D digital objects and information.

AR and MR are ideally suited for applications that have a strong spatial element, need real-time, and are connected to the real world. On the other hand, VR is the ideal solution to fully immerse the user into a completely digital environment.

EXTENDED REALITY

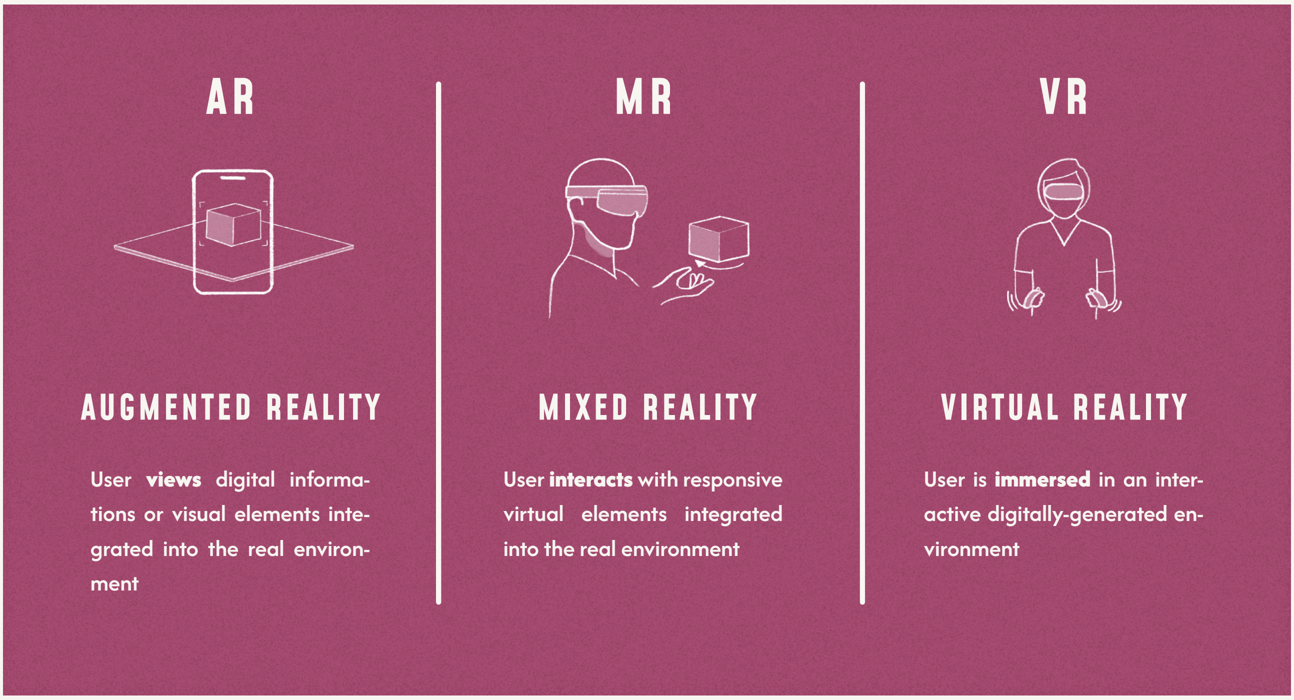


FIG. 1 - AR, MR AND VR

(Source: Science & Tech Spotlight: Extended Reality Technologies, n.d.)

FIG. 2 - A MAN WEARING A MR HMD

AI gnerated image with FLUX.1 [dev]

HEAD-MOUNTED DISPLAY

After having defined the core general function of the MR, it is also essential to understand the more specific functions of it. This device is a combination of different technologies, and even within the same category of Mixed reality, there can be various combinations that offer different types of interaction.
In this project, the technologies that are considered to define the MR are the following:

- ***Head-mounted display (HMD)***
  The device is worn on the user's head and the binocular displays are positioned right in front of the eyes. The display is necessary to allow the user to see the digital elements, by positioning it close to the eyes it offers a wide angle of view and by having it resting on the head it allows to keep the hands free. XR, especially AR can be done through any display, however, the HMD is the one that offers the best immersion in the digital space.
- ***Passthrough or transparent display***
  The user has constant visibility of the surrounding real environment, maintaining the experience of it. MR and AR offer other solutions such as optical see-through display where the user can directly see the environment as the screen does not block the light from the surrounding. Otherwise, if the displays are not transparent, the environment is recorded and projected in real-time on the display on the HMD, this technique is called passthrough.
- ***Input tracking system***
  The user's motion and inputs need to be tracked so that interaction with the digital content becomes possible. This can be achieved with hand tracking, controllers, eye tracking and other devices. The most common system in recent headsets is hand tracking as it has reached good usability and requires minimal hardware, However, the specific technology for input will be discussed later.

These are the technologies used today, however, currently, the device has a low usability (Section 1.2.2), and the technology, to be accepted and adopted as a tool to be integrated into the workflow, must go through some development and innovation that reduces usability issues. Since the MR is a device formed by a combination of technologies, and the innovation to reach the usability level to be implemented will take time, these technologies could be replaced with others that perform better. And, even though MR would maintain the core definition, the interaction modality could significantly change. So, in order to understand how the interaction that the MR offers in the time frame it will be adopted, the next chapter defines what will be the interaction modality by analysing what are the possible channels that humans can interact with, and what technology could be implemented in mixed reality that can translate and interpret such interaction correctly.

DISAMBIGUOUS TAXONOMY

MR was found to have different definitions in the literature. Different studies (Nee & Ong, 2022, Milgram et al., 1994) used the word Mixed Reality as a general group of technology that includes VR and AR. Differently, a prominent company in the XR field (Meta, 2024a), have started using the word *mixed reality* to differentiate the type of display used: both AR and MR allow the user to interact with the digital content, however MR use passthrough to allow the user see the environment on a non transparent display, while AR use transparent displays that allow the user to see directly the environment (without need for passthrough). It is likely that this latter definition will become more common than the one selected for this project, as META, currently the major player to develop such technology, is using this definition.

SECTION 1.1.1

CHANNELS OF COMMUNICATION

Introduction

MR concept is defined, but to proceed on the understanding of what mixed reality is capable of and the interactions it can offer, the technologies that form the device need to be defined, as these are what dictate the interaction modality. However, while the definition of MR is static and not related to time, the technologies within it are products of their time. Considering the current MR technologies, which offer a suboptimal experience and are not going to be adopted in the workflow, wouldn't make sense as this project aims to design a MR interaction in the workflow. The technology to be considered should be in the time frame of when the device has developed enough to offer an experience that is perceived as usable, and therefore adopted in the workflow.

Technologies can evolve or be replaced with other solutions, potentially altering or enabling different types of interactions. In order to define what is the interaction modality that will present in that time frame an analysis is carried out.

This analysis is defined in two steps: understand what are the possible technologies and interaction modalities that can be implemented in the headset, and which ones are the ones that are more likely to be developed, and adopted.

The first step for this analysis is to understand what are the possibilities. These possibilities are defined by two elements: the human interaction channels (what are the possible channels that humans can use to interact and perceive), and the technologies that can capture and understand such interaction.

STRUCTURE OF THE INTERACTION WITH MR

People interact with their environment through a closed feedback loop, where the user perceives the environment, provides input, and receives feedback, which is necessary to inform their next action. Without feedback—i.e., the perception of the environment—the user cannot sustain the interaction. This interaction consists of two elements that, in this project, will be referred to as '***input***,' representing the user's actions or commands, and '***output***,' referring to the user's perception or the system's response.

SECTION 1.1.1.1

CHANNELS FOR THE PERCEPTION – OUTPUT

In the context of MR, understanding how the user can perceive the environment shows what are the ways the headset can communicate the digital information to the user. And by identifying the technologies that can be implemented in the MR that can transfer such information, it will be possible to define what is the type of output the MR will have.

Human perception happens through a specific set of senses. These senses are used to either perceive the external world, in which case are called exteroception, or, instead, used to perceive the inner world, for which case are caller interoception.
MR primarily focuses on the exteroceptive senses, as they are the ones that are directly describing the environment around the user. However the interoceptive senses can also play an important role in increasing the sense of immersion, control and experience. However, the interoceptive senses are found to be much more challenging to be achieved compared to the exteroceptive ones.

The sense in humans are the following:

Exteroceptive Senses

- Vision
- Audition
- Tactile Perception
- Olfaction
- Gustation

Combination

- Proprioception
- Nociception
- Thermoception
- Equilibrioception
- Baroreception

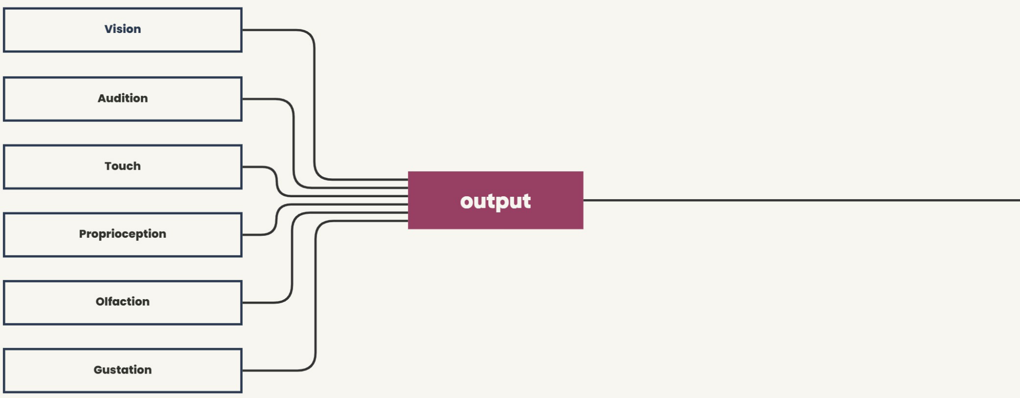
Interoceptive Senses

- Viscral senses
- Chemoreception

SECTION 1.1.1.2

CHANNELS FOR THE COMMUNICATION - INPUT

People have different ways (channels) to interact with the surroundings. There are different inputs that people can use to convey information.
Humans interact with their environment through different channels, each allowing them to convey or receive information. These interactions can be broadly categorised into two types: those aimed at communicating with the environment (such as giving commands or expressing emotions) and those aimed at performing actions (such as manipulating objects or engaging with physical tasks)
The channels we use for these interactions can be either naturally available to us—like vision, touch, and speech—or extended through technology
Some interactions are instinctive and require no learning, like moving your hand to grasp an object.



Others, particularly those involving technology, may require training and adaptation to become effective The input that is expressed through these different channels is then captured and interpreted by the MR device, enabling interaction with digital content.
In today's interaction systems, technology has advanced to capture a wide range of cues from these interaction channels, even before they are fully externalised. Following the Interpersonal Communication Book, Book by Joseph A DeVito, communication starts in the brain and progresses through implicit and explicit stages, where various forms of input can be detected. Technologies like Brain-Computer Interfaces (BCIs) (Sussillo et al., 2024, study, Abiri et al., 2018,) and neuromotor devices (Pezent et al., 2019) can tap into brain activity and neural signals, capturing intent directly from the user's cognitive processes. Additionally, implicit communication cues, such as eye gaze (Pfeuffer et al., 2017) and facial expressions, can be tracked, enabling smoother and intuitive interactions.
Once communication becomes explicit, technologies like gesture and voice recognition allow users to interact directly through body movements and speech. Furthermore, the use of tools such as controllers and keyboards extends even further the interaction methods.

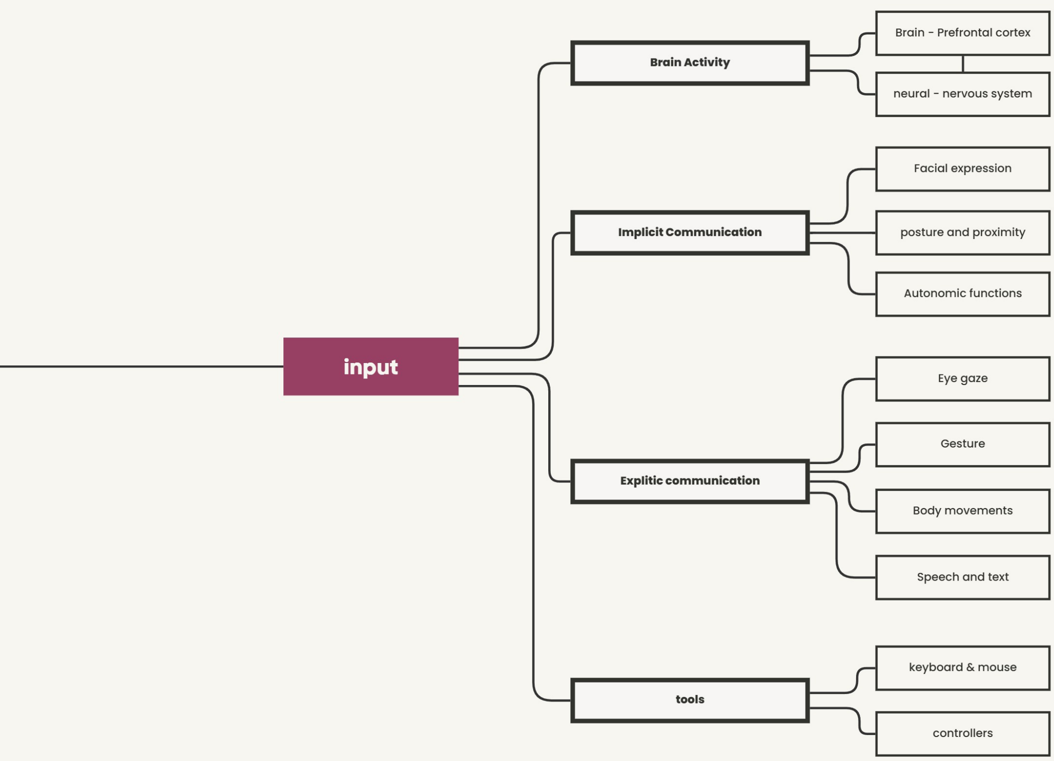


FIG. 3 - INPUT AND OUTPUT CHANNELS DIAGRAM

The type of technology used to communicate (input and output) can significantly influence the interaction modality. As in this project the goal is to propose an interaction that can improve the experience of workers using MR in a professional context, it is crucial to understand the type of interaction being used, along with its limitations and potential problems. However, currently, MR is rarely implemented, except in a few cases.
Given that MR has not been widely integrated into professional environments, focusing on today's technologies and interaction modalities would not be relevant to the project. By the time MR reaches sufficient usability for acceptance, the technology may have evolved, potentially leading to different forms of interaction. Therefore, it is essential to analyse the development trends of MR to estimate when it will be accepted by the target users who will experience the interactions proposed in this project. Once the time frame is identified, it will be possible to estimate the likely combination of technologies that will define MR at that point, and how the interaction is likely to unfold.

Conclusion

The role of mixed reality is to enable users to experience and interact with digital content alongside the real world. The technologies integrated into MR devices define how users perceive and engage with this content. Humans gather information through various channels (such as vision, touch) and interact through others (like speech, gestures, or text). The availability of these channels depends on the capabilities of the technology. Therefore, to define the interaction modality, it is essential to:

Define the time frame
Identify when MR will be widely adopted in professional environments, which is related to when its usability limitations will be resolved, allowing the device to become functional for professional use.

Available channels
Analyse which communication channels will be available at that time, based on the technologies developed and ready for commercial implementation.

The optimal interaction modality
The channels of communication that best support MR's role in enabling interaction with digital content must be identified, focusing on those most likely to be adopted in professional settings.

SECTION 1.1.2

BENEFITS AND LIMITATION OF MIXED REALITY

This section explores the benefits and limitations of mixed reality. The goal of this exploration is to identify the limitations that must be addressed for MR devices to become usable and accepted by workers, and also to identify the benefits, which are essential for determining the most likely communication channels to be implemented in MR—when the technology is adopted.
Additionally By understanding both the advantages and limitations of MR, this knowledge will inform the design of the interaction, allowing for effective integration of MR in tasks that leverage its strengths while avoiding areas where the technology may introduce challenges.

SECTION 1.1.2.1

BENEFITS OF MR

Benefits

This section begins presenting a structured analysis of various applications of Mixed Reality and Augmented Reality as identified through a comprehensive review of academic literature.
The aim of this review is to gain a clear understanding of the different reasons to which MR is currently being applied across disciplines, with a focus on HRI, and to categorise its various uses and benefits to define capabilities and potential of the MR.
The information obtained is presented in a graph, in which each row represents a MR/AR application, sourced from relevant journal articles. There are described for each application:
The Area of Application column identifies the primary field or context in which MR is used, defining the overarching goal of the implementation.
The Task of MR column describes in detail the specific task for which MR is utilised, explaining how the technology contributes to task execution or enhances the user's capabilities.
The Benefits column outlines the specific advantages that MR brings to each application.

SECTION 1.1.2.1.1

APPLICATIONS OF MR

Source	Application of MR
(Ong et al., 2007)	**Assembly planning** Improves assembly planning by enabling faster and more efficient detection of errors, such as collisions and inconsistencies, between virtual planning data and the real-world assembly environment.
(Pentenrieder et al., 2007)	**Model comparison** Allows for real-time comparison between virtual models and physical parts. By overlaying virtual data onto real-world components, AR enables quick and accurate verification, ensuring that the parts match their digital counterparts
(Pentenrieder et al., 2007)	**Factory planning** Facilitates the simulation of spatial obstructions by allowing planners to visualize potential collisions between virtual objects and real-world elements. This interfering edge analysis helps detect spatial conflicts early in the planning process
(Ong et al., 2007) (Yuan et al., 2005) (Pang et al., 2006) (Sääski et al., 2008)	**Assembly guidance** Enhances assembly guidance by providing real-time visual feedback and step-by-step instructions directly in the worker's field of view, improving accuracy, reducing errors, accelerating learning curves, minimizing the need for physical prototypes, and increasing overall efficiency while reducing worker fatigue.
(Keller et al., 2022) (A. Nee et al., 2012) (Fang et al., 2011) (Michalos et al., 2016)	**Robot intentions and trajectory planning** Enables real-time visualization and interactive manipulation of robot trajectories, allowing users to plan collision-free paths more intuitively and make adjustments before actual execution. This reduces programming time, minimizes the risk of collisions, and enhances efficiency in dynamic environments, improving task fluency, safety, and trust in human-robot collaboration, while reducing errors and collision risks in shared workspaces
(Fang et al., 2011) (A. Nee et al., 2012)	**Robot simulations** Allows users to simulate and visualize robot movements and actions in real-time, providing an opportunity to evaluate the feasibility of paths and tasks without needing the physical robot. This enables early detection of errors, reduces costs, and improves accuracy by ensuring tasks are tested and optimized in a virtual environment before execution
(Hincapie et al., 2011) (A. Nee et al., 2012)	**Product maintainance workflow** Improves product maintenance workflow by providing real-time visual guidance and instructions, allowing technicians to quickly access part specifications and follow step-by-step procedures, which reduces errors and enhances efficiency during maintenance tasks

(A. Nee et al., 2012)	**Visualise in context** Enables intuitive visualization of the 3D models in their intended context. This helps designers and engineers experience the spatial relationships and physical characteristics of the objects in real environments, improving design accuracy and reducing the need for physical prototypes
(Mascareñas et al., 2020)	**infrastructure inspections** Overlays high-resolution visual data directly onto physical structures, allowing inspectors to gather precise 3D measurements in real-time reduces the variance in inspections. Enhances safety by allowing inspectors to assess structures remotely, limiting the need for physical proximity to potentially dangerous areas. Facilitates better communication of inspection data over time by creating a digital record that can be referenced later
(Birlo et al., 2022) (Condino et al., 2018) (Li et al., 2017)	**Surgical training** Enhances training by providing real-time, immersive visualizations, allowing trainees to interact with 3D models and simulations using intuitive gesture controls. This approach improves hand-eye coordination, facilitates skill acquisition through realistic practice, and enables better mental mapping of 2D images into 3D space, closely mimicking real-life tasks and improving overall learning outcomes
(Mitsuno et al., 2017) (Sauer et al., 2017)	**Intraoperative assesment** Enables real-time superimposition of 3D images of the body surface and internal structures, allowing surgeons to visually compare preoperative models with the actual surgical field. improves spatial-visual accuracy and ensures the surgeon's actions are aligned with preoperative planning, which is especially beneficial in complex visceral surgeries where manual alignment can be challenging
(Borgmann et al., 2016) (Jalaliniya & Pederson, 2015)	**Data visualisation** Improves patient data visualization by allowing surgeons to access and review electronic patient records, medical images, and other relevant data hands-free and in real-time during surgery, maintaining focus on the operative field, enhancing workflow efficiency, and reducing interruptions compared to traditional methods
(Rojas-Muñoz et al., 2020)	**Telementoring** Allows remote experts to provide real-time, visual guidance directly into the mentee's field of view through 3D overlays, improving accuracy, reducing errors, and increasing the confidence of less-experienced surgeons
(Baashar et al., 2023) (Dhar et al., 2021)	**Medical education** Simplify the delivery and enhance the comprehension of complex information. enhances medical training by providing immersive, real-time visualization and interaction with 3D anatomical models, allowing students to practice and refine their skills in a highly realistic environment, which improves comprehension, spatial awareness, and hands-on proficiency
(Fotouhi et al., 2020) (Qian et al., 2018)	**Robot placement** Allows users to visualize the robot's position in real-time with superimposed 3D models, enabling more precise alignment and positioning, particularly in complex surgical environments. This capability reduces setup time and enhances accuracy in aligning the physical robot with its virtual counterpart.

(Borgmann et al., 2016) (Sauer et al., 2017)	**Teleconsultation** Enables remote experts to provide real-time audio and video guidance during surgical procedures, allowing them to mark anatomical structures directly on the AR interface and improving the clarity of communication and decision-making in complex interventions
(Gil et al., 2021) (Baashar et al., 2023)	**Rehabilitation** Provides real-time feedback through visual and auditory cues, helping patients adjust movements during exercises. It enhances balance and mobility by creating immersive, guided environments, offering engaging scenarios, and allowing therapists to track and personalize exercises remotely
(Gao et al., 2015) (Baashar et al., 2023) (Carbone et al., 2020)	**Guidance** Projecting real-time 3D overlays directly onto the physical workspace, allowing users to precisely follow procedural steps without shifting focus on 2D monitors, which also lacks in spatail awereness informations. This technology ensures seamless navigation by providing continuous, accurate visual cues that improve speed and accuracy in complex tasks
(Schlosser et al., 2019)	**Monitoring** Enables continuous, hands-free monitoring of multiple patients simultaneously. Improving situational awareness and response time by providing constant access to critical data while performing other tasks.
(Jensen & Konradsen, 2017) (Yildiz, 2021) (Alzahrani, 2020)	**Education** Allows students to interact with both real and virtual objects in real-time, creating more engaging and flexible learning environments. It facilitates students' understanding of complex concepts by offering 3D visualizations and immersive experiences, which improve their spatial awareness and knowledge retention
(Soltani & Morice, 2020)	**Sport training** Provides interactive visual overlays that guide athletes through specific techniques, enabling them to correct their form. Allows athletes to receive real-time feedback and additional information during their training sessions, enhancing their understanding of complex movements, avoiding detrimental positions, increasing the diversity of movements. Enables direct comparison with expert techniques, enhances awareness of game-related information, and can assist to predict the future trajectory of objects, such as a ball, for improved decision-making.
(Blundell & Harris, 2023) (Livingston et al., 2011)	**Enhanced situational awareness** Provides real-time, spatially-referenced overlays that enhances awareness of critical information and navigations informations directly on the user-s field of view. It present peripheral information in critical tasks to improves the user-s ability to perceive and comprehend their environment, reducing, reducing cognitive load and enhancing decision-making particularly in high task-load or low visibility scenario
(Livingston et al., 2011)	**Avoidance of line-of-sight loss** Facilitates the recognition of hidden or obscured threats by displaying virtual cues over the real-world view This capability enhances the user's ability to make rapid, informed decisions, thus increasing safety and effectiveness in critical scenarios

TABLE. 1 - BENEFITS IDENTIFIED IN STUDIES THAT IMPLEMENTS MR

SECTION 1.1.2.1.2

BENEFITS - HOW IS MIXED REALITY USED

Kim and Dey (2008) describes the benefits of MR as a combination of three features: ***intuitive observation***, ***informative visualisation***, and ***immersive interaction***. From the findings of the studies reported in the table in Section 1.2.1, a similar conclusion can be drawn. It is possible to categorise all the implementations of MR and AR in 4 different categories: to ***instruct*** the user, to ***inform*** the user, to ***simulate*** around the user and to allow the user to ***interact*** with the digital space.

INSTRUCT

The instruct function in MR is primarily used to guide users through specific tasks by providing real-time visual instructions overlaid onto the real environment. This is especially effective in fields like manufacturing and healthcare, where MR offers spatial guidance during complex procedures such as assembly instructions or surgical operations. MR's ability to overlay contextual information directly onto real-world tasks reduces reliance on external manuals and minimises errors, significantly enhancing workflow efficiency. For example, in manufacturing, MR can provide path guidance, helping users complete complex assembly processes with greater accuracy. Similarly, in healthcare, surgical navigation systems using MR can offer real-time insights, enabling surgeons to perform procedures with enhanced precision.

INFORM

The inform function allows MR to provide information about objects or environments without directing the user to take specific actions.MR offers users the ability to provide subject information, such as technical data overlays in industrial settings or displaying contextual information in healthcare during surgical procedures. MR can also enhance situational awareness. In these contexts, MR helps users access critical, real-time information such as 3D models for part verification or spatial layouts for planning. In healthcare, MR can display real-time patient data during surgery, enhancing intraoperative awareness and enabling surgeons to make better-informed decisions. The predict and show intentions feature also allows users to foresee potential outcomes, further improving decision-making processes in dynamic environments.

SIMULATE

The simulation function of MR enables users to predict and verify outcomes by interacting with digital objects in a real-world context. This capability is widely applied in industries like manufacturing and healthcare, where task simulation is critical for safety and accuracy. MR allows users to simulate spatial layouts, predict task outcomes, or verify robot trajectories, ensuring precision before real-time execution.

It also provides an immersive platform to experience tasks, improving the learning curve by allowing users to engage with simulated scenarios. This is particularly useful in medical training, where MR can simulate complex surgical procedures, allowing professionals to gain hands-on experience in a controlled environment.

INTERACT

The interact function of MR enables users to manipulate digital content within their physical environment in real-time. MR's 6 Degrees of Freedom (6DOF) manipulation allows for intuitive interaction, enabling users to create, move, or adjust digital objects seamlessly. This function is especially relevant in design, architecture, and manufacturing, where professionals interact with virtual prototypes and 3D models to refine their designs.In human robot interaction, MR facilitates the robot programming by allowing the user to directly interact and manipulate the planning of the trajectory, providing real-time visual feedback.

While these functions—instruct, inform, simulate, and interact—are essential in understanding the roles MR plays across different fields, they do not fully explain why MR should be used over other technologies like PCs or tablets. These functions, though valuable, are relatively generic and can be achieved through other means. Thus, to better determine where only MR offers the most value in relation to the user experience in HRI, and justify its implementation, it is crucial to identify the unique benefits that MR provides, which cannot be replicated by traditional devices.

FIG. 4 - HOLOLENS 2 FOR HEALTHCARE

Microsoft. (n.d.). HoloLens in healthcare. Retrieved from page

SECTION 1.1.2.1.3

UNIQUE BENEFITS OF MR

identify the unique benefits involves pinpointing the specific advantages MR provides that other solutions cannot. By determining these unique characteristics, it will become evident why MR should be prioritised for certain applications.

The functions of MR, as outlined in the previous chapter, reflect tasks that could potentially be achieved by other devices. In fact, the role of MR lays not in the content itself, but rather on how it is experienced and interacted with, as suggested by the study that describe the benefits of MR, the benefits are described with words such as intuitive observation and immersive interaction, suggesting that MR's interaction methods, rather than the content itself, offer its most significant advantages.
By analysing various studies that describe the implementation of MR, it was possible to identify a series of characteristics that can be defined as its unique benefits. The combination of these specific characteristics creates a level of interaction that is truly unique to MR. These unique benefits are detailed as follows:

REDUCTION OF THE LEARNING CURVE

Mixed Reality has been demonstrated to improve the learning process, especially in areas where understanding spatial relationships or complex procedures is crucial. By offering immersive, hands-on experiences, MR reduces the need for users to mentally translate 2D information into 3D space. For instance, in medical training, MR assists students by simulating surgical procedures in real-time, allowing them to practise and experience the task virtually, significantly reducing the learning curve. Studies have shown that MR allows learners to understand 3D spatial information more intuitively, enhancing the comprehension of complex tasks .

QUICK ACCESS TO INFORMATION

MR devices allow users to quickly access relevant information in real-time without needing to look away from their work or switch between devices. In the medical field, for example, MR headsets can overlay real-time patient data directly into the surgeon's line of sight during surgery, reducing the need for constant attention shifts between monitors and the operative site. This enhanced situational awareness improves efficiency and accuracy in high-stakes environments like healthcare or military.

3D VISUALISATION

One of the most significant advantages of MR is its ability to provide users with 3D digital content that enhances their understanding of objects and environments. MR is frequently used to create 3D models that can be visualised in a real-world context, offering users a more intuitive and direct experience of spatial layouts and object structures. In architecture and design, for example, MR enables professionals to visualise and manipulate 3D models of buildings or products directly in their intended physical environments, improving both design accuracy and decision-making. Studies show how this visualisation can be especially beneficial in difficult tasks, especially when they rely on depth information or spatial understanding.

EXPERIENCING THE REAL ENVIRONMENT

Unlike Virtual Reality, which fully immerses users in a digital environment, MR allows users to maintain their line of sight on the real environment while interacting with digital content. This capability is crucial in fields such as industrial maintenance and medical procedures, where users need to stay engaged with their physical surroundings while benefiting from digital overlays of relevant data or instructions. For instance, during surgery, MR can display critical patient data and guidelines without obstructing the surgeon's view of the operating area.

HANDS-FREE INTERACTION

A key benefit of MR is that it does not require users to hold devices or controllers to interact with the system, freeing up their hands to focus on the task at hand. This feature is particularly valuable in settings like manufacturing, where workers can interact with digital overlays and receive real-time instructions while physically manipulating machinery or tools. This hands-free interaction increases efficiency and reduces distractions during complex tasks.

NATURAL INTERACTIONS

MR also allows users to interact with digital content using natural hand movements, making the experience more intuitive and aligning with the way people naturally interact with the physical world. This ability to interact with objects using 6 Degrees of Freedom (6DOF) and no controllers provides an immersive, user-friendly experience, particularly in design and manufacturing, where professionals need to manipulate digital models as if they were physical objects. By using their hands, users can seamlessly blend digital and real-world interactions .

Benefits conclusion

Mixed Reality (MR) should be implemented to enhance the interaction of acquiring information and engaging with digital content.
It is particularly beneficial for information retrieval when:

- mantain experience of the real environment,
- informations are three-dimensional,
- access to information is required to be quick and without distractions,
- operation needs to be hands-free.

For active participation in interactions, MR is useful when:

- The interaction requires realistic simulation,
- Spatial manipulation with digital content.

FIG. 5 - HOLOLENS 2 FOR MANUFACTURING

Microsoft. (n.d.). Instruction guides in production overview. Microsoft Learn. Retrieved from [page]

SECTION 1.1.2.2

LIMITATION OF MR

Limitations

While the benefits of MR are significant, it is equally important to acknowledge the limitations that affect the usability and application of this technology. Just as understanding MR's strengths helps identify which Human Robot Interactions could benefit from its implementation, recognizing its limitations allows to avoid applying MR in contexts where it may not be suitable.
A thorough literature review and desktop research provide a comprehensive overview of the current limitations of MR across various fields. To better assess the limitation a broad approach is adopted, by considering different applications, ranging from sports to surgical procedures, it is possible to identify more limitations. However, special focus will be placed on human robot interaction, as it is most relevant to this project.
The exploration of MR's limitations reveals two distinct categories: limitations related to the current state of the technology (time-related), and inherent limitations that stem from the fundamental nature of MR itself. The time-related limitations, such as those associated with hardware or software maturity, are expected to improve over time as technology advances. In contrast, the inherent limitations are more deeply rooted in the core characteristics of MR and may persist as long as MR relies on the same communication channels defined in its current form.

SECTION 1.1.2.2.1

TECHNICAL LIMITATION OF MR

(Chen et al., 2021)	**Size**	The need for battery and processing result in a bulky device design. This reduces the device's ergonomics and lowers social acceptance due to its intrusive appearance.
(Zhan et al., 2020)	**Low resolution**	low resolution displays limits the clarity of virtual elements, making it difficult to distinguish fine details, which negatively impacts user experience and task performance
(M. Livingston et al., 2009)	**Overlay**	Digital overlays require high contrast for clear visualization, but achieving this reduces the transparency of the see-through display, resulting in a trade-off that compromises either the clarity of the overlay or the visibility of the real-world scene
(Zhan et al., 2020) (Lee et al., 2019)	**Limited field of view**	The display angle for overlays is often narrow, leaving large portions of the user's field of view without digital augmentation, which limits the immersive experience and reduces the effectiveness of the AR system
(Carbone et al., 2020) (M. Livingston, 2005) (Pladere et al., 2021) (Kaufeld et al., 2022)	**Depth perception problem**	Superimposed digital overlays degrade depth perception, especially for far-field depth, and make it difficult to resolve spatial relationships. The fixed focal plane prevents users from seeing both virtual and real content in focus simultaneously, leading to conflicts that cause diplopic vision, discomfort, and a decrease in performance.
(Azuma, 1997)	**Registration and sensing**	limitation in the accuracy of tracking system decrease the quality of the experience and the performance of controls
(Buker et al., 2012)	**Latency**	delays between user movements and the corresponding updates of virtual content, creates a sensory mismatch that can lead to motion sickness
(Kaufeld et al., 2022)	**Motion Sickness**	these issues cause symptoms of motion sickness, nausea, fatigue, dizziness, eyestrain, and headache, especially in dynamic environments with moving virtual objects.

SECTION 1.1.2.2.2

INHERENT LIMITATION OF MR

(Katić et al., 2014)	**Sensory overload**	increase visual complexity, making it harder to collect relevant information and process them efficiently, especially during critical interventions
(Borkin et al., 2011) (Katić et al., 2014) (O'Hagan et al., 2022)	**Occlusion**	causes visual clutter and occlusion by introducing virtual overlays that obscure important real-world information. It decreases awareness by overloading users with unnecessary visual complexity
(Lecuyer et al., 2002)	**Sensory illusion**	causes users to misperceive force or movement when visual feedback overrides their proprioceptive sensations, leading users to believe they are interacting with objects differently than they actually are
(Bonnail et al., 2023)	**memory manipulation**	can be misused to cause memory issues by inducing absent-mindedness or misattribution, weakening memory encoding, or distorting memories by blending real and virtual elements
(Tseng et al., 2022)	**perceptual manipulation**	can be misused to cause perceptual manipulation by overriding sensory perception, leading users to misinterpret real-world objects or actions, which may result in disorientation and potential physical harm
(Burns et al., 2005)	**Sensory discrepancy**	cause sensory discrepancy when visual and proprioceptive cues conflict, leading users to misinterpret their body's position or movement. This can result in disorientation, reduced performance, or increased error rates
(Hansberger et al., 2017)	**gorilla arm syndrome**	can cause gorilla arm syndrome when users engage in prolonged mid-air gestures, leading to arm fatigue, discomfort, and reduced interaction efficiency

TABLE. 2 - LIMITATIONS IDENTIFIED IN STUDIES THAT EXPLORE MR

Limitation conclusion

Mixed reality presents several limitations, both technical, which are likely to improve as technology advances, and inherent, which stem from the nature of the device itself.

TECHNICAL LIMITATIONS:

The battery and other hardware components contribute to weight, heat, and bulkiness, all of which affect comfort and restrict movement when the device is worn. Display technologies face issues such as limited resolution, latency, clarity and a restricted field of view, all of which reduce the quality of the digital experience and can lead to motion sickness and eye strain. Additionally, tracking and mapping technologies are prone to errors in capturing the surrounding environment.

INHERENT LIMITATIONS:

Visual overlays introduce elements into the field of view, potentially causing information overload and obscuring parts of the environment. Interaction with digital content is limited to a few senses, leading to sensory discrepancies and illusions. Furthermore, interactions often require mid-air gestures, which can be uncomfortable over time. MR can also be misused for memory and sensory manipulation, potentially causing harm to the user.

WHEN TO AVOID MR:

These technical limitations suggest that MR might be unsuitable for certain tasks, such as physical activities, due to the device's bulkiness, which restricts movement. However, this project considers the use of MR within a time frame where the major usability challenges will have been addressed (see next chapter), so these limitations may no longer apply. In contrast, the inherent limitations can be used to determine which tasks should be avoided, though they seem more related to interface and interaction design issues rather than the compatibility of specific tasks.

The information gathered in this chapter is essential to proceed with identifying the interaction modalities for MR devices.

By understanding the benefits MR offers (benefits conclusions), it becomes possible to determine which technologies are most likely to be adopted to interact with the user (input and output), when the device reaches wider use.

On the other hand, the limitations (limitation conclusions) of MR are equally important, as they highlight the issues that need to be resolved in order to reach a level of usability that will be accepted by workers. These limitations help to identify areas such as hardware, interaction design, and sensory feedback that require improvement to ensure that MR integrates smoothly into various tasks.

FIG. 6 - AN ADBANDONED HEADSET

AI gnerated image with FLUX

SECTION 1.1.3

MR ADOPTION

Introduction

To define the interaction modality for MR devices, it is essential to estimate when MR technology will be ready for adoption by professionals in industry. The state of the technology at that time will determine the interaction modalities that need to be considered in this project. The approach used in this process is outlined as follows:

- ***Why MR is not implemented today – what are the requirements for its acceptance?***
  To understand the barriers preventing the widespread adoption of MR, the Technology Acceptance Model can be applied. By using the previously identified limitations of MR, it is possible to pinpoint the critical features that currently hinder the adoption of MR devices. This will help define the limitations that must be resolved in order for MR to be accepted in professional environments.

- ***Which communication channels (technologies) are most relevant to MR?***
  By analysing the current applications of MR and the benefits identified, and by applying a usability framework that assesses effectiveness, efficiency, and user satisfaction, it is possible to determine the most appropriate communication channels for MR (input and output). This process helps filter out which technologies can effectively enable interactions through these channels. However, to determine the specific technologies, an additional step is required:

- ***When will the technologies enabling these channels achieve good usability?***
  By examining current trends in the development of technologies identified as suitable for MR interactions, it is possible to estimate when these components will be advanced enough to reduce the limitations preventing MR adoption in professional settings. This will highlight which technologies, and thus interaction modalities, will be implemented in MR devices when they are widely adopted.

SECTION 1.1.3.1

WHY MR IS NOT IMPLEMENTED TODAY

The Technology Acceptance Model (TAM), introduced by Davis (1993), provides a framework for understanding the factors that influence the acceptance and adoption of new technologies. According to TAM, two main factors drive technology acceptance:

- ***Perceived Usefulness***
  The extent to which users believe that a technology will enhance their job performance.

- ***Perceived Ease of Use***
  The degree to which users believe the technology will be easy to use, with minimal effort required for learning and implementation.

These two factors are key in determining whether a technology will be adopted by users, especially in professional settings where time and efficiency are critical. In the context of MR, this framework can be used to assess why MR has not yet been adopted widely, particularly in industries where Human-Robot Interaction and other professional uses, which could benefit from its application.

PERCEIVED USEFULNESS

Problems

Limited Applications:
Many tasks in professional settings can still be performed without MR, reducing the perceived value. For tasks where MR could be useful, the technology has not yet reached a level where it offers significant improvements over existing tools.

Negligible Benefits:
Current MR devices do not consistently offer a tangible advantage in productivity or accuracy. Professionals are unlikely to adopt a system that doesn't show clear benefits compared to their current tools and methods.

What needs to change:

Expanded Application Range:
MR must offer a broader range of useful applications that clearly enhance job performance. More MR is adopted the more systems will be designed around it. Once MR ease of use reaches an acceptable level, it is likely that more systems will start implementing interaction based on the MR, making MR consequently a more useful tool.
This shows how usefulness comes only as a consequence of ease of use. With ease of use, applications would be created, and thus usefulness would increase.

PERCEIVED EASE OF USE

Ergonomics and Comfort:
Current MRs have bulky size, heavy weight, display that obscures the real environment and have extremely limited field of view. These features make the experience of the device not enjoyable and negatively affects the performance of tasks in the workflow, especially if worn for extended periods, in physically demanding tasks.

Usability Challenges:
Issues with limited field of view, low resolution, tracking precision, and latency make it difficult to integrate MR into everyday workflows seamlessly. The interaction methods currently available are often imprecise, reducing ease of use for professionals who require quick, efficient, and reliable interactions.

Social acceptance
The bulkiness and unique look of the device makes it socially uncomfortable to use it in a workplace.

Ergonomics and Comfort:
Devices must be significantly lighter, less bulky, and more comfortable to wear and move with it for long periods, addressing issues of weight size and heat management. Also optical issues (high latency, low resolution, fixed focus plane) need to be taken care of as current devices cause stress to the eye and motion sickness after some time.

Interaction:
The interaction methods need to be more reliable and precise, allowing for seamless, natural interactions with digital content at an equal precision as interactions without the MR.

Social acceptance:
the current large size and barrier of interaction with other people needs to be addressed as the work place is a social environment. Making the MR a less intrusive device on the head of the user might increase the acceptance.

