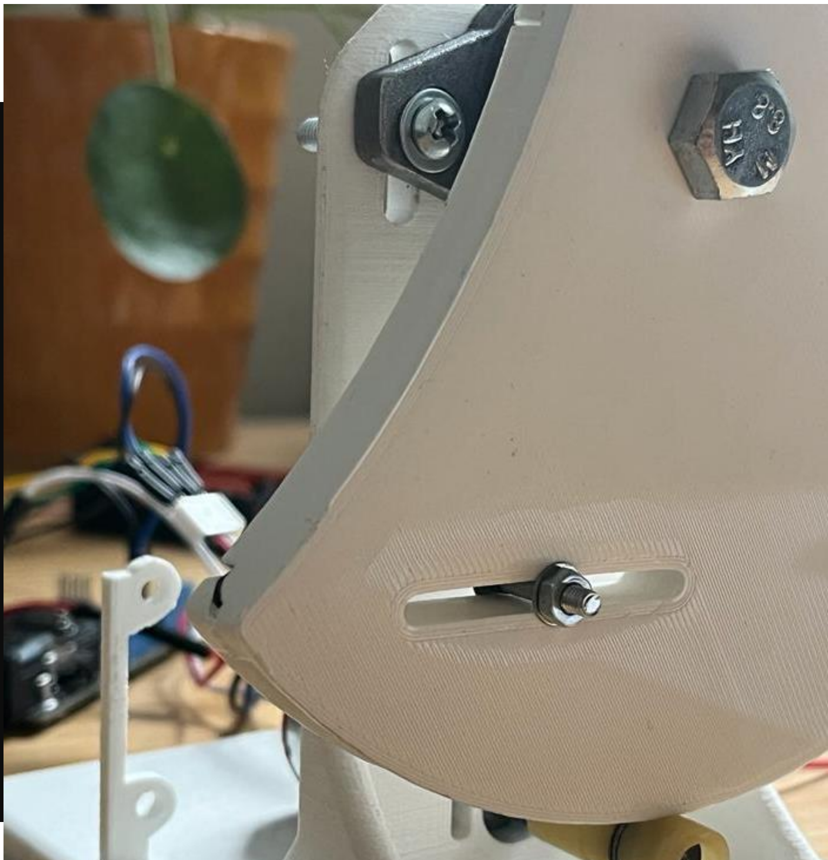
TELEOPERATION WITH FORCE FEEDBACK

FORCE FEEDBACK

A CASE STUDY ON ANTI-SWAY FOR OFFSHORE APPLICATIONS



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ABSTRACT
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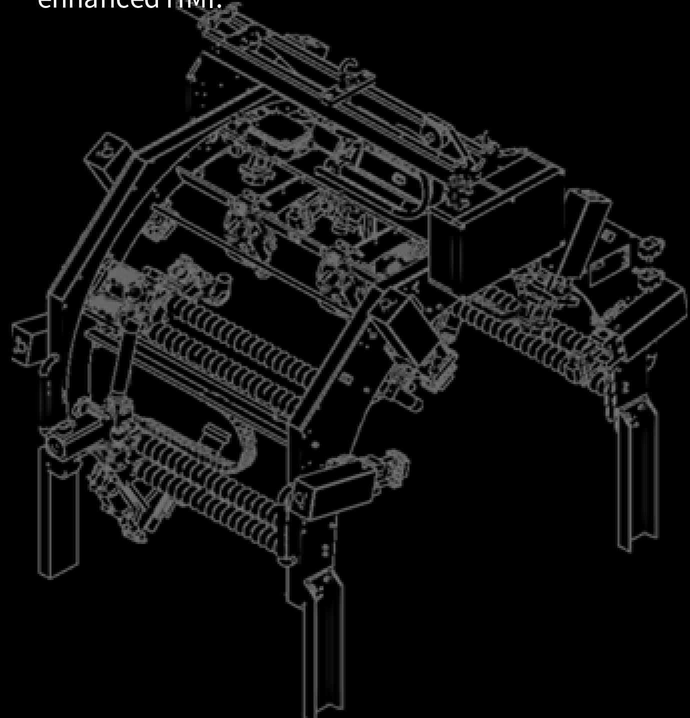
This master's thesis is an exploration of force feedback in offshore applications with the intention of teleoperating heavy machinery. Specifically, Allseas provided their field joint coating machine handling for offshore pipelay as the subject and scope of this study. The anti-sway use case is identified through literature research, user and expert interviews, and observation of machine handling. Due to the nature of offshore dynamics coupled with heavy machine movement, sway of these machines is relevant to all specifics of handling and placing the machine on the pipe.