SECTION 1.1.3.2

WHICH COMMUNICATION CHANNELS ARE MOST RELEVANT TO MR

As discussed in Chapter 1.1, humans utilise various channels to communicate and receive information (input and output). Each of these channels offers a distinct type of interaction, making it essential to determine which ones need to be the one to be considered in this project.

Currently, MR systems support a variety of interaction types, and this diversity is likely to persist, as different tasks may require different modes of interaction. However, as MR can be defined as a device that enables users to experience and interact with digital content while maintaining a connection to the real world, some channels better facilitate this dual interaction than others.

To estimate the most suitable channel for MR interactions, it is possible to apply the characteristics of usability as a framework to guide the decision. Usability, as defined by ISO 9241-11 (ISO, 2018), refers to the effectiveness, efficiency, and satisfaction with which specified users achieve their goals in a particular context of use. By evaluating potential input channels against these usability criteria, it is possible to develop a clearer understanding of which ones are most likely to enhance user interaction and be adopted.

THE INPUTS

In the literature, several input systems have been identified as being used for interaction with MR devices, each offering different capabilities and interaction methods.

Brain-Computer Interface (BCI):
BCIs allow users to interact with MR systems by directly translating brain activity into commands. This technology bypasses traditional input methods, enabling hands-free interaction by interpreting electrical signals from the brain. (Sussillo et al., 2024, study, Abiri et al., 2018)

Neuromotor Systems:
Neuromotor input systems utilise muscle signals to detect user intentions, allowing for precise control within MR environments. By interpreting motor neuron activity, these systems provide an alternative means of input that can be particularly useful in scenarios requiring high precision or where conventional input devices are less effective. (Pezent et al., 2019)

Eye Gaze Tracking:
Eye gaze systems track the user's point of focus and translate this into inputs for MR devices. This input method is particularly valuable in scenarios where the user's gaze can select objects or navigate menus without relying on physical gestures or commands. (Apple, 2024, Pfeuffer et al., 2017)

Gesture Recognition:
Gesture recognition systems detect and interpret specific hand movements to control MR devices. These predefined gestures allow users to interact with virtual objects or interfaces by performing recognizable hand motions, offering an intuitive way to manipulate digital content in MR environments.

Body Movements:
Tracking body movements allow for direct manipulation of virtual objects through real-world hand movements. These systems capture and translate physical movements into corresponding actions within the MR space, providing an immersive and intuitive experience.

Voice Commands:
Voice recognition systems enable users to control MR devices through spoken commands. This hands-free input method can be beneficial in situations where physical interaction is limited or impractical. Voice commands allow users to interact with the MR system without interrupting ongoing tasks. (RayBan, 2024)

Tools (Keyboards, Controllers):
Traditional input tools, such as keyboards and controllers, can be used in MR environments. These tools provide familiar and reliable input compared to more advanced input systems.

The selection of the most usable channel (efficient, effective, and satisfying) is directly related to the type of interaction that needs to be performed. Interactions in 3D space can generally be categorised into two modalities:

- Navigation within the 3D space
- Manipulation of 3D objects

Given the limited value of a system that only allows navigation but not direct manipulation of digital content, it makes sense to focus on manipulation as the interaction where MR offers the most benefits. This doesn't mean that navigation will be less used—it may, in fact, be more widely implemented, as it provides significant advantages and may be technically easier to achieve. However, manipulation unlocks the full potential of MR, even though it presents greater technical challenges.

So, which channel is more usable for manipulating digital content in MR?

Implicit channels are primarily used to convey the user's emotional state, making them inefficient for communicating specific types of input. Bowman et al. (2004) in 3D User Interfaces: Theory and Practice explains that in 3D interfaces, where manipulation of virtual elements is required, an input that provides six degrees of freedom (6DOF) is the most effective choice.
Channels such as eye gaze, voice commands, and many tools like keyboards do not provide 6DOF, which makes them impractical for complex interactions with digital content in MR (although they can still be useful for non-manipulative tasks). Among the remaining options, preference is given to channels that offer intuitive interactions, facilitating more seamless and natural engagement with the

system.
While tools offering 6DOF often require some learning and provide non-intuitive, limited interactions (such as the space mouse), gesture recognition—though frequently labelled as natural—also requires learning and is not as intuitive as it might seem (Norman, 2010; Malizia & Bellucci, 2012). The most favoured channels for manipulation seem to be ***body movement*** or inputs linked to body motion, such as ***neuromotor*** systems and ***brain*** input (BCI).

THE OUTPUT

Among the senses presentedin chapter 1.2.1, current MR devices show capabilities to interact with the senses of vision and audio, as, similarly to most digital devices, virtual content finds the most effective representation in such form. Vision (Meta Quest 3, Apple Vision Pro) and auditory (Ray-Ban) interaction are already being implemented in many commercially available devices
However, from the literature there can be often found haptic feedback as another important component of the interaction. Haptic devices are found in a more experimental stage, minimal feedback might be present in some controllers, but for more complex feedback the costs become prohibitive (Sense Gloves, 2024, A. Nee et al., 2012).
For the other senses there is a limited research effort, as the usefulness of such perception is not perceived and technical barriers make it even harder to achieve. Olfaction and gustation are exclusively found in small quantities in the research field (Wang et al., 2018, Spence, 2021, Hoffman et al., 1998). The rest of the senses do not have signs to be implementable soon as they seem to be a very niche research field.

In conclusion ***vision***, ***audio***, ***haptic*** (tactile and proprioception—force feedback) are common. With vision being the most adopted, in every MR device, showing how it represents the core of this technology.
To present a general overview of the current landscape, though not intended to be an exhaustive or highly precise analysis, a search on the research engine Scopus using the keywords 'Extended + Reality + *sense-related term*' yielded the following results: 700 for vision, 235 for audio, 273 for haptic, 21 for olfactory, 18 for smell, 23 for taste, and 7 for gustatory.

From the literature (Schraffenberger & Van Der Heide, 2016, Hauptmann, 1989) emerged that there is a benefit of having a device that is capable of a multimodal interaction, that makes the user perceive information through more senses, as it reinforces the quality of the perception and decreases the mental load.

With this information, it is possible to conclude that the most usable output channels are, first, the display, which faces several technical limitations; second, auditory feedback, which is easier to implement technically within the device; and lastly, haptic feedback, highly effective in certain specific interactions, which also presents significant technical challenges.

FIG. 7 - MEDIUMS FOR ACCESSING COMMUNICATION CHANNELS IN MR

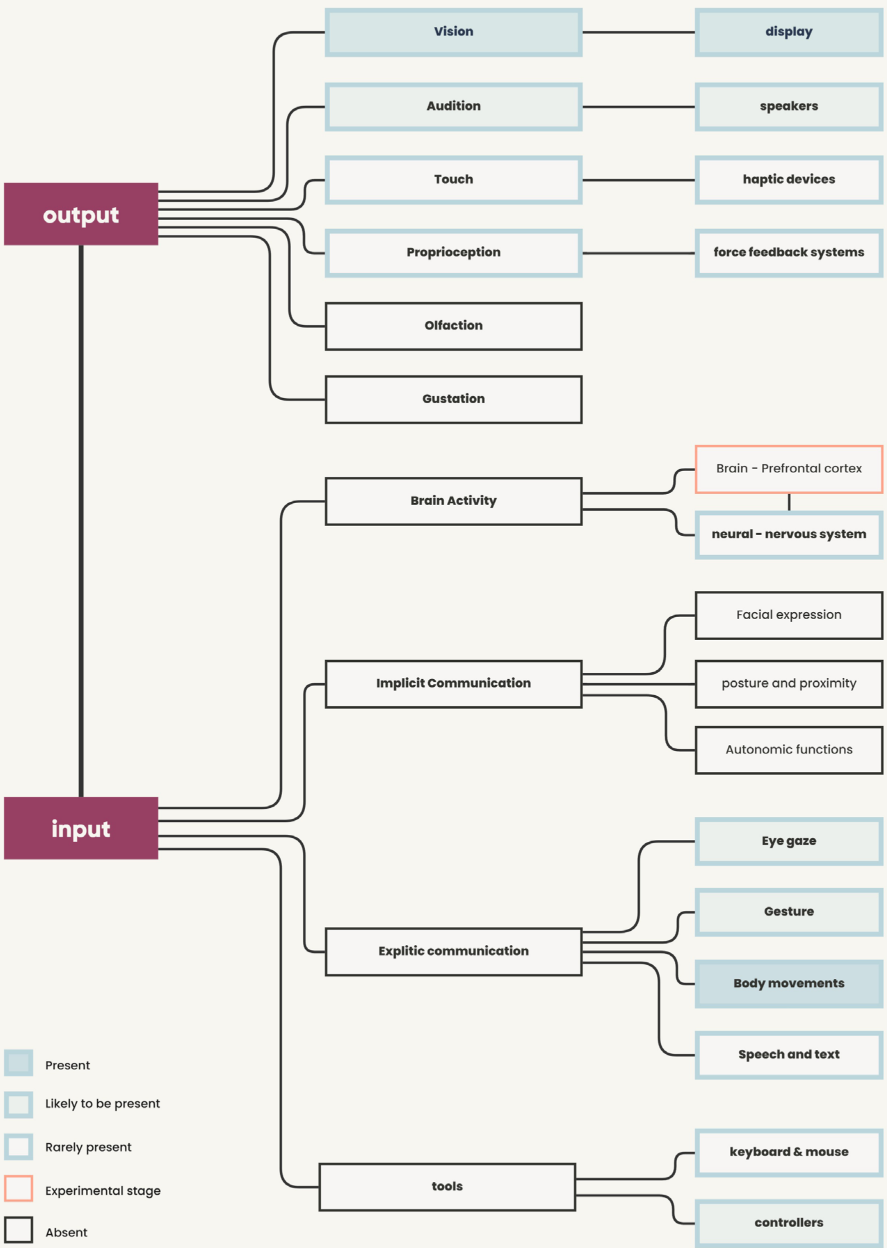


FIG. 8 - META ORION AR GLASSES

Meta. (2024, September). Introducing Orion: Our first true augmented reality glasses. Facebook Newsroom. Retrieved from [source]

SECTION 1.1.3.3

WHEN WILL THE TECHNOLOGIES ENABLING THESE CHANNELS ACHIEVE GOOD USABILITY?

The final step in defining the interaction modality for MR is divided into two key points:
First, identifying the time frame in which the technological limitations that currently degrade usability will be overcome, allowing the device to reach a level of usability suitable for adoption in a professional environment.
Second, determining how the technologies enabling interaction through the channels identified as compatible with MR (from the previous section) will have advanced within this time frame, and which of these technologies is most likely to be implemented in MR devices.

IDENTIFICATION OF THE TIME FRAME

To create a truly usable AR device, many elements must be balanced—field of view, transparency, brightness, focal point flexibility, resolution, bulkiness, and battery life (Yin et al., 2021). Achieving all these requirements in one device will take time due to the complexity involved in each area.
Field of View: Current systems offer around 50° FOV, but technologies like lightguide-based systems and freeform prisms are pushing this forward (Magic Leap 2 with 70°FOV). The increase is slow but steady. Given that past improvements in FOV have been gradual, a slow steady advancements over the next few years is plausible, making it likely to achieve a FOV close to the human eye in 7-10 years.
Brightness and Clarity: To improve display transparency while maintaining visibility of digital overlays in outdoor settings, MR devices require enhanced brightness, potentially up to 10,000 nits, to counter high ambient light levels. Microdisplay technologies, such as OLED and micro-LED, are advancing to balance transmittance and brightness, though achieving both true transparency and high brightness outdoors remains challenging (Hsiang et al., 2022). Based on the pace of development in microdisplay technologies, addressing issues like contrast and efficiency in outdoor environments as well as successful integration into compact MR devices, may still take several years to resolve.
Focal Point Flexibility: Though prototypes for varifocal displays exist (Lin et al., 2022), the technical challenge of making these systems affordable and practical remains significant. This goal is still far off, with commercial viability likely a decade away due to cost and complexity.
Resolution: Over the past few years, MR displays have moved from low-pixel density screens to more refined OLED panels. These developments have significantly improved resolution compared to earlier AR systems, showing an upward trend, which shows that achieving high-resolution displays seems realistic in the next 3-5 years.
Tracking and Registration: Advances in computer vision and sensor fusion have greatly improved vision-based hand tracking, though single-finger pre-

cision and responsiveness remain challenges. Progress is steady, but achieving error-free registration in dynamic environments will take time, likely another 5-10 years.

Bulkiness and Battery Life: Battery technology is slow to advance, making it difficult to power high-performance displays without adding weight. Improvements in efficiency and the use of cloud-based processing (as seen in Nvidia's rendering systems) or separating components (like Apple's Vision Pro) are helping reduce bulk. Current device like the Meta ORION shows that it is possible to miniaturise the component enough oma ke a small functional AR, however before the technologies that are able to solve the other issues analysed before can be implemented in a small and ergonomic and fully compact, could still be 10+ years away.

In summary, while significant resources are being invested in MR technologies, solving all the current challenges will likely take a minimum of 10 - 15 years. At that point, MR, although not yet issue free, could offer usable interaction, and be adopted in areas where its implementation could greatly enhance the workflow, such as the improvement in communication between humans and robots in HRI.

THE INTEREACTION SYSTEM

To understand what will be the interaction system that will be adopted in the time frame defined 10-15 years. It is necessary to explore what will be the technology available for that time frame that offer communication in the channels identified as compatible with the MR will develop,, and which one can enable the best, in terms of usability (efficient, effective, and satisfying), related to the professional use.
By separating the technologies in two categories, for the output (the digital feedback), and for the input (the instructions from the users), the trends of the technology that offer different types of interaction are explored.

Input trends
BCI
This technology is currently adopted almost exclusively in the research environment, especially considering that to capture a clear brain signal it is necessary to use invasive procedures. Non-invasive BCI are not usable due to the low clarity of the signal, limiting applications to only extremely simple commands, something not suitable for a manipulation interaction in the MR.
Research and development in this field are progressing with an increasing interest in it (Rapeaux & Constandinou, 2021), however the limited knowledge of the brain and the technical difficulty in achieving a clear signal shows that the technology is still very far from implementation in commercial devices. In 10 years it will be very unlikely to see such technologies used in MR devices of use outside of the research environment.

Neuromotor devices
Recent developments from Meta (Pezent et al., 2019) have shown a prototype of an EMG bracelet that can capture the user nervous system input from the wrist. This shows how this technology, although not present in the market yet, might soon be implemented as a way to interact. This technology offers various benefits, such as maintaining hands free, capture with more precision gesture and micro gestures, while keeping a socially acceptable look due its similar size and look to a bracelet. It is very likely that similar devices will be implemented in the near future making it the new normal.

Body tracking.
Body tracking can be achieved using physical devices or vision-based systems.
Vision-based tracking, particularly for hand track-

ing, is a major focus in MR and has seen rapid development. Advances in machine learning and multi-camera systems have improved gesture recognition, while improvements in computing power and predictive algorithms reduce latency.
Considering the improvement in sensing and registration, it is reasonable to assume that, in the time frame defined, vision based hand tracking could develop to work almost flawlessly for wide movement; finger tracking could remain challenging due to camera visibility limitations on finger finger movements
Controllers for detecting body movements are already a well-established technology, offering reliable, accurate, and low-latency input. Unless controllers that integrate complex haptic feedback, the capabilities of these controllers are unlikely to change significantly from current standards, as they already meet most requirements for precise and responsive tracking.

The output
Knowing which channel will be used to receive the information is equally important to define the interaction modality.
Visual
Visual feedback is the primary means through which MR delivers digital content, making it a critical component of the user experience. Audio and haptic elements are supplementary, enhancing immersion and enabling a multisensory experience. Given the importance of visual elements for MR, the devices in the time frame defined must provide digital overlays with the already explored issues resolved (sufficient

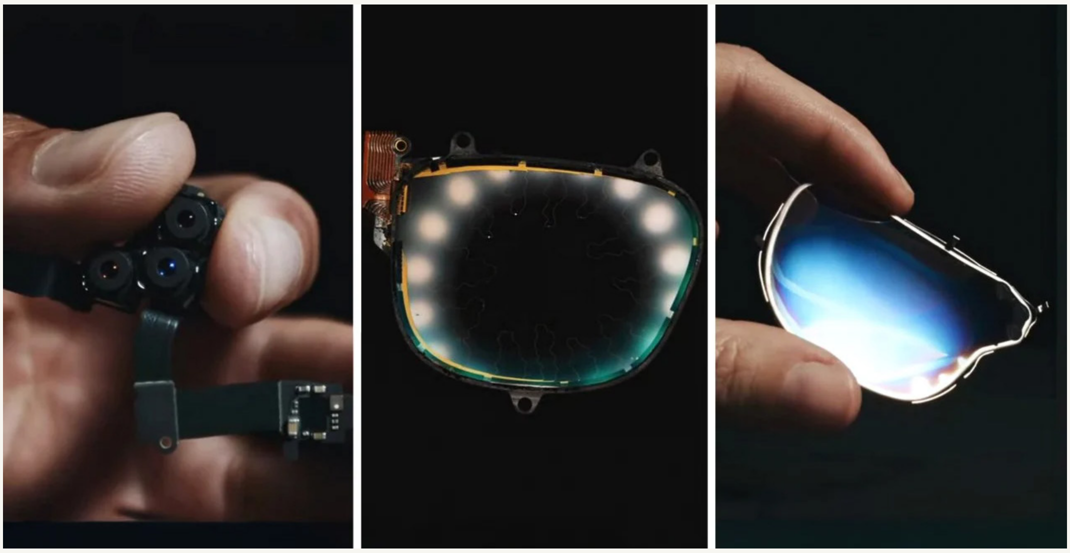


FIG. 9 - META ORION AR GLASSES

Teqnoverse. (2024). How Meta's holographic glasses blend digital elements with reality. Medium. Retrieved from source field of view, brightness, transparency, and size, etc.).

Audio
Audio technology, being well-established, is unlikely to see major shifts in interaction methods over the next decade. While improvements in sound quality and performance may occur, the interaction with audio in MR will remain present and unchanged.

Haptic Feedback
Like audio, haptic feedback plays a secondary role compared to visual elements in MR. Current haptic feedback in MR headsets and controllers is basic, typically limited to simple vibrations, and lacks realistic feedback. Realistic haptic sensations, which are very beneficial in some specific applications, require complex and expensive hardware, limiting their widespread use. The mechanical challenges make it difficult to reduce costs and improve affordability. In the next decade, haptic feedback will likely remain limited to applications where it adds significant value, with more common interactions relying on simple stimuli to enhance the experience without altering the interaction modality.

Conclusion

To design effective MR interactions, it is essential to understand the interaction modalities that will be used when MR becomes widely adopted. This requires identifying why current MR systems are not yet adopted and which future modalities will be most effective.

Current MR devices are not widely used in professional environments due to poor ergonomics, unreliable interactions, and low social acceptance.

The timing of MR adoption depends on when these usability challenges—caused by technical limitations such as display field of view, brightness, resolution, battery life, and processing power—are resolved. Given current development trends, MR devices suitable for professional use will likely emerge in a decade or slightly longer.

The interaction modality that suit the MR, specifically for tasks that involve manipulation of the digital content, are identified. For inputs, body movement and motion-based systems—such as neuromotor devices and brain-computer interfaces (BCI)—offer promising possibilities. For outputs, visual feedback through displays is essential but currently limited by technical challenges such as field of view, brightness, and resolution. Audio feedback is easier to implement and already provides effective enhancements to interaction, but it serves primarily as a supplementary feature. Haptic feedback, which has a supplementary role, similarly to the audio, is powerful in specific contexts but faces significant technical and cost-related barriers to broader adoption.

By that time frame identified, in reaction to the inputs, neuromotor systems will likely provide precise, hands-free input for micro-gestures. While for outputs, displays will remain essential for delivering digital content, audio feedback will enhance interactions and realistic haptic feedback will likely be reserved for tasks that justify the high cost of implementation, with simpler haptic stimuli used more broadly.

SECTION 1.2

MIXED REALITY IN HUMAN ROBOT INTERACTION

Introduction

While now the capabilities of MR and the types of interactions it can enable, both today and in the future, are clear, it is too early to determine how these technologies can be successfully integrated in HRI in a way that preserves the enjoyment, engagement, and meaning of the tasks involved. Before exploring whether and how MR can be implemented in HRI, it is necessary to take a more foundational step.
MR can be applied across a broad range of contexts, each presenting unique requirements and challenges, with distinct interactions that may be more suitable depending on the specific application. Therefore, before moving forward, it is important to narrow down the type of context to focus on within the HRI field. Additionally, narrowing the topic by identifying gaps in the current research can provide a direction for this project that ensures the outcomes contribute meaningfully to advancing MR implementation in professional and industrial settings.

SECTION 1.2.1

THE RESEARCH FOR THE GAP IN THE HRI FIELD FOR MR

Interaction in human-robot systems is dynamic and cyclical, it relies on input from the user and feedback from the robot (Dubberly et al., 2008). This process, often referred to as a feedback loop, ensures that the human and robot work together in a synchronised manner. The effectiveness of this loop is crucial in tasks where communication between the two entities is key to successful outcomes. This loop typically unfolds as follows:

Instruction:
The user provides a command to the robot, which serves as the input to the system. This can be done through various means, such as a graphical user interface, voice command, or physical interaction.

Robot Action:
The robot processes the instruction and performs an action based on the command. This could involve navigating to a specific location, performing a manipulation task, or carrying out another action.

Feedback to User:
The robot provides—or the user simply perceives—feedback, such as visually seeing the robot move. This feedback helps the user understand the robot's state and actions, which can be communicated visually, auditorily, or through haptic signals.

Human Adjustment:
Based on the feedback, the user might adjust their instructions or issue new commands to the robot. The loop then repeats as necessary.

In most human-robot collaborations, robots need reliable channels to communicate feedback to the user, allowing this loop to continue. Without proper feedback, the interaction goal might be impossible to achieve. MR technology has proven particularly valuable in enhancing this communication, offering a seamless, intuitive, and efficient way to relay digital information from the robot to the user, substantially enhancing the interaction.

A study by Suzuki et al. (2022), by examinating 460 publications on the use of AR and MR devices in human-robot interaction, identified five key purposes for implementing MR. Of these, three focus on communicating feedback from the robot to the user, accounting for 309 of the 460 studies. These three elements are as follows:

IMPROVING SAFETY:

AR/MR interfaces enhance safety awareness by using visual augmentation. For example, spatial colour mapping highlights safe and dangerous zones (Makhataeva et al., 2019; Hietanen et al., 2019), and virtual barriers help users avoid unintended collisions with robots (Hoang et al., 2021)

COMMUNICATING INTENT OR ISSUES

AR/MR interfaces also serve to convey the robot's intentions or problems to the user through spatial information. This can include indicating the robot's task status, such as warnings or task completion (Andersen et al., 2016), visualising system feedback (Tian & Paulos, 2021), and displaying the robot's intended path (Chandan et al., 2021; Walker et al., 2018; Bolano et al., 2019; Andersen et al., 2016) or troubleshooting faults (Avalle et al., 2019).

INCREASING EXPRESSIVENESS:

AR/MR can augment the robot's expressiveness, enhancing the user's understanding of the robot's actions or emotions through virtual enhancements (Groechel et al., 2019; Young et al., 2007).

Of the 460 studies analysed, nearly 70% focused on these 3 categories about improving the user's awareness of the robot's status, demonstrating the significance perceived of the AR and MR in improving the user's awareness of the robot status. However, these applications are taking advantage of only the output capabilities of the MR.

Shifting the focus of MR from a one-sided, output-only interaction to a two-way interaction—where both input and output are integral—reveals two additional categories of MR and AR applications. These categories go beyond simply communicating the robot's status or information; they involve using the device as a tool for users to directly interact with and manipulate the digital space. These encompass the remaining 151 studies in the analysis:

FACILITATING PROGRAMMING:

MR and AR interfaces provide powerful tools for simplifying robot programming (Cao et al., 2019; Ong et al., 2019; Gong et al., 2019; Bambusek et al., 2019; Rosen et al., 2019). By allowing users to simulate and visualise programmed behaviours in the real environment, these devices streamline the programming process, minimising the need to switch between the physical and digital worlds. The ability to select objects and manipulate the robot's behaviour visually enhances efficiency and reduces the complexity of traditional programming methods This creates an intuitive, seamless experience where users can program the robot requiring minimal learning and effort.

SUPPORTING REAL-TIME CONTROL AND MANIPULATION:

AR and MR interfaces also facilitate the real-time control, navigation, and teleoperation of robots. Unlike programming, which is more about setting behaviours in advance, this category focuses on active, real-time operation, whether the robot is remote or co-located (Sita et al., 2017; Just et al., 2018).

These two categories highlight the potential of MR not only to improve feedback from the robot but also to enhance the way users communicate instructions to it. The majority of research in this area concentrates on robot programming, an application that well takes advantage of the MR benefits, making it an ideal fit. However, the inputs generally remain indirect instructions, which will eventually be executed by the robot autonomously, leaving the user to experience the task only in a detached way.
There is still a significant gap in exploring MR's potential for more real-time, direct manipulation. Most research has focused on programming and indirect instructions, yet the spatial manipulation capabilities of MR suggest possibilities beyond this approach, potentially allowing users to become more engaged in the experience of the task. Regarding this real-time manipulation, the few studies that have examined this interaction tend to focus primarily on performance and execution quality, often neglecting the experiential aspects. This presents an opportunity for research to expand the scope of MR applications, potentially opening new possibilities for interactions that foster a more positive and meaningful human-robot interaction experience.

Conclusions

While MR's capabilities in HRI are increasingly applied to enhance user awareness of robot status through output-focused applications, the field remains underexplored in terms of real-time manipulation, particularly from an experiential perspective. Most current research emphasizes programming and performance, often neglecting opportunities for more immersive, hands-on engagement with tasks. Given MR's unique potential for spatial and real-time interaction, this project will focus on direct manipulation, allowing users to become more engaged in the task itself. This direction aligns well with MR's capabilities, addressing critical gaps in current research, and advancing MR applications in HRI to foster a richer, experience-centered interaction.

SECTION 1.2.2

ROBOTIC MANIPULATION

WHAT IS REAL TIME DIRECT MANIPULATION

When focusing on interactions involving robot manipulation, it is important to clarify what exactly constitutes manipulation and which specific characteristics need to be instructed to the robot.
Real-time direct manipulation requires the user to continuously guide the physical state of the robot. This instruction involves several key elements:

- Spatial changes
  - Location
  - Rotation
- Changes in applied force

Such manipulation can be carried out remotely, commonly referred to in the literature as telemanipulation, or through direct physical contact.
When MR is considered as a tool for input control, it becomes unnecessary in situations involving direct physical interaction with the robot, such as with co-robots, where the user can manually guide the robot's joints. In these cases, manual manipulation generally yields the best performance and user satisfaction. Thus, MR's potential for input control is most significant in telemanipulation scenarios, particularly when the user is co-located with the robot and has a direct line of sight. In scenarios of remote telemanipulation, where visual contact is not possible, a Virtual Reality system is more suitable.

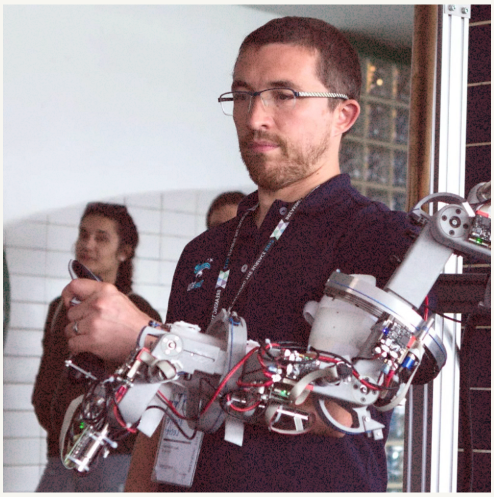
CURRENT SITUATION IN ROBOT TELEMANIPULATION

From the exploration of MR in HRI from the previous section, it became clear that telemanipulation within MR is an area that remains underexplored. However, outside the scope of MR, telemanipulation is a well-researched field. Typically, telemanipulation systems employ haptic feedback, where the user interacts with a physical interface (referred to as the master or leader) that transmits commands to the robot (the slave or follower) and relays feedback from the robot back to the user. These systems are generally preferred over body movement tracking without force feedback, as they provide bilateral control system (Dede & Tosunoglu, 2006), where the communication is two-directional: the operator sends commands to the robot, and the robot sends feedback (such as force or position information) back to the operator, "closing" the feedback loop.

As discussed earlier, haptic feedback has been identified as a potential output in MR systems, particularly for specific applications that rely on this form of feedback. However, implementing haptic feedback is resource-intensive. A physical master-slave system, designed to transmit force feedback to the user, requires a robust physical structure capable of withstanding user input forces, making such solutions costly and challenging to integrate easily. Various haptic systems have been developed to provide a range of feedback, differing in complexity.

PHOTO BY MAXIME GUYON

MORE FEEDBACK



Space Applications Services. (n.d.).
Dual force-feedback arm & hand exoskeletons – DEXO. Retrieved from source

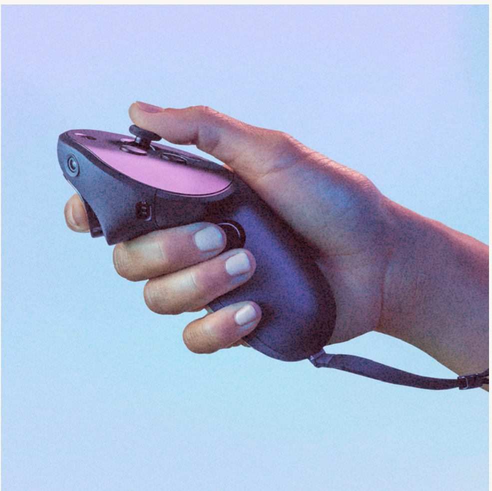
HaptX. (n.d.).
HaptX Gloves G1. Retrieved from source

Comprehensive force-position control
Some systems allow for full control over both force and position of the robot. Examples of these include the Phantom Omni (3D Systems, 2023), the Da Vinci Surgical Robot (Da Vinci, 2023), and the Haptic Master (Van Der Linde & Lammertse, 2003). These comprehensive force-position control systems offer highly reliable and precise control but come with several limitations. They are restricted by the physical constraints of the master device, which may limit the interactable area and reduce mobility. Additionally, these systems are highly susceptible to latency issues; any delay in the feedback can severely disrupt the user's control. Furthermore, they are expensive and cumbersome. In some cases, when force sensors cannot be implemented, these systems are not feasible For instance, in robotic surgery, the integration of force feedback is often limited due to the difficulty of embedding force sensors in small, intricate instruments. As noted in the literature, "the challenge lies in creating force sensors small enough to be integrated into surgical instruments, while maintaining an adequate measurement range for effective feedback" (Naerum et al., 2011).

Wereable force feedback control
Another category of solutions involves wearable devices, which cannot offer the same comprehensive feedback as the previously discussed systems. These wearables, such as haptic gloves, can only provide feedback in the areas where the device is worn. For instance, with a haptic glove (Sense Glove), force feedback is limited to the wrist and fingers, while movements in other areas, such as the shoulder, remain unaffected. Devices like these are well-suited for tasks that require fine finger dexterity.

LESS FEEDBACK

Fluid Reality. (n.d.).
The future of touch. Retrieved from source



Meta.
Quest Touch Pro Controllers. Source

Tactile feedback

A more refined class of devices takes this further by replacing force feedback with tactile sensations. These systems focus on simulating surface textures rather than physical forces, providing a more subtle form of feedback. These systems are valuable in applications where texture perception is crucial. Examples of such tactile feedback solutions include (Shen et al., 2023; Richardson et al., 2022; Schorr & Okamura, 2017; Carter et al., 2013).

Haptic signals

Another category of haptic devices focuses not on representing the digital content itself, but on signalling specific events through simple tactile cues, such as vibrations (Friesen & Vardar, 2023). These haptic signals are commonly used due to their ease of implementation, low cost, and compact size. Examples can be found in everyday devices like simple controllers, or smartphones, where vibrations are triggered to signal user actions.

These types of feedback are primarily used as redundant information, enhancing multisensory communication to reinforce feedback that is already being conveyed visually or audibly. For instance, when a key is pressed, the visual confirmation is present, but the accompanying vibration helps to make the interaction more intuitive and noticeable, even though it doesn't provide new or unique information.

The previous section (2.1) concluded that an interesting area for MR exploration is the real-time manipulation of robots, as it leverages MR's capabilities and has the potential to preserve the positive aspects of task performance. This type of interaction appears to be best achieved through comprehensive force-position control systems. Other systems like haptic gloves are limited to providing force feedback to the fingers, and tactile feedback or simple haptic signals are insufficient for effective robot manipulation.

While the literature demonstrates that telemanipulation is well-explored outside the field of MR, current solutions predominantly focus on devices that are prohibitively expensive and are generally applied only in situations where force feedback is essential.

Considering that:

1. MR offers numerous advantages in Human-Robot Interaction—such as visualising robot trajectories, identifying safe areas, and enabling spatial programming—all of which have been demonstrated in the literature to be highly effective, it is likely that MR devices will become commonly used for communication and interaction with digital interfaces, particularly in scenarios where these interfaces need to be integrated into real-world environments, such as in Human-Robot Interaction.
2. Over the next 10-15 years, body tracking, which is integrated into MR headsets by default (using vision-based or neuromotor inputs), will offer a precise, convenient, and cost-effective (still without haptic) method for achieving intuitive 6DOF manipulation without requiring additional hardware.

Although body tracking consist in a unilateral control system, that does not match the performance of comprehensive force-position control systems, its low cost and ease of implementation make it a scalable solution that could lead to broader adoption of telemanipulation systems. This would allow users to maintain the positive characteristics of manual task engagement in a more accessible way.

Conclusions

This leads to a more specific question: How can a unilateral tracking control system, implemented via a Mixed Reality headset, be designed to enable telemanipulation of robots while preserving the positive experience of the task, based on the identified potential and limitations of MR in Human-Robot Interaction?"

SECTION 1.2.3

CRAFTING TASKS

To answer this question, a context for exploration must first be established. This context should allow for the interaction capabilities to be explored and examined, particularly in terms of preserving the positive experience of a task while telemanipulating the robot through MR.

The task selected for this exploration must emphasise both manipulation requirements and an user experience that holds a significant meaning for the user. A task that challenges the interaction capabilities and provides insight into whether MR truly offers benefits in this regard.

Crafting tasks meet these criteria.

Crafting is physically demanding, often requiring machinery or tools, making it a context where robot implementation could be implemented. However, for craft makers, the experience is deeply rooted in their direct involvement. The act of manipulating materials fosters an emotional connection to the task, creating a sense of accomplishment and fulfilment that cannot be replicated when automation takes over. When the user is reduced to merely supervising the robot, the process loses its richness, and the emotional depth of the experience is lost.

Additionally, crafting tasks demand a high degree of manipulation—requiring complex, precise movements.

This makes crafting an ideal scenario for exploring Mixed Reality in relation to the question defined. MR has the potential to allow users to manipulate the robot and maintain the control over these complex actions, preserving the emotional and experiential value of the task.

By using crafting as a test case, it is possible to explore how MR can maintain the personal involvement that makes craftsmanship meaningful. If MR can facilitate such an experience while maintaining the positive aspects of the task, it would confirm the viability of this approach for broader applications.

This set the design challenge of this project:

"Based on the identified potential and limitations of MR in HRI, how can a unilateral vision-based control system, implemented through a Mixed Reality headset, be designed to enable telemanipulation of a robotic arm for crafting purposes, without disrupting the user's crafting experience and performance?"

2
CHAPTER
CRAFTMANSHIP

SECTION 2.1

UNDERSTANDING THE POSITIVE ASPECTS OF CRAFTING

Introduction

In order to explore whether Mixed Reality can be used to maintain the experience of crafting tasks, it is first essential to define what constitutes a positive crafting experience. Crafting is an activity deeply rooted in physical manipulation and personal engagement, with various psychological and sensory components that contribute to its value. Understanding these components is critical to designing an interaction framework that preserves them when MR technologies are introduced.
This chapter reviews existing literature on the positive aspects of crafting. By identifying these essential characteristics, this chapter establishes a foundation of requirements that must be considered when designing and evaluating the integration of MR in crafting environments, ultimately addressing whether MR can support the preservation of the positive aspects of crafting in a meaningful way.

SECTION 2.1.1

LITERATURE REVIEW ON THE EMOTIONAL EXPERIENCE

Numerous studies highlight how creativity in crafting, particularly when done for leisure, has a clear positive impact on the development and well-being of individuals across all age groups (Burt & Atkinson, 2011). Crafting is often associated with meaningful activities that lead to various positive outcomes, including enhanced well-being and improved mood (Collier, 2011; Riley et al., 2013).
Pöllänen (2015) takes a holistic approach to explore the elements of crafting that contribute to well-being, another study from Riley (2008) offers an in-depth analysis of the values held by professional craft makers.
These studies, along with others that examine the positive characteristics of crafting, offer valuable insights into the key values that contribute to the positive crafting experience. From this body of research, a list of core values has been identified:

- The material
- Achievement
- State of mind
- Engagement
- Anticipation
- Sense of self

In the following sections, each of these values will be explored in greater depth to understand the specific characteristics of the interaction that allow users to experience them. From this analysis, clear requirements will be defined to guide the design of interactions to preserve these essential values when implementing the MR.

SECTION 2.1.1.1

THE MATERIAL

Crafting involves a deep connection between the maker and the materials, rooted in a bodily experience and embodied cognition.
Materials in crafting are not merely conditions for the crafting. They serve as sources of inspiration that shape the creative process and decision making process, enabling a deeper expression of the maker's inner feelings (Pöllänen, 2015). This embodied interaction fosters a strong connection to the task and a dynamic interaction, often described as a dialogue between the maker and the medium (Brinck & Reddy, 2019).

EMBODIED COGNITION

Cognitive processes are deeply influenced by bodily interactions with the environment. Thinking is not separate from doing; rather, perception, action, and cognition are interconnected. Research shows that the act of design thinking involves the body as a source of knowledge (Groth, 2016). The physical manipulation of materials and active sensorimotor engagement with the environment and materiality shape cognitive processes such as problem-solving and creativity (Kimmel & Groth, 2023).
Hands have an exceptionally high representation in the brain and motor cortex, which causes physical and bodily experiences in craft-making to be closely involved in mental activities such as planning, control, and the execution of voluntary motor functions. As an activity, crafting draws on both the intellectual and physical characteristics of the maker (Pöllänen, 2015).

While this interaction between the maker and the material significantly influences the process and outcome, the material's influence on decision-making does not necessarily generate a positive emotional experience on its own.

SENSORY DELIGHT

Materials, in addition to contributing through bodily experience, enhance the crafting process by offering sensory qualities that can influence the overall experience. When objects are touched, their physical properties are not only perceived, but they also evoke affective sensations. The perceptual experience of a material's properties occurs through multiple senses—touch, smell, sight—each with the potential to generate positive emotional responses due to the hedonic nature of the stimuli. As Gale and Kaur (2002, p. 63) state, "The sense of touch can carry a status at least equal to visual aesthetics."
Certain types of stimuli are perceived as more pleasurable than others; for example, in tactile experiences, softness and smoothness are generally preferred over hardness and roughness (Pasqualotto et al., 2020; Essick et al., 2009). This hedonic sensation can be achieved during crafting, especially when working with materials that offer rich tactile and olfactory experiences, such as wood. The visual aspect also plays an important role, not only as a source of sensory pleasure but also as feedback on the progress and quality of the craft, which can lead to a sense of achievement, a topic that will be explored in more detail in the section 1.1.2.

Further positive emotional experiences of the perception of the materials are in relation to the object's functions. An object's functional beauty, perceived also through the modality of haptic touch, can be considered as a characteristic in the aesthetic domain. An object appears functionally beautiful to an observer who knows its purpose when it has features that are indicative of its ability to perform its job well, and feeling them can thus feel the positive aesthetic quality of functional beauty (Roberts, 2021)

Shutterstock. Retrieved from source

REQUIREMENTS

- Multisensorial perception the material:
  Plaeasing hedonic experience + bodily interaction (enhance creativity, skill learning an connection with the artefact)

SECTION 2.1.1.2
ACHIEVEMENT

A powerful emotional experience in crafting arises from the achievement of a pre-established goal. Since crafting involves the physical manifestation of effort through intentional actions, the resulting artefact embodies the maker's choices and actions, symbolising the successful realisation of the intended outcome. This accomplishment significantly impacts the emotional experience of the maker, influencing their sense of fulfilment and satisfaction.

SELF-ESTEEM AND PERSONAL GROWTH

The emotional impacts of crafting can be explored in detail, beginning with the enhancement of self-esteem that occurs upon the successful achievement of a goal. Research by Pöllänen (2015) highlights how participants describe crafting as a self-chosen, voluntary activity aimed at realising their own designs, goals, and decisions.

This sense of individual autonomy, identified as a key factor contributing to satisfaction (Leversen et al., 2012), in accomplishing self-set objectives, strengthens the craft makers' self-esteem, particularly in the feeling of self-efficacy (Riley, 2008) and self-confidence (Pöllänen, 2015). Craft makers frequently report that the process of creating a new artefact, learning a new technique, or adapting an existing pattern fosters the development of both physical and cognitive skills. Thus, crafting becomes not only an entertaining pursuit but also a form of personal growth.

Feeling of pride

The positive emotional experience described in the previously is further amplified by feelings of pride, particularly achievement-oriented pride. This emotion arises when individuals successfully complete a task, reflecting a positive evaluation of their own effort, competence, and ability to meet or exceed personal or social standards (Tracy et al., 2008).

For pride to be experienced, the interaction must possess specific characteristics. Pride is felt when individuals attribute the cause of their success to internal factors, taking personal credit for the outcome. In the case of achievement-oriented pride, the attribution is linked to an "unstable" aspect of the self, such as the effort invested in a particular task (Tracy et al., 2008). Research also indicates that the intensity of pride increases when individuals succeed in more challenging tasks compared to easier ones (Lewis et al., 1992).

Feeling of success

Additionally, the tangible results of crafting, such as the creation of a concrete artefact, further reinforce the feeling of success. Whether it involves learning a new technique through ready-made instructions, modifying an existing pattern, or designing a project from scratch, the process of crafting elicits a deep sense of accomplishment. This feeling of success is so rewarding that it often creates a desire to engage in the activity repeatedly (Pöllänen, 2015).

Thus, the combination of pride and success plays a crucial role in shaping the overall positive emotional experience of crafting, making it not only a fulfilling but also a motivating activity for individuals.

AI gnerated image with FLUX 1.1 pro

REQUIREMENTS

- Accomplishment of self-set objectives
- Decisions and actions need to be taken in autonomy, self-consciously
- Results need to be achieved through effort
- Results need to be tangible

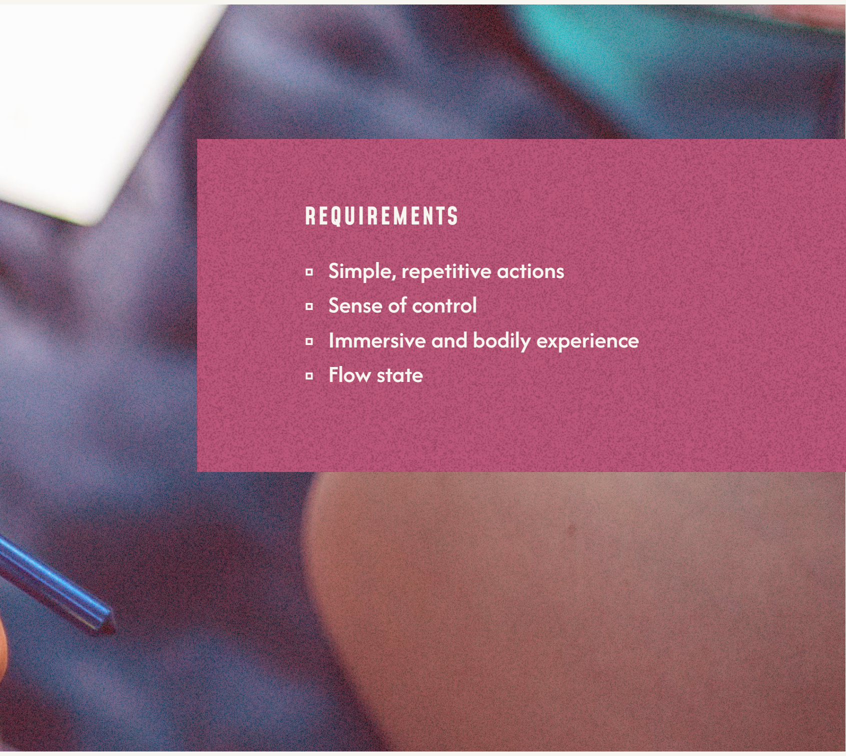
SECTION 2.1.1.3

STATE OF MIND

Another common experience associated with crafting is its ability to produce a calming effect. Pöllänen (2015) reports that craft makers, through their engagement in physical crafting activities, were able to alleviate feelings of frustration and agony. The hands-on interaction with materials and tools, combined with the task's structured nature, created a sense of control that promoted emotional calmness.
Also, from Pöllänen (2015) , craft-making is linked to the satisfaction of achieving something tangible, providing a sense of accomplishment amidst the routine pressures of daily tasks and deadlines. Findings suggest that crafting helps counteract the fast-paced nature of modern life, offering a way to cope with the constant pressure of being rushed.
Nartker (2022) observed similar therapeutic benefits during the COVID-19 pandemic, particularly among senior living residents. Textile crafting, such as knitting, was found to have a calming effect through its repetitive motions, helping participants

manage anxiety and emotional discomfort. This calming effect was attributed both to the tactile engagement with the materials and the immersive nature of the activity, allowing individuals to momentarily set aside worries and stress alleviating isolation and distress during challenging times (I. Chen, 2023).

Research has further supported these findings, showing that activities like knitting can induce a meditative state, allowing individuals to unwind from daily stress. The rhythmic and repetitive nature of such activities plays a key role in this calming effect (Riley et al., 2008, 2013). Once the skills have been mastered, the repetitive process leads to a creative end result, contributing to a state of flow—a harmonious balance between body and mind.



REQUIREMENTS

- Simple, repetitive actions
- Sense of control
- Immersive and bodily experience
- Flow state

SECTION 2.1.1.4

FLOW STATE

The sense of engagement and loss of track of time observed in the user tests aligns well with the concept of flow, as described in Csikszentmihalyi's Flow Theory (Csikszentmihalyi, 1990). Flow is widely recognized in psychological literature as a highly enjoyable state, characterised by complete immersion in an activity. It arises from the voluntary effort to accomplish something challenging yet meaningful. When in flow, individuals experience intrinsic motivation, feeling deeply involved and interested in the task for its own sake.

Research indicates that flow is achieved when there is a balance between the individual's skills and the demands of the task. If the task is too easy, it leads to boredom, while if it's too difficult, it can cause anxiety or frustration. Striking the right balance enhances enjoyment and involvement, two key components of the flow experience (Landhäußer & Keller, 2012). Flow occurs when the individual is focused on clear, realistic goals that align with their abilities. These goals allow for concentrated attention, making it easier to set aside distractions and become fully absorbed in the task. A key characteristic of flow is that the activity becomes an end in itself—known as an autotelic experience, where the process is rewarding regardless of any external outcomes (from the Greek auto meaning "self" and teleos meaning "goal"). This experience can elevate engagement to a deeper level.

Csikszentmihalyi describes how the flow state is characterised by eight major components:

- Tasks with a reasonable chance of completion
- Clear goals
- Immediate feedback
- Deep but effortless involvement, which removes the frustrations and worries of everyday life
- A sense of control over one's actions
- Lack of concern for the self
- Altered perception of time, where hours can feel like minutes and vice versa

In conclusion, to design an interaction that fosters the flow experience, certain requirements must be met. These include balancing the skill level and task demands, providing clear goals, ensuring immediate feedback, and giving users a sense of control over their actions. These elements are essential for creating a positive and engaging user experience in the crafting interaction

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REQUIREMENTS

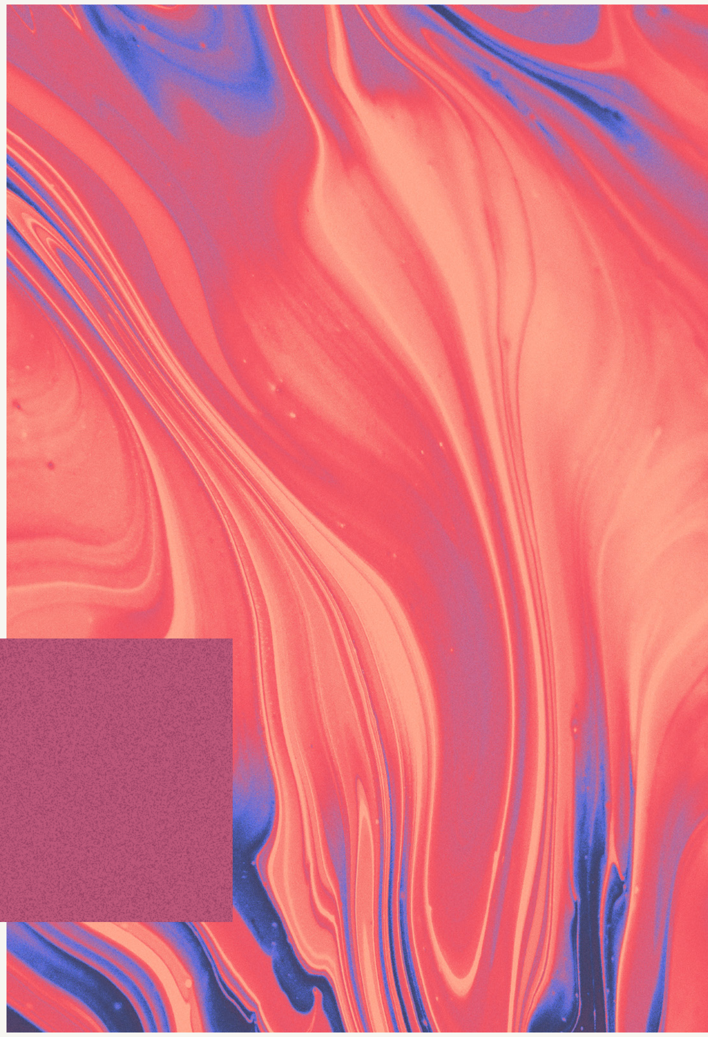
- Balance between user's skills and task's demands
- Deep but effortless involvement
- Sense of control ower own's actions
- Clear goals
- Immediate feedback

SECTION 2.1.1.5

SENSE OF SELF

Another aspect of the crafting experience is the deep connection between craft-making and a sense of identity. This aspect becomes more prominent as craft makers evolve a deep involvement in their craft, particularly when crafting becomes a central occupation.

Through the act of creating, craft makers express personal narratives and cultural identities, making craft a powerful form of self-expression. This process serves as a critical motivator, allowing makers to continuously explore and affirm their identities and sense of belonging within a community. This connection between craft, identity, and community ultimately contributes to individuals' overall quality of life, as well as their perceptions of health and well-being (Riley et al., 2008).



REQUIREMENTS

- Allow for self experession

REQUIREMENTS

- Multisensorial perception the material:
- Accomplishment of self-set objectives
- Decisions and actions need to be taken in autonomy, self-consciously
- Results need to be achieved through effort
- Results need to be tangible
- Actions needs to be simple and repetitive
- User needs to feel a sense of control of one's actions
- Task demands needs to balanced with user's skills
- Deep but effortless involvement
- Clear goals
- Immediate feedback
- Allow for self expression

CHAPTER 3

THE INTERACTION

SECTION 3.1

PROTOTYPE

Introduction

This chapter focuses around user testing structured in two distinct parts, each with its own specific focus: the first aims to broaden the identified emotions and values users associate with crafting, while the second explores the user experience within a mixed reality interaction prototype, providing insights into how MR can enhance or challenge traditional crafting experiences.

Identifying the Emotions and Values Users Associate with Crafting

While the literature offers insights into the deeper human aspects behind positive crafting experiences—essential for defining the requirements to achieve these outcomes—it often lacks a holistic perspective. Many studies focus on specific details, which provide valuable insights, but for this project, a broader understanding of the diverse aspects users seek in crafting activities is needed. Although some papers attempt this wider perspective, a more comprehensive, 360-degree view is required for this project.

This additional exploration forms the first phase of the test, involving interviews where participants reflected on their past crafting experiences, particularly on the positive aspects they found valuable. By analysing these responses, the research aimed to identify the full range of emotions and values associated with crafting and craftsmanship. The results were then combined with the literature findings to build a broad yet thorough understanding of these values.

Analysing the Mixed Reality Interaction

The second phase centres on the MR interaction itself. Following the requirements drawn from the literature, a preliminary prototype was created to explore users' experiences with crafting interactions in a mixed reality and HRI environment. This prototype was tested with participants, providing valuable feedback and highlighted the aspects of crafting that users value in MR settings, while also presenting general interaction feedback on the prototype.

SECTION 3.1.1

CREATION OF THE CONTEXT

THE TASK

To develop the interaction, "crafting" is too broad of a concept to consider, as it encompasses a wide range of activities such as sculpting, carving, grinding, and more. Additionally, without defining the specific goal of the activity, it would be impossible to explore or test the interaction in a meaningful way. Therefore, it became necessary to clearly define the task and goals of the crafting activity for which the interaction would be designed.
Various activities were considered, taking into account the complexity of manipulation required and the resources needed for testing. After evaluating the different possibilities, the task selected was grinding. Grinding was chosen for several reasons that made it an ideal fit for this project.

1. It requires continuous and complex control of both position and force, making it suitable for testing and challenging the MR system's capabilities in spatial manipulation.
2. Additionally, it directly connects to the Bright Sky project, where collaborative robotic applications are being explored, such as using a robot to assist with grinding tools for sharpening fan blades. The insights gained from this thesis aim to contribute to these ongoing research efforts.
3. Lastly, grinding is easier to simulate compared to other crafting activities, further supporting its selection.

The last point refers to the fact that developing a fully functional robotic teleoperation system combined with mixed reality control presents requirements that are too demanding given the resources available for this project. Given the time and resource constraints, it was found more practical to create a mixed reality interaction system to teleoperate a robot in a fully simulated environment using virtual reality. While this approach introduces certain limitations—such as resolution issues and others, which are further explored in the Limitation chapter—it allows for a more agile development process, better suited to the resources and expertise available for this project.

The grinding task

In the virtual simulation, the user stands a few metres away from a robot, with a wood panel positioned near the robot. This wooden piece has a specifically shaped left top corner (fig. 10). The goal of the task is to use mixed reality to teleoperate the robot and make the top right corner of the wood, initially presented with a standard shape (fig. 11), to match the filleted shape of the left corner. The robot presents a grinding tool, which the user can teleoperate and use to interact with the wooden piece, shaping it at his discretion.

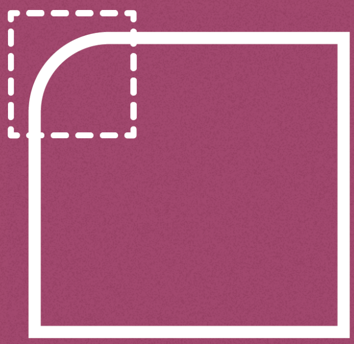


FIG. 10

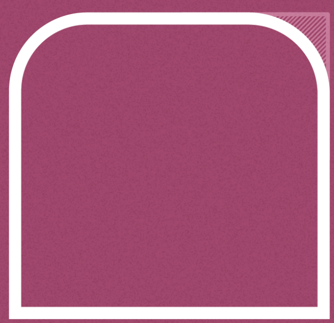


FIG. 11

THE CONTEXT

To create a realistic experience for the crafting task, it was essential to define the context, as the user experience is influenced by various contextual factors, such as the environment, time pressure, and other conditions that are not solely determined by the interaction itself.

The environment

The decision to focus on a factory setting was based on the understanding that mixed reality for robotics is expected to be primarily adopted in professional environments within the selected time frame. By situating the task in this context, the research aims to reflect the conditions in which such technologies are likely to be utilised.

The robot

The robot's movement, functionality, and appearance significantly affect the user experience, particularly in how user inputs are translated into the robot's movements. A robotic manipulator was selected because it is the most common and capable type of robot for this type of task, and it is expected to remain relevant in the next decade. Given its complex articulation, which closely mimics the human arm, it is well-suited for tasks requiring intricate movements. A robot manipulator with six degrees of freedom was used for this research, without adhering to any specific reference model or imposing joint constraints, unlike current robots. While the aim is to replicate a realistic context, using today's robotic limitations for a scenario projected ten years into the future was deemed impractical. However, speed limitations were applied to ensure the robot's movements resembled those of an actual robotic arm (for further details, see Appendix section 4). This setup requires a robot capable of controlling both force and position, critical capabilities for enabling the proposed interaction.

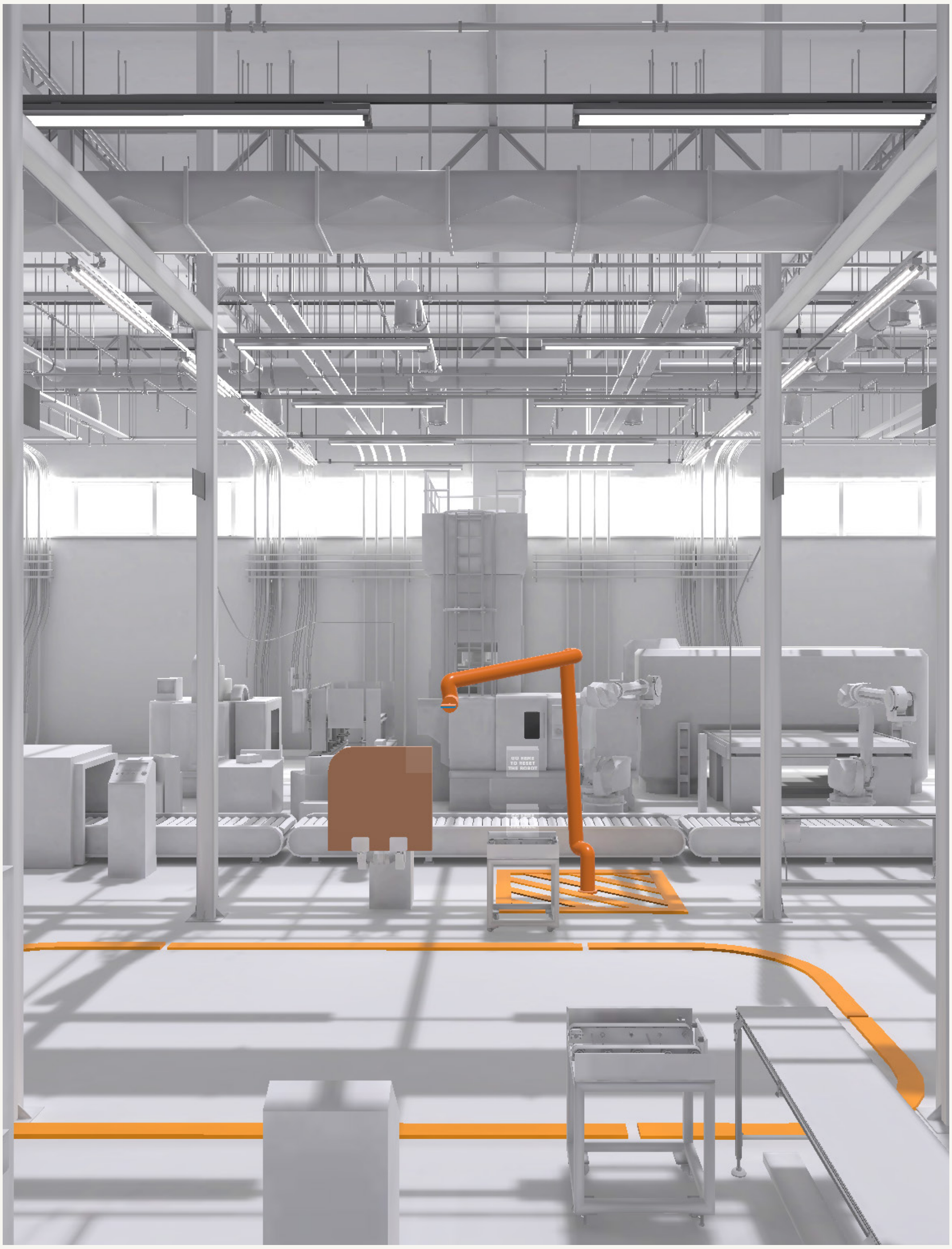


FIG. 12 - THE VR ENVIRONMENT

The digital environment within the virtual reality headset depicts a factory setting featuring a robotic arm.

SECTION 3.1.2

CREATION OF THE PROTOTYPE V1

Following the requirements defined in the literature review, a preliminary prototype was developed. Introducing a prototype early in the design process, applying the research through design methodology, allows it to serve as a tool for gathering insights specific to the contexts of MR and HRI, rather than focusing solely on generic crafting experiences. Alongside this hands-on exploration, the prototype also enables user feedback collection, revealing which aspects of the interaction users perceive as most important and to prioritise for achieving the desired experience. This approach makes the development of interaction agile through quick and many iterations.
Although this initial prototype follows guidelines from the literature review, it is still preliminary and does not yet implement all identified requirements. Through successive iterations, the prototype will progressively integrate more solutions, aligning it more closely with both the defined and emerging requirements.

DESIGN OF THE PROTOTYPE

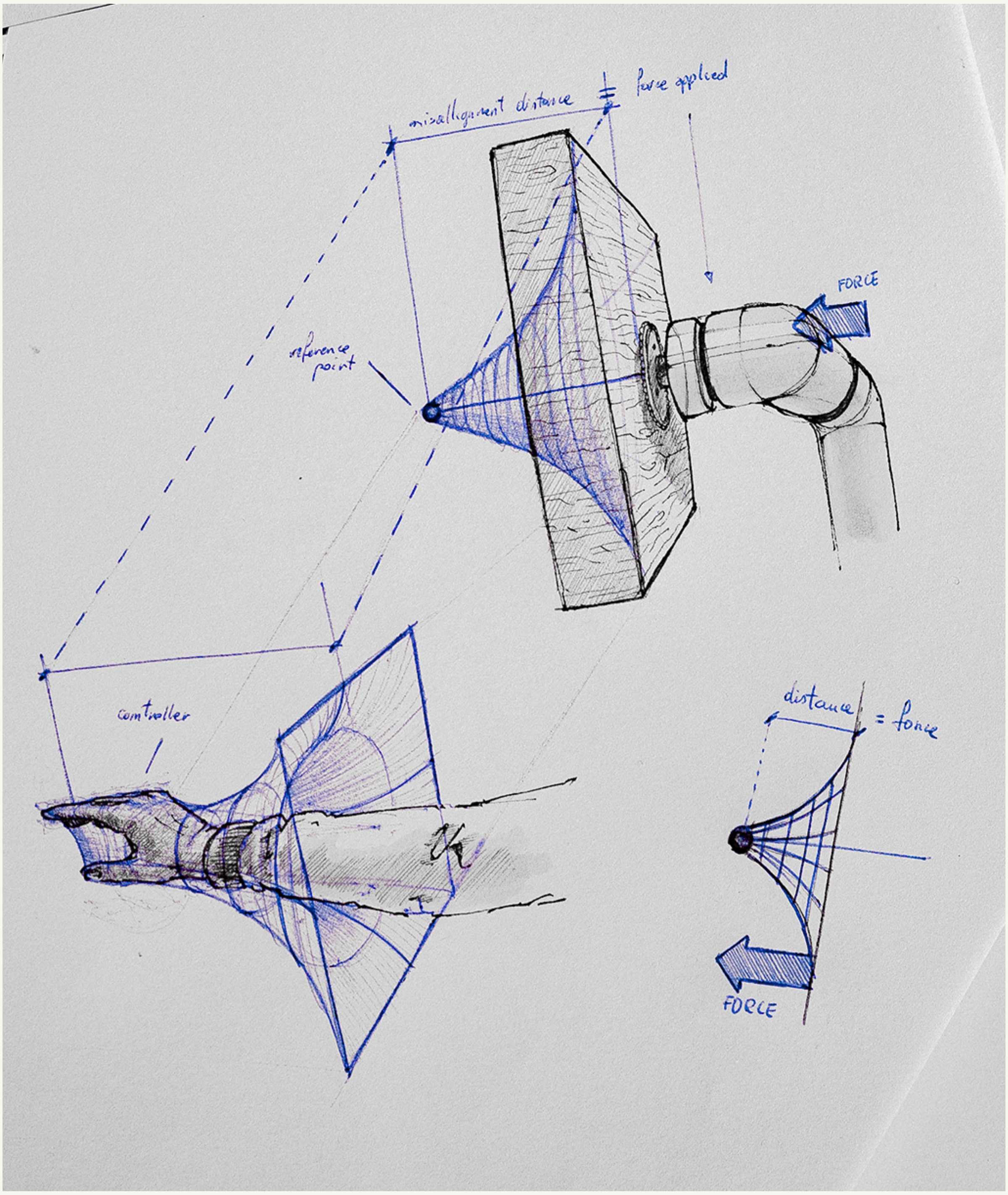
As anticipated, the use of a real robot and a mixed reality setup was not feasible given the resources available for this project. Therefore, a virtual reality simulation was used to recreate the environment and interaction. The scene and interaction were developed using Unity, version 2022.3.23f1, and the application was tested on Meta Quest 2 and 3 headsets. For more information on the technical details of the simulation, refer to the Appendix section 4.

THE CONCEPT

This prototype is conceived as a preliminary concept, informed by requirements from the literature and the identified benefits of mixed reality. The goal of the interaction is to establish a communication loop between the user and the robot, enabling the user to guide the robot's movements (adjusting position and force) while receiving feedback on the robot's interaction with the environment.

PHOTO BY XRSPACE

FIG. 13 - SKETCHES



Task requirements

- Clear and self-set objectives
- balance between task demands and users' skills
- Objective needs to be accomplished

Input requirements

- User needs to feel in control
- User needs to be able to perform the desired actions
- Decision needs to be taken in autonomy (self set objectives)
- Inputs needs to be simple and instructed effortlessly

Feedback requirements

- Bodily experience
- Results needs to be tangible
- Immediate feedback

With this goal in mind, the requirements can be further refined to align more closely with the specific type of interaction needed. These requirements are categorised into three groups: task requirements, input requirements, and feedback requirements.

To fulfil the ***task requirements***, the user must be able to set their own goals and achieve them, but only with a certain level of effort.
To fulfil the ***input requirements***, the user needs complete control over the robot's movement, with freedom to move it as desired, without restriction. The input should be simple and effortless.
To fulfil the ***feedback requirements***, feedback should be immediate and, ideally, perceived through multiple senses.

It appears that the core of the crafting experience lies in autonomy—setting one's own goals, choosing the preferred approach, and executing the actions. This autonomy, paired with multisensory feedback and an effortless input system (though not an effortless task), creates the foundation for a positive crafting experience.
This autonomy over actions is the central criterion around which the preliminary prototype is designed. The actions involve instructing the robot's movement, specifically changes in position and force. This prototype focuses on enabling the user to have full control over movement instructions in an intuitive and natural way, aiming to create an interaction where the user effortlessly and confidently directs the movement, successfully achieving goals with autonomy.

However, controlling force presented a challenge. Since the digital elements used to control the robot lack physical features, and therefore no physical resistance, the user cannot apply force directly, making natural control force interaction impossible—unlike for position control. In a task such as crafting, controlling force is essential. This limitation required exploring methods for instructing forces that do not depend on natural muscle contraction, which would otherwise necessitate a bilateral system with counterforces.
Among the various ideas considered, one seemed to offer the best potential, at least theoretically. The intensity of the force could be easily visualised through the MR display, and a sketch was developed to conceptualise how force could be represented in the interface.

This concept was developed using Unity and integrated into the headset. The prototype has the following characteristics:

POSITION CONTROL

The user can grab and release a virtual element that represents the end effector of the robot. This virtual element is always attached to the user's hand. When the user's hand is open, the movement of the hand is not transferred to the robot. However, when the user closes their hand, as if making a fist, the position and rotation control becomes active, causing the robot to mirror the movement of the virtual element on the user's hand.

FORCE CONTROL

To address the challenge of instructing the force, a method commonly used in existing literature was selected, which involves simulating force in a way similar to a stretched elastic band. While this approach is not as natural as hand navigation, it remains intuitive to some extent.

The system uses a reference point, which is the digital element being controlled by the user and where the robot attempts to move its end effector (figure A). However, if environmental forces prevent the end effector from reaching the reference point, a misalignment is created as the reference point (being a virtual point unaffected by physical forces) detach-

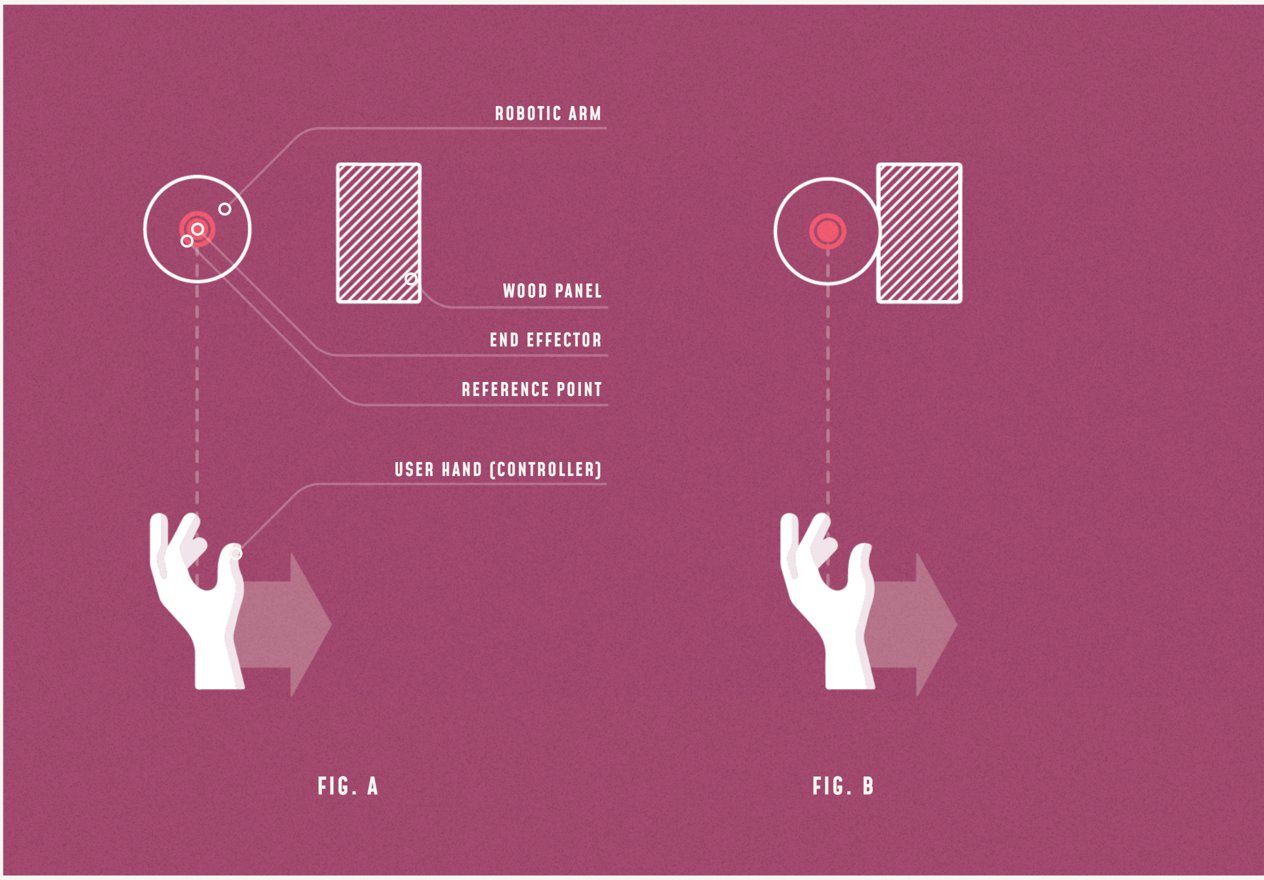


FIG. 14 - POSITION CONTROL AND FEEDBACK

es from the robot's end effector (figure B).
This misalignment increases the intensity of the force, similar to an elastic band stretching. Thus, the farther the reference point is from the end effector, the greater the intensity of the force becomes (figure C).

FEEDBACK

Since force is not communicated through familiar means, such as muscle contraction, additional feedback mechanisms are needed to close the communication loop. To address this, a visual line is created between the end effector and the reference point, displaying the extent of the misalignment. This line serves as an indirect representation of the force intensity.
Additionally, to mitigate the absence of haptic feedback—an issue that could make it difficult for users to perceive when the tool is in contact with an object—a virtual element is introduced into the scene. When the tool makes contact with an object and starts applying force, this virtual element appears on the end effector, signalling the contact. Once the tool is no longer in contact with the object, the virtual element disappears.

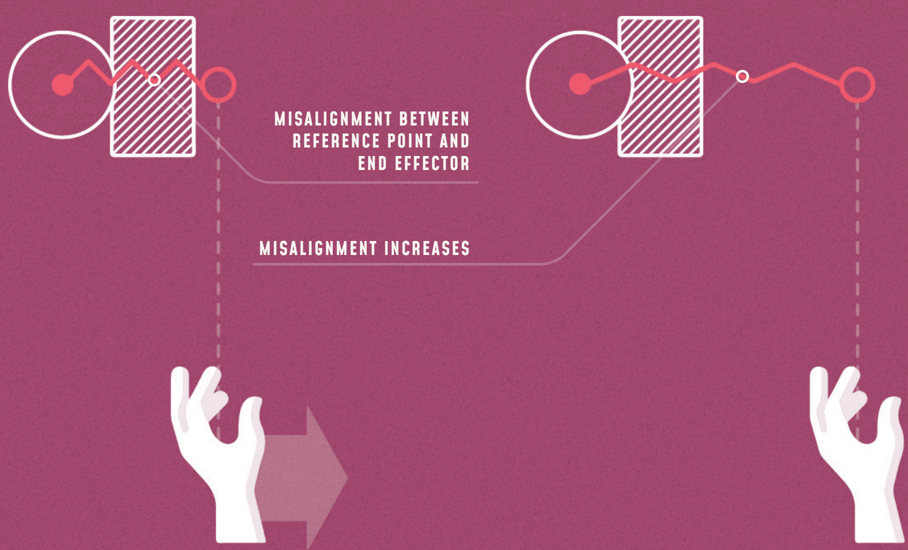


FIG. C FIG. D

SECTION 3.2

USER TESTS

SECTION 3.2.1

METHODOLOGY

The characteristics that define the crafting experience are varied, as crafting is a complex activity that combines different aspects of both body and mind. Due to this complexity, it can be difficult for individuals to precisely articulate what specific characteristics of the interaction elicit a particular emotion.
This has led to concerns that simply conducting interviews with open questions to identify various characteristics may not be sufficient to capture the origin of the emotions in the interaction, especially considering that these characteristics can vary from person to person and from one task to another.
To avoid this issue an approach that would yield more insightful results has been designed.

The approach combines reflective and behavioral methods to gather data on emotional and practical engagement. In the reflective approach, interviews with open questions allow participants to articulate their emotional needs and values associated with crafting, aiming to capture the essence of their experience from a holistic perspective. The behavioral approach, on the other hand, focuses on real-time user interactions during the crafting tasks, emphasizing immediate perceptions and interactions.

STRUCTURE

The test is structured into three distinct parts. For detailed information on the test design, refer to Appendix section 1):

- ***Questions on Past Crafting Experience:***
  Participants are interviewed on the emotional and reflective aspects of their past crafting experiences, with memory-based questions that focus on the positive aspects of craftsmanship. Emotional cards featuring positive emotions are used to facilitate the interview.

- ***Prototype Test:***
  After a familiarization period, participants perform the task using the MR interaction, with only observational data collected during this stage.

- ***Questions on the Prototype Experience:***
  Participants are interviewed to reflect on the emotions experienced during the MR interaction, comparing it to traditional crafting. Emotional cards are used to help identify both the missing positive emotions and any negative emotions present in the experience.

METHOD OF ANALYSIS OF THE RESULTS

The analysis of the user test results will involve a structured approach, focusing on two aspects: the Ideal Experience and the Prototype Experience. Audio recordings from the user tests will be transcribed to capture key insights.

For the Ideal Experience, characteristics that users identified as essential to a positive crafting experience will be extracted, transcribed, and categorised into themes. The frequency of each theme will be noted, non-interaction-related factors will be filtered out, and patterns or differences in user responses will be identified. These insights will then be synthesised into an "experience tree," supported by literature research to structure and contextualise the findings.

For the Prototype Experience, characteristics that detract from the interaction—whether due to a lack of positive elements or the presence of disruptive factors—will be similarly extracted and categorised. Characteristics unrelated to the interaction itself, such as those influenced by the simulation, will be filtered out. Each pain point will be mapped within the experience tree, highlighting areas for improvement. To prioritise these findings, the analysis will focus on aspects that allow for concrete improvements, are crucial to enhancing the experience, and are not artefacts of the test setup (e.g., limitations due to VR simulation). This method ensures that findings are actionable and directly relevant to refining the user experience.

FIG. 15 - BRAINSTORMING

SECTION 3.2.2

CRAFTING EXPERIENCE

The responses during the tests went beyond simply identifying emotions; they provided descriptions of the characteristics that caused these emotions. The emotion cards, rather than serving as a tool to capture the full range of emotions, proved more effective in sparking conversation and uncovering the factors that contribute to a pleasant crafting experience. By gathering and clustering the responses, it became clear not only which emotions were experienced during the interaction but, more importantly, which specific characteristics of the interaction led to these emotions.
The emotions identified

- Pleasant surprises
- Satisfaction
- Sensory delight
- Anticipation
- Joy
- Confidence
- Determination
- Pride
- Serenity
- Relaxation
- Desire

More importantly, the characteristics that evoke these emotions:

ACHIEVING THE RESULT (6 MENTIONS)

The prominence of results indicates that one of the most positive aspects of crafting is the sense of fulfilment reached upon the successful conclusion of a task. However, this sense of achievement is not limited to the task's outcome; it can also emerge throughout the process whenever actions are performed correctly, and positive feedback is received. For instance, the simple precision of a straight line in a drawing can bring satisfaction on its own. These individual successful actions can give a sense of satisfaction throughout the task, building to a peak of fulfilment once the crafting task is completed.

> ***Requirements:***
> the user must be able to successfully control the tool and be able to achieve the result desired.
> There must be able to immediately verify the result of the action

SENSORY DELIGHT (4 MENTIONS)

The sensory delight of the activity—including visual, tactile, kinesthetic, and olfactory senses—is one of the most immediately gratifying aspects of crafting. There's pleasure in the aesthetic quality of the process and the physical interaction with materials. These sensations enhance the experience, potentially reducing the boredom of low-engagement and repetitive tasks.

> ***Requirement***
> the user must be able to perceive the characteristics of the material.

ENGAGEMENT (5 MENTIONS)

When the task is challenging, it creates a complete immersion, focusing entirely on the crafting process and the actions, leading to a state of flow. Participants have reported experiencing this flow as a positive aspect of the activity.

> ***Requirements***
> Get into the flow state

STATE OF MIND (6 MENTIONS)

Crafting is often perceived as a meditative state where the user's mind is fully absorbed in the activity, leaving everything else behind and entering a calm, relaxed state. This experience is described as one of serenity and peacefulness, especially during simple tasks, with no worries—just steadily moving toward completion.

> ***Requirements:***
> Relaxing activity. Simple tasks that are engaging but doesn't require too much effort

PLEASANT SURPRISES (3 MENTIONS)

When the outcome exceeds expectations, it creates a positive surprise that is highly valued by the makers. Similarly, during the process, discovering a new way to interact with a material brings the same sense of pleasant surprise.
The craft makers must be unrestricted, free to decide how to approach and interact with the material. This allows to explore novel ways to interact, try new processes and get unexpected outcomes.

> ***Requirement***
> Unrestricted interaction.

ANTICIPATION (2 MENTIONS)

Some participants mentioned a positive feeling of anticipation, looking forward to the joy that crafting—both the process and the outcome—will bring. However, this feeling is not part of the crafting task per se.

MERGING OF REQUIREMENTS FROM THE USER TEST AND LITERATURE REVIEW

- **The user must be able to control the tool effectively and achieve the desired result.**
  This requirement aligns with the literature-based need for users to feel in control. Regarding achieving the desired result, the requirement of balancing task demands with user skill levels appears to address this aspect.

- **The user must receive immediate feedback on the result of their actions.**
  This requirement corresponds with the literature's emphasis on the importance of immediate feedback.

- **The user must be able to perceive the material's characteristics.**
  This requirement aligns with the literature's focus on a multi-sensory perception of the material.

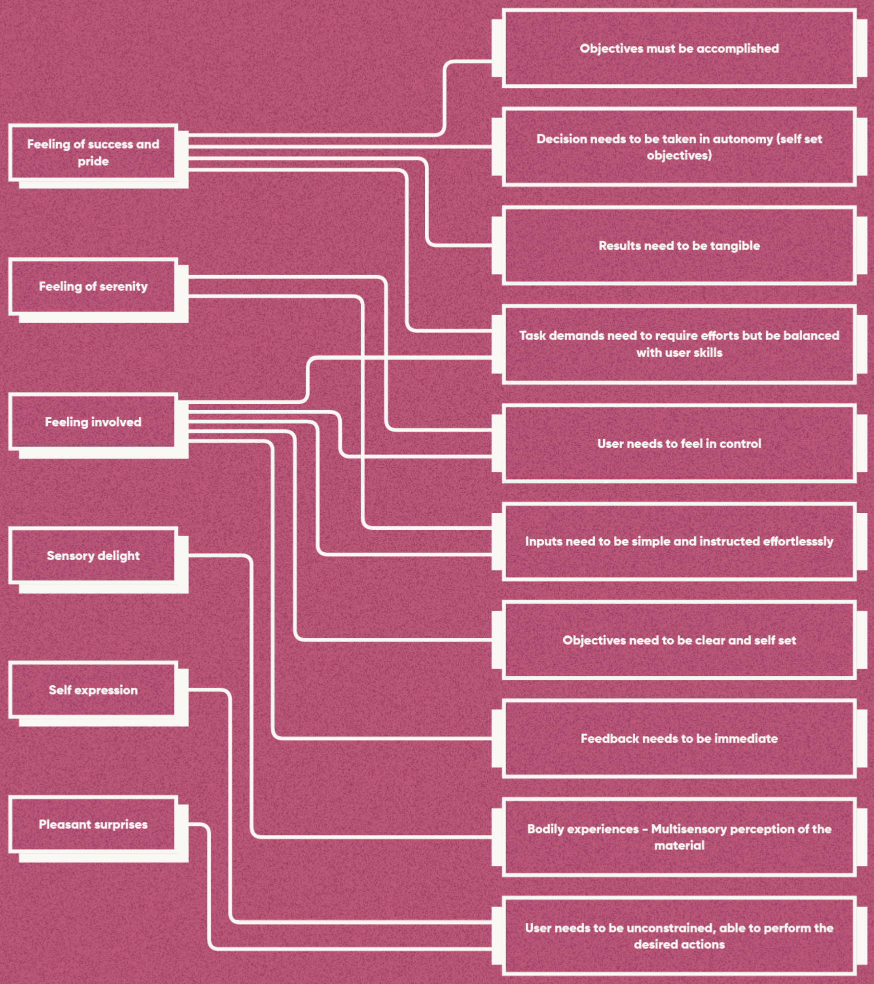
- **Achieving a flow state.**
  This requirement mirrors the literature's section of the flow state, where the user needs to experience a balance between skills and task demands, clear goals, immediate feedback, and control over actions.