Operators rely on their intuition and experience when manually operating these machines. For the proposed teleoperation of machine handling, the operator is now distanced from the machine, removing their sense of control, direct force contact, and now making them trust in automation. This is where a force feedback tele-manipulator can increase situational awareness and human machine performance. This is achieved through returning the direct contact forces back to the operator and providing them intuitive control from afar. With more research, rapid prototyping, and machine simulation, Paddy (the teleoperation force feedback test set up) is designed and developed. The proof-of-concept test set up is built using open-source frameworks such as Stanford Hapkit and Vanderbilt Simulink model, but with substantial redesign for offshore anti-sway use case.

To validate the design and use case, a user test with 12 Allseas engineers is conducted. The task is to mitigate the swing of the FJC simulation via the handheld manipulator with and without force feedback. The results imply that the main hypotheses are valid: (1) force feedback yields faster stabilization times, (2) the perceived workload from NASA-TLX scores is lower for force feedback (3) the user requirements and ease of use UMUX-Lite scores is favourable with force feedback, and (4) embodiment and hand placement influences expectations and feeling the feedback mechanisms. Future research could explore different feedback types (assistance vs. error prevention), feedback basis (sway angle vs. angular velocity) or further confirm these hypotheses.

Force feedback is not typically studied in industrial engineering. Thus, design guidelines are created based on this thesis exploration, emphasizing that force feedback is not an add on, but should be considered from the start of the design process. Lastly, recommendations for force feedback in Allseas and other relevant applications are stated for increased situational awareness, task efficiency, and enhanced HMI.



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This chapter introduces the initial assignment of this exploratory master's thesis. The project approach depicts the design problem to reach the intended goal, including methods to guide information acquisition. Due to collaboration with Allseas Engineering, company context and stakeholder analysis is conducted. Allseas provided their field joint coating machines as the subject of this haptic technology exploration. In their endeavour to start pipelay automation, teleoperation of machine handling is assumed as a first step and scope limit. Lastly, research questions are defined with the intention of developing a proof-of-concept test set-up to analyse the implementation of force feedback in human-machine interfaces.

1.1 INTRODUCTION
1.1 INTRODUCTION

This thesis is conducted at Allseas Engineering, specialists in offshore projects and equipment design.

For pipeline installation, their ships contain the firing line, a production street of equipment and crew that weld pipe segments into one continuous string. Before the pipe enters the water, the welded bare steel is coated to prevent corrosion. To do this, the fleet of large field joint coating machines are suspended from the ceiling and maneuvered on top of the pipe by hand (Fig. 1). These machines weigh up to 500kg and are subject to environmental and ship dynamics.

This manual process can be prone to human error, safety concerns, and intense repetitive workload. Hence Allseas's desire to start automation to improve speed while maintaining safety.

Teleoperation is a first step to semi-automate FJC handling by distancing the operator to a safe location. However, the direct and constant physical feedback from manual operation is removed, which could decrease operator and thus machine performance. This provides an opportunity to test the potential of force feedback in enhancing teleoperation control.

Figure 1: Two operators preparing the field joint with machine hanging on left.

ASSIGNMENT

The assignment is to explore the applications of force feedback for offshore heavy machine handling while upholding Allseas standards. The goal is to identify a use case for haptics, specifically for FJC machine handling, to design a force feedback teleoperation test set up. This proof-of-concept set up will evaluate the assistance, speed, intuition, and control of force feedback in teleoperation.

This thesis aims to shift the focus from machine optimization back to operator control, as they remain in the loop during the transition from manual to automated.
Furthermore, while machines excel at repetition and error prevention, humans can quickly adapt to dynamic situations. Therefore, offshore applications could benefit from keeping humans in the loop, especially if haptics can allow operators to meet the same requirements .

1.2 APPROACH
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The Research Through Design Approach is adopted to scientifically address future-oriented design challenges. RtD implies creating "an artefact that cannot be wholly described" and that enables the designer to "dialog with the situation and learn from it" (Godin, 2014). While it starts with research in the classical sense (literature, expert interviews, etc) the rest of the research is conducted through physically building the manipulator for the future scenario.

This approach to research is chosen since force feedback must be actively felt as touch is not as easily recalled like sight or vision (Anton, 2006). While discussions with experienced haptic users are necessary to understand design elements, to create a specific experience requires iterative designs, prototypes, and tests with users. Hence research on force feedback is conducted through designing the manipulator.