- **A relaxing, engaging activity.**
  This requirement aligns with literature describing the flow state and a calm state of mind. Tasks that are balanced and not overly challenging (flow state) and involve simple, repetitive actions can create a meditative effect.

- **Unrestricted interaction.**
  This is a newly identified requirement, not present in the literature.

It appears that nearly all identified requirements were already covered, as the literature review provided a comprehensive overview of interaction characteristics. The user interviews revealed requirements that, with one exception, had already been identified. An additional element from the interviews is that they offered preliminary insights into which interaction elements are more frequently perceived as positive aspects of crafting, based on the frequency of mentions. However, given the small number of participants, this insight should be considered with caution.

FINAL REQUIREMENTS



THE IDEAL CRAFTING EXPERIENCE

The craft maker feels completely in control, with clear goals on what to do. Each action feels simple to perform but requires deep focus, achieving the desired outcome takes effort. Every movement yields immediate feedback, allowing the craft maker to perceive the success of each action and the progression made toward the final result. All senses engage with the materials, creating an intense sense of connection and immersion in the crafting process. Through exploration of different approaches and discovery of new and unexpected outcomes, the craft maker finds a personal path to self-expression.

SECTION 3.2.3

PROTOTYPE EXPERIENCE

The interviews revealed various issues with the crafting experience. However, many of these were due to the simulated environment, rather than actual interactions with a real robot and real materials. Below is a list of problems that have been filtered to exclude those unrelated to the interaction itself and instead connected to the simulation's lack of realism.

NOT IN CONTROL

- **Lack of Control**: users reported not feeling fully in control of the robot's end effector. One user described the experience as similar to controlling a tool while looking in a mirror. However, this contrasted with feedback from others who found the control system intuitive after a few minutes of practice. Additionally, frequent issues with hand tracking and occasional simulation errors during testing may have contributed to confusion with the control system. When asked to elaborate on this issue, users did not specifically mention difficulty controlling the grinder's position, leaving it unclear which movements they found challenging to control. It is assumed that this lack of control stems from a combination of simulation issues, other interaction challenges, and potential user confusion about the control system, which suggests a lack of intuitiveness.

LACK OF SYSTEM STATUS INFORMATION

- UI feedback: users reported that the intensity of the applied force is unclear, as there is no clear indicator to help them gauge how much force is being used.
- Perspective:
  Distance: The area of interest feels too far away, making it challenging to work on fine details.
  Depth Perception: Movement along the depth axis relative to the user is difficult to gauge, increasing the likelihood of tool misalignment and errors
  Ability to **Adjust Perspective** or Rotate the Object: Users noted difficulty in changing viewpoints or rotating the object as needed for detailed work.
- obstruction:
  The grinder **obstructs the view** of the area of interest, and since visual feedback is the only available information, this limits accuracy in correctly guiding the robot.

LACK OF SENSORY FEEDBACK

- One user reported that the task felt boring due to the **lack of tactile interaction** with the material, highlighting that tactile experience is important to maintain engagement, especially during simple tasks.
- Users reported the absence of multi-sensory confirmation, mentioning that relying on a single sense to monitor task progress provides a **less satisfying** experience than having multisensory feedback (such as feeling the smoothness of a curve both by touch and sight).
- Users also pointed out a general **lack of feedback** regarding the interaction, resulting in moments where they couldn't tell if the robot was performing the desired action, the state of the progress being made, and the correctness of the action.

BAD ERGONOMICS

- Users reported discomfort from keeping their **arm raised** for extended periods, with the issue becoming more noticeable after about 10 minutes of continuous interaction without rest. This concern was mentioned by a few users (3 times), likely due to varying levels of user endurance.
- Additionally, users noted that controlling the robotic arm demands continuous extensive **wrist rotation** throughout the task.

EXCESSIVE ACTIONS

- Users reported that the interaction system requires **repeatedly grabbing and releasing** the controller (the UI element on the user hand that represents the end effector), which becomes irritating over time.
- Some users also found the unrestricted movement of the end effector undesirable, noting that using their **hands felt too imprecise**.

NOT RELAXING

- Users reported a high **amount of mistakes** made during the interaction, which caused an **impossibility to feel relaxed**. In addition to the mistakes, the perceived complexity of the control system feels too demanding to allow the user to relax. However this latter issue emerged to be present only in the learning process, thus not directly caused by the interaction system.

SECTION 3.3

CAUSE OF ISSUES

Introduction

Currently, the results from user tests highlight the problems but lack insight into their causes, which are essential for developing effective solutions. To improve the interaction, it is crucial to understand why disruptions in the experience are occurring. This chapter uses feedback from user tests, identified requirements, and supporting literature to determine the characteristics of the interaction that cause these disruptions and their underlying reasons.

An important note is that some issues discussed here were not directly identified in the user tests. Instead, they emerged from insights gained through the literature on crafting and mixed reality and from the development and testing of the interaction. Reporting these additional issues is valuable, as they may not be as immediately visible as the user-identified ones, but equally important. When issues arise from sources outside user tests, this distinction is noted.

The current interaction experience is that it has so far focused only on the positive aspects of crafting. However, satisfaction alone does not fully encompass the requirements for a well-rounded interaction. According to the ISO 9241 framework, a successful interaction must also include effectiveness and efficiency, alongside user satisfaction. Effectiveness ensures that users can accurately and thoroughly accomplish their goals with quality outcomes and minimal errors, while efficiency relates to achieving these goals with optimal use of resources, minimising unnecessary effort or time. Together, effectiveness, efficiency, and satisfaction create a balanced interaction that feels rewarding while being reliable and productive, supporting a seamless user experience.

The issues identified touch on all aspects of usability: effectiveness (frequent mistakes are made), efficiency (the control system is challenging to use), and satisfaction (the interaction lacks many enjoyable elements of crafting). Once the causes of these issues are thoroughly identified, a clustering system will be developed to visualise the interaction experience. This system will differentiate between positive characteristics (desired features) and negative aspects (disrupting features), represented through two graphs, providing a clear distinction between elements that enhance or detract from the crafting experience.

SECTION 3.3.1

CONTROL SYSTEM

SECTION 3.3.1.1

ERGONOMICS

GORILLA ARM SYNDROME

Keeping the hands raised is a common cause of discomfort in extended reality interactions. This issue is explored in the literature and is named "gorilla arm" (Hansberger et al., 2017). This phenomenon can be attributed to the mismatch between the natural resting position of the arms and the sustained elevated position required during XR interactions. In the interraction it is necessary to interact with the user interface (UI) without having any support to the arm, making the interaction tiring after a prolonged amount of time. Additionally, the hands, in order to have their motion captured by the cameras on the VR headset, usually need to be in an area in front of the user, preventing the user from resting the arms. Considering that crafting interaction is a task that requires time, and users after 10 minutes started to feel discomfort, this issue is a critical problem that must be solved.

> " I stopped because the arm started to bother me "

Low usability: uncomfortable interaction

WRIST ROTATION

The interaction requires extensive adjustments to the orientation of the end effector, placing considerable strain on the wrist, as it is the only joint used for these adjustments. The wrist is known to be sensitive and prone to discomfort, especially with repetitive movements, high force, and awkward postures (Bernard & Putz-Anderson, 1997).

One rotation more straining than others

Extensive wrist rotations occur frequently in all directions, but one specific rotation is reported as more painful. For two of the wrist's rotation axes—pronation to supination and flexion to extension—achieving the desired end effector orientation is usually possible within the wrist's comfortable range of motion. However, the rotation needed for radial to ulnar deviation (from the DINED database, ranging from 23° radial to 45° ulnar) often exceeds the comfortable range, leading to either excessive rotation or multiple small adjustments, both of which are likely to cause discomfort for the user.

After a while the wrist was painful ”

Low usability: uncomfortable interaction

*NOT IDENTIFIED BY USER TESTS

SECTION 3.3.1.2

CONTROLS

HAND MISALIGNMENT*

To apply force, the reference point of the robot, controlled by the hand, needs to misalign from the robot end effector, the more the distance between the reference point to the end effector is, the more the robot increases the intensity. However, the misalignment creates a series of problems:

unintuitive way to control the force
The issue with this force control mechanism is that it differs from the natural way we typically interact with objects. In natural arm biomechanics, force intensity can be individually and directly controlled. However, in the prototype, force is generated as a consequence of movement, specifically through misalignment. This indirect control requires users to adjust movement to apply force, making it feel unintuitive.

Unintended movements
A situation that illustrates this issue occurs when force is applied to an object (causing misalignment between the end effector and the reference point), and suddenly the force overcomes the object's resistance. When this happens, the end effector immediately "snaps" to the reference point position. This outcome may not be what the user intended: the reference point was set specifically in that location to apply a certain force, not to dictate the end effector's position. Once the end effector overcomes the resistance, the user may not want it to move; however, due to this mechanism, the snap occurs before the user has a chance to adjust the reference point and avoid the movement. This issue arises because changing the force input—from applying force to ceasing it—requires a physical movement, which takes more time compared to human biomechanics, where force control feels almost instantaneous. This unintended movement can cause the end effector to go to an undesired location, potentially leading to issues such as colliding with other objects or people.

Confusing control system
Another issue occurs when the user applies force, causing the reference point (which determines the direction of movement) to become misaligned with the end effector. To control movement, the user must now account for this offset, as the reference point is no longer aligned with the end effector. This differs from natural movement, where the hand itself acts as the reference point, keeping control intuitive. As a result, the user's movements feel less natural and require additional adjustment to account for the misalignment.

" It feels like [the robot] has a mind of its own "

lack of feeling in control

Less achievements

UNCONTROLLED FREEDOM

Users reported that using the hand alone feels too imprecise for the task: "*the issue was the use of hands instead of more precise tools, which would seem more fit for the task.*" Despite this, the concern over imprecision did not appear frequently in user tests, suggesting it may be perceived as a minor issue. However most users indicated they would feel more confident if they could lock movement along a specific axis.

The feeling of imprecision stems from several factors: hand-tracking can lack precision, the hand itself is inherently less accurate, the task demands high hand-eye coordination without having proprioception of the robotic hand, and other issues (such as distance from the object).

Handling objects in the physical world typically involves resistance—such as weight or friction—which naturally slows movement and improves precision. For example, when engraving on a physical material, the resistance of that material helps control the movements and increase precision. For the same task but on a virtual material, without any resistance, the movement may struggle to follow the surface's contours with high accuracy.

In the current prototype, although there is physical material to work on, it interacts only with the end effector, and this feedback is not relayed to the user's hand. Consequently, this lack of feedback fails to guide hand movements, limiting precision and control during the interaction. More about haptic feedback in section XX.

> " I can't be more accurate using my hands "

Less achievements

LOW SENSITIVITY

Almost every participant pointed out the excessive movement required to translate the end effector, as if the controller's sensitivity were too low. This issue arises because the movement scale between the hand and the robot is set to 1:1, while the robot covers a relatively large area compared to the reach of human arms—especially within the limited range of hand tracking. Currently, to move the end to reach the desired position, the user must repeatedly grab, drag and release the controller, multiple times, which many found irritating.

The frequency with which participants raised this issue suggests it is a significant problem that impacts nearly everyone's experience.

> " the robot moves too little, it's annoying "

Low usability: slow controls

ALLOCENTRIC VIEW*

The near-teleoperation setup requires users to observe the robot and its movements from an allocentric perspective, which creates a sensory mismatch between visual and proprioceptive feedback. Research indicates that when sensory inputs are incongruent, the brain struggles to integrate them, leading to various issues. studies from Fink et al. (1999), Babu et al. (2023) and Katayama et al. (2016) have found that mismatched sensory feedback requires the brain to actively monitor these discrepancies, increasing mental effort to resolve conflicts and maintain accurate motor control.

These issues also emerged in a study by Just et al. (2018) that examined an interaction with mechanics similar to the prototype, where a trackball (controller) was used to move the robot in-directly (co-located teleoperation). Participants reported that this method was more difficult, less intuitive, and slower than direct grasping (egocentric view), confirming that sensory mismatches complicate control and add to the cognitive load.

*NOT IDENTIFIED BY USER TESTS

Low usability: mental strain

Lack of control

SECTION 3.3.2

FEEDBACK SYSTEM

Studies show that our brains have evolved to integrate information from multiple senses to form a coherent perception of the environment (Ghazanfar & Schroeder, 2006). Typically, this feedback from various senses is combined, or "stacked," creating a clear understanding of what is happening, which in turn allows us to provide the next input with greater precision and performance. This layering process is known as multisensory feedback.

In a crafting task, understanding the object—its shape, material, and appearance—is essential, as this perception provides the feedback needed to plan the next action and eventually achieve the desired outcome. However, in the mixed reality interaction, the distance between the user and the object introduces challenges, significantly reducing the user's ability to perceive the object's characteristics, as the tactile information is inaccessible.

SECTION 3.3.2.1

HAPTICS

DECREASED OF CONTROL

The human mind is optimised to use multiple senses together, creating a clear and accurate picture of objects and actions. When fewer senses are engaged, this "picture" becomes less accurate, reducing the quality of perception. Since this interaction relies on a closed-loop feedback system, a reduction in feedback clarity makes it harder to gauge task progress, leading to uncertainty in the next steps and potentially resulting in errors.

Numerous studies report that the absence of haptic feedback impairs the ability to perceive and manipulate objects effectively (Miall et al., 2019). For this reason, industrial applications frequently incorporate tactile feedback to enhance interaction with remotely operated robotics, especially for tasks requiring contact, such as surface finishing operations (Rodríguez-Sedano et al., 2023).

Lack of control

Low usability: increase of mistake making

REDUCED FEEDBACK OF ACHIEVEMENT

During the task, each successful action provides a sense of achievement, as the user confirms progress and sees each step as a small accomplishment. As discussed in the Sense of Achievement chapter, these small successes build positive emotions throughout the process. Removing tactile feedback limits the information available to confirm success, reducing the user's positive experience.

Less achievements

DECREASED SENSORY DELIGHT

Tactile sensations often provide pleasure, with chemical and psychological responses contributing to a pleasant experience. Without these sensations, the overall enjoyment of the task decreases, diminishing the hedonic aspect of crafting.

" I miss the feeling of the smoothness of the curve I just made "

Lack of tactile sensory delight

SECTION 3.3.2.2

VISUAL

OBSTRUCTIONS

In typical interactions, craft makers rely on multisensory feedback to accurately gauge progress, with one sense often compensating if another is limited. For example, when vision is obstructed, users can use haptic feedback to estimate changes to the object and tool's movement. However, in the prototype interaction, haptic feedback is absent, and only visual feedback—supplemented by a simulated sound that does not reliably convey progress—remains to inform the user. This reduction to a unisensory feedback degrades the robustness of the information available, making it harder to accurately monitor the object's state. Especcially considering the frequent visual obstructions caused by the grinder tool on the end effector, which blocks the user's view of how the material is being modified. "It's hard to tell if I am grinding or not. I often wonder if I haven't done enough or if I've gone too far." This uncertainty forces users to proceed very cautiously, often stopping to check their progress to minimise mistakes. This constant need to pause and verify disrupts the workflow, leading to frustration, as research shows that interruptions can increase frustration (Mark et al., 2008).

In a traditional crafting scenario, users would adjust their perspective to gain a clearer view, but in the MR setup, they are positioned at a distance from the robot, requiring a significant repositioning (several metres) to alter the viewing angle, making it impractical. This setup forces users to work with limited feedback, reducing confidence in task accuracy and increasing the potential for errors.

“ I grinded more than i thought

Low usability: increase of mistake making

LOW DEPTH PERCEPTION

In the MR interaction, the user is co-located with the robot, as maintaining a line of sight is essential. The user must also remain at a safe distance to avoid entering the robot's range of motion, especially with non-collaborative robots, which pose safety risks. This distance between the user and the robot leads to recurring issues reported in user tests.
Users frequently mentioned that positioning the end effector accurately along the depth axis was challenging, often resulting in tool misplacement. This difficulty can be attributed to the way depth perception diminishes with distance, unlike vertical and horizontal perception, which remains relatively stable. Depth perception relies heavily on binocular cues, particularly stereopsis, which detects depth through slight differences in images (binocular disparity) seen by each eye (Wilcox & Harris, 2010). Although these binocular cues are still present at greater distances, their effectiveness declines (Allison et al., 2009), and the brain relies more on monocular cues—such as texture gradient, linear perspective, and parallax—which provide general depth information but are less precise for exact positioning.
This indicates that the depth cues available in the interaction are insufficient: binocular cues become less effective due to the distance, while monocular cues lack the accuracy needed for precise positioning. Some users expressed a desire to move around the object to change perspective, which would enhance depth perception through monocular cues and likely improve tool positioning. However, users were rarely observed moving around, likely due to the substantial effort and frequency required (as previously noted, a significant perspective change requires movement of several metres).
It's important to note that the VR screen lacks the natural depth cues found in a real environment. While stereoscopic vision is simulated through dual displays, the focal point remains fixed at a specific distance across the scene, which may further impact depth perception. Thus, this issue might be less perceived in an actual MR interaction, outside of the VR simulation.

“ I often misplaced the tool and had to reposition it ”

Not feeling in control

Low usability: increase of mistake making

TOO FAR FOR SMALL DETAILS

In a typical interaction, it's natural to move closer to examine small details and step back for a broader view. However, in this interaction, the user cannot approach the object, and this distance makes it difficult to see fine details clearly. This limitation restricts the interaction to tasks that don't require high precision.
A decrease in visual information also reduces the sensory delight associated with the material and the task, diminishing the pleasure of the experience.

“ I want to get closer to see better ”

Less achievements

SECTION 3.3.2.3
CLARITY

UNCLEAR FEEDBACK

Users reported difficulty in determining the intensity of the force applied with the end effector. The current prototype attempts to compensate for the lack of force feedback with additional interface elements, specifically using visual feedback as a substitute. However, users noted that this representation does not clearly convey the force intensity at a given level of misalignment (which is representative of the force intensity). As a result, users often believed they were applying significant force, leading to frustration when progress was slow due to the actual force being minimal.

This challenge is common in sensory substitution applications, as they typically require users to learn how to interpret new feedback patterns before they can automatically correlate certain cues with specific information. It's likely that this issue will diminish with practice, as users become familiar with associating misalignment distance with grinding speed, which represents the applied force.

“ I don't understand why is it grinding so slowly ”

Low usability: increase of mistake making

DISTRACTING FEEDBACK

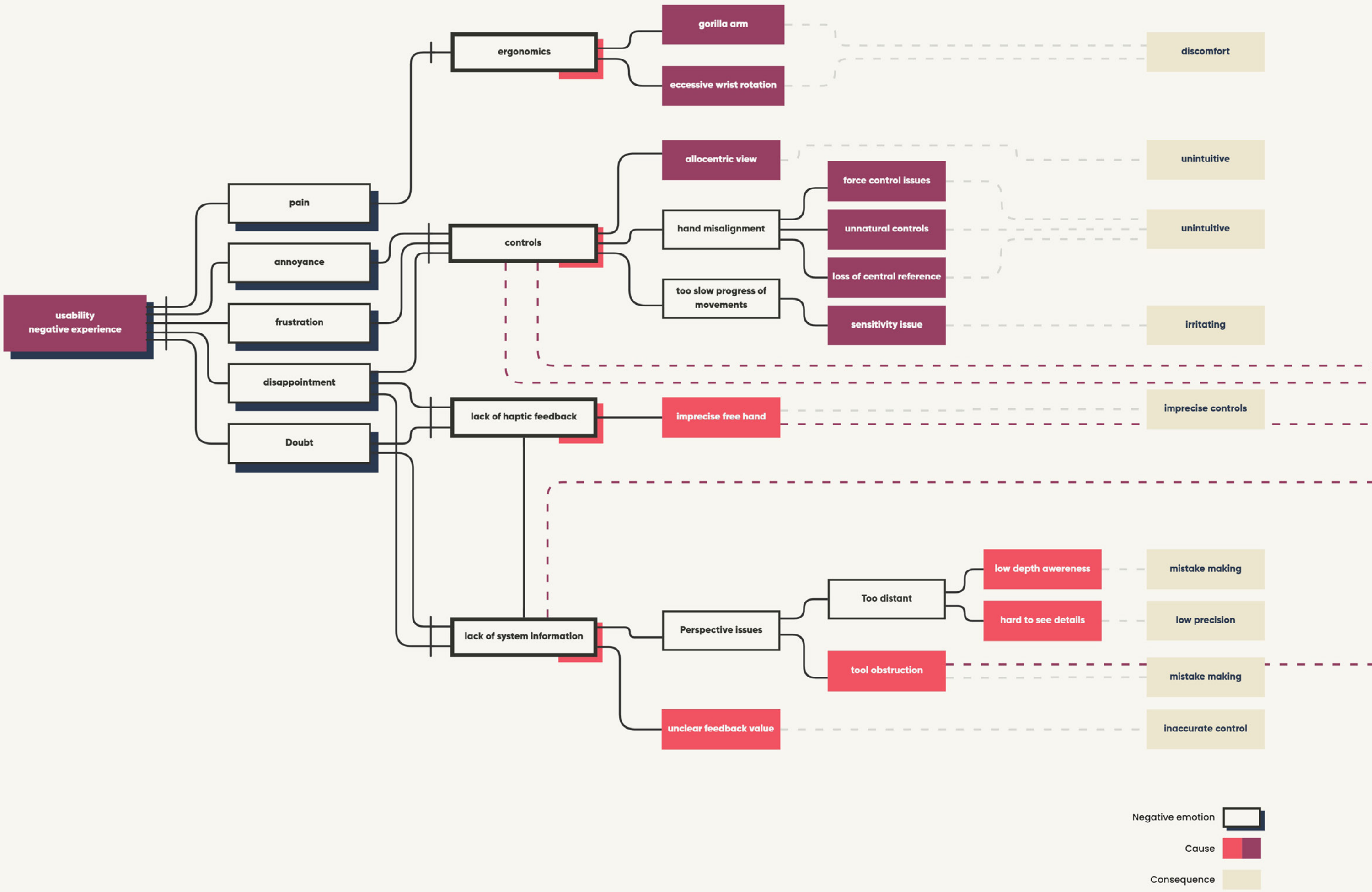
One user reported that the UI element was somewhat distracting, noting that their attention was more focused on the reference point than on the material's progress. Although the exact cause was unclear, it's possible that extracting necessary information from the UI requires direct attention, shifting focus away from the interaction between the tool and material and leaving the task progression “unchecked.”

This situation is undesirable, as monitoring the task's progress is the most crucial feedback for a successful interaction. Ideally, the UI should be designed to convey information passively when within the user's field of view, allowing users to maintain their focus on the task progression.

Low usability: increase of mistake making

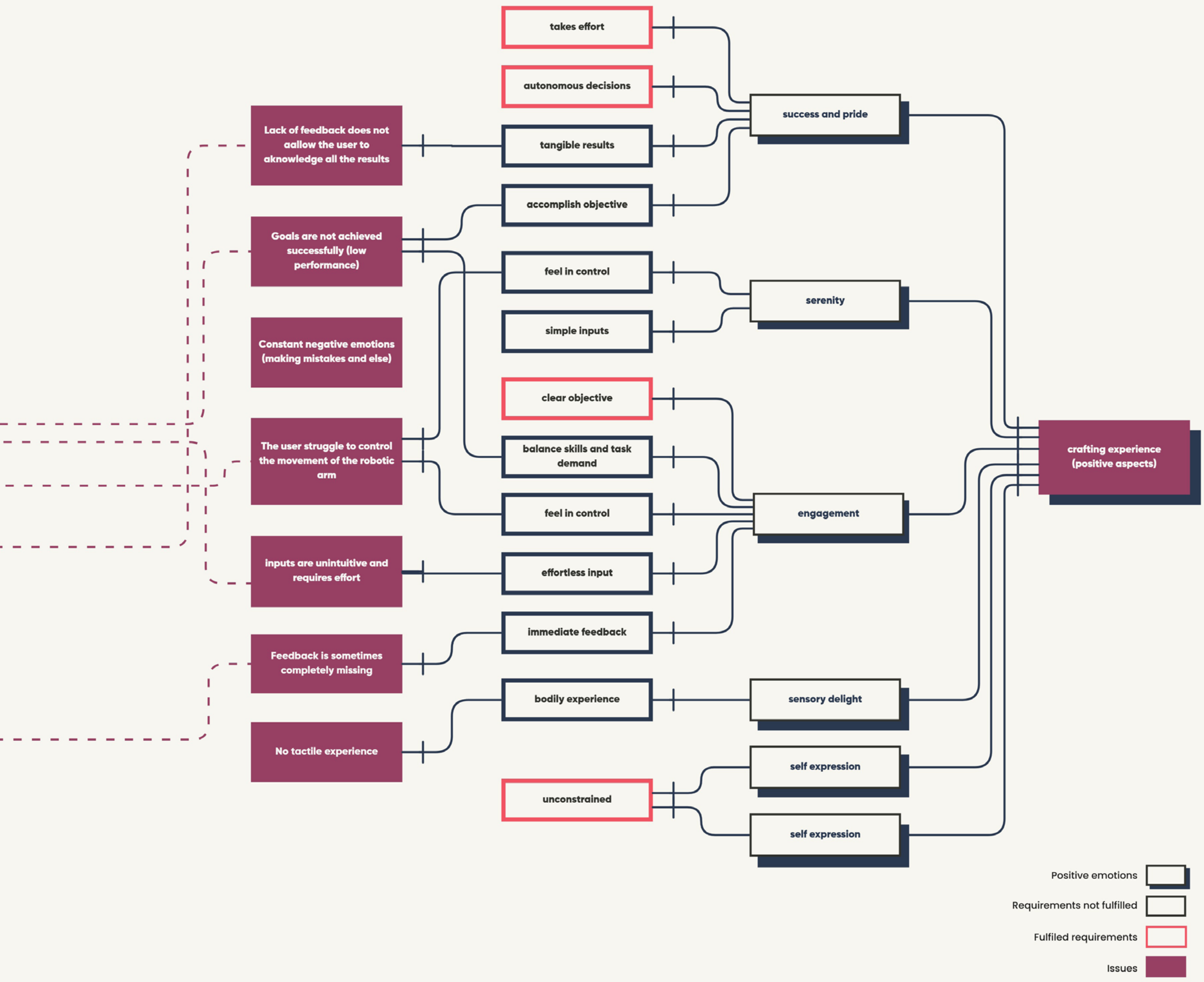
SECTION 3.3

SUMMARY OF THE ISSUES



Looking at the issues of the prototype and their analysis, two different types of issues emerge:

- Presence of negative experiences (low usability): These are based on the utilitarian need for a functional interaction.
- Lack of positive experiences (unmet requirements): These relate to the absence of hedonic characteristics that a crafting task would normally include.



CHAPTER 4

FREE CONTROL

SECTION 4.1

NEXT STEPS

What to do

The analysis reveals that the emotional experience of crafting is deeply connected to the "functional" aspects of interaction, such as control over actions and achieving desired results. For instance, relaxation and engagement only occur if inputs feel simple and effortless; feelings of achievement, pride, and success are only attainable when goals are accomplished. This connection shows that characteristics like control over movement and outcomes, which may initially seem purely functional, also serve as foundational elements of the emotional experience, supporting both practical and emotional needs.

Some aspects of crafting, like sensory delight, are purely hedonic and unrelated to functionality, but on their own, they form only a small part of the overall experience. Given that much of the emotional experience relies on functional characteristics (such as effective control and successful outcomes), it's reasonable to consider these characteristics as foundational components of a positive interaction experience. Without resolving these issues, the interaction will lack sufficient functionality and cannot fully embody the crafting experience.

Additionally, the presence of negative emotions related to the lack of control highlights that focusing primarily on hedonic aspects rather than on functional aspects, while potentially feasible in other contexts (Hassenzahl, 2010), in this interaction leads to a dissatisfying experience, with negative emotions like frustration and distrust. Negative experiences tend to have a stronger impact on overall perceptions than positive ones, as shown in Baumeister et al. (2001). Therefore, it seems crucial that the interaction avoids negative emotional triggers while meeting the requirements of the crafting experience.

The current prototype has focused on giving full control to the user, as autonomy was identified as one of the key pillars of the crafting experience. However, this level of control has proven overwhelming for users. How can the design be improved to resolve usability issues while preserving and integrating crafting experience requirements?

The next section discusses the focus for the next iteration phase—whether to reduce autonomy or to enhance the interaction to improve usability.

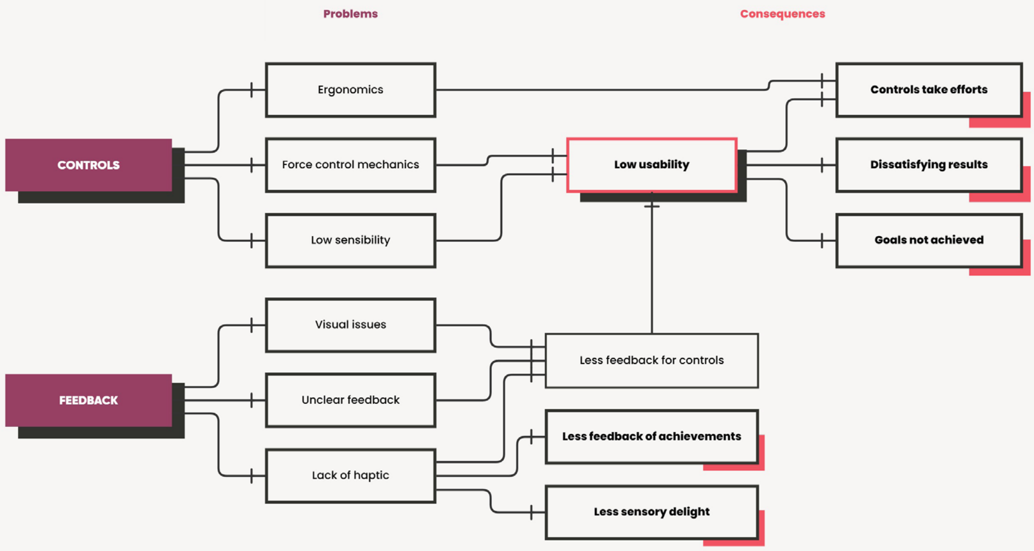


FIG. 16 - PROBLEMS AND CONSEQUENCES IN CONTROL AND FEEDBACK SYSTEMS

This diagram illustrates the relationship between various issues in control and feedback mechanisms, leading to the central consequence of low usability, which in turn results in greater effort in controls, unsatisfactory outcomes, and unmet goals.


PHOTO BY MAXIME GUYON

SECTION 4.1.1

SHOULD ROBOT AUTONOMY BE CONSIDERED

In this study, the interaction has been presented as a feedback-and-input loop, with issues emerging from both aspects. However, an additional element influences the interaction, as it involves not only the user and the object but also a robotic arm capable of autonomous movement or controlling its motion without direct input. Therefore the components that forms this interaction are as follows:

- **Control System** (through hand tracking): How the user's movements provide input to the system and how these movements are interpreted.
- **Information Feedback** (through the UI): The feedback that the system returns to the user.
- **Robot Autonomous Behaviours** (through the robotic arm): Movements or constraints executed by the robot autonomously, without direct manipulation.

The core of the interaction lies in the first two elements—control system and information feedback—since these form the foundation of a closed-loop interaction (input and feedback). Automation, however, could be introduced to enhance the interaction by allowing the robot to support user actions, either to improve the task outcome or enhance the overall experience.

Automation Presents Challenges for the Crafting Experience

However, sharing control of actions with the robot introduces problems. The research carried out for the requirements suggests that reducing user autonomy and effort can diminish characteristics essential to a positive crafting experience. A well explored example, from a different context, is the driving experience, where studies have found that enjoyment tends to decrease with increased automation.

Automation Can Improve the Experience, Depending on the Context

Conversely, some studies show opposite findings, where automation can provide benefits, especially in situations where users need support to complete tasks. Automation often has a positive functional impact, improving precision, speed, or consistency. In terms of user experience, automation doesn't always lead to negative outcomes; its influence varies depending on the type of automation implemented. The user's need for support in performing certain tasks can make automation beneficial, suggesting that a carefully considered level of automation may enhance both functionality and user satisfaction.

Constraints as a Form of Automation

In this project, constraints have been chosen as the most suitable form of automation, rather than fully autonomous actions. Constraints function as a form of automation because they re elaborate the user's input by guiding or limiting specific movements. By applying constraints, the system can help users achieve better performance and precision without detracting from the hands-on experience or sense of ownership that are essential in crafting tasks. This approach might strike a balance between assisting users in avoiding mistakes and preserving their autonomy within the interaction.

- ***Focus and Direction – Usability***
  By setting "constraints to guide the actions" (Norman, The Design of Everyday Things, 2013, p. 67), these can reduce ambiguity, supporting sustained focus and engagement. When effectively applied, constraints can help the user to focus and to reduce errors, ultimately enhance usability and the overall user experience.

- ***Flow Theory***
  Although the more constrained the directions, the less autonomy will be perceived by the subject, constraints can be used to adjust the difficulty level of a task to better match an individual's skill set, keeping the challenge neither too hard nor too easy. This balance between skill and challenge is key to maintaining flow.
  Additionally, appropriate constraints can help define clear goals (which needs to remain self-set), a requirement for getting in the flow.

- ***Creative Thinking***
  Paradoxically, constraints can sometimes boost creativity. In a study from Candy (2007) is reported "Constraints are restrictions that limit what the individual wishes to do, but such restrictions may also be seen as having a more positive and indeed, necessary function by providing the creative person with a more manageable creative space."

PREMATURE STAGE TO IMPLEMENT AUTOMATIONS

To conclude, to implement automations it is necessary to find the optimal balance between autonomy and assistance require.However, to determine this it is necessary to have knowledge specific to the context of the interaction in question. Knowledge that is not provided by the literature. Leaving it impossible to determine it without experiments.

In the current interaction, mistakes occur frequently, and applying constraints would likely improve the user experience by reducing these errors and minimising negative triggers. Even if constraints reduce the quality of the crafting experience, they would still likely be perceived as an improvement due to the decrease in mistakes that heavily impact the current experience.

However, applying automation at this stage is premature. Although it may appear as improving the interaction, it might be only

because the interaction prototype is yet at a preliminary stage, with various critical issues, therefore, implementing a solution that carries negative characteristics might not yield the best outcome. Instead, focusing first on improving input and output elements will enhance the interaction without compromising autonomy. Once these aspects reach a better state, automation can be introduced with a more critical perspective, ensuring any negative consequences are carefully considered, and the design context isn't pressured by the need for drastic fixes.
Therefore, initial improvements should target input and output, with automation introduced only after the interaction has undergone several iterations.

How Many Iterations Before Considering automation?

Design iterations typically follow a logarithmic improvement scale: the first iteration yields significant gains, with each subsequent iteration providing smaller improvements. Going through a few iterations can be enough to substantially enhance the current situation. Rapid testing with a limited number of users can be an effective approach to do multiple iterations, allowing a quick resolution of major issues. This will establish a solid foundation, enabling a more meaningful exploration of constraints later, ensuring the final interaction design reaches its fullest potential.

SECTION 4.2

THE FINAL PROTOTYPE

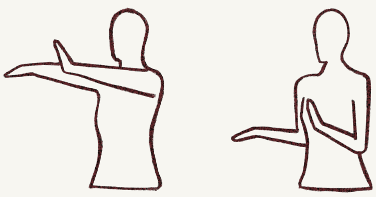
The iterative process was structured into several phases. It starts with a desktop research that explores the solutions already adopted for some of the issues that have already been explored, this covers only some aspects of the issue, and only a few issues. This is followed by ideation sessions that build upon the previous findings to address each identified issue. After the ideation, there is a filtering and selection phase to ensure that only ideas with potential move forward to user testing, where the practical applicability of the proposed solutions is evaluated. The initial desktop research is presented hereafter, while the details of the rest of the iteration procedures are discussed in Appendix section 2.

SECTION 4.2.1

DESKTOP RESEARCH FINDINGS

GORILLA ARM

Users find it more comfortable to use wrist motion rather than full arm movements. Additionally, movement accuracy improves when participants brace their arms against their body (Boring et al., 2009).
When performing mid-air gestures, users often adopt a high-fatigue posture, with the arm fully raised (Posture A). In contrast, during natural gestures, such as in face-to-face communication, users adapt Posture B, where the arms are positioned in a lower-fatigue state (Hincapié-Ramos et al., 2014).
Studies show that interactions involving physically supported gestures lead to significantly less fatigue than mid-air gestures (Hansberger et al., 2017).



POSTURE A POSTURE B

HAND MISALIGNMENT

Given that the root cause of the issue lies in the mechanics of the control system, desktop research was conducted to explore alternative control techniques for telemanipulation. This is a broad field, but a general categorization of control systems can be outlined as follows:

FORCE-POSITION CONTROL

This category includes force control (Yu & Bowman, 2018), position control, and hybrid-position control. Each of these methods focuses on either force or position as the primary control variable, but they do not enable fully simultaneous control of both force and position along the same axis.

IMPEDANCE CONTROL

Impedance control, widely used in telemanipulation, can be subdivided into two systems:
Fixed Impedance Control: The robot maintains a constant stiffness level, which determines its resistance to external forces. This predefined rigidity lacks adaptability when environmental conditions change.
Variable Impedance Control: In this approach, the robot's stiffness adapts dynamically based on interaction parameters. The prototype currently uses a form of variable impedance control, where stiffness increases as the reference point moves further from the end effector. More advanced implementations include ellipsoidal control, where impedance varies differently according to movement direction, enhancing (Peternel et al., 2021).

AUTONOMOUS CONTROL

In automated control solutions, such as adaptive force control, the robot autonomously adjusts the applied force in real time based on environmental feedback, without continuous operator input. Here, sensor feedback and AI-driven algorithms allow the robot to adapt to varying conditions (Zeng et al., 2021).

SENSORY SUBSTITUTION FOR UNCLEAR FEEDBACK

WHAT IS SENSORY SUBSTITUTION?

Sensory substitution refers to the process of capturing feedback that a user would typically perceive through one sense and translating it into another sense. For instance, when haptic feedback is unavailable (as in this MR setup where control is managed without physical contact), feedback can be translated into visual or auditory signals, which are channels accessible in the device. This enables the MR system to actively communicate information to the user that would otherwise be perceived passively, such as the shape or texture of an object being modified.

In the initial prototype, sensory substitution is used to replace missing haptic feedback, but as test results indicate, it does not yet provide the feedback necessary for effective interaction. To explore ways to enhance this, additional desktop research on sensory feedback is conducted to better understand its mechanisms and potential design improvements.

HOW THE PERCEPTION OF REALITY IS CREATED

The perception of reality is constructed through a combination of sensory stimuli that allow us to experience the environment around us. This experience does not capture the full essence of reality but only a portion, limited by the available senses, this limited reality we perceive is known as the "umwelt."

These senses detect stimuli from the environment, which are then converted into electrical impulses sent to the brain. The brain receives these signals, decodes them, and combines them to create our perception of reality. Essentially, the brain itself operates in a "dark and quiet" vault, relying solely on electrochemical signals from nerves to reconstruct the external world. It doesn't inherently "know" where these signals come from but is highly skilled at identifying patterns and assigning meaning to the data it receives (Eagleman, 2015).

The brain has evolved to use information from multiple senses to form a coherent perception of the environment. Typically, feedback from multiple senses is combined, creating a clearer and more precise understanding of what is happening and allowing people to respond accurately (Ghazanfar & Schroeder, 2006). This stacking up of sensory information is called multisensory feedback.

ROLE OF SENSORY SUBSTITUTION

Sensory substitution expands the umwelt by introducing new information to the brain. Once the brain decodes this information, it integrates it into the perception of reality, enriching the experience with an additional layer of detail (Eagleman & Perrotta, 2023). This approach is already been implemented to enhance the interaction in HRI (Jourdes et al., 2022) and VR fields (Cooper et al., 2018).

SENSORY SUBSTITUTION LILMITATIONS

In everyday experiences, sensory perception is a highly efficient, automatic process managed by the brain's specialised neural pathways. For example, sound vibrations reaching the ear are naturally processed by the auditory cortex, creating the perception of sound. This processing is innate to the brain's structure, allowing stimuli like sound, light, and touch to be perceived without conscious effort.

Sensory substitution replaces one sense with information delivered through an unfamiliar channel. Unlike automatic perception, sensory substitution uses artificial feedback which does not match with the natural pathway the brain would use to process the information. This requires a learning process to let the brain adapt, associating these new signals with specific meanings related to the original sensory experience.

Therefore, unlike synesthesia, where one sensory perception automatically influences another, sensory substitution requires the user to consciously learn and interpret the feedback from different pathways. This means that even after adaptation, substituted feedback remains less natural and lacks the clarity of perception provided by specialised senses, making it inherently less precise and more effortful to process.

A MULTI SENSORIAL EXPERIENCE

Multi-sensory integration enables the combination of information from different senses into a single, coherent experience (Senkowski et al., 2008). For this integration to be effective, certain conditions must be met, actors such as spatial and temporal proximity significantly impact the efficiency of this process Eagleman & Perrotta, 2023). Research by Jonetzko et al. (2023) shows that multisensory integration is feasible in mixed reality interactions, where users respond particularly well to combined visual and auditory feedback. However, when feedback isn't well integrated, it can reduce performance, making unisensory feedback preferable in such cases (Misselhorn et al., 2015).

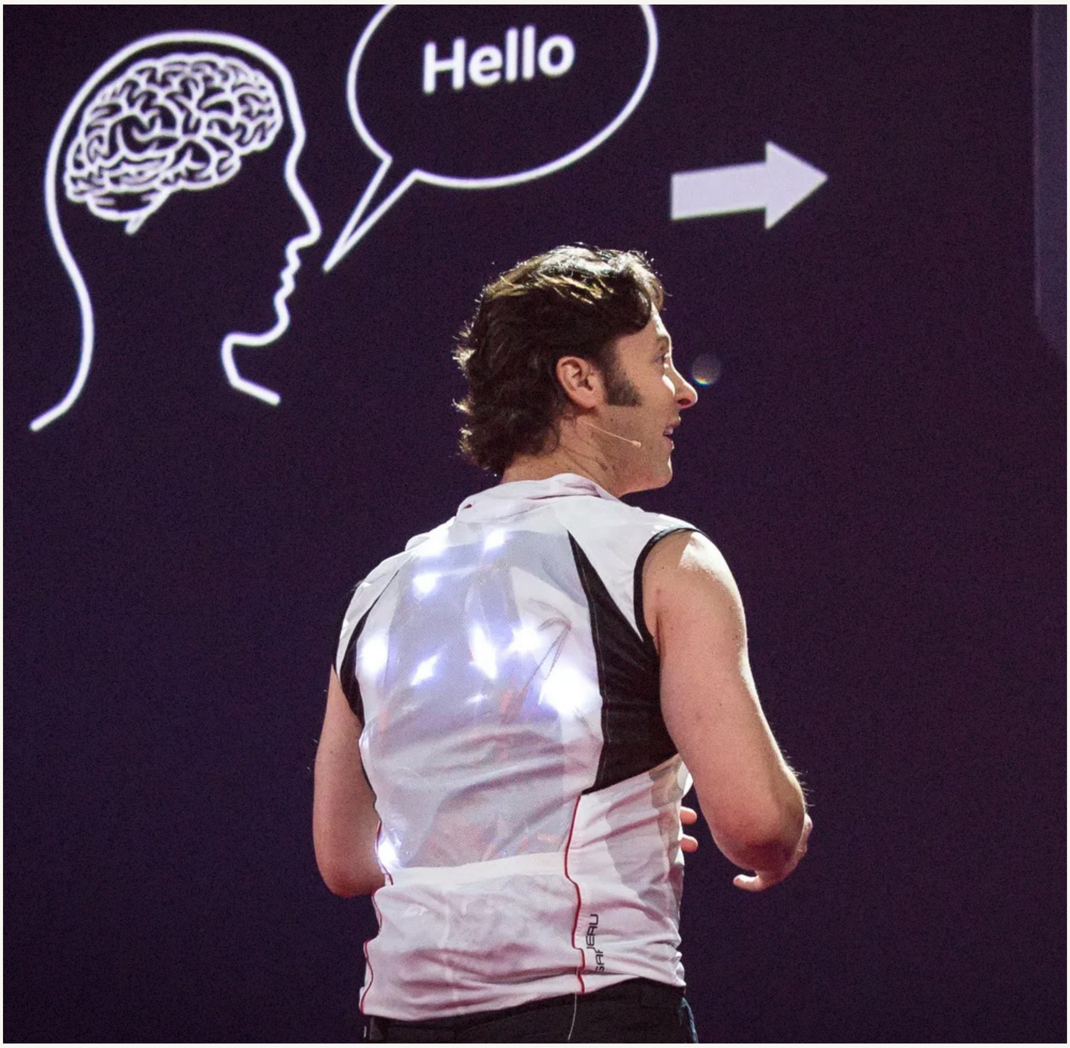


FIG. 17 - DAVID EAGLEMAN'S SENSORY VEST

Neuroscientist David Eagleman has designed clothing that translates audio signals into vibration patterns. The haptic feedback is intended to help deaf people learn to "hear".

SECTION 4.2.2

IMPLEMENTATIONS

After selecting the most promising ideas, testing the new prototype, and iterating on it several times, the design of this fully free version was finalized.
The presented solution managed to enhance certain characteristics but failed to address all the remaining issues.

SIMULATION IMPROVEMENTS

First, several key updates were made to the simulation environment. A control panel was added to the virtual environment, providing users with options to address issues like regaining control if the controller disconnects, and correcting some misalignment or unresponsiveness of the robot movements. While these refinements do not directly relate to the interaction design, they resolve simulation-specific problems that previously caused frustration and confusion, ultimately impacting the overall experience. More details on these developments are provided in the Appendix section 4.

THE FINAL PROTOTYPE

Not all the identified issues were addressed. While various solutions were ideated, many proved unviable, leaving some issues unresolved. The following section outlines the implementations included in Prototype V3 (the final prototype), along with proposed implementations that were not realized, and finally, the remaining unresolved issues.

SECTION 4.2.2.1
ISSUES TACKLED

ROTATION ISSUES

The wrist rotation that generates the most discomfort is ulnar-radial deviation. This rotation is primarily needed when setting up the tool in the correct orientation on the x-z plane. Once the tool is oriented, this alignment usually remains constant throughout the interaction. To position the tool correctly, users may need to rotate it up to 180 degrees, requiring multiple full ulnar-radial deviations, which causes discomfort. Allowing this rotation in a single, comfortable movement may help alleviate the strain.
A rotation gizmo would allow users to perform straight, comfortable movements that translate into rotational values, reducing the strain of direct wrist rotation. This gizmo is added to the controller in the right hand, while the left hand can be used to interact with it.
Using the rotation gizmo is intended to reduce the wrist rotation needed for setup positioning, thus lowering discomfort.

From the test results with the gizmo, participants showed not to be in a high level of discomfort (table 3 Appendix), although it is still present. However, another issue becomes more evident, still related to the rotation: the frequent need to adjust the end effector's orientation, described as bothersome, which requires extending the wrist beyond comfort and becomes a notable source of frustration.
This ongoing adjustment was noticed to be caused by the mechanics used to control the force intensity. The user needs to move the robot's reference point, causing misalignment with the end effector (as if stretching an elastic). To achieve this, the user must move the hand position, and since the arm moves along a circular trajectory, maintaining the same orientation requires continuously adjusting the angle between the hand and forearm (fig. 18).
Although these discomforts related to the rotation were not reported to be a major issue, considering the small number of users and the short duration of

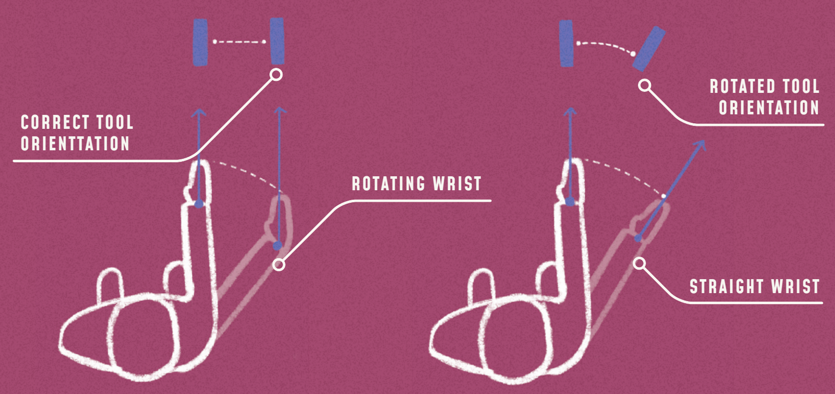


FIG. 18 - RATOATION ISSUES

the tests, they could be more critical in long-term interaction and thus require additional improvements. To reduce this unintended rotation, which causes wrist pain and the annoying need for frequent adjustment, the force intensity sensitivity has been increased. This adjustment allows the desired force to be achieved with a smaller degree of misalignment, thus decreasing unintended rotation. A solution to fully eliminate this issue was not identified, except using constraints, which will be explored in the next development phases.

Additionally, to discourage users from making excessive movements, the maximum extension of the force line has been capped. Previously, users could extend it indefinitely in an attempt to apply high forces, even going beyond the robot's capacity. Now, the range is limited to match the robot's maximum achievable force, reducing the tendency to overextend and further minimizing misalignment.

To maintain precise control within this now-limited range, a force multiplier slider has been added to the UI. This feature allows users to amplify the force generated by misalignment, enabling them to reach high force levels without excessive misalignment while still allowing for fine control at lower forces. This improvement provides a balanced experience with precise control across a wide range, all within a limited range of misalignment.

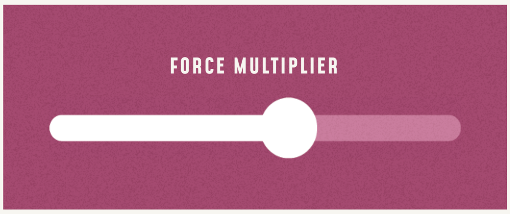


FIG. 19 - SLIDER FOR PRECISE FORCE CONTROL

GORILLA ARM

To reduce the discomfort of keeping hand raised for a prolonged amount of time, it is implemented a dynamic scaling of the sensitivity of the movement, a technique commonly found in interfaces using a mouse, known as "mouse acceleration." In this system, sensitivity varies based on the speed of movement: slower movements have low range, maintain precision, while faster movements increase range, allowing to reach further without needing to stretch the arm.

This solution addresses not only user fatigue but also the excessive movements required to translate the robotic arm, which participants reported as a more prominent issue than the discomfort caused by the gorilla arm.

After implementing the dynamic sensitivity, participants reported that for slow and precise movement, the robotic arm moved too little, making precise control challenging. To address this, a minimum sensitivity was defined, ensuring that during slow motions, the movement always matches at least the scale of the user's hand motion.

However, even after implementing the dynamic sensitivity, low discomfort (table 3 Appendix) was still reported by participants. Since no previous data was collected, it's not possible to determine whether the current implementation—increasing sensitivity and allowing the arm to be kept lower—has improved comfort. Observations during the test indicated that participants still tended to keep their arms elevated and make large movements, suggesting that, even if the interaction can be done with a lowered elbow, users feel compelled to raise their arms.

The current level of arm fatigue does not appear to significantly impact the user experience; therefore, no further solutions will be implemented at this stage. Over time, as users become more familiar with the interaction and control system, they may naturally optimize their movements, potentially reducing the need to lift their arms as frequently as during the initial moments of use. Further exploration is recommended to evaluate how this issue affects longer sessions.

FIG. 20 - USER TESTING

FORCE FEEDBACK

The feedback system needs to naturally communicate the magnitude of force, enabling even inexperienced users to intuitively understand it. Two key elements must be conveyed:

1. Intensity: The strength of the applied force;
2. Direction: The orientation of the force, crucial for understanding how the robot interacts with the environment.

Several options were considered for visually representing force, and two options emerged:

- Frequency (e.g., blinking speed): Time-related features inherently convey intensity.
- Color Range or Saturation: A color gradient could effectively convey intensity.

Participants struggled to perceive the color gradient, which shifted from red to purple, used to indicate force intensity, finding it only helpful for distinguishing between strong and weak forces, and inadequate for finer gradations. Although a wider color range (such as green to red) might have improved sensitivity to small changes, it was found to be visually disruptive and thus removed.

So frequency-based feedback was selected as the better option, as it conveyed a stronger impression of intensity. Its dynamic nature made it more noticeable, particularly in peripheral vision, enhancing its effectiveness in conveying force cues.

The perception of speed or frequency can convey intensity without a reference for comparison, unlike spatial cues. Humans have evolved to perceive time through familiar biological reactions like reaction time and daily experiences, making judgments about "fast" or "slow" (which can translate in low or high intensity) instinctive, making it a more cognitively efficient choice to convey force intensity.

Maintaining visual clarity of the force direction was also crucial. The blinking line caused issues with force direction visibility when it was "off," disrupting users' ability to gauge the position and movement of the end effector. To resolve this, the feedback was modified into a series of moving dots along the force line, providing constant visibility for both force intensity and direction.

Results after this implementation showed that force feedback still had some issues (table 3 Appendix). Participants reported that the visual representation of the force line was somewhat helpful but noted some usability problems. One key issue was the low visibility of the force line: the small white dots composing the line lacked sufficient contrast against the background, making them difficult to distinguish.

To address this, the size of the force line was increased to enhance visibility. It is important to note that this issue is likely due to the low resolution of the VR headset, which makes smaller elements harder to discern. A higher-resolution display could potentially maintain smaller line sizes while still providing adequate visibility.

After increasing the thickness of the force line, a new issue emerged. The thicker force line, together with the digital element representing the reference point (now positioned closer to the end effector due to decreased misalignment), often obstructs the point of contact—the primary focus area of the interaction. This creates visual clutter, a well-documented issue in MR interactions, as noted in the literature.

To address this, the force line's starting point was moved away from directly originating at the end effector to a short distance away, clearing the area of interest from any overlay elements and allowing for an unobstructed view. However, this adjustment brings its own challenge: when very low force is applied, the shortened force line becomes less visible and almost disappears. Although it doesn't occur frequently and isn't significantly disruptive, this issue remains unresolved.

User reported also that determining the direction of force along the depth axis (perpendicular to the user) was also difficult, likely linked to previously noted depth perception issues.

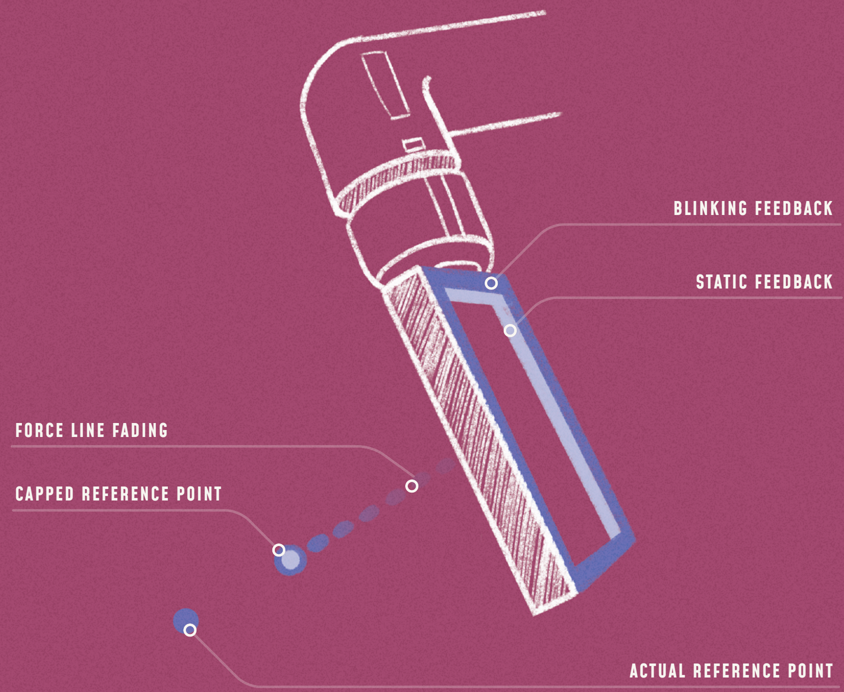


FIG. 21 - IMPROVED UI FOR FORCE FEEDBACK

CONTACT (NEW IDENTIFIED ISSUE)

A newly identified problem, referred to as the "retracting motion" issue, emerged when users attempted to pull the tool back from the object. Participants would sometimes assume the tool had disengaged, only to later realize it was still in contact.

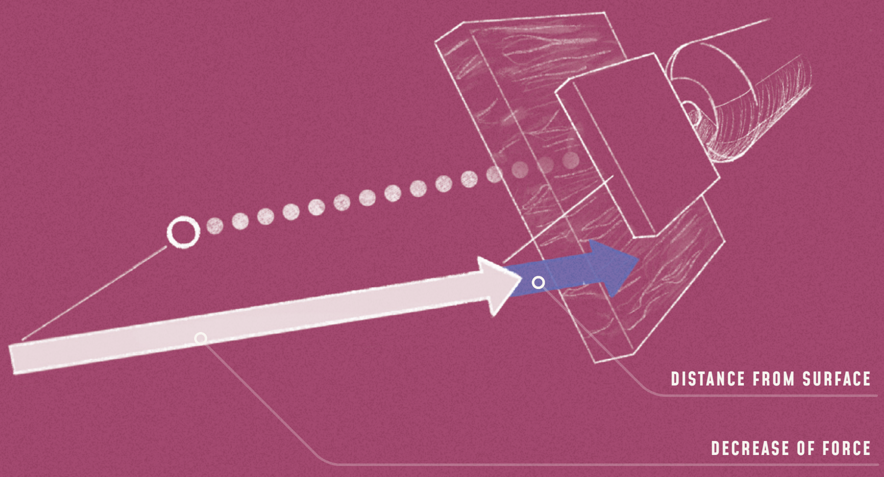
This issue likely arises because users, oppositely on when approach is made, where they rely on visual feedback (a digital overlay) to signal when contact is made, for disengaging, users instinctively assume the tool will fully separate from the object with a backward motion, as it would in a typical physical setting, and do not pay attention to the digital overlay. Since the reference point in this interaction is offset from the end effector, users need to move a certain distance to fully clear the tool from the surface, which is an unnatural mechanic that can feel unintuitive. An initial backwards distance to decrease the force (fig. 22 - decrease of force), and only after it, an additional distance to detach from the surface (fig. 22 - distance from surface).

The current feedback system, while effective at indicating initial contact, fails to keep users consistently aware of the contact state. The overlay remains static when contact persists during retraction, which makes it easy to overlook. As a result, users may mistakenly assume they are no longer in contact with the object, even though the feedback indicator remains active.

The decrease of misalignment achieved thanks to the previous solutions have a positive influence on the retraction issue. With reduced misalignment, a shorter backward movement is now required to detach the tool from the object, though this alone does not significantly resolve the problem. To address this further, various solutions are implemented.

The first implementation introduces a system that detects backward movement based on a quick reduction in misalignment. When a user retracts after applying force—essentially moving back to disengage

FIG. 22 - RETRACTION MOTION



the tool from the surface—the movement is typically faster and more extended than normal force control adjustments. By tracking the speed and length of this retraction, the system can identify this as an intention to detach from the object surface. Upon detection, the reference point instantly aligns back to the end effector, even if the user's backward motion hasn't yet completed the necessary distance. As this realignment happens instantly and the user's retraction motion still continues for an extra instant, the reference point (and end effector) move slightly further away from the surface before the motion stops, creating the detachment the user expects. This process achieves the desired separation from the object in an intuitive way, closely mimicking a physical retraction experience. Additionally, this feature allows for a slight improvement in force control agility, as a simple backward motion now effectively halts force application.
The second implementation enhances contact feedback by making it continuously noticeable, eliminating the previous static and easily overlooked signal. The new feedback consists of two concentric digital overlays at the back of the tool. One overlay blinks intermittently, drawing attention with its pulsing effect, while the second remains static, providing a constant indicator even when the blinking element is off (for less than half a second). This dual-element design ensures that users remain constantly aware of contact status throughout the interaction.

UI OVERLAY

It was also noted that the UI element to feedback the contact happening, is positioned on the surface of the tool on the side that is grinding the object. Like if when the object touches the object side touching it lights up. However the fact that it is a digital overlay, which means it is overimposed over any other physical element (but still positioned in the 3 dimensional space in the environment) seem to create visual confusion as it appears as a visible object inside another object
By seeing an object that even though it should disappear, because it goes behind another object, not doing so, seems to cause problems on how well the spatial situation of the objects in the scene can be comprehend.
Also the force line has the same effect, as it is often exactly placed on the spot where the interaction is happening, partially covering the object, reducing the visual feedback of it and causing the confusion described earlier.
To mitigate this issue, the UI overlay for the other solutions (the force line and the contact feedback) was designed to avoid obstructing or being too close to the point of interest, thereby preserving spatial perception. The force line now starts farther away, and the lights indicating contact feedback have been repositioned to the back of the end effector tool, having them become visible only when that side is facing the user.

SECTION 4.2.2.1
SUGGESTIONS

HAND MISALIGNMENT

To improve the control system, a solution aimed at reducing hand misalignment was proposed. However, due to the complex technical challenges of implementing it in the prototype, it was decided to leave it as a suggestion without implementing it.
This approach is documented in the literature and has been shown to be usable. However, further exploration is needed to determine its compatibility with the interaction system used in this project.
This solution still defines force based on misalignment but utilizes a system similar to the ellipsoidal model (Peternel et al., 2021). In the grinding task, the force that requires the most precise control is the one applied perpendicularly to the material, as this determines the depth and effectiveness of the grinding. In contrast, the lateral forces, which are parallel to the material, are primarily used to position the grinder tool rather than control the applied force. This distinction suggests that separating these controls could improve maneuverability. A system where lateral movements are handled independently of force control—leaving precise force adjustments only for perpendicular movements—could provide a more intuitive experience for the user. This way, users could focus on positioning the tool laterally without the need to adjust force in those directions, while maintaining fine control over the force applied directly into the material.

SECTION 4.2.2.2
ISSUES NOT TACKLED

OBSTRUCTION

No solutions effectively addressing the obstruction issue have been identified. The proposed solutions were either economically unfeasible, reduced ease of control, or introduced technical limitations and visual clutter.

Obstruction is an issue found to be relatively severe compared to the other issues. Users noted that the tool often blocks their view of the grinding area, preventing them from observing progress unless they stop the action and move the tool away to reveal the progress on the object beneath.

Interestingly, users reported the main issue in relation to obstruction to be the disappointment when revealed progress did not meet expectations (lack of achievement goals), while the frequent need to check progress was not found as disrupting their experience, despite the requirement for immediate feedback in achieving a flow experience.

Additionally, participants felt that changing their perspective to gain a better view was not feasible, as movement could destabilize their hand, potentially causing them to lose control of the tool. As a result, they preferred to remain immobile during the interaction.

Creating a more comprehensive sensory substitution to replicate the multidimensional aspects of haptic feedback is a solution that could resolve obstruction issues. However, implementing such an advanced feature requires extensive investigation and testing. Given the complexity and the project's limited resources in terms of time and expertise, this solution will not be incorporated in the current interaction design but is recommended for future development.

POINT OF CONTACT

Another issue identified is the uncertainty regarding the specific point of contact. While the feedback system indicates when contact occurs, it does not clarify the exact location on the tool. This ambiguity leaves users uncertain about whether the grinding is occurring on the intended spot or if they are inadvertently grinding an unintended area.

The cause of this issue can be attributed to the low simulation quality, which fails to replicate a fully realistic environment. It provides textures with low contrast, low-resolution shadows, and limited detail—elements that make it challenging to define the boundaries of objects precisely. This lack of clarity can impair the user's understanding of the tool's position relative to the object and obscure where contact is occurring.

However, the simulation is not the only factor; the absence of haptic feedback also contributes to the issue. In a physical setting, holding a tool allows the user to feel how it interacts with the object; for instance, a flat tool on a flat surface feels stable, while positioning it on a corner feels unsteady. In the simulation, this stability feedback is missing entirely. As a result, the tool may make contact only on an edge or corner, but without visual feedback, the user has no reliable way to understand it.

Similarly to the obstruction issue, resolving this problem through sensory substitution requires extensive investigation. No solutions have been proposed in this project.

DETAILS

Given that the task proposed in the test does not require precise movements or work on fine details, it is possible that the user feedback regarding visibility for details was a usability concern for other contexts rather than an immediate issue for this application. With this consideration, no adjustments were made. However, this issue highlights an important limitation of the interaction, as it cannot achieve precise movements.

HAPTIC FEEDBACK - TACTILE SENSORY DELIGHT

Haptic feedback could not be implemented due to the vision-based hand-tracking system used in the interaction, which inherently lacks tactile or force feedback capabilities. While sensory substitution is an option, it does not replicate haptic perception. Additionally, as discussed earlier, this iteration prioritizes improving usability issues over hedonic factors like sensory delight.

GENERIC CONTROL SYSTEM

Users expressed that the control system still feels unstable and not entirely under their control. Results indicate that this issue is perceived as relatively severe compared to other problems. Many users reported experiencing the robot to do unintended movements in both rotation and position, which created a sense of unreliability. This lack of control emerged not only during instances where force was applied (which is known to cause misalignment and related issues) but also occasionally while not grinding material, where users tended to overshoot their intended position.

Additionally, participants reiterated that the lack of haptic feedback contributes to a feeling of imprecision. One user described controlling the tool, when force is applied, to feel like balancing it in an unstable equilibrium, where unintentional shifts or slips would occasionally occur, causing a sense of imbalance and lack of fine control.

Causes of this problem are not fully identified. It is assumed they result from a combination of various factors, such as low depth perception, allocentric view, obstruction issues, and the general complexity of the control system, which simultaneously manages both force and position based on hand movements and may be too complex to perform intuitively.

SECTION 4.3

CONCLUSIONS

LOW USABILITY EVEN AFTER IMPROVEMENTS

The development of the initial prototype, designed around the requirement to give users full control and ownership on the robot movements, provided valuable insights but revealed significant limitations. Despite multiple iterations to improve feedback and input mechanisms, the overall usability remained low.

Users faced high cognitive demands, with the interaction feeling far from intuitive or effortless, leading to frequent mistakes. Sensory substitution through visual feedback, while somewhat helpful, could not significantly replace the guidance usually provided by haptic feedback, crucial for achieving precision.

While the prototype succeeded in meeting autonomy requirements, it fell short in providing a true sense of control. Additionally, it struggled to deliver on aspects like effortless input, goal achievement, and a rich sensorial experience.

ADDITIONAL FEEDBACK FROM A PROLONGED INTERACTION

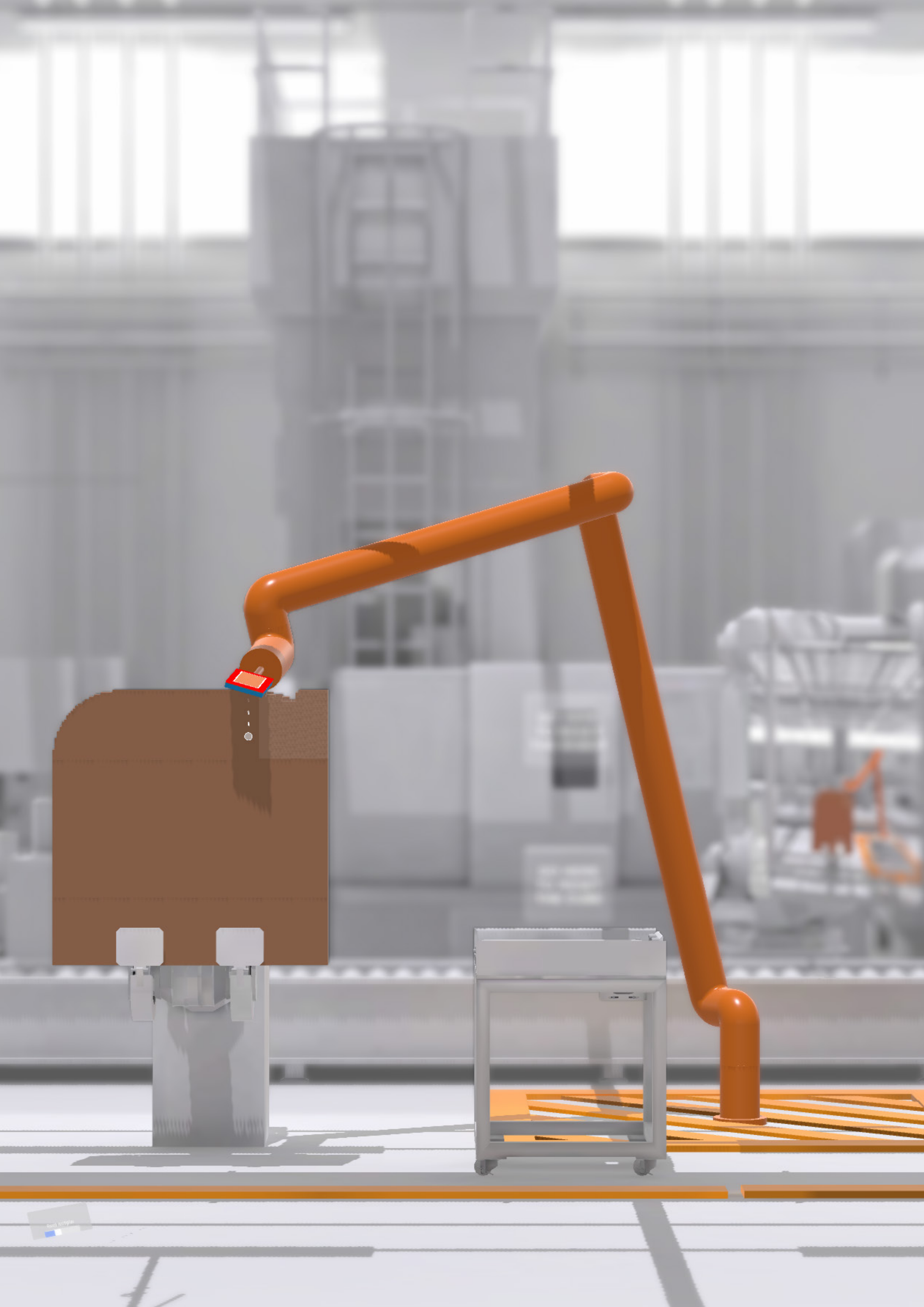
Familiarisation time appears to play a crucial role in shaping users' interaction performance and experience. Initially, users felt disoriented and struggled with the controls. The time required for users to become comfortable with the system varied significantly; some users gained confident control within five minutes, while others required over an hour and still experienced difficulties. After this initial calibration phase, continued practice gradually improved user performance and control precision. However, due to limited testing time, providing users with extended training was not feasible.

Given this limitation, before concluding this chapter regarding the interaction prototype with full control and no automations implemented, sharing insights from extended personal experience with the system may provide valuable perspective on the interaction's potential after a substantial period of familiarisation. With prolonged use, the interaction begins to feel similar to using a computer mouse but in a three-dimensional space. Over time, it becomes easier to make quick, more-or-less precise movements with minimal mental effort. The force control feels limited, suitable for simple crafting tasks, like the one explored, where adjusting force intensity along a single direction is sufficient. However, for tasks that require varying force across multiple directions in a short time (such as carving or writing), this interaction would likely be unsuitable, revealing its limitations for universal application.

In conclusion, the control system seems adequate for completing low-dexterity crafting tasks.
The distance from the object and the tool's obstruction of the view, aside from complicating precision and accuracy, contribute to a feeling of detachment from the craft—though the simulation aspect may also influence this—impacting the sensory-engaging experience. Despite these sensory limitations, the interaction achieves a relatively engaging crafting experience due to users' sense of ownership in the action and accomplishment within the interaction.

LIMITATION OF MR AND VISION BASED TELEOPERATION- GO FOR THE AUTOMATION

After multiple iterations, it is clear that further refinements alone would not resolve these issues, suggesting that the technology itself—specifically the lack of sensory feedback— might be a limitation.
Given these findings, the progression towards implementation of constraints, to ease the controls seems unavoidable. This next step will focus on reducing user errors and shifting the user's effort from avoiding mistakes to focusing on the actual creation process. By integrating automation, the system can potentially enhance both the functional performance and the overall crafting experience, allowing for a smoother interaction and better task execution.



CONSTRAINED CONTROL

CHAPTER 5

SECTION 5.1

THE CONSTRAINTS

This chapter introduces automation through constraints, the third and final element of interaction yet to be explored, following input and feedback. As established in chapter 4.1.1, after multiple iterations addressing input and feedback to mitigate the critical challenges in the interaction, it is now time to examine the potential of the robot's automation.

Constraints frequently emerged as potential solutions during ideation, suggesting they may offer valuable improvements to this interaction. Although constraints inherently limit user autonomy and freedom—both crucial to the crafting experience—they also retain user control over actions. Therefore, constraints appear to be a promising fit, balancing guidance with user freedom.

The aim of this chapter is to enhance the interaction system by finding the optimal balance between the application of constraints to improve usability and the preservation of autonomy and a sense of ownership.

SECTION 5.1.1

CONSTRAINTS DESIGN REQUIREMENTS

THE GOAL OF THE CONSTRAINTS

The role of constraints in the system is passive: they can block specific movements to reduce errors and improve performance but can't actively guide the user's actions. Constraints should be designed to maintain, and even enhance, the crafting experience, respecting the requirements previously defined.
The struggle for control over movements is a critical issue impacting both user experience and functionality. To address this, constraints should focus on reducing unintentional slips while still allowing intended movements, preserving the user's autonomy and sense of control. In this way, constraints should feel effective but invisible, quietly supporting the interaction without imposing on the user's freedom.

CONSTRAINTS REQUIREMENTS

The literature reviewed throughout the project provides insights into the negative aspects that constraints can lead to.

- ***Frustration and Interruption:***
  Constraints may interrupt the user's intended actions to some extent. interruptions in workflow can have negative consequences, such as increased stress, frustration, time pressure, and effort (source). Constraints, therefore, should be designed to minimise such interruptions, ensuring they do not compromise the user's experience.
- ***Reduction of Autonomy:***
  Flow requires a sense of personal control over the task, and constraints that reduce autonomy risk reducing this sense of control. Constraints should avoid making the user feel as if they are merely following instructions, aiming for not self-set goals can disrupt flow and diminish the experience..
- ***Task Challenge and Engagement:***
  Flow is achieved when task demands align with the user's skill level. Constraints that overly limit mistakes could eliminate the need for the user's skill, making the interaction feel too easy or uninteresting. Constraints, therefore, should find a balance, reducing errors without making the task overly simple, so the experience remains engaging and skill-based.

  Considering this information and the challenges present in the interaction, it is possible to outline a set of requirements for constraints that can guide the design toward a well-balanced user experience.

REQUIREMENTS

Maintain autonomy

- The constraints must not interfere with the decision making of the user
- Constraints must maintain the user feel in control of the actions

Regulate difficulty of the task

- Constraints must maintain the task to require some effort to be completed
- Constraints must balance user skills and demand of the task
- Constraints should allow the user to achieve the desired goal;

Increase usability

- Constraints must reduce unintentional mistakes
- Constraints must not feel too restricting, or interrupting the intended action
- Constraints needs to improve comfortability

General requirements

- Constraints needs to maintain efficacy and effectiveness of the task

SECTION 5.1.2

PROTOTYPE DESIGN

To determine the optimal balance between movement freedom and constraint, two different versions of constraints will be developed and tested, as the correct level cannot be estimated in advance. The first prototype will apply a relatively low level of constraint, while the second will implement a more rigid constraint type. These two prototypes will be tested alongside the unconstrained version (Prototype V3), providing a range of controls from full freedom to high constraint.

This test will reveal the extent to which constraints impact both user experience and performance, helping to determine where the optimal balance between autonomy and constraints is, identify which approach best supports user satisfaction and sense of accomplishment, with minimal frustration from unintentional errors.

SPECIFICITY OF THE CONSTRAINTS

The design of these constraints is highly tailored to this interaction type; even minor adjustments to the task could render them incompatible and potentially problematic. The goal here is to find the ideal balance—understanding to what extent constraints can be applied without compromising the crafting experience. Once the optimal balance is identified, future studies could focus on adapting the constraints to suit a broader range of tasks, adjusting for various actions. This project will conclude upon defining this balance, leaving further development to enhance the constraints' versatility for future research.

SECTION 5.1.2.1
LOW CONSTRAINTS

The first version of the prototype with constraints, Prototype V4, will apply minimally invasive constraints. The aim of this prototype is to reduce mistakes by restricting control only in movements that don't determine the final result.

What movements don't determine the result?
Considering the shape of the material and the goal to be achieved, it is possible to determine which types of movement are necessary to perform in order to achieve the goal. For example, in a task that needs to be performed on a two-dimensional plane, movement in three dimensions may not be required (though there are exceptions, like drawing, where hand movement is three-dimensional). Therefore, limiting movement to only the required dimensions can help the user accomplish the task more easily, reducing a degree of freedom that only adds complexity while still allowing complete autonomy to achieve the goal.
Similarly, the grinding task presented for testing, although carried out in three-dimensional space, can be executed with two-dimensional movements. Thus, it's possible to constrain the extra dimension and still allow the user full freedom in the dimensions relevant to achieving the result.
Applying the right constraints depends on knowing the user's goal, as different tasks and goals may require different movements, and the constraints should adapt accordingly. Achieving this adaptability is complex, and therefore, these constraints are designed to apply only within this specific context. Using these constraints in tasks that actually require three-dimensional movement would not be feasible, so the results of this exploration should serve only as a guide to define the balance point rather than defining exact constraints for other tasks.

THE ISSUES TO TACKLE

The previous user test revealed several ongoing issues, some more disruptive than others. While some issues may lend themselves well to resolution through constraints, others may not be as suited to this approach. During the initial ideation session, various ideas were generated around the use of constraints, though they were set aside at the time. Now, however, is the opportunity to revisit and consider these ideas.

Overshooting and Depth Spatial Awareness
Overshooting emerged as a frequent issue observed during user tests, with users often unintentionally moving the tool beyond the desired position due to limited spatial awareness along the depth axis. In this task, grinding occurs on a surface that is expansive in two dimensions but thin along the depth axis, making depth movement unnecessary and primarily a source of user frustration.
Implementing a constraint on a plane perpendicular to the z-axis and locking the end effector to that plane would allow users to focus solely on relevant movements, free from depth perception errors. This approach preserves full control over the movements necessary for grinding while eliminating the common misalignment mistakes caused by unintentional depth shifts.

Rotation discomfort and lack of control
Another issue that can be effectively improved with constraints is the tool's orientation. Rotation presents multiple challenges: the constant need for adjustments and the extent of rotation required are both annoying and uncomfortable for the wrist, and they make it harder to maintain control over the tool's orientation.
Applying a constraint to allow rotation only on the

depth axis can alleviate these issues. As explained earlier, the grinding task only requires two-dimensional movement, thus the task does not require rotation on the other two axes. In fact, rotation on the other axes only adds difficulty without benefiting task execution. Limiting rotation to a single axis removes the need for constant adjustments caused by misalignment, keeping the orientation stable, reducing wrist strain, annoyance, and confusion—all without reducing the user's ability to achieve the desired outcome.

These constraints are designed to meet the requirements by preserving the user's control and freedom of movement, limiting only those actions that would not affect the achievement of the task, but rather are done unintentionally due to the lack of control. This approach aims to support successful task completion and a positive crafting experience by effectively guiding the movement within a two-dimensional space.

SECTION 5.1.2.2
HIGH CONSTRAINTS

The second version of the constrained prototype, the one with high constraints, prototype V5, takes a more invasive implementation of constraints. The aim of this prototype is to completely eliminate unintentional mistakes by reducing controls. Unlike the previous version, it also constraints movements directly related to the outcome of the crafting action.
Given the frequency of mistakes and resulting frustration, the lighter approach of prototype V4 may not sufficiently prevent negative emotions from arising. Therefore, prototype V5 is designed with a focus on reducing mistakes and minimising negative experiences, even if this comes at the expense of the crafting experience.
Presenting multiple different levels of constraint is necessary to gauge where the optimal balance lies concerning user experience.

THE ISSUES TO TACKLE

From previous ideation sessions, several ideas involving the application of rigid constraints emerged and are outlined below:

Overshooting and Spatial Awareness
The same depth-axis constraint from the low constrained prototype, V4, is applied, allowing the tool to move only along the two dimensions necessary to complete the task. This eliminates the option to move along the depth axis, which only increases complexity that leads to mistakes.

Rotation
Rather than being limited to a single axis, rotation can be fully constrained, leaving the user focused solely on positioning the tool within the 2D plane. This complete rotational constraint is feasible due to the simple geometry presented in the task, where the tool's orientation can be predefined relative to its position. (fig. 23)
This solution entirely eliminates issues arising from orientation control, reducing mistakes and effort, allowing the user to concentrate fully on just one control element: position.

Unexpected Results
An additional constraint is introduced to address the obstruction issue during interaction. When the area of interest is obstructed by the tool, it becomes challenging to perceive the grinding progress, often resulting in more grinding than intended and leading to frustration. To prevent the risk of overgrinding—which could cause an irreparable mistake—a constraint limits the tool's position beyond specific coordinates in space, ensuring that areas that should not be ground remain untouched. Even if the user applies force to grind in a restricted area, the tool will not respond, preventing excessive grinding when the area of interest is obscured.

This prototype offers an interaction designed to enable the user to achieve optimal results with minimal effort while still maintaining control over certain aspects of the action. The constraints reduce unnecessary movements needed to achieve the result, while also partially automating some movements that directly influence the outcome. Although this decrease in control and freedom conflicts with the requirements for autonomy and effort inherent in the crafting experience, the reduction in negative experiences may reveal a more balanced demand between task and user skill. Only through user testing will this balance become clear.