These design methods are relatively new to the offshore application. Furthermore, force feedback is not typically classified as an industrial design topic due to its origins in mechanical engineering research. However, in order to create a desired experience using haptic feedback, the user involvement is essential, allowing a solution space where industrial designers can apply relevant methods. The human-machine interaction via haptics could benefit greatly from designer methods and vice versa. This way the potential added value of haptics in HMI can benefit the human and the machine. Therefore, multi-disciplinary methods allows a view of haptics through a designer lens, while utilizing a mechanical engineering background to fully understand and define the haptic HMI design process. Bridging the gaps between mechanical engineering research methods and industrial design engineering methods could potentially expand the limits of haptic applications.

DESIGN CHALLENGES

As mentioned in the assignment, the goal of the project is to explore possible applications of force feedback in FJC handling with the intention of designing a haptic teleoperation proof-of-concept test set up. After research, the design challenge is divided into three, recognizing the importance of the user perspective of haptics, and how to implement the complex mechanisms into a functioning system. To design a suitable test set up for evaluation of force feedback integration in HMI, the challenges are adapted to identifying the use case, understanding user perception, and implementing haptic technology and mechanisms.

DESIGN CHALLENGE 1
Teleoperation with force feedback has not been implemented for offshore applications.

DESIGN CHALLENGE 2
User experience factors and cognitive perception of force feedback could have more prevalence at the start of the design process.

DESIGN CHALLENGE 3
Design guidelines for human machine interfaces with force feedback are not readily available.

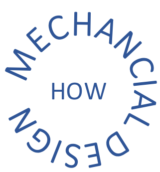
Figure 2: Design Challenges

MIXED METHODOLOGY

A mixed methodology is utilized in order to address the complexity of the haptic design process. The three methods below correspond to the three challenges depicted in the previous section.

To design for the future: need to understand how technology can be used to match user expectations. Context-driven approach is a basis for conceptualizing use case interaction before ideation. *Information will be acquired through literature and desktop research, and expert interviews.*

To design for the user: need to understand the current use case and environment to effectively design for user experience & task. Includes human-centre approach such as ergonomics, etc. *Information will be acquired through FJC engineer and operator interviews and observation.*



To enhance, simulate, or reconstruct reality through haptic technology. Focused on mechanisms, gains, transmission, control loops, and optimizing these mechanisms to create the desired experience. *Information will be acquired though literature and desktop research, control and haptic engineer interviews, and rapid prototyping.*

PLANNING

The project plan is based on the double diamond adapted to better suit the project and methods. Both diamonds embody the vision centered design method equally, since the future vision is maintained through the project. The user centered design method has priority during the Research phase in understanding the FJC operators and human perception, with secondary research on haptic technology and principles. The mechanical design has more weight in the second diamond especially Development when designing the feedback in the prototype. However, all methods are used throughout the project as their research or development results highly depend on one another.

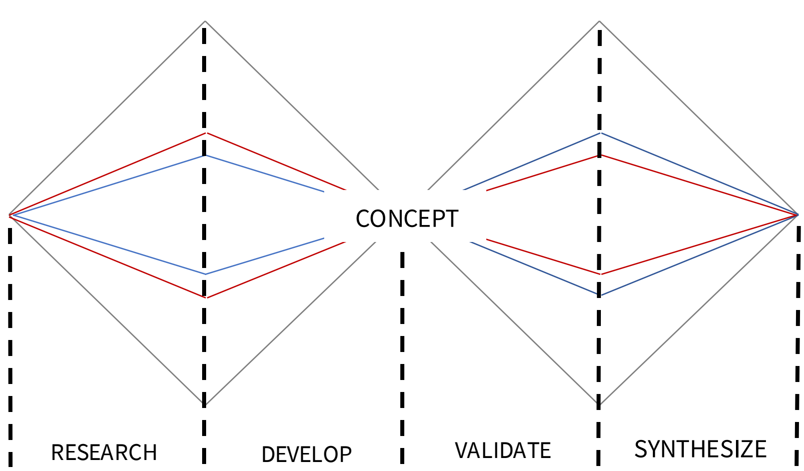


Figure 3: Project Plan

1.3 CONTEXT

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ALLSEAS ENGINEERING

To remain the sustained frontrunner of their industry, “we dare to push the boundaries of technology. We dare to pioneer” (Allseas Group S.A., 2022). This pioneering spirit fuels the continuous development of specialized tools and equipment designed in-house, allowing for novel advances in the offshore market. From constructing the world’s largest ship, to creating the first compact auto-welder (Fig. 4), Allseas drives