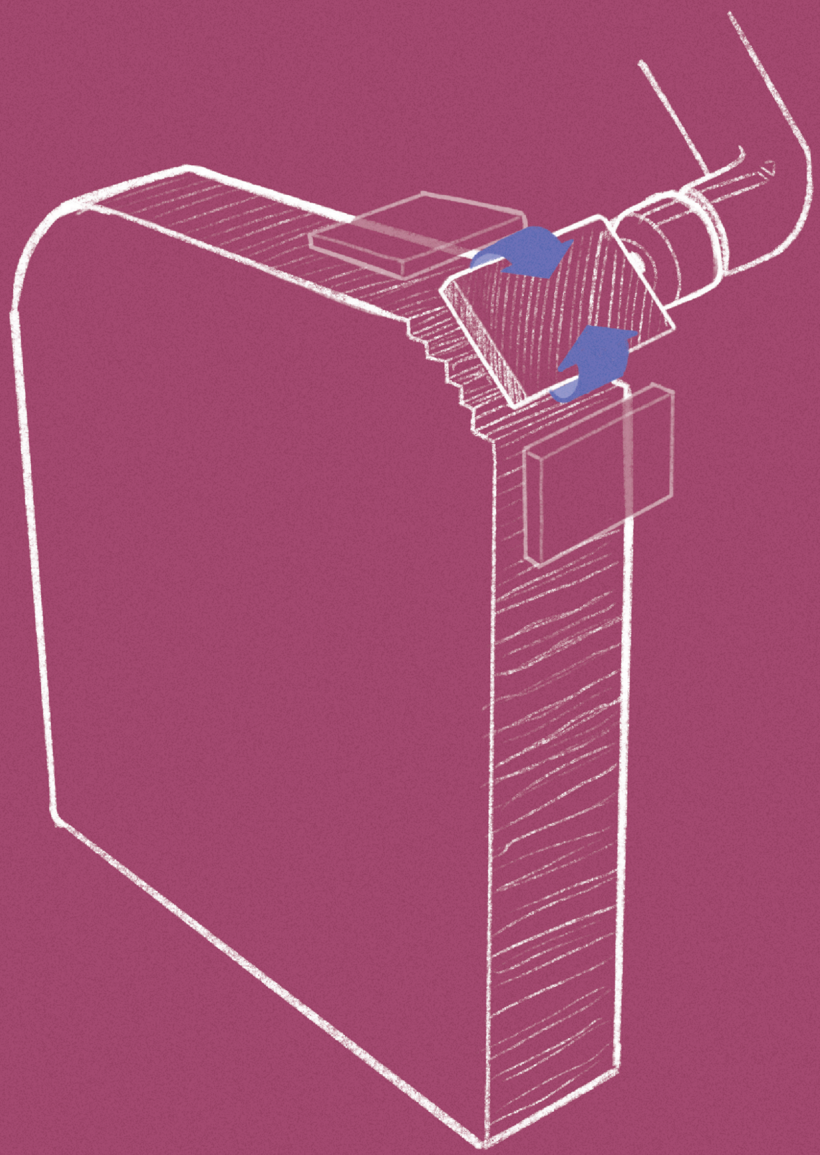


FIG. 23 - CONSTRAINTS

The blue arrows indicate the only allowed direction of rotation. The two additional boxes on the sides of the end effector represent possible positions of the end effector within the plane where movement is possible

SECTION 5.2

THE TEST

THE GOAL OF THE TEST

The aim of this test is to assess how constraints impact user experience and to identify the optimal balance between constraint (or automation in general) and freedom of movement that best supports usability and the crafting experience within the MR interaction.

Three control types are presented, each with a different level of constraint: none (prototype V3), low (prototype V4), and high (prototype V5). At one end, there is unrestricted interaction, which may lead to more mistakes but potentially greater satisfaction. At the other end, there is a highly limited control system, where mistakes are unlikely, though satisfaction may also decrease. Between these extremes, the intermediate level of constraint, offering some limitations to reduce errors while still providing the user with a sense of responsibility for the result—and, consequently, satisfaction in their successes.

SECTION 5.1.2

METHODS AND SET UP

The test setup builds on previous user tests and is structured in the following phases:
Familiarisation: The user begins with a tutorial session to become familiar with the control system.
Task Execution: Following familiarisation, the user starts the first task—grinding one corner of an object to match the opposite corner. Different corner types will be used in a specified sequence (fig. 25). The task will be performed with a selected control type (prototype V3, V4, or V5), chosen according to a specific order to prevent order effects on the final results (refer to the randomization chapter). After completing the task, the user's performance is evaluated.
Questionnaire: After task execution, the user exits the simulation and completes a questionnaire regarding their experience with the task.
The task execution and questionnaire phases are then repeated multiple times, each with a different control type and corner configuration. For each repetition, the user performs a new task, the performance evaluation is recorded, and completes the corresponding section of the questionnaire.

FAMILIARISATION WITH THE CONTROLS

Observations from previous tests indicate that users need time to become comfortable with the control system. The time required to reach a confident level of control varies widely—some sessions took less than 3 minutes, while others required over an hour to achieve similar performance levels. To gather meaningful results, only feedback given after the user has familiarised themselves with and learned the control system should be considered. Otherwise, the feedback may be influenced by frustration from the learning process, which is unrelated to the actual interaction and instead reflects the challenges of learning itself.
In previous tests, users were given time to try the simulation and perform the task multiple times to familiarise themselves with the controls. However, some users, perhaps eager to begin the actual test, would start performing the task quickly, possibly without fully understanding the control system.
Another observed issue was that users struggled to comprehend the control system. The only instructions provided were through a brief demonstration on a screen displaying the VR environment, and the researcher, wearing the headset, explained the interaction while performing it. Due to the volume of information, the delay between the headset scene, with relative explanation, and the display the participants watched, users were not absorbing all the details, resulting in an ineffective demonstration.
Once the user puts on the headset and enters the simulation, the researcher does not have the opportunity to guide or correct them, which can lead to ineffective control techniques. For instance, in one session, it was observed—after more than 10 minutes of user struggle—that the participant was using the side of the tool instead of the proper grinding face.
To address this, a more effective method for introducing the control system was deemed necessary, ensuring users understand all functionalities and how

to use them properly. To enhance learning, users should be able to try out controls as they are being demonstrated, rather than receiving all information at once and only then being able to try them. To facilitate this, a video tutorial was recorded and embedded in the simulation, allowing users to follow it step by step while actively practising.

Initially, to ensure the familiarisation was successful, a "test" was planned to evaluate the user's familiarity with the controls. However, due to time limitations, it was decided instead to rely on the user's self-assessment to determine when they feel ready to start the task or if additional time for familiarisation is needed.

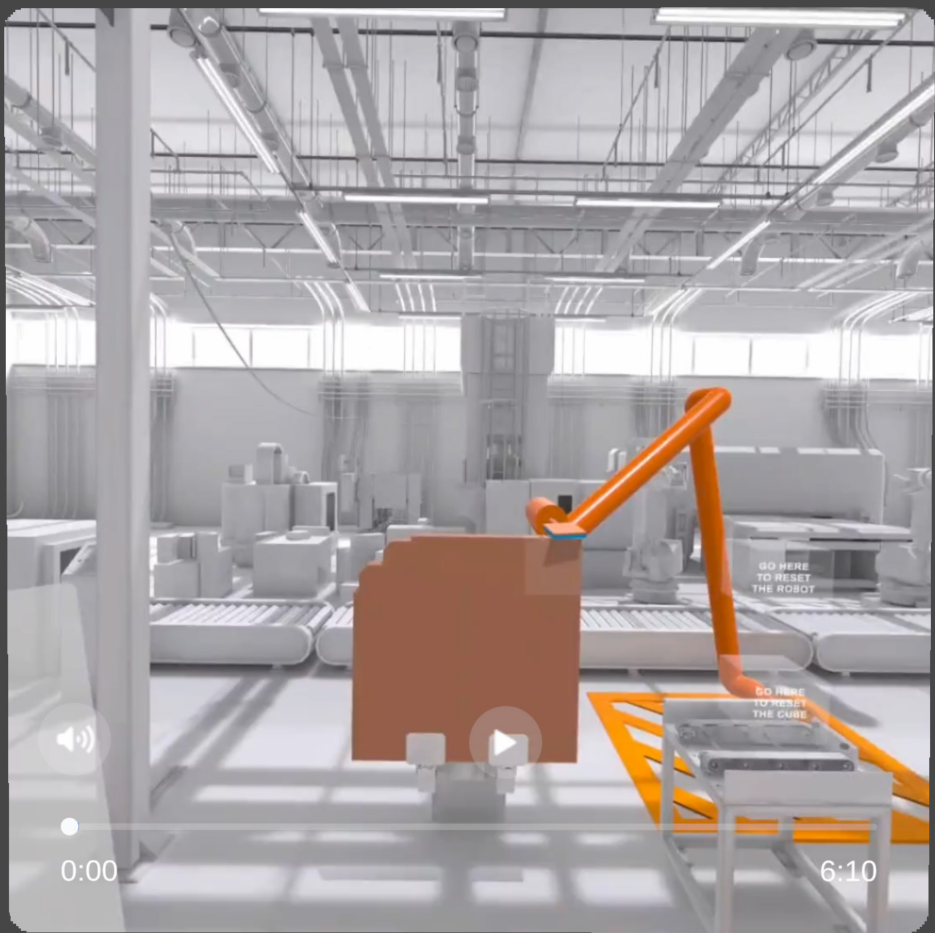


FIG. 24 - VIDEO TUTORIAL

Video tutorial link: https://youtu.be/oFNXak_k-fQ

SCENARIOS

An important environmental factor that can shape the user experience is the level of pressure applied during the task. In a high-pressure environment, users may find a control system with higher constraints easier and faster, making it appear better suited to the situation. Conversely, in a more relaxed environment, a freer, more exploratory approach to crafting may feel preferable. Recognizing these potential differences, it was initially decided to explore both scenarios:

- Explorative Scenario: With no time constraints, the user receives the task assignment and is free to choose their preferred approach to achieve the desired result.
- High-Pressure Scenario: Time constraints are imposed, requiring the user to complete the task within a specified timeframe, and their result is evaluated accordingly.

The test was initially designed to allow users to experience both types of contexts, assessing how the controls would feel in each. However, the pilot test revealed that each phase within a single context already took between 30 to 50 minutes. Repeating the entire test twice would have extended the duration significantly, reducing the number of available participants. Additionally, task completion times varied widely among users; some could perform the task quickly, while others required more time. This variation wasn't solely due to attention to detail but also differences in users' ability to control the robot, meaning that a fixed time constraint might be too long for some and too short for others.
Ultimately, it was decided to focus only on the context without time constraints, as it provided a better opportunity to explore the crafting experience. A time-constrained context, given the limited learning time, would likely emphasise task execution over experience. Although this might align better with a professional environment, it doesn't fully address the crafting experience, which is central to this project.

DIFFERENT TASKS

The task chosen to evaluate the crafting experience is a grinding task; however, even within grinding, the movements to do vary depending on the desired outcome. With the addition of constraints, it became apparent that the effectiveness of these constraints—and thus the experience of using them—depends on the type of movement needed to shape each corner.
This means that users might experience the controls differently based on the specific movements required. Crafting one corner shape may feel different than shaping another. Currently, the task involves a wooden panel with a right-angle corner on one side and a filleted corner on the opposite side, with the goal of grinding the right-angle corner to match the filleted shape.
To make the balance between constraints and freedom less task-specific, multiple tasks were created to better evaluate how constraints impact user experience across various shapes. Four different types of corners have been developed:

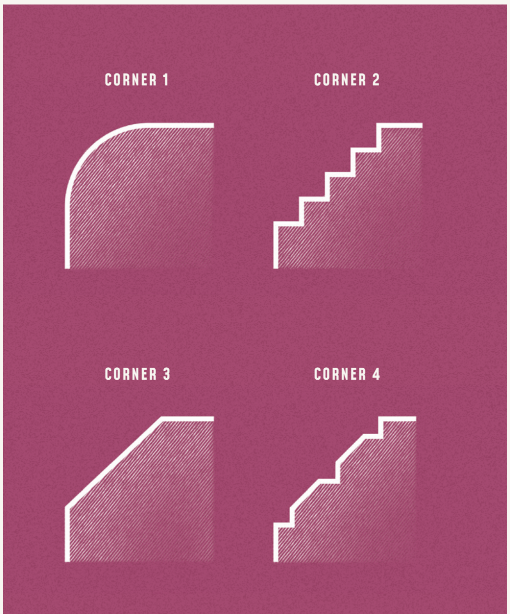


FIG. 25 - CORNER TYPES

ORDER BALANCING

In the test, results can be influenced by the order in which constraint types are presented. Given the short familiarisation period, users continue to grow more comfortable with the controls even during task execution, meaning that the initial task may feel more challenging than later ones. Similarly, tasks might seem more engaging at first but could become repetitive and less exciting over time, potentially making the final task feel different from the first.

To account for these effects, the three types of constraints (presented consecutively) must be presented in varying orders an equal number of times, so that order does not impact the overall results when all participants are considered. A counterbalanced design is used to achieve this. This method ensures that each constraint type appears in every position (first, second, third) equally across all participants, eliminating potential order effects.

With three constraint types—No Constraints (A), Low Constraints (B), and High Constraints (C)—there are 3! = 6 possible unique sequences:

- A, B, C
- A, C, B
- B, A, C
- B, C, A
- C, A, B
- C, B, A

These sequences will be repeated until the required sample size is reached.

Similarly, the order of corner types can also influence results, as one corner may feel easier to shape with a specific control type compared to others. Therefore, each corner type must be paired with each control type an equal number of times to prevent this variable from biassing the results.

SAMPLE SIZE

To calculate the necessary sample size for this test, the software G*Power (Faul et al., 2007) was used. Since the anticipated differences in user experience across control systems are expected to be of medium to large effect, an effect size *f* of 0.3 was chosen. This value allows for the identification of moderate differences while keeping the required number of participants manageable.

F tests – ANOVA: Repeated measures, within factors
Analysis: A priori: Compute required sample size

Input:
Effect size fff = 0.3
This represents the estimated strength of the relationship or difference being tested, with a medium effect size indicating a moderate expected difference between the prototype variants.

α err prob = 0.05
This is the threshold for statistical significance, meaning there is a 5% chance of falsely rejecting the null hypothesis (Type I error).

Power (1 - β err prob) = 0.80
This indicates an 80% likelihood of correctly rejecting the null hypothesis when an effect exists (avoiding Type II error).

Number of groups = 1
This reflects that all participants are part of a single group, each exposed to all three prototype variants.

Number of measurements = 3
The number of conditions or prototype variants being compared during the test.

Corr among rep measures = 0.5
This estimates the average correlation between measurements from the same participant across the three conditions.

Nonsphericity correction ϵ = 1
This value assumes sphericity, meaning variances of the differences between conditions are equal.

Output:
Noncentrality parameter λ = 10.8
This is a derived value used to determine the statistical power of the test under the given conditions.

Critical F = 3.2448184
The cutoff value for the F statistic; a result above this value would indicate a statistically significant effect.

Numerator df = 2.0
This represents the number of conditions minus one, used in the calculation of the F statistic.

Denominator df = 38.0
This reflects the sample size and number of measurements, accounting for within-participant variability.

Total sample size = 20
The minimum number of participants required to achieve the desired statistical power and significance level.

Actual power = 0.8141908
The achieved power of the test, confirming it exceeds the threshold of 0.80, ensuring sufficient sensitivity to detect the expected effect.

THE QUESTIONS OF THE TEST

The test, as mentioned, aims to understand how constraints impact both user experience and performance. Since the crafting experience is defined by values identified earlier in this study, a series of questions have been developed based on these values. The focus areas for experience include:

Positive Triggers

Sensory Delight: Although sensory substitution techniques to replace tactile feedback could be considered, they do not vary between prototypes, making comparison irrelevant; hence, no questions are included for this area.

Engagement (Flow State):
- Was the user engaged or bored?
- Did the user find the task too hard or too easy?

Acknowledgement of Success (Pride and Accomplishment):
- Did task progression lead to satisfaction or disappointment?
- Did the user feel proud upon achieving the result?

Serenity (Relaxation):
- Was the user able to feel relaxed during the interaction?

Negative Triggers

Physical Discomfort:
- Did the user experience physical discomfort (e.g., in the wrist or shoulder)?

Mistake Making:
- Did the user feel confident in controlling the tool as though it were in their hand?
- Did the user feel negatively (e.g., confused, doubtful) or positively (e.g., confident, optimistic) during the interaction?

Annoyance:
- Did the user feel annoyed due to slowness or imprecision of the controls?

In addition to questions about the crafting experience, it is also useful to assess the control system's effectiveness. To capture this, the questionnaire includes a question regarding the quality of the task's outcome:

Performance

- Accuracy: How closely does the user's shaped corner match the target shape?

Finally, a few general questions are included to provide a direct comparison of the different constraint options, allowing for broader feedback on user preferences beyond specific values:

General Feedback

- Enjoyment: How enjoyable did the user find each control system?
- Preference: Which control system did the user prefer?

THE QUESTIONNAIRE

Using these points, a series of questions and a questionnaire is formulated. The questionnaire can be found a the following link: https://60zaikpvx95.typeform.com/to/A98eWppI

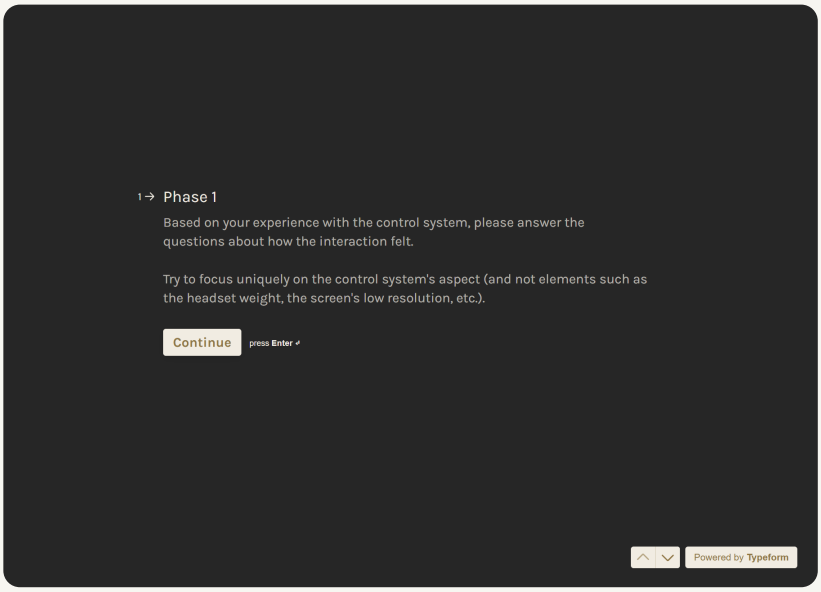


FIG. 26 - QUESTIONNAIRE

FINAL STRUCTURE

- Learning Phase
  - Tutorial
  - Familiarisation
- Test Phase
  - Perform task with Corner Type X using Control Type X
  - Evaluate final result
  - Remove headset and fill out questionnaire regarding the control type just used
  - Repeat for each remaining control type
- Final Questionnaire
  - Complete general questions in the final section of the questionnaire

SECTION 5.3

RESULTS

The test involved 13 participants, randomly recruited at the university library. The group included individuals with varying levels of familiarity with VR, ranging from those with prior experience to those without, as well as participants with differing interests and skills in crafting activities. The results for each question were averaged across all participants, and an ANOVA test was conducted to ensure the findings were not due to random variance.
The ANOVA test (Analysis of Variance) is a statistical method used to check if the differences between the means of three or more groups are significant or just random. It does this by comparing the variance within each group to the variance between the groups. A larger variance between groups compared to within groups suggests that the differences are unlikely to be random. The test calculates an F-ratio, which is compared to a critical value at a significance level of $p < 0.05$. If the F-ratio exceeds this value, the null hypothesis—stating that all group means are equal—is rejected.
The analysis revealed significant differences in the experiences provided by the three prototypes for certain characteristics, while other aspects did not show statistically significant variations.
The questions were grouped into categories aligned with the key requirements for achieving the desired crafting experience. These categories included engagement, pride and satisfaction, usability, relaxation, and others, complemented by additional questions offering a broader view of user experience and preferences. Each category is analysed in detail in the subsequent sections.

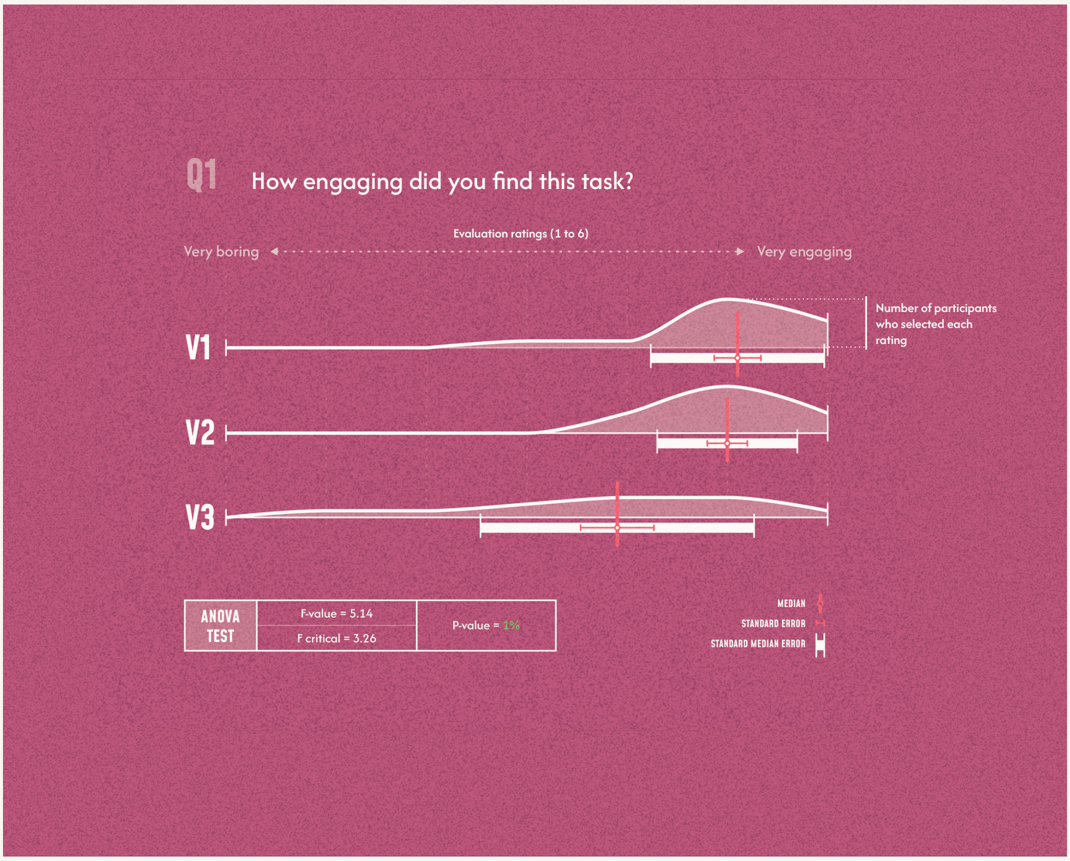
CATEGORY OF QUESTIONS

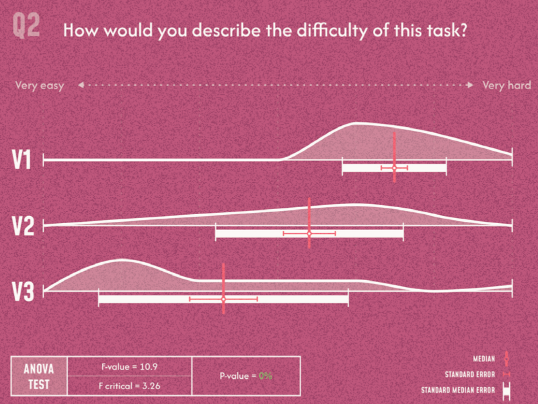
Flow experience	State of mind	Ergonomy	General	Perfromance	Succsess and pride
Q1	Q3	Q11	Q5	Q13	Q7
Q2			Q12		Q8
Q4			Q14		Q9
Q6					Q10
					Q15

THE FLOW EXPERIENCE

For Question 1, the average engagement ratings were 5.1 for the no-constraints prototype, 5.0 for the low-constraints prototype, and 3.9 for the high-constraints prototype. An ANOVA test confirmed a significant difference among these results, with a p-value of 0.01. The data indicate that participants perceived engagement levels as similar between the no-constraints (V1) and low-constraints (V2) prototypes, whereas the high-constraints (V3) prototype resulted in a noticeable reduction in engagement.

This suggests that the high-constraints prototype includes features that do not align with the engagement requirements, as anticipated. Conversely, the low-constraints prototype, despite imposing some limitations, appears to maintain a positive experience, demonstrating that its constraints are compatible with the crafting experience's engagement goals. Further insights into this difference are provided by the analysis of the next questions.





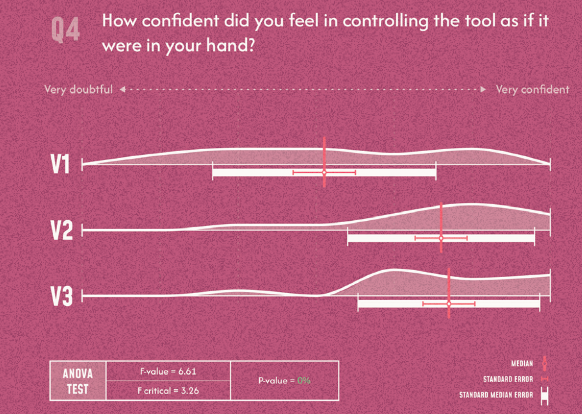
For Question 2, the average difficulty ratings were 4.5 for the no-constraints prototype, 3.4 for the low-constraints prototype, and 2.3 for the high-constraints prototype. The ANOVA test confirmed a significant difference, with a p-value of 0.0002. These results highlight a clear trend: participants perceived the task as progressively easier with increased constraints. While the no-constraints prototype was considered relatively difficult, the high-constraints prototype was rated as much easier.

This reduction in difficulty does not directly explain the decrease in engagement observed in the high-constraints prototype, as the difference in difficulty between the no-constraints and low-constraints prototypes did not result in a corresponding difference in engagement. This suggests that as long as the task difficulty remains within an acceptable range, engagement is maintained, with variations in difficulty causing minimal changes to engagement levels. However, when the task becomes too easy, as in the case of the high-constraints prototype, it falls outside this range, leading to a loss of engagement.

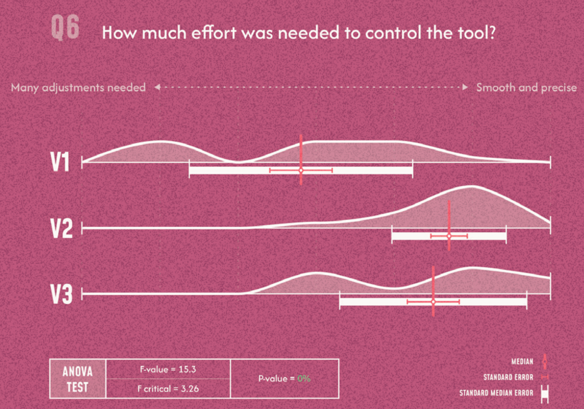
The opposite happens for the no-constraints prototype, rated as the most difficult, but still achieved the highest engagement scores. This indicates that high difficulty can remain engaging even when perceived as challenging but within an acceptable range, and no constraints fall within this range. Notably, participants who found the no-constraints task very difficult and performed poorly still rated engagement positively. In contrast, participants who encountered no challenges with the high-constraints prototype rated its engagement very low.

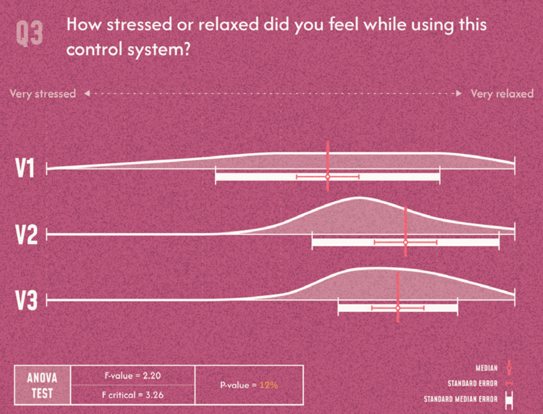
These outcomes could be interpreted in two ways: (1) difficulty perceived as “hard” may remain engaging if it stays within an acceptable range, whereas “easy” tasks risk falling outside the range necessary for engagement; or (2) task difficulty has a greater negative impact when it is too low rather than too high, explaining why overly easy tasks were rated lower in engagement, while challenging tasks were still seen positively.

For Question 4, the average confidence in tool manipulation was rated as 3.1 for the no-constraints prototype, 4.6 for the low-constraints prototype, and 4.7 for the high-constraints prototype. The ANOVA test confirmed a significant difference, with a p-value of 0.003. These results suggest that both the low- and high-constraints prototypes allow users to feel confident and experience an effortless input during tool manipulation. The minimal difference between these two prototypes indicates that the improvements implemented in the low-constraints version are sufficient to ease the control system to a level where users feel in control. The additional constraints applied in the high-constraints prototype do not appear to significantly enhance this sense of control. This finding highlights that the low-constraints prototype strikes a balance between task demands and user skills, providing effective support without over-constraining the user. In contrast, the no-constraints prototype was rated lower in perceived control, demonstrating that the introduction of constraints played a crucial role in improving the control system. Further insights into these dynamics are explored in the subsequent question.



For Question 6, the average effort required to control the system was rated as 2.5 for the no-constraints prototype, 4.6 for both the low-constraints and high-constraints prototypes. The ANOVA test confirmed a significant difference, with a p-value of 0.00015. This question, closely related to the previous one, focuses specifically on the effort involved in controlling the system, which directly impacts the user's confidence in their ability to manipulate the tool. The results follow a similar pattern: the no-constraints prototype received a lower evaluation, while the low- and high-constraints prototypes were rated equally well.
The no-constraints prototype was perceived as requiring significantly more effort, reflecting the difficulty participants experienced in controlling the system. Showing that the lack of constraints negatively impacted users' confidence.
For the low- and high-constraints prototypes, the results reaffirm that the features introduced in the low-constraints version effectively reduce the effort





required to control the system. This makes the additional constraints in the high-constraints prototype unnecessary, as they do not provide further improvements in perceived effort. Together, these findings suggest that the low-constraints prototype successfully strikes a balance between support and freedom, enabling users to achieve a high level of control without undue effort.

The results indicate that both the no-constraints and low-constraints prototypes are engaging, while the high-constraints prototype is less so. However, the no-constraints version requires significant effort and leaves users feeling less confident in control, whereas the low-constraints version achieves engagement with effortless manipulation. In contrast, the high-constraints version, despite requiring little effort, lacks engagement. This highlights that the low-constraints prototype strikes the best balance between task difficulty and user skills, improving control without compromising engagement.

THE FEELING OF RELAXATION AND SERENITY

The results for Question 3 show average ratings of 3.6 for the no-constraints prototype, 4.2 for the low-constraints prototype, and 4.5 for the high-constraints prototype. However, the ANOVA test did not indicate a significant difference, with a p-value of 0.12, suggesting a 12% probability that these results occurred by random chance. While the averages suggest a potential trend of increased relaxation with more constraints, this pattern is not statistically supported.

The data imply that the no-constraints prototype, requiring greater effort and being harder to control, may hinder relaxation. In contrast, the low-constraints prototype appears to support a more relaxed state, with the high-constraints prototype showing a slightly higher average. However, the minimal difference between the low and high constraints could be coincidental, given the high p-value.

These findings suggest that constraints may help users achieve a more relaxed state, improving the experience in this regard, but the lack of significant differences between prototypes means further testing is needed to confirm this insight.

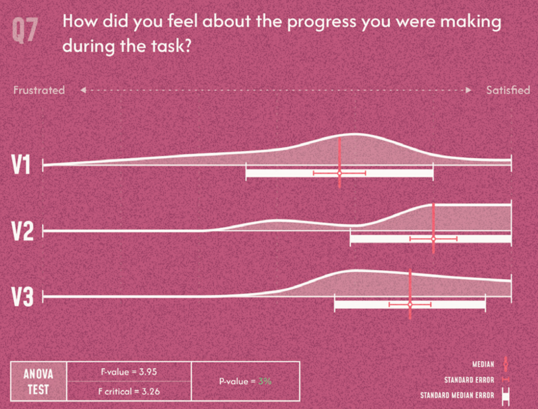
THE ACKNOWLEDGMENT OF SUCCESS – PRIDE

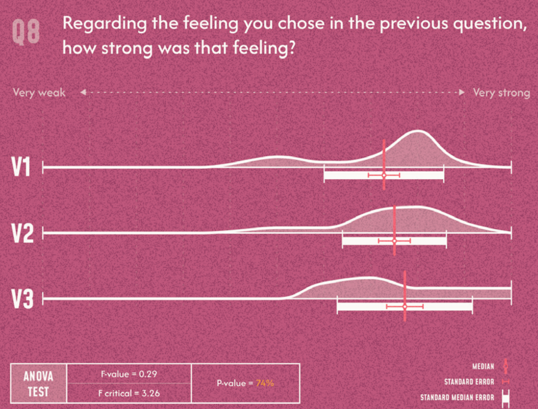
For Question 7, participants evaluated their feelings about task progress, with the no-constraints prototype scoring 3.8, the low-constraints prototype 5.0, and the high-constraints prototype 4.7. These results indicate that the no-constraints prototype led to a mixed experience, with participants expressing both frustration and satisfaction due to the challenging controls. The low-constraints prototype achieved the highest satisfaction, showing that it provided a balanced experience that minimised frustration while maintaining user control. The high-constraints prototype scored slightly lower than the low-constraints version, suggesting that additional constraints did not significantly enhance the user experience.

For Question 8, which assessed the intensity of the feelings from Question 7, the scores were 7.3 for the no-constraints prototype, 7.5 for the low-constraints prototype, and 7.7 for the high-constraints prototype. Despite these variations, the ANOVA test showed no significant differences (p-value = 0.74), indicating that the intensity of emotions was consistent across all prototypes.

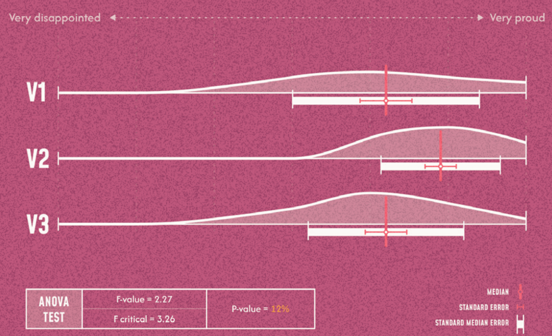
The expectation was that fewer constraints would result in lower evaluations for Question 7 due to the frustration caused by difficult controls, balanced by higher intensity ratings in Question 8, as greater autonomy should lead to more pride in the results. The results confirm that the no-constraints prototype provided a mixed emotional experience, combining both negative and positive feelings. The low-constraints prototype outperformed the high-constraints version, reinforcing that the additional constraints in the high-constraints prototype did not provide a better control experience than the low-constraints version. However, Question 8 revealed no significant differences in the intensity of emotions across prototypes, with similar ratings from no constraints to high constraints.

This indicates that the progression of the task did not affect the intensity of pride and satisfaction based on the constraints applied. The higher autonomy and effort required for the no-constraints prototype did not lead to higher intensity ratings.





Q9 How proud did you feel about what you achieved?



Q10 Regarding the feeling you chose in the previous question, how strong was that feeling?

It is not possible to determine the specific reason, but it is possible that the differences in emotional intensity were too subtle to be detected.
Otherwise, considering that the high-constraints prototype appears to provide sufficient autonomy to achieve similar levels of pride and satisfaction as the low-constraints version, there could be a threshold where the autonomy that once surpassed these feelings are ensured to equal amounts.
Another possibility is that the mixed emotions experienced with the no-constraints prototype led participants to "average out" their feelings, resulting in a lower evaluation of intensity. While the exact reason for the similar intensity across prototypes cannot be determined from these results, it is clear that the constrained versions achieved an equally intense emotional experience as the no-constraints version, but with a more positive balance.

For Question 9, which focuses on pride and satisfaction with the final outcome, the results were 4.2 for both the no-constraints and high-constraints prototypes, and 4.9 for the low-constraints prototype. The ANOVA test showed no significant difference, with a p-value of 0.12. Similarly, for Question 10, which evaluates the intensity of these feelings, the results were 7.0 for the no-constraints prototype, 7.1 for the low-constraints prototype, and 6.2 for the high-constraints prototype, with no significant difference and a p-value of 0.34.
Unlike previous questions focusing on task progression, these questions address the user experience after achieving the final outcome. While the results lack statistical significance, a pattern emerges. During task progression (Q7), the no-constraints prototype received lower ratings due to frustration. However, in Q9, the satisfaction and pride in the final outcome were rated equally for the no-constraints and high-constraints prototypes, despite the no-constraints prototype's lower performance evaluation. This suggests that users may feel more pride in outcomes achieved with greater autonomy (no constraints), even when performance is poorer, while the lack of autonomy in the high-constraints prototype reduces pride, balancing the ratings between the two. The low-constraints prototype re-

ceived the highest ratings, likely reflecting a balance of autonomy and performance that led to pride in the outcome and satisfaction with the process.
For Question 10, while the high p-value suggests limited differences in the intensity of pride and satisfaction, the high-constraints prototype reported the lowest intensity, aligning with findings in the literature that less autonomy results in diminished pride and satisfaction. This pattern, though not statistically significant, highlights a potential relationship between autonomy and emotional intensity, requiring further study to confirm.

Question 15 asked participants to compare the three control systems directly and select the one that provided the most satisfying experience. To analyze these rankings, a pairwise comparison method was used. In this approach, each prototype was compared against the others in all possible pairs to determine which one was preferred more frequently. Each "win" represented a scenario where one prototype was ranked higher than another in a direct comparison. The analysis revealed a clear preference for the "Low Constraints" prototype, which received 22 wins across all comparisons, consistently ranking higher than both the "No Constraints" and "High Constraints" prototypes. The "No Constraints" prototype ranked second, with 9 wins, indicating moderate satisfaction, while the "High Constraints" prototype ranked lowest, with only 8 wins, suggesting it was the least preferred. These results strongly highlight the "Low Constraints" condition as the most satisfying, reinforcing its effectiveness in balancing autonomy and control to provide an optimal user experience.

NO CONSTRAINTS PREFERRED OVER		LOW CONSTRAINTS PREFERRED OVER		HIGH CONSTRAINTS PREFERRED OVER	
LOW CONSTRAINTS	HIGH CONSTRAINTS	NO CONSTRAINTS	HIGH CONSTRAINTS	NO CONSTRAINTS	LOW CONSTRAINTS
	X	X	X		
		X	X	X	
		X	X	X	
	X	X	X		
		X		X	X
		X		X	X
		X		X	X
	X	X	X		
X	X		X		
	X	X	X		
	X	X	X		
	X	X	X		
	X	X	X		

Each row represents an individual participant's preference. The three main columns represents different constraints being evaluated, each of them has subcolumns showing which constraint each is being compared against. An 'X' indicates that the participant preferred the constraint in the main column over the one in the subcolumn.

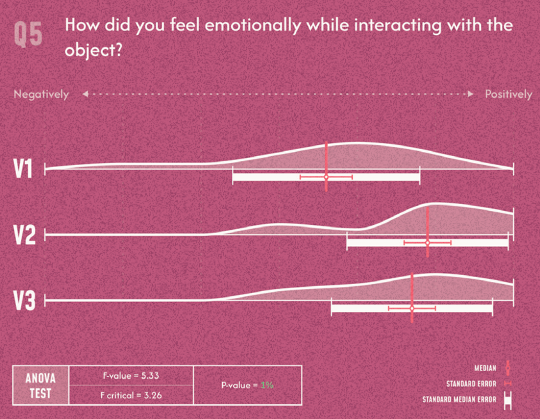
THE ERGONOMY - COMFORTABILITY

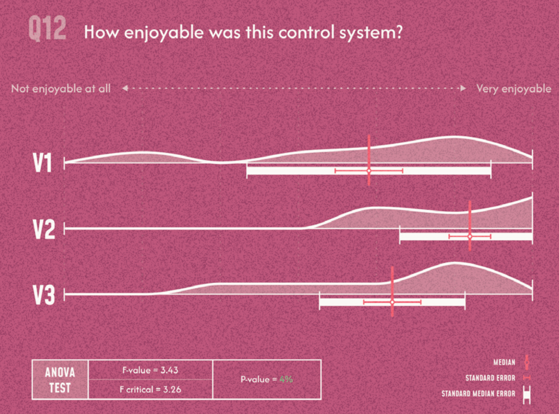
For Question 11, the comfort ratings were 3.8 for the no-constraints prototype and 4.9 for both the low-constraints and high-constraints prototypes. The ANOVA test revealed a significant difference, with a p-value of 0.042. These results indicate that the no-constraints prototype was perceived as relatively uncomfortable, while both constrained prototypes demonstrated a notable improvement in comfort, achieving equally positive evaluations.
This outcome aligns with expectations, as the ergonomic issue of excessive ulnar-radial rotation was addressed in the constrained versions. The reduction of this rotation successfully resolved the discomfort, elevating the ergonomic evaluation from mediocre to significantly more positive in the constrained prototypes.

GENERAL PREFERENCES

For these questions, which assess the general perception of the control systems, the results highlight clear patterns.
For Question 5, regarding the emotional state during interaction, the ratings were 3.6 for the no-constraint prototype, 4.9 for the low-constraint prototype, and 4.7 for the high-constraint prototype, with a significant difference (p-value = 0.01). Similarly, for Question 12, concerning how enjoyable the control system was, the ratings were 3.9 for the no-constraint prototype, 5.2 for the low-constraint prototype, and 4.2 for the high-constraint prototype, with a significant difference (p-value = 0.04). The last question, Question 14, directly asked participants to choose their preferred control system, providing a clear comparison of the options.
Results from Q5 and 12 show a similar pattern, with the no-constraint prototype evaluated as the lowest, followed by the high-constraint prototype, and the low-constraint prototype rated as the best option among them.
For Question 5, the difference between the high-constraint and low-constraint prototypes was smaller, while the no-constraint prototype received significantly lower evaluations. This indicates that the interaction with the no-constraint prototype elicited negative emotions that affected the experience. Both constrained prototypes successfully addressed these issues, successfully adding constraints that did not emerge as a strong limitation that made users feel frustrated or overly restricted (and ruining the experience), achieving a significantly better result than the no-constraint prototype.

For Question 12, the no-constraint prototype was also evaluated as the least enjoyable option, followed by the high-constraint prototype, and finally the low-constraint prototype as the most preferred. As expected, the multiple issues, such as higher effort, poorer outcomes, and lower control, in the no-constraint prototype experience made it the least enjoyable.
Interestingly, the difference between the low-constraint and high-constraint prototypes is particular-





ly notable. It is possible that the factors contributing to the low-constraint prototype's success—such as improved control, reduced effort, and better performance—accumulated in this more general evaluation, making the result more pronounced.
Although the high-constraint prototype provided a better emotional experience than the no-constraint prototype by reducing negative feelings, it still fell short of the enjoyment provided by the low-constraint prototype. The high-constraint prototype's more restrictive nature likely prevented it from being perceived as highly enjoyable, unlike the low-constraint prototype, which was consistently regarded as very enjoyable.
In summary, the no-constraint prototype performed poorly in both emotional impact and enjoyment. The high-constraint prototype improved the emotional experience compared to the no-constraint prototype but failed to deliver the same level of enjoyment as the low-constraint prototype, which provided the most positive and satisfying overall interaction.

These results become even more evident in Question 14, where a pairwise comparison analysis was conducted to evaluate participants' preferences for the type of constraints. The analysis shows that the low-constraint prototype was the clear favourite, with 13 wins against the no-constraint prototype and 9 wins against the high-constraint prototype. The no-constraint prototype demonstrated moderate preference, achieving 10 wins against the high-constraint prototype but none against the low-constraint prototype. The high-constraint prototype was the least preferred option, securing only 3 wins against the no-constraint prototype and 2 wins against the low-constraint prototype. These findings strongly highlight the low-constraint prototype as the most favourable condition.

NO CONSTRAINTS PREFERRED OVER	
LOW CONSTRAINTS	HIGH CONSTRAINTS
	×
	×
	×
	×
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	×
	×
	×
	×
	×

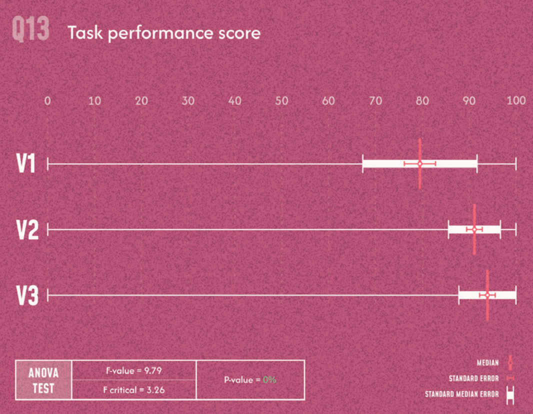
LOW CONSTRAINTS PREFERRED OVER	
NO CONSTRAINTS	HIGH CONSTRAINTS
×	×
×	×
×	×
×	×
×	×
×	
×	
×	×
×	×
×	×
×	×
×	×
×	×

HIGH CONSTRAINTS PREFERRED OVER	
NO CONSTRAINTS	LOW CONSTRAINTS
×	
×	×
×	×

PERFORMANCE

Performance is a crucial consideration for evaluating the viability of the control system, even though it is not directly part of the user experience. Question 13 was used to assess performance by analyzing how well the object created during the task matched the desired shape, as evaluated by the program. The results revealed a significant difference, with a p-value of 0.0004.

The no-constraint prototype demonstrated mediocre performance, achieving an average score of 79 out of 100, which is likely unacceptable and potentially dissatisfying for craft makers in a professional setting. In contrast, the low-constraint prototype scored an average of 91, and the high-constraint prototype achieved a slightly higher average of 94. While both constrained prototypes delivered good performance, the improvement seen in the high-constraint prototype compared to the low-constraint prototype was relatively small. This raises a key consideration: while the additional constraints in the high-constraint prototype improved performance slightly, this marginal gain comes at the cost of a noticeable decrease in user experience. This trade-off calls into question whether the small performance benefit is worth the corresponding reduction in enjoyment and engagement.



CHAPTER 6
CONCLUSIONS

SECTION 6.1

CONCLUSIONS AND DISCUSSION

INTRODUCTION TO THE CONCLUSION - SUMMARY OF THE PROCESS

This thesis aimed to explore how Mixed Reality can be used to integrate robots into task execution while preserving the positive aspects of user experience in crafting. The central research question guiding this investigation was:

"How can a Mixed Reality system be utilised to maintain the positive aspects of the user experience during Human-Robot Interaction in crafting tasks?"

This project specifically focused on the scenario where robots are controlled directly by the user rather than functioning as autonomous collaborators. The objective was to investigate whether and how MR could mitigate the experiential losses associated with automation by allowing the user to remain actively involved in the task execution.

MR was chosen as the core enabling technology because of its potential to provide immersive, interactive environments that allow users to engage with virtual task-related elements, maintaining their role in the process and avoiding the detachment caused by full automation.

To ground this exploration, crafting was selected as a representative task due to its rich sensory, cognitive, and emotional qualities. By investigating this context, the project sought to understand the implications of robotic integration on task experience and identify methods to preserve the essence of craftsmanship in Human-Robot Interaction.

Craftsmanship, a deeply human and rewarding process, derives its positive experience from various sensory, cognitive, and emotional qualities. As robotic automation increasingly enters crafting workflows, it risks decreasing these qualities.

The literature identifies the following characteristics as essential to maintaining a positive craftsmanship experience during HRI:

Engagement: flow state, involvement and immersion in the task creates an activity engaging to the user.

Sense of Satisfaction and Pride: Crafting provides a tangible sense of accomplishment. The ability to directly shape materials and witness the outcomes of one's effort is integral to fostering pride of self.

Relaxation and Serenity: Many crafting tasks are associated with a meditative state, where repetitive motions and focus on materials bring a sense of calm and stress relief.

Sensory Pleasure: the multisensory bodily experience elicits positive emotions.

Self-Expression: Craft makers express personal narratives and cultural identities, making craft a powerful form of self-expression.

Exploration: Discovering a new way of interacting with a material brings a sense of pleasant surprise.

To retain these qualities in HRI, literature and user tests outlined specific requirements that must be met:

- Self-set goals
- Goals need to be accomplished
- Tangible results
- Balance between task demands and user skills
- Users feel in control
- Effortless inputs
- Clear objectives
- Immediate feedback
- Multisensory perception
- Unconstrained control

TECHNICAL LIMITATIONS

An interaction that allows full autonomy from the user, that uses mixed reality to enable co-located teleoperation of a robotic arm to perform a crafting task is designed and tested.
While the study provided valuable insights, several technical limitations influenced the results and should be considered when interpreting the findings.

Quality of VR Simulation
The VR simulation had to be optimised for performance, which compromised the visual quality of the grinding interaction. The use of voxel-based cubes to simulate material grinding resulted in a pixelated appearance and unrealistic tool behaviour. Additionally, the manually constructed physics caused interactions to feel unnatural, negatively affecting the overall user experience.

Robot Simulation Quality
The robotic arm used in the simulation was not modelled after a real robot, leading to differences in movement and behaviour from a real scenario. This lack of realism may have influenced how users interacted with the system and affected the overall accuracy of the test results.

Limitations in User Testing
Feedback from user tests was often superficial due to time constraints and participants' limited experience with crafting tasks, particularly for those unfamiliar with such activities. Additionally, the learning curve for the control system varied across participants, while limitations in the VR simulation—such as hand-tracking errors and unrealistic physics—further hindered their ability to provide meaningful feedback.

Limited Experience with the Control System
Participants had limited time to familiarise themselves with the interaction system. Given the complexity of the new control system, it likely requires a longer learning period to achieve proficiency. One of the primary challenges observed was the participants' ability to effectively control the robotic arm. It is reasonable to assume that with extended training, their control performance could have improved significantly beyond the levels demonstrated during the tests.

FIRST FINDINGS - MR INTERACTION IN THE TASK

The results indicated that this interaction system was largely unusable in terms of usability, which directly impacted the user's ability to achieve their goals. This, in turn, affected the sense of satisfaction and pride—key positive aspects of the crafting experience. Despite iterative improvements, the usability issues could not be resolved sufficiently.
This leads to the first conclusion: the interaction system designed cannot provide a level of control over manipulation that allows users to maintain the positive aspects of crafting experiences.

Key Problems Identified

- Unnatural Manipulation: Controlling position and force lacked the intuitive feel of natural interactions.
- Insufficient Feedback: Reduced feedback made task progression more difficult compared to traditional interactions.

These resulted in:

- Low control over manipulation
- Frequent mistakes due to missing feedback
- A diminished sensory experience

Which, overall, made the system to be perceived as:

- Frustrating
- Unusable to achieve user's goals

While the lack of time for participants to learn and train with the system may have contributed to these results, however, even with training, the control achievable with this interaction is limited due to the severe lack of feedback. This lack of feedback imposes a cap on how much control can realistically be achieved, even with training. Determining this cap would require further testing with trained participants.

Addressing the Issue with Automation

To improve usability, it was necessary to introduce automation into the interaction control system. Automation may address some of the usability challenges by simplifying certain tasks and making the interaction more manageable. However this introduction reduces user autonomy, which, from the literature, can negatively compromise the experience. Therefore, it is crucial to find the optimal balance between user autonomy and robotic automation. To investigate this, tests were conducted with three versions of the system, each implementing different levels of automation. These tests aimed to identify the optimal balance where usability is improved without sacrificing the user's sense of control and the positive aspects of the crafting experience.

SECOND FINDINGS - AUTOMATIONS

The interaction that offer the better crafting experience

Results show that the implementation of the low constraints version successfully improved usability, allowing users to have an experience that more closely matches with the positive crafting experience.
The low constraints version proposed an interaction usability improvements significantly enhanced the user's enjoyment by making the interaction smoother and more intuitive, where users' skills aligned with the task's challenges, allowing the user to direct its efforts toward interacting with the object rather than avoiding mistakes. This increased sense of control and performance led to better accomplishment, increased sense of satisfaction and pride, creating an overall more enjoyable experience.
These results demonstrate that the variant with the best balance is the low constraints version, which

aims to maintain the user in control over the movement responsible for the outcome result, while limiting the interaction's difficulty by reducing degrees of freedom that were not essential for task execution. Higher ratings were observed across all emotional characteristics important to the crafting experience, such as engagement, satisfaction, pride, and serenity. Instead, the version with stronger automation from the robot resulted in a less interesting interaction, as it reduced the user's involvement in the task execution. Conversely, the variant with no constraints at all, as found in previous tests, was not usable enough to provide a satisfying interaction.

How to balance user Control and Automation

These results suggest that the best approach to integrating robotics while maintaining the experience of the task is to identify the optimal balance where users retain control over few key aspects of the interaction.

On one hand, achieving a crafting experience in a vision-based co-located teleoperation system by attempting to replicate the original interaction—where the user manipulates materials directly with their own hands—presents significant technical challenges. The limited feedback available in the system fails to enable natural interactions, necessitating the creation of a control system, which however is bound to fall short of replicating the intuitive qualities of natural controls, such as human hand movements, leading to a system that feels too complex to control efficiently. On the other end, if users are confined to controlling a single element or interacting with overly simplified components, the task becomes less engaging and less fulfilling.

Control does not need to replicate the original interaction without robotics, but should still require skills and focus from the user to ensure the results remain rewarding. The recommended approach is to determine which elements (the few key aspects of the interaction) the user can control effectively and effortlessly while still achieving good results.

Different effort, different emotions

This results shows how important is to distinguish the type of effort that the user spend in the interaction:

- Effort in Control Mechanics (Negative Experience)
  If a significant amount of effort is spent just trying to operate or control, users often feel frustrated. This happens because the interaction mechanism becomes an obstacle rather than an enabler. Users want their inputs to feel natural and intuitive so that they can focus on achieving their goal, not on fighting the controls.

- Effort in Task outcomes (Positive Experience)
  When users can intuitively control the mechanics (e.g., effortless manipulation), they can channel their effort into engaging with the challenge of the task itself. This type of effort allows users to focus on strategy, creativity, or skill-building, leading to flow-like states where the challenge matches their abilities.

Mixed Reality Compatibility

Regarding the use of Mixed Reality, the results from the constrained version showed that it is possible to achieve decent performance, but only for simple, large shapes without intricate details. Even with the introduction of automation, the interaction lacked the precision required for detailed tasks. The primary cause of this imprecision is likely to be the absence of force and haptic feedback. Force feedback helps users regulate their actions, and haptic feedback provides critical cues about the state of the task. Without this feedback, users were forced to rely heavily on visual information, which proved insufficient for achieving the level of precision needed for detailed crafting tasks. This limitation significantly impacted both task performance and the overall user experience. This issue is particularly inherent in co-located teleoperation tasks. Although users maintain a direct line of sight to the object, the physical detachment reduces visual depth and completely eliminates haptic feedback. Additionally, perspective-related issues further increased the likelihood of mistakes.

While functional for basic object manipulation, the interaction system would be suboptimal for real-world crafting tasks where accurate work is essential due to the low level of detail achievable. Co-located teleoperation using MR could only be effective for tasks that do not require high precision or involve small details. For tasks that require precision it might be appropriate to have full teleoperation tasks, where the user wears a VR headset and controls the robot via a camera system placed near the object.

Beyond its limitations for detailed work, MR faces challenges also in substituting the lost sensory feedback. Relying solely on a visual overlay is problematic because the amount of information the user can process at once is limited and must not obstruct critical elements of the environment.

Feedback is essential both for maintaining the interaction loop, necessary to progress in the task, as well as for creating a sensory experience that fosters positive emotional values. Replacing these feedback mechanisms becomes more challenging as the complexity of manipulation increases, as the risk of overcrowding the view with digital overlay gets higher.

When attempting to replicate a traditional hands-on interaction, it becomes necessary to substitute many of the feedback mechanisms typically present. This requires numerous additional digital overlay elements, which strain the user's limited processing capacity and overcrowd the digital space. As a result, it becomes impractical to implement additional feedback aimed at enhancing the overall experience. This suggests, once again, that the control system should remain simple, minimising the need to substitute too much feedback. Such an approach could ultimately contribute to a better overall user experience, as it would preserve space for hedonic elements.

PROTOTYPE CONSTRAINT VERSIONS

No constraints version	The user has complete control over the movement of the end effector, with no restrictions or assistance of any kind.
Low constraints version	The user has partial control over the movement of the end effector, with constraints limiting the degrees of freedom, while still allowing the user's decisions to fully define the outcome.
High constraints version	The user has partial control over the movement of the end effector, with constraints that reduce the degrees of freedom and assist the user by limiting certain movements, thereby restricting decision-making to influence only specific characteristics of the outcome.

Suggestions on ***how a Mixed Reality system can be utilised to maintain the positive aspects of the user experience during Human-Robot Interaction in crafting tasks.***

Based on the findings of this project, it is recommended to approach the use of Mixed Reality for improving Human-Robot Interaction not as a means to replicate normal, hands-on interaction experiences, but as an opportunity to explore new ways to enhance the user experience. The following suggestions provide a framework for addressing the design challenges:

Create an Effortless Control System:
Ensure the control system is intuitive and does not require excessive effort, as difficult or cumbersome controls can result in negative emotions and frustration.
Allow users to direct effort toward the challenge of achieving the task. This effort should feel like skill development or problem-solving, not fighting against an overly complex control system;

Avoid Full Replication of original Interactions:
Instead of mimicking traditional, hands-on controls (which rely heavily on sensory feedback unavailable in MR), identify and limit the aspects of interaction that the user needs to control. The focus should be on the elements of the interaction that define task outcomes and can be easily managed by the user.

Incorporate Robot Automation Strategically:
Identify areas where automation can improve performance and ensure good outcomes while still keeping users in control of the task's final result

Avoid Co-Located Teleoperation for Precision Tasks:
Co-located teleoperation is not suitable for tasks requiring high precision or fine details.

Optimise the Use of Limited Display Space:
Even MR systems have limited display real estate, so only a few user interface elements can be shown at a time unless they can be seamlessly integrated into the environment.

- Consider using simpler controls systems to avoid overcrowded interfaces with feedback substitution.
- Avoid adding overlays on or close to critical environmental elements, as this can cause distractions or disrupt depth perception.

Explore Unique Opportunities of MR:
Limiting MR systems to replicating traditional hands-on experiences restricts the potential to discover new and unique interaction methods. This conservative approach may overlook novel benefits specific to MR technology.
Although the MR is limited by the lack of haptic feedback and other sensory feedback, it might offer opportunities for novel experiences through different stimuli.
By shifting focus away from replicating traditional interactions and instead exploring MR's unique capabilities, designers can overcome the inherent limitations of the technology and create engaging, innovative experiences that support Human-Robot Interaction in crafting and other tasks.

SECTION 6.2

FUTURE STUDIES

As this study highlighted several areas for improvement and potential exploration, future research should focus on addressing the limitations and expanding the scope of Mixed Reality systems in Human-Robot Interaction. The following areas are suggested for further investigation:

Incorporating Hedonic Characteristics
The interaction was designed with a focus towards the requirement around autonomy and usability, as these were found to be the most important to tackle to a positive experience. While these elements positively impacted the user experience, they did not fully preserve all aspects of traditional crafting experiences. The improvements addressed key performance factors, such as precision and control, but failed to include hedonic aspects like tactile pleasure and similar sensory engagement. While the interaction resulted in a positive user experience, they only partially captured the full depth of the crafting experience. Future studies should prioritise implementing hedonic qualities of crafting which were not addressed in this prototype.
To address these gaps, the following points outline key considerations for future research:

- The bodily experience extends beyond just tactile sensations; all senses contribute to creating a rich and engaging sensory experience, and each is equally worthy of exploration. While traditional crafting heavily relies on tactile feedback, in the context of MR, other senses may take on a more significant role in enhancing the hedonic aspects of the experience.
- Multisensory experiences offer greater depth and engagement compared to unisensory ones. Exploring the implementation of additional feedback channels, such as auditory, visual, or even olfactory cues, may be essential to achieving a comparable level of sensory richness in MR interactions.

The following approaches are recommended to refine future systems and address these challenges:

- Engage participants with prior crafting experience to refine the systems. Their expertise can provide nuanced insights into what constitutes a fulfilling crafting experience.
- Interaction systems need to be tested with participants who have undergone sufficient training to develop proficiency. Longer-term studies would provide a better understanding of how user control and satisfaction evolve as participants gain mastery over the system.

- The reliance on simulated environments in virtual reality was a significant limitation of this study. Future research should aim to validate the findings in real-world settings, where more practical and comprehensive solutions can be tested under realistic conditions.

Testing the Influence of Design Elements on experience

Further studies should focus on isolating and examining how specific elements and requirements of the interaction influence the overall experience. By analysing these components individually, future research can develop a more precise understanding of how to optimise the interaction design for the best achievable experience.

The current findings indicate that introducing reasonable constraints can enhance the experience, rather than detracting from it. However, these results leave several critical questions unanswered. For example, does the improved satisfaction stem from achieving better results, or is it due to the reduced effort required when constraints are present? Understanding these nuances is essential for creating structured, detailed guidelines for designing interactions that achieve a better balance between usability and user satisfaction.

To address these gaps, it is recommended to conduct further testing with a refined set of research questions. These questions should aim to uncover the relationships between different interaction elements, allowing designers to weigh the requirements and identify the optimal balance. By doing so, future studies could establish clear guidelines on which compromises are acceptable and which should be avoided, reducing the need for extensive iterative testing in future designs.

For this study as well, it is recommended to transition to real-world applications. The simulated environments in virtual reality have a significant influence on the user experience; therefore, future research should aim to explore these interactions under realistic conditions in real-world settings.

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APPENDIX

SECTION 1

USER TESTS

Reflective Approach
Objective: To identify the user's values and emotional needs in crafting from a reflective, holistic perspective.
Method: Interviews with participants who have prior crafting experience, focusing on emotional and reflective aspects through memory-based questions.

Behavioural Approach
Objective: To explore user values and needs with a focus on in-the-moment perceptions during crafting.
Method: Think-aloud, contextual inquiry during a crafting activity, emphasising immediate perceptions.

Prototype Test
Objective: To understand user needs in relation to the prototype by directly comparing it with traditional **crafting** technique experience shortly before (in the behavioural approach).
Method: Think-aloud and contextual inquiry while using the prototype.

Final Reflection
Objective: gather comprehensive feedback on the entire experience with the MR interaction.
Method: Post-prototype interviews and concept mapping with users, fostering discussion to uncover additional insights and refine earlier findings, encouraging holistic reflections on expectations and outcomes.

This process was initially designed to be repeated consistently for each participant to gather comparable insights across all sessions. However, findings from the pilot tests highlighted several issues that required adjustments to improve the testing approach. A key issue was the excessive amount of time each session demanded, making it challenging to recruit and retain participants. To address this, changes were implemented to streamline the process, ensuring it remained efficient while still capturing high-quality, in-depth data.
Pilot test findings:

Test methods iterations

Reflective Approach:
The questions about what the user sees as positive in the crafting task were insightful but lead to much repetition. Questions need further elaboration to push the user to explore more than the most evident positive characteristics.

Behavioral Approach:
Participants struggled to focus on speaking aloud due to the high concentration required by the task, particularly when using the electric grinder, which added an element of danger. No valuable data was collected. Additionally, the busy, loud environment added stress, potentially skewing sensory-focused results.

Prototype:
Unexpected difficulty arises with controlling the robotic arm, the user does struggle to control the movement, demonstration and clear instructions are required to show how the interaction works. Additional time to let the user familiarise and feel more confident with the interaction is also necessary. The cable connection from the VR to the computer limits mobility and discouraged movement.

Final Reflection:
Users preferred to explore one topic rather than several. Support for broader exploration would help in this phase.

Test methods iterations

New questions:
Updated question sets have been designed for the first and last phases.

Removal of physical grinding phase:
The physical grinding phase was removed as it provided limited useful data, required location changes, and significantly extended testing time. This simplification also facilitates easier recruitment of participants.

Control system enhancements:
Implemented improvements to the control system based on feedback, including a new feature where the robotic arm stops applying force once the interactable object is released. This behaviour more closely simulates natural interactions with physical objects.

Added interactable object reference:
A visible reference of the interactable object was added near the user's hand, making the interaction more intuitive and helping users orient themselves.

Program optimization for standalone headset use:
Optimised the program to run standalone on the headset, allowing users to move more freely and enabling testing outside the VR Lab at TU Delft. This modification broadens participant accessibility.

Familiarisation period added:
Thanks to the time saved with the previous adjustments, a familiarisation period has been introduced, allowing users to gain confidence in controlling the robotic arm. This ensures the analysis reflects a more accurate experience, and not only the ease of learning the manipulation.

Emotional cards:
A new tool has been introduced to help users identify and articulate the emotional aspects of their experience. Participants will use emotional cards (based on Desmet, 2012; P. Desmet & Fokkinga, 2020) to help identify a broad range of possible emotions associated with the interaction.

Final methods

Questions on Past Crafting Experience:
Participants are interviewed on the emotional and reflective aspects of their past crafting experiences, with memory-based questions that focus on the positive aspects of craftsmanship. Emotional cards featuring positive emotions are used to facilitate the interview.

Prototype Test:
After a familiarization period, participants perform the task using the MR interaction, with only observational data collected during this stage.

Questions on the Prototype Experience:
Participants are interviewed to reflect on the emotions experienced during the MR interaction, comparing it to traditional crafting. Emotional cards are used to help identify both the missing positive emotions and any negative emotions present in the experience.

SECTION 2

IDEATON

FIG. 26 - VUDEATION SKETCHES

SECTION 2.1.1

GORILLA ARM SYNDROM

THE ISSUE

Keeping the arm raised for a prolonged amount of time is ergonomically uncomfortable.

IDEATION

Lowering the Elbows to Increase Sensitivity

The goal for this new implementation is to reduce the fatigue that accumulates in the arm caused by the mid air gesture and allow the user to interact comfortably for a prolonged amount of time. However, the implementation must maintain a performance that allows the user to manoeuvre the tool with ease.

The goal of this new implementation is to reduce arm fatigue from mid-air gestures, allowing the user to interact comfortably over longer periods while maintaining easy tool manoeuvrability. Research indicates that keeping the elbows in a lower position significantly decreases fatigue. By lifting only the forearm while letting the upper arm (above the elbow) rest, the user can maintain a more comfortable posture, reducing shoulder strain—one of the primary sources of discomfort.

While a physical support could further reduce fatigue, it would introduce new challenges, such as restricting arm movement and requiring a stable support surface.

Increasing Sensitivity for Maneuverability

Switching from shoulder-driven to elbow-driven movements reduces the range that can be covered in a single motion. To maintain a wide range of manoeuvrability, sensitivity must be increased so that less movement from the user results in greater range from the tool. This sensitivity adjustment can also address the annoyance of constantly grabbing and releasing the tool (see Chapter 3.3.1.2), which arises from low sensitivity.

Currently, user movements transfer to the robot on a 1:1 scale. To increase sensitivity, this scale needs to be adjusted so that the robot covers more distance per unit of user movement. However, simply increasing the scale would reduce the user's ability to perform precise, small movements, which are already challenging due to technical limitations. Therefore, a solution is needed that allows for both quick, wide-ranging movements and small, precise adjustments as required.

CONCEPT 1: ADAPTIVE SENSITIVITY

An effective approach could be to implement dynamic sensitivity scaling, a technique commonly found in interfaces using a mouse, known as "mouse acceleration." In this system, sensitivity varies based on the speed of movement: slower movements maintain precision, while faster movements increase range. This adaptive approach would enable users to transition seamlessly between precision and speed, enhancing usability and reducing fatigue.

While a physical support could further reduce fatigue, it would introduce new challenges, such as restricting arm movement and requiring a stable support surface.

SECTION 2.1.2

WRIST ROTATION

THE ISSUE

the interaction requires the wrist to rotate beyond its comfortable position, leading to discomfort, especially the ulnar and radial deviation

CONCEPT 1: CHANGE ROTATION JOINT

To decrease wrist rotation, the required rotation could instead be distributed to other joints that are less prone to discomfort, thereby engaging the whole arm. This approach would have the advantage of reducing the rotational strain on the wrist, which is particularly beneficial for avoiding discomfort in repetitive movements.

However, a drawback of this solution is that it requires the entire arm to move, which conflicts with the solution for gorilla arm syndrome. Engaging the whole arm would mean lifting the elbow, increasing shoulder activity and thus making it harder to keep the shoulder in a low-effort position.

CONCEPT 2: GIZMO FOR SET-UP POSITIONING

The wrist rotation that generates the most discomfort is ulnar-radial deviation. This rotation is primarily needed when setting up the tool in the correct orientation on the x-z plane, and once the tool is oriented, this alignment usually remains constant throughout the interaction. Currently, to position the tool correctly, users may need to rotate it up to 180 degrees, requiring multiple full ulnar-radial deviations, which causes discomfort. Allowing this rotation in a single, comfortable movement could help alleviate the strain.

A rotation gizmo would allow users to perform straight, comfortable movements that translate into rotational values, reducing the strain of direct wrist rotation. This gizmo could be added to the controller in the right hand, while the left hand could be used to interact with it.

Using the rotation gizmo would reduce wrist rotation needed for set-up positioning, thus lowering discomfort. However, the added gizmo may increase visual clutter, and it is only helpful during the setup phase, not during active tool use.

CONCEPT 3: LOCK ROTATION AXIS

Locking rotation along certain axes could be beneficial, as it would prevent unintended changes in the orientation of the end effector. During interaction, many orientation changes occur unintentionally due to the arm's natural circular motion rather than a straight path. While this solution wouldn't address setup rotation, it would reduce the need for frequent adjustments to maintain the end effector's orientation, a common task in the interaction.

By locking rotation, the system would reduce the number of rotations required to keep the tool steady, alleviating wrist strain. However, this would come at the cost of some freedom of movement, as the user's control over certain orientations would be restricted.

SECTION 2.1.3

HAND MISALIGNMENT

THE ISSUE

Unnatural Force Control: unintuitive force control mechanism, force is defined by movement misalignment
Force Snap and Control Delay: unwanted movements and difficulty in regaining control
Loss of Central Reference: unintuitive control when misalignment cause offset of the reference point

IDEATION

Adaptive force control is a form of automation that autonomously adjusts force input based on environmental feedback, which reduces the user's control over the interaction. Since maintaining user control is a key focus, adaptive force control will not be considered at this stage. Among the remaining options, force and position control each manage only one aspect of movement—either force or position— which does not allow for full control over movement in this interaction. This leaves impedance control as the most promising approach.

The goal is to create a system where the user experiences a natural and intuitive interaction, minimising mental load while achieving precise control. In the preliminary prototype V1, force instruction was a byproduct of position misalignment, which presented certain issues. An ideal system would biomimic human force control, allowing stiffness to be controlled independently from position changes.

Solutions should explore alternative methods for directly instructing impedance without relying on the misalignment between the end effector and target point. This challenge has proven difficult, as finding a way to control movement and force simultaneously, with consistent precision, remains complex. Many ideas were generated, but the screening process found most to be unusable. Two solutions were identified, but they still do not fully resolve the issue. Given the engineering complexity of this problem, further exploration was limited due to a lack of expertise in the field.

CONCEPT 1: ELLIPSOIDAL FORCE CONTROL

Force is defined by misalignment, following a system similar to the ellipsoidal model (Peternel et al., 2021). In the grinding task, the most precise control is required for the force applied perpendicularly to the material, as it determines grinding depth and effectiveness. In contrast, lateral forces, parallel to the material, are primarily used to position the grinder tool rather than control the applied force. Separating these controls could improve maneuverability. A system where lateral movements are independent of force control—leaving precise force adjustments only for perpendicular movements—could provide a more intuitive experience for the user, allowing intuitive lateral positioning while maintaining fine control over perpendicular force.

CONCEPT 2: DIFFERENT VARIABLE

Misalignment will persist regardless of the control system used, as the absence of force feedback means the user's hand may extend beyond the end effector's physical limits. However, the control of the force intensity can be separated from misalignment and instead controlled by an independent value. By using misalignment solely as a directional vector, force intensity could be controlled by the user's other hand—for example, by opening and closing the fist to adjust the applied force level.

SECTION 2.1.4

UNCONTROLLED FREEDOM

THE ISSUE

A feeling of imprecision on the instruction of the movement. The main cause is the lack of a force feedback to guide the motion.

CONCEPT 1: HAPTIC FEEDBACK

The natural imprecision of hand movements is a limitation of our body. To increase user precision, haptic feedback could be implemented, which would require physical hardware to create a bilateral system, similar to a standard master-slave robotic setup. This setup would allow users to feel resistance, enhancing control and precision.

CONCEPT 2: CONSTRAINTS

Through constraints a filter can be applied to the input commands, so that only necessary and correct inputs are transmitted to the robot, which could make the control system less prone to errors. By seeing accurate results from their actions, users may also stop perceiving the control as imprecise.

CONCEPT 2: POSITIVE REINFORCEMENT

Another option is to help the user feel comfortable with the current level of movement precision, regardless of the actual precision achieved. Instead of focusing on improving action outcomes, the goal is to enhance the user's emotional state by reinforcing the sense that their hand precision is sufficient for the task. This can be achieved through positive feedback and by reducing emphasis on performance metrics, alleviating stress around precision.

SECTION 2.1.5

OBSTRUCTION

THE ISSUE

The only avaiable feedback is obstructed during the interaction, limiting the infromations about the progression of the task

A factor that may have contributed to these issues is the immobility of users. In a typical setting, when manipulating an object, users naturally rotate or move around it to view its 3D shape and characteristics from all angles. However, during the user tests, participants remained stationary. This lack of movement could be due to a restricted feeling from using a VR headset in a confined space, or the perceived excessive effort needed to move around the object, which, due to the distance, to change viewing angles large movements were necessary, or perhaps a combination of both factors.
Since the sense of restriction in VR is an artefact of the test environment rather than the actual MR interaction, the test setup in future tests will be designed to avoid inducing this feeling. However, if the cause is indeed the effort required to change perspective, various solutions are proposed to address this challenge.

CONCEPT 1: ROTATE THE OBJECT

If the user cannot move, then the object would need to be rotated to achieve different perspectives. This would require an additional mechanism to move the object, making this concept likely to have low feasibility due to the high costs of such an implementation, which would undermine the advantage of using a vision-based tracking control system alone.

CONCEPT 2: ADDITIONAL PERSPECTIVES

In many robot teleoperations using a 2D display, multiple viewpoints are provided to help users understand depth and spatial relations. Similarly, in this interaction, an additional perspective could allow the user to maintain a line of sight to the area of interest, re-establishing the feedback loop needed for accurate manipulation and task progression. However, performing movements from a different view point requires significant mental effort, as the user must mentally transform the observed movements from that viewpoint into their own. This increases cognitive load, making this approach less suitable for complex manipulation tasks where ease of control is essential.

CONCEPT 3: DIGITALLY RECONSTRUCTION

Since the feedback being obstructed is required to allow the user to understand the current state and shape of the object, directly recreating the shape of the material being covered by the tool could provide the feedback even during the obstruction. However, adding additional digital overlays risks causing confusion and visual clutter, which could make the experience unusable.

SECTION 2.1.6

DEPTH PERCEPTION AND DETAILS

THE ISSUE

distance from the toll and artefacr cause difficulty in positioning the tool on the right depth and to visualise the details of the material

DEPTH PERCEPTION

Outside of the user test, it was observed that the simulated environment appeared relatively flat, primarily due to the absence of shadows. Shadows were only cast by static objects for performance reasons, meaning the tool itself lacked a shadow. Enabling this feature improved the perception of the tool's position, as shadows provide valuable monocular depth cues. As a result, shadows will be implemented in the next test. However, depth perception still remains affected by the distance, so additional solutions to enhance this aspect are explored.
Similarly to the obstruction issue, the depth perception problem could be addressed by making it easier for users to change perspective. A change in perspective introduces parallax cues, allowing users to estimate the tool's position more precisely. Therefore, in the next tests, the test set up should be designed to encourage user movement.

CONCEPT 2: ADDITIONAL PERSPECTIVE

Another approach, similar to the obstruction's solutions, would involve adding an alternate viewpoint to give users a clearer view along the depth axis. This could be particularly effective for the setup, as the depth axis provides information crucial to the positioning of the tool at the start rather than during a continuous interaction.

CONCEPT 3: CONSTRAINTS

Alternatively, reducing the need for precise depth perception could be achieved by locking the tool at the correct depth once positioned and allowing movement only along a 2D plane (horizontal and vertical), preventing unintended shifts in depth. However, as this is a form of constraint, it conflicts with the requirements for the crafting experience and will not be considered at this stage.

SECTION 2.1.7

FEEDBACK CLARITY

THE ISSUE

A feeling of imprecision on the instruction of the movement. The main cause is the lack of a force feedback to guide the motion.

IDEATION

The absence of haptic feedback presents a significant challenge, making necessary the use of sensory substitution through visual and auditory channels in MR. The goal is to recreate the missing haptic information, giving users cues about force and movement through other sensory modalities.
In prototype v1, a line was used to represent the force intensity, by showing the misalignment between the reference point and the robot's end effector. However, users found it difficult to interpret this feedback without prior experience. The line's length lacked semantic congruence with force intensity, meaning users couldn't intuitively understand whether a certain length represented high or low force. This required them to learn through trial and error, as the feedback lacked a clear, intuitive reference for force intensity, making it hard to gauge the applied force accurately.
While training could help users gradually understand the feedback, a more effective solution is needed—one that provides semantic congruence. Semantic congruence refers to a feedback that aligns with a pattern that users recognize intuitively without needing conscious interpretation.

CONCEPTS: SEMANTICALLY CONGRUENT FORCE FEEDBACK

The aim was to design a feedback system that naturally communicates the magnitude of force, enabling even inexperienced users to intuitively understand it. The feedback needed to convey two key elements: **Intensity**: The strength of the applied force. And **Direction**: The orientation of the force, crucial for understanding how the robot interacts with the environment.
Several options were considered for visually representing force:

- ***Frequency*** (e.g., blinking speed): Time-related features inherently convey intensity.
- ***Transparency***: Provides a clear sense of intensity; however, when transparency is too low, feedback may become invisible.
- ***Progress Bar***: Clearly indicates intensity but may lack clarity if not directly in the user's line of sight.
- ***Expanding Shape***: Shows increasing force through growth in size; however, it lacks reference points (similar to line length) and may create visual clutter, obstructing important elements.
- ***Color Range or Saturation***: A colour gradient could effectively convey intensity.
- ***Pitch***: The auditory channel is already occupied by feedback from the grinding motor, making additional feedback sounds impractical.

SECTION 2.2

PROTOTYPE V2 FINAL DESIGN

With the solutions now ideated, a filtering process is required to select which ones to implement in Prototype V2. When multiple solutions are presented for an issue, the selection is based on both viability and feasibility, considering their application in this project as well as in a real-world context. This approach led to certain issues remaining unresolved, as no implementable solutions were identified for them.

IMPLEMETED SOLUTIONS

Wrist Rotation
After evaluating various concepts to address wrist rotation, Concept 2, a rotation gizmo, was chosen as the most feasible solution. Concept 1 was discarded due to ergonomic concerns, while Concept 3 was dismissed as it imposed constraints on the user's movement, which conflicted with the project's aim of preserving autonomy over the controls.

Gorilla Arm and Low Sensitivity
To address both the "gorilla arm" fatigue and low sensitivity issues, adaptive sensitivity was selected. This solution appears promising, not only in addressing user fatigue but also in resolving the amount of movements required to translate the robotic arm due to the low sensitivity.

Unclear feedback
Among the options presented to convey force intensity, frequency-based feedback (e.g., blinking speed or movement rate) and colour range appeared to be the most intuitive and effective. After experimenting with both, frequency-based feedback was selected as the better option, as it conveyed a stronger impression of intensity. Its dynamic nature made it more noticeable, particularly in peripheral vision, enhancing its effectiveness in conveying force cues.
The perception of speed or frequency can convey intensity without a reference for comparison, unlike spatial cues. Humans have evolved to perceive time through familiar biological reactions like reaction time and daily experiences, making judgments about "fast" or "slow" (which can translate in low or high intensity) instinctive, making it a more cognitively

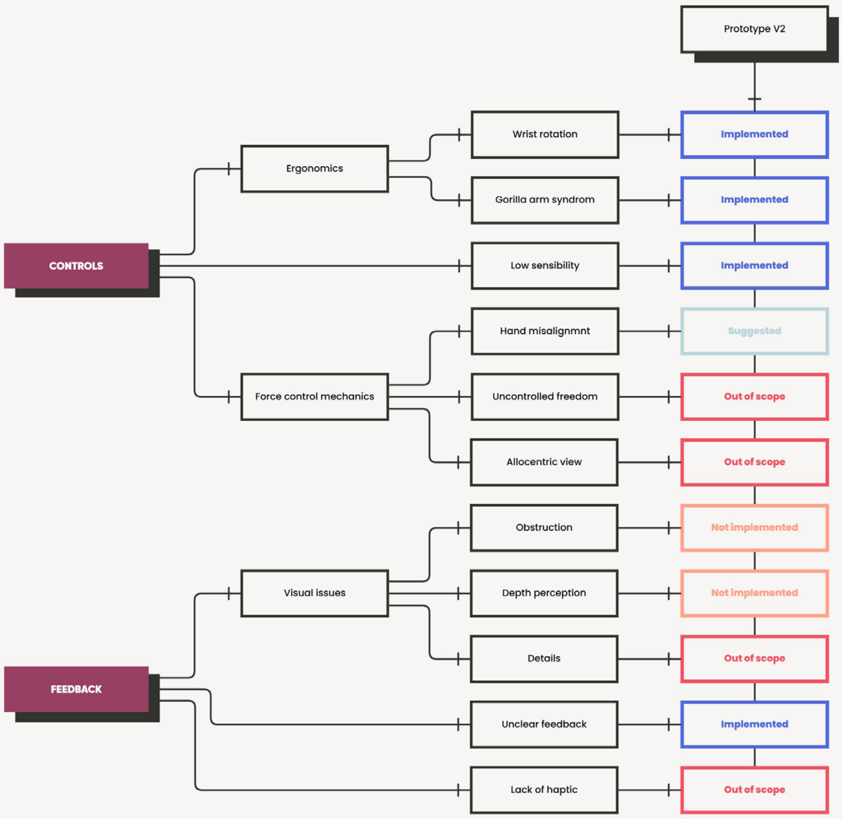


FIG. 28 - ISSUES TACKLED WITH IMPLEMENTATION FOR PROTOTYPE V2

efficient choice to convey force intensity.
Maintaining visual clarity of the force direction was also crucial. The blinking line caused issues with force direction visibility when it was "off," disrupting users' ability to gauge the position and movement of the end effector. To resolve this, the feedback was modified into a series of moving dots along the force line, providing constant visibility for both force intensity and direction.

SUGGESTED IMPLEMENTATION FOR FUTURE WORK

Hand Misalignment

Concept 1, which utilises ellipsoidal force control, is suggested for future work as a solution for hand misalignment. This approach has shown effectiveness in literature and, compared to Concept 2, maintains hte control in a single hand. However, for this project, implementing Concept 1 proved technically complex and was not crucial for immediate usability improvements. Therefore, it was not implemented but remains a promising option for future work.

NOT IMPLEMENTED

Obstruction

None of the proposed solutions effectively addressed the obstruction issue. Each concept was either economically unfeasible, reduced control ease of use, or introduced technical limitations and visual clutter. Therefore, it was decided to leave this issue unresolved in Prototype V2 and revisit it in future iterations, after the immobility of the user in the simulation is tackled.

Depth Perception
Similarly, none of the proposed solutions adequately addressed depth perception issues. Therefore, Prototype V2 will not implement any of the proposed solutions. This issue will be revisited in future iteration after the test setup will be made to encourage user mobility, which can potentially lead to reductions of the depth perception issue.

Uncontrolled Freedom
Rather than introducing new solutions, it was determined that improving the control system itself is the best approach to address the challenge of uncontrolled freedom. If issues with control persist, alternative solutions will be explored in future iterations.

OUT OF SCOPE

Allocentric View
The mental adjustments required by the allocentric view are considered to have minimal impact on the overall usability of the interaction. As a result, this issue was not explored further, and no solutions were implemented.

Details
Given that the task proposed in the test does not require precise movements or work on fine details, it is possible that the user feedback regarding visibility for details was a usability concern for other contexts rather than an immediate issue for this application. With this consideration, no adjustments were made for Prototype V2. However, if it becomes a recurring concern in future tests, appropriate solutions will be considered.

Haptic Feedback
Haptic feedback could not be implemented due to the vision-based hand-tracking system used in the interaction, which inherently lacks tactile or force feedback capabilities. While sensory substitution is an option, it does not replicate haptic perception. Additionally, as discussed earlier, this iteration prioritises improving usability issues over hedonic factors like sensory delight.

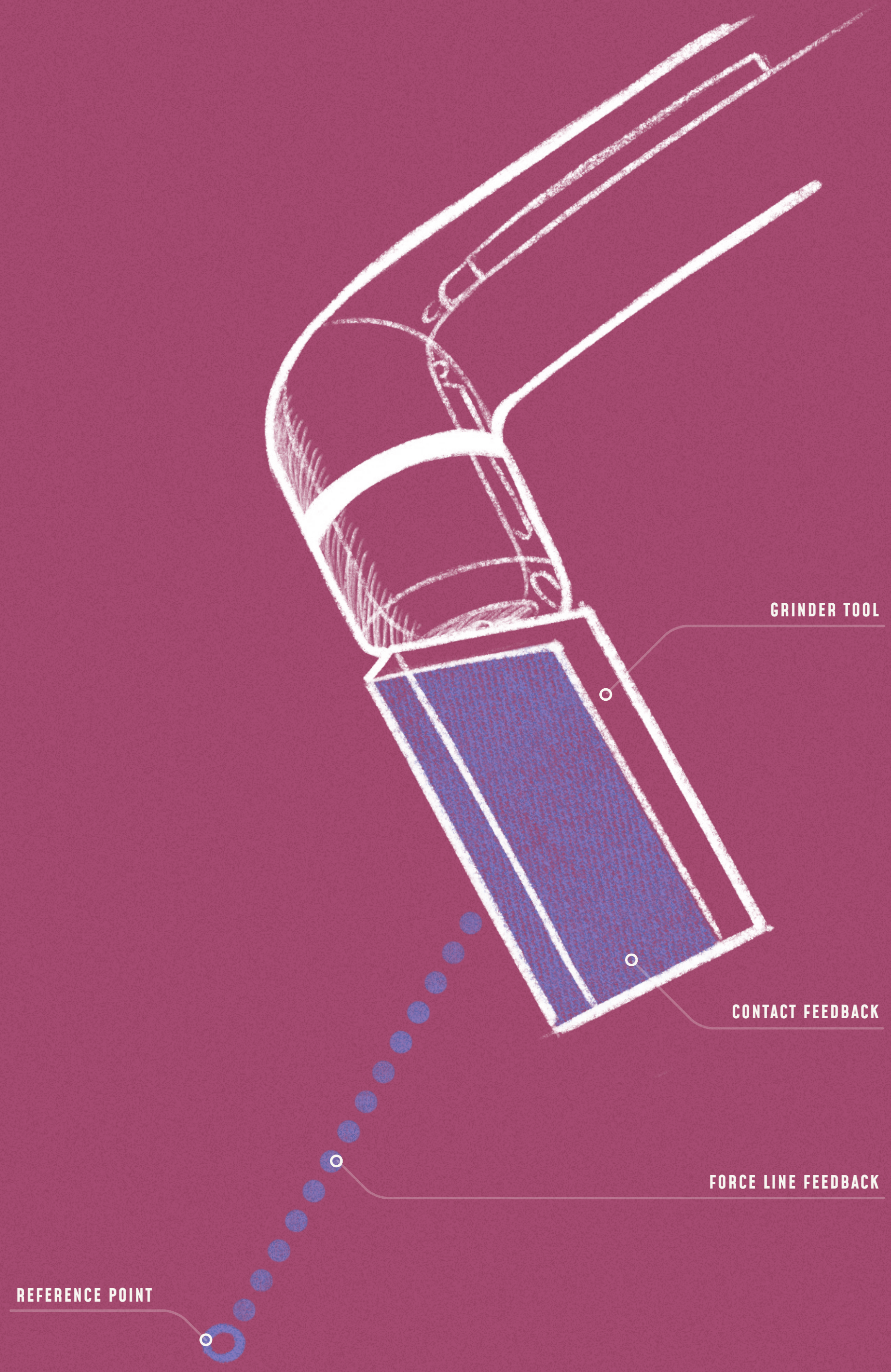


FIG. 29 - PROTOTYPE V2

The image represents the implementation in Prototype V2, with the force line shown by moving dots and contact feedback through a color changing surface

SECTION 2.3

USER TEST

A user test was conducted to determine whether the recent implementations successfully improved the interaction system's usability.

TEST SET UP

Participants were randomly recruited from students within the faculty. To ensure they could move comfortably, a spacious room was reserved, providing ample space for unrestricted movement.
The test followed a setup similar to the second stage of the previous test. First, participants watched a video demonstration explaining the interaction modalities. This was followed by a familiarisation period, where participants could practise at their own pace until they felt comfortable. Once each participant confirmed feeling confident with the control system, they proceeded to perform the task again.
After removing the VR headset, participants completed a series of usability questions. As part of an agile iteration process, this test involved only five participants, who nonetheless provided valuable insights into the interaction's usability issues.
The usability questions focus on the specific aspects of the interaction previously identified as sources of issues that negatively impacted the user experience. These questions aim to capture user feedback on areas such as control accuracy, feedback clarity, overall ease of use and enjoyment of the interaction.
For each question where users provide a low score, indicating that the issue still persists, follow-up questions are included to delve deeper into the specific reasons behind the problem. This step helps uncover the root causes of the issue, providing actionable insights for further refinements.

ANALYSIS OF THE RESULT

The results are analysed to identify which issues are most impactful for users. By reviewing the scores given by participants, low scores on specific characteristics highlight which aspects of the interaction present the greatest challenges and need further improvement. Additionally, follow-up questions provide insights into the specific reasons behind these issues, helping pinpoint exactly what users perceive as problematic. This analysis offers a clearer understanding of the prototype's current usability, highlighting the main issues and the contributing factors behind them.

SECTION 2.3.1

RESULTS

Questions	Target	Answers user 1	user 2	user 3	user 4	user 5	Defect
How much discomfort have you experienced during the interaction?	1	2	3	2	1	2	1
How tired were your arms during or after the interaction?	1	1	2	1	2	3	0,8
How much pain or discomfort did you experience in your wrist?	1	2	2	1	1	1	0,4
How excessive did you find the amount of movement required to control the robotic arm?	1	4	2	2	4	2	2,2
How confident did you feel while interacting with the object?	5	3	3	4	3	4	1,4
How uncertain did you feel regarding the object state while interacting?	1	1	4	1	2	3	2,3
How aware of the object state did you feel at any time?	5	5	2	5	3	4	1,2
How confident did you feel while approaching the object?	5	4	2	5	3	5	1,2
How confident were you in knowing when the tool was touching the object?	5	4	3	4	4	3	1,4
How confident were you in knowing how much force you were applying?	5	2	3	4	4	4	1,8
How well did the force representation convey the intensity of the force applied?	5	3	2	5	4	4	1,4
How many distractions or switches of focus from the object did you experience while interacting?	1	2	1	2	1	1	0,4
How much did you need to shift your attention to the UI elements away from the object?	2	2	2	2	1	2	0,8
How difficult was the task?	1	1	3	2	2	2	1,2
Did you find the experience of the task to be positive?	5	5	3	5	3	3	1,2
How frustrated did you feel during the task?	1	3	3	2	4	2	1,8
How much control of the robotic arm did you feel?	5	3	4	4	2	3	1,8
How confident did you feel about the accuracy of your actions?	5	2	2	5	1	2	2,6

TABLE 3 - PROTOTYPE V2 - USER TESTS RESULTS

This table reports user feedback on their experience interacting with prototype V2. The 'Defect' column shows the difference between the ideal experience and the actual user experience for each question, highlighting areas for improvement.

SECTION 3

FREE CONTROL
PROTOTYPE V3

SECTION 3.1

SOLUTION IDEATION

To work on the issues that have emerged regarding the interaction, a new round of ideation is carried out, exploring solutions that can be implemented into a prototype v3.
The recent implementations showed some improvement in user experience, yet core issues with the control system persist, especially in users' ability to control the system effectively. This limitation results in less-than-satisfying performance and, consequently, a restricted overall experience. The findings suggest that the primary challenges relate to the fundamental workings of the control system itself, which may require constraints to effectively reduce these issues and achieve a positive crafting experience. This signals that further refinements to the current interaction may only address minor details, while core issues remain unchanged and difficult to resolve without taking a different approach. Therefore, a final iteration will be conducted to refine the current interaction based on the issues identified in this test before exploring constraint-based solutions.
To address the emerging concerns in the interaction, a new round of ideation will take place, focusing on solutions that can be incorporated into a prototype V3.

ROTATION

The issue with rotation arises from unintentional adjustments that occur each time the user moves, making it necessary to constantly readjust orientation. This differs from the previously addressed issue with the rotation gizmo, which was designed to aid in handling single, large rotations. Here, the problem involves a continuous need to fine-tune orientation and an unnatural wrist position that must be maintained to keep the tool aligned correctly.
To resolve this, it's essential to reduce unintentional rotations without interfering with deliberate, intentional rotations.

IDEATION:

Increasing Force Intensity Sensitivity: By adjusting the force intensity to increase more with smaller misalignments, users can reach the required force level without moving the controller as far, thus minimising unintended orientation changes. However, this approach would shorten the force line, potentially making it less visually clear.

Finger Stabilisation: Similar to how it was noticed that rotation is stabilised when using a physical controller by the fingers, the same principle could be applied to stabilise the rotation without a controller, helping compensate for unintentional wrist movements. However, current vision-based hand-tracking has limitations in detecting finger movements, making this solution infeasible with the current prototype but potentially viable in future applications. Even with controllers, though, finger adjustments only partially mitigate rotation, suggesting this may not entirely solve the issue.

Body-Relative Rotation Anchoring: Calculating rotation relative to the user's body position, such as anchoring to the chest, could reduce unintended rotational changes caused by natural arm motion. This setup could make arm rotations more linear in effect. However, anchoring may interfere with intentional rotations, as users instinctively adjust wrist orientation to compensate for arm motion. Changing this point of reference could make the interaction unintuitive and mentally straining.

Splitting Controls Between Hands: Dividing control functions between hands (position in the right hand, orientation in the left) may address unintended rotations. However, coordinating both hands to perform a single action would increase complexity, making the interaction more difficult to manage.

Axis-Specific Constraints: Adding constraints to limit rotation along specific axes, a concept discussed during the ideation for Prototype V1, could reduce unintentional rotation. However, this approach is not implemented at this stage to preserve the crafting autonomy requirement.

Threshold Filtering for Rotational Adjustments: Applying a threshold filter to rotations, so that only changes above a certain speed or angle register, could filter out small, unintended rotations. This could inadvertently filter some intentional adjustments as well, possibly limiting user control accuracy.

GORILLA ARM

This is a commonly observed issue in VR simulations, but the current level of arm fatigue does not appear to significantly impact the user experience, therefore, further solutions will not be implemented at this stage. It is possible that over time, as the user becomes more familiar with the interaction and control system, users may start to optimise their movements, which could reduce the need to lift their arms as frequently as they do in the initial moments they try the interaction. Further exploration should assess how this issue affects longer sessions.

ANNOYANCE

The excessive length of motions proved to be an issue mainly during the initial learning phase of the control system, suggesting it does not require further implementation.
The annoyance caused by frequent rotation adjustments is being addressed by minimising unintended rotations, as discussed in the previous section.

IDEATION:

> The issue of low sensitivity during slow movements can be resolved by adjusting the adaptive sensitivity system to maintain a closer ratio to the hand movement.

> Otherwise by implementing a minimum threshold to prevent the movement from becoming excessively slow.

CONTACT FEEDBACK

RETRACTION ISSUE

The retraction issue arises because, unlike in a typical interaction where pulling back the hand immediately breaks contact, here, substantial backward movement is required due to misalignment created to apply the force, leading to confusion when users believe they've retracted but are still in contact.

IDEATION:

> By increasing the sensitivity of the force intensity (higher force is reached with a smaller misalignment), the required misalignment and corresponding travel distance for retraction would be reduced, lowering the likelihood of this issue arising.

> Implement a system that detects the user's intent to retract, allowing contact to automatically cease without needing full travel distance. This would require identifying a reliable indicator of the user's intent to retract.

> Enhanced Contact Feedback: Improve the clarity of the contact feedback to keep users consistently aware of its presence. A clear, salient signal would help users notice immediately if they haven't retracted enough to stop contact.

POINT OF CONTACT

To address the issue of limited haptic cues that would typically indicate tool positioning and relative point of contact on an object various solutions are explored.
First of all, solutions to improve the simulation are explored, as explained the quality of the environment has an important consequence on the clarity of the feedback to determine positions and shape of the elements in the scene, to read more about them go to Appendix section 4.

IDEATION:

Highlighting the contact area could be achieved by determining the precise contact point based on the force applied and the opposing force on the joints. However, since UI overlays on the area of interest tend to create spatial confusion, this approach may lead to further issues.

To improve clarity, the contact feedback can be repositioned to the back surface of the tool (opposite of the one in contact with the material), avoiding placement on an obscured face, as aligning it with the bottom surface does not add visual benefit. Additionally, rather than filling the entire surface with colour, a thick line around the edge is used. To reduce unnecessary overlay effects, this feedback should only be visible when the back face is in view, similar to how a physical element would behave. When the back face of the tool faces away, the visibility on the object is unobstructed therefore contact feedback would be redundant.

Others ideas where revolving around automations implementation that would allow the tool to have the correct orientation and point of contact all the time, but as for other constraints, these solution will not be considered at for this prototype

OBSTRUCTION

User feedback showed that immobility was not influenced by the test setup but rather by the destabilisation that can occur when moving. Observing that users did not opt to move after pausing the interaction suggests that changing perspective cannot be effectively achieved by moving around. Thus, a solution is needed to provide feedback on interaction progress that compensates for the tool's obstruction.

IDEATION:

Given the limitation in changing perspective, an interesting approach could be sensory substitution to replace the haptic feedback, which enables controls even when the progress made is visually obstructed. Addressing this and related issues, by implementing a more multidimensional sensory substitution—beyond the current unidimensional feedback for contact and force—appears to be a promising way to enhance the interaction experience.

FORCE FEEDBACK

The issues related to force feedback mainly concern its visual representation, with users reporting inadequate visibility in terms of size and colour.

IDEATION:

Increase the size and contrast of the force line to improve its visibility.

Implement a gradient that allows even small changes in force to be clearly noticeable.

SECTION 4

SIMULATION SET UP

THE ENVIRONMENT

The scene takes place in a prefab from the Unity Asset Store's "Unity Factory" by Unity Technologies Japan (source), which represents a factory environment. Only the structural elements, such as the floor, walls, and ceiling, are used, as the original interior props contained too many polygons to perform efficiently in VR (fig. 30). These high-polygon interior props were replaced with assets from the Metal Machining Workshop Pack by Megapoly Art, which features low-polygon industrial machinery suitable for VR applications (fig. 31).

THE ROBOT

The robot was designed in Fusion 360 without the use of reference materials (fig.32). It was colored orange to reflect the typical appearance of factory robots with similar functions. The robot was then placed within the factory environment and surrounded by the previously inserted machinery that recreated a generic factory setting.
The robot features six degrees of freedom. To enable its manipulation, an inverse kinematics script from the Unity Asset Store's Bio IK asset was utilized. The robot's movements are only minimally constrained,

FIG. 30 - THE FACTORY STRUCTURE

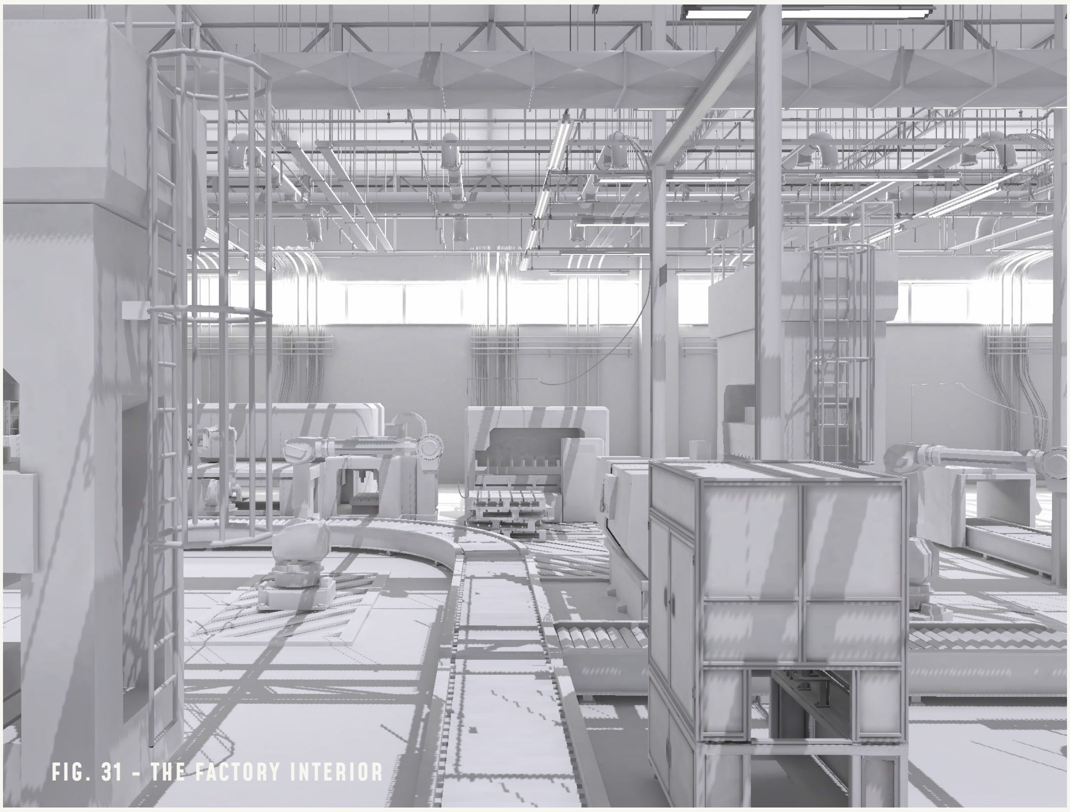


FIG. 31 - THE FACTORY INTERIOR

allowing each joint to rotate freely without angle limitations. Additionally, the robot does not have collision detection, making it theoretically capable of moving through other elements in the scene.
At the end of the robot, a parallelepiped object is attached as an end effector. Unlike the robot itself, the end effector has collision detection enabled and is designated as the grinding tool for the simulation.
In the Bio IK settings, the robot's motion type is configured as instantaneous. However, the actual movement of the robot appears smooth and gradual, as explained in the following section "*The interaction*".
An audio system has also been implemented. Using different audio samples, the end effector emits sounds mimicking a grinder. Separate audio effects are used for when the robot is being manipulated without contact and for when it is grinding material. The pitch of the sound dynamically changes based on the intensity of the applied force.

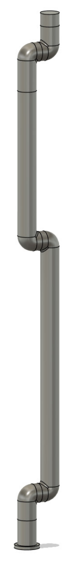


FIG. 32 - THE ROBOTIC ARM

THE INTERACTION

The interaction is implemented using the Meta XR Interaction SDK, leveraging hand tracking for control.

The user interacts with the system at a distance from the robot. A virtual object, referred to as the controller, is linked to the user's right hand. As the user moves their hand, the controller object follows the hand's movements instantaneously. This controller object is also grabbable, meaning that when the user closes their right hand in proximity of it, it triggers the grabbing action for the controller object.
Grabbing the controller activates its connection to another object, called the target. When activated, the target object mirrors the movements of the controller at a distance, in the area around the robot. The grinder's end effector is programmed to follow the target object, using it as a destination point for its motion.
To ensure realistic behavior, the grinder's speed is limited with a LERP motion system, causing it to take time to reach the target object. This introduces a smooth and natural animation to the robot's movements, enhancing the overall experience.

To simulate the grinding process, several solutions were explored. Initially, using a voxel cube composed of numerous smaller cubes was considered (fig. 33), but it proved too computationally demanding for collision calculations in VR. A mesh deformation by vertex was also tested but failed to provide a realistic simulation. Ultimately, the chosen solution was to use a voxel cube while redesigning the collision system from scratch to optimize calculations specifically for this interaction, making it feasible for VR headsets.
The voxel implementation was limited to the area required for grinding, minimizing the number of cubes generated to save resources. The grinder object interacts with these cubes by colliding with them, and after a certain time—determined by the applied force intensity—the colliding cube is destroyed, simulating the grinding effect.

The custom collision system employs a grid of raycasts emitted from the grinder object in the direction of the applied force vector. The raycasts' length corresponds to the force intensity, determining the distance the grinder will travel in the next frame. This ensures that the raycasts detect any cubes in their path before the grinder moves through them.
When the presence of one or more cube is detected, the collision is calculated by identifying all the points where the ray vector intersects the cubes. These points are used to compute the average surface angle and define the rebound vector. This rebound vector causes the grinder object to "bounce back," recreating the collision effect achieving a relative realistic simulation.

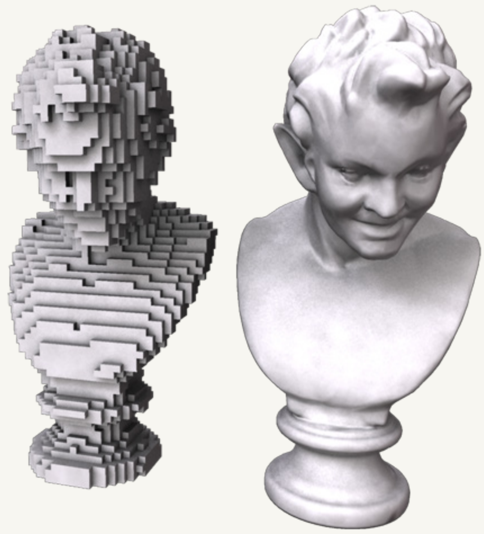


FIG. 33 - VOXEL

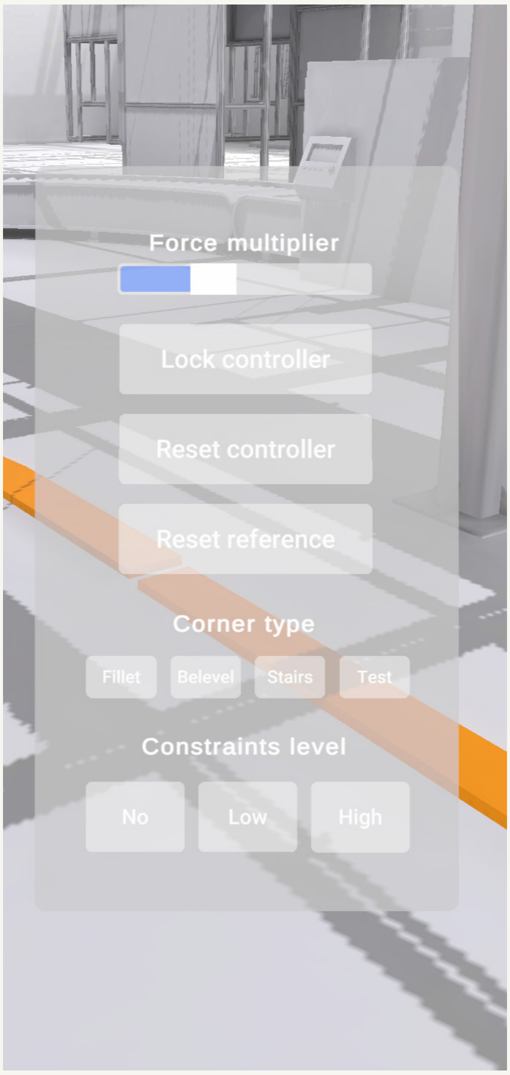
On the left side, the voxel sculpture is composed of cubes that fill the entire volume, creating a pixelated effect. In contrast, the sculpture on the right defines only the exterior surface, without filling the inner volume.

SECTION 5

SIMULATION IMPROVEMENT

USER CONTROL PANEL

A control panel is added beside the user, offering several options to customize and manage the interaction.



Force Multiplier
This feature allows the user to adjust the intensity of the force control, providing a broader range of force options for greater precision and flexibility during the interaction.

Lock Controller
This option addresses an issue related to the controller's position. By default, the controller is linked to the user's right hand, but when grabbed with the left hand, it can be repositioned. This allows users to adjust the controller's placement according to their body, ensuring that when they close their right hand, the controller is correctly grabbed.
However, some users used this adjustment feature for unintended purposes, such as moving the controller with their left hand to manipulate the robot. This occasionally resulted in the controller being repositioned to a location beyond the right hand's reach, making it impossible to activate the grabbing and relative functionality such as control the robotic arm. Users would then need to reposition the controller manually to restore functionality.
To prevent this issue, a "lock controller" feature was implemented. When enabled, the controller automatically returns to its correct position if moved out of reach, ensuring the user can consistently activate

the grabbing function and continue manipulating the robotic arm without interruption.

Reset Controller
This option resets the controller to its original coordinates, ensuring it returns to the correct position regardless of prior adjustments. This is particularly useful if the lock controller feature is activated while the controller is out of reach, allowing the user to regain proper functionality.

Reset Reference
Initially implemented to address a simulation issue during development, this option is now obsolete as the issue has been resolved. It remains in the system but is not intended for user interaction.

Corner Type and Constraints Type
These options are included for testing purposes. Each user is required to evaluate the system with three different constraint types and varying corner configurations. These controls allow for quick adjustments to these parameters after the simulation has started, ensuring seamless test setup transitions.

IMPROVED VISIBILITY: SHADOWS AND LIGHTING ADJUSTMENTS

Previously, the lighting in the scene was entirely baked to conserve rendering power. However, this setup failed to cast shadows from the grinder tool onto the wooden panel. Shadows are a critical depth cue, especially for positioning the tool relative to the wooden panel, which was identified as a challenge in the interaction. To address this, a light source rendered in real-time was added in the interaction area to provide dynamic shadows without significantly increasing computational load.
Additionally, the angle of the lighting was adjusted to enhance surface differentiation on the wooden panel. Previously, the edges of the panel were difficult to distinguish due to low contrast between surfaces. With the improved lighting setup, the panel's faces now exhibit greater variation in shading, making the edges more visible and easier for the user to recognize.

PROJECT BRIEF

DESIGN FOR our future

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name: Firrao

Initials: T

Given name: Tomaso

Student number: 5615712

IDE master(s): IPD ✓ / DfI ☐ / SPD ☐

2nd non-IDE master:

Individual programme (date of approval):

Medisign ☐

HPM ☐

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Marco Rozendaal	dept./section	Human-Centered Design
mentor	Jordan Boyle	dept./section	Sustainable Design Engineering
2nd mentor	David Abbink		
client:	KLM Engineering & Maintenance		
city:	Amsterdam	country:	Netherlands
optional comments			

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Name: Marco Rozendaal   Date: 13th Feb. 2024   Signature: [signature]

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total ______ EC

Of which, taking conditional requirements into account, can be part of the exam programme ______ EC

X	**YES**	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Name Robin den Braber Date 14-02-2024 Signature RdB

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	V	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

V	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Name Monique von Morgen Date 14/2/2024 Signature MJvonMorgen

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Tomaso Firrao **Student number** 5,615,712

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Augmented Collaboration: Integration of Augmented Reality to Enhance Interaction Between Human and Corobot

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; 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)

The domain of this project is in industrial automation, more specifically it is about the integration of collaborative Robots (CoBots) in manufacturing and production environments.

The implementation of robots is an opportunity to help workers ease their efforts and reduce the dangers of performing some tasks, making the work more efficient and safer, opportunities that bring value also from the perspective of safety managers and production supervisors.
This implementation will eventually open the path to achieving a collaboration where the robot can be perceived as a companion to support or work alongside a worker.
But to achieve that level of collaboration many challenges have to be resolved. This project aims to resolve one of those challenges that stand on this path: the communication between the worker and the robot. Here it emerges, thanks to the advancements in Augmented Reality (AR) technologies, another opportunity: the use of AR to improve the communication between humans and robots, allowing a much easier collaboration and acceptance from the workers. This could substantially help and increase the impact of implementing robots in industrial settings.

The project concentrates on the Bright Sky Project. Within this project, a specific task will be identified for the introduction of collaborative robots, serving as a case study for implementing the AR Head Mounted Display (HMD) system. This exploration aims to shed light on how AR technology can be leveraged to enhance human-robot interactions.

→ space available for images / figures on next page

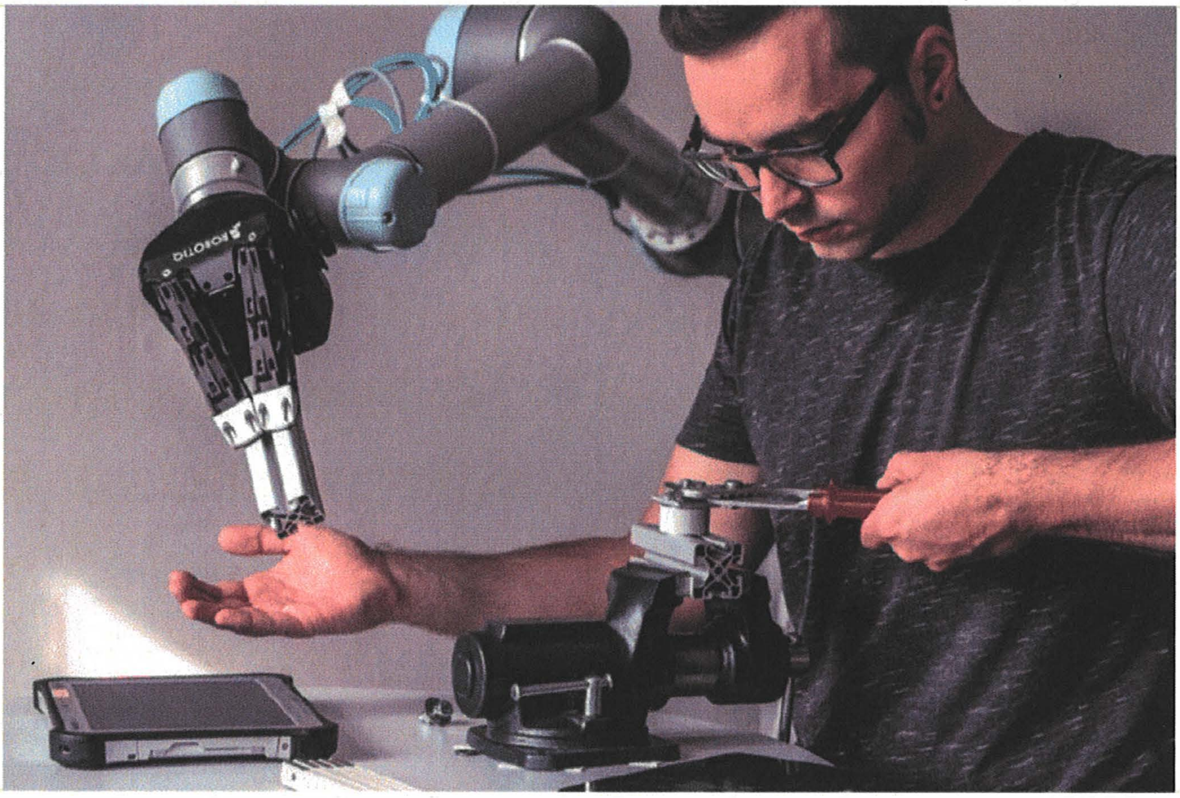


image / figure 1 A collaborative robot assisting an operator in an assembly task. (Gervasi et al., 2020)

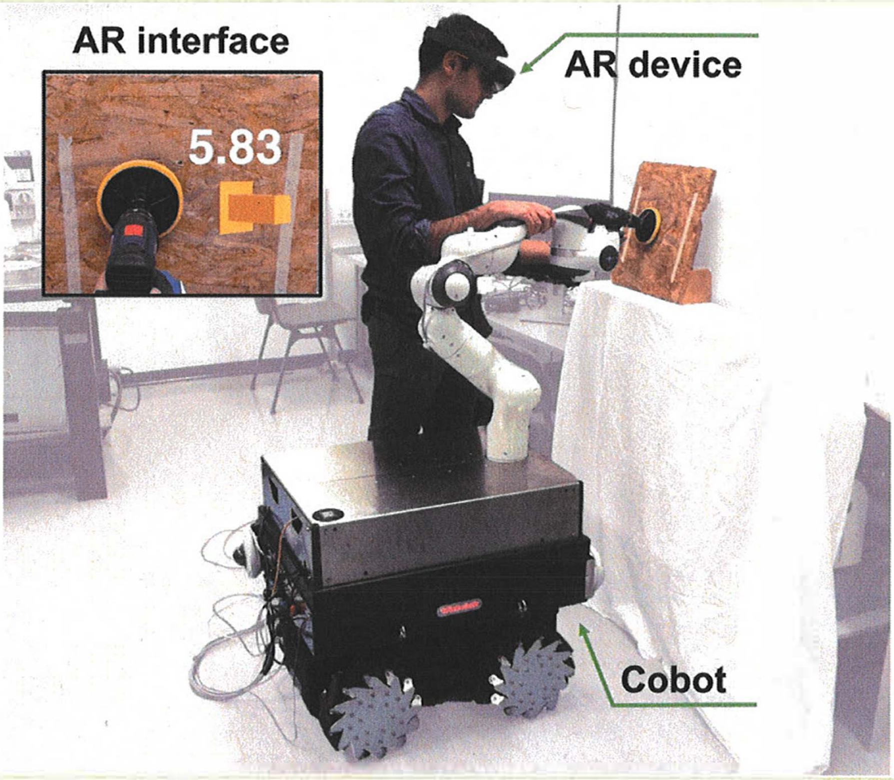


image / figure 2 Human-Robot collaborative task supported by an augmented reality interface. (De Franco et al., 2019)

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

In a collaborative environment, it is critical that a good understanding is reached between the two parties to ensure a safe and efficient environment. But humans prefer communication modalities that employ natural language and gestures, contrary to robots, whose language relies on information in digital forms, such as text-based commands. This difference causes poor communication which leads to inefficiencies, potential safety hazards, and a general reluctance among workers to embrace robotic technology.
This challenge is already being tackled with different approaches, but we are still far away from achieving an interaction that seems intuitive and seamless.
However, with the recent development of AR systems, a new opportunity is emerging: the different communication modalities can now be translated in real-time by the AR headset, allowing one party to easily communicate its own intentions and to understand the intentions of the other party, intuitively and effectively.
This solution creates substantial value for all stakeholders by unlocking new operational efficiencies, elevating safety standards, and fostering a more adaptable and dynamic work environment where humans and robots can collaborate seamlessly.
The improvement in communication will also significantly expand the capabilities and application of CoBots, unlocking the possibility of performing tasks that are currently unfeasible.

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 yourself 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 (Design/Investigate/Validate/Create), and you may use the green text format:

Design an AR-system that enhances the collaboration between humans and robots in physical work settings.

Then 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)

1. A literature review will be conducted to gather existing knowledge about human-robot interaction and AR applications in industrial environments and physical work settings.
2. Observational studies and interviews will be carried out in industrial settings to understand the current challenges and dynamics of human-robot collaboration in the practise of work.
3. The project will also involve collaborating with industry experts to ensure that the solution is practically viable and meets the stakeholders' needs.
4. Tests will be initially performed in a fully virtual environment, by non-end users, to gain a generic understanding and feedback on the usability and user experience concerns of the developed digital prototype.
5. Subsequently, an experiment with end-users will be conducted within their physical working environment to gain more specific understandings of how such a AR system will become embedded.

Project planning and key moments

*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 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

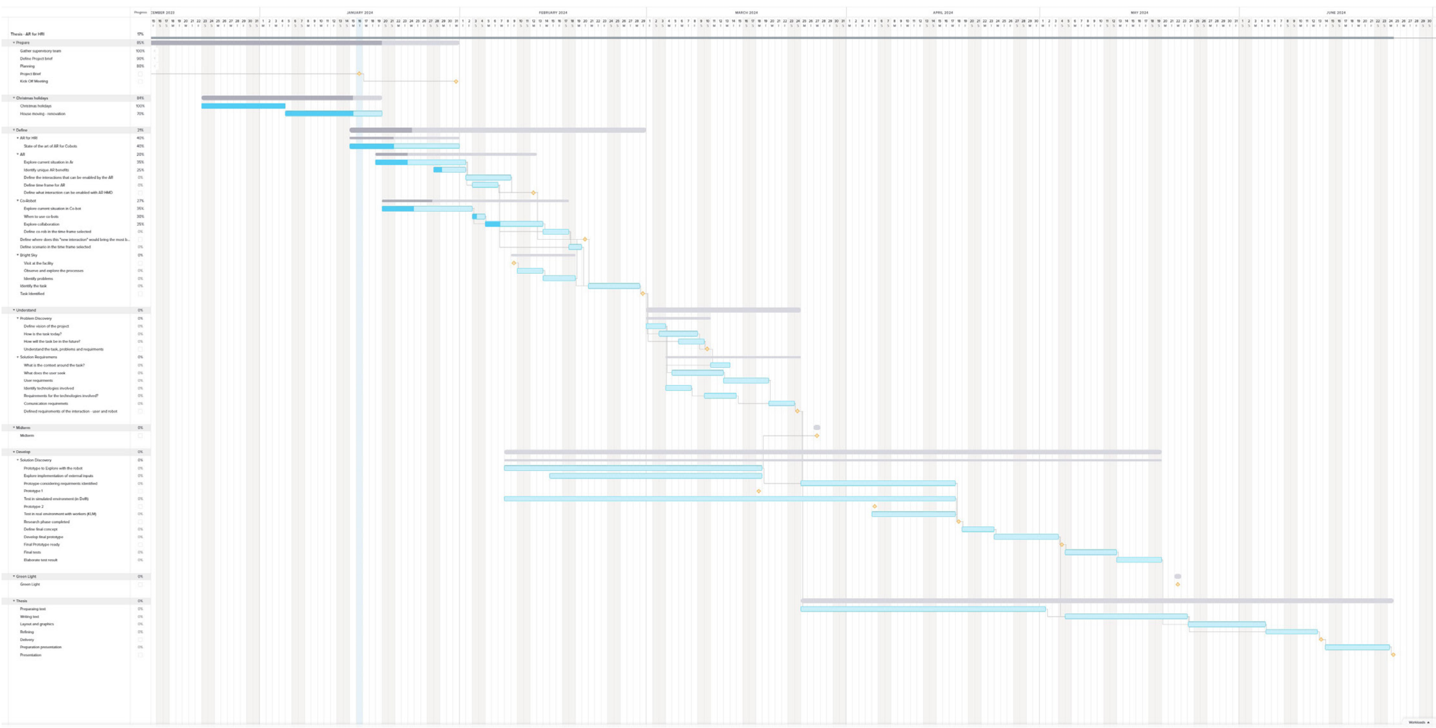
Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	27 Feb 2024
Mid-term evaluation	22 Apr 2024
Green light meeting	24 Jun 2024
Graduation ceremony	22 Jul 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:



Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project was chosen as it would cover various personal goals that I set to be achieved before the end of my master.
Connection to industry: to enter the work environment more seamlessly I have chosen a thesis that would allow me to work in close contact with companies and workers, allowing me to make personal connections in the industry and facilitating an eventual future entrance into this field.
Topic with potential: these years have seen a boom in robotics and augmented reality technologies, robotics has reached a level where autonomy can allow the machine to execute an enormous amount tasks that were not possible until recently, making it reasonable to believe that robots will have an important increase of presence in our society and personal lives. AR/VR is a technology with enormous potential that only recently became usable in terms of costs and user experience, it still needs a lot of development but I believe it will be used very frequently in our lives in a few years.
Personal interests: Other than the interest that I have personally in AR/VR, and the goal to learn to code, I wanted to try to explore the design of interaction. I have only worked on product design so far, so I want to explore nearby fields to better define my interests before entering professional life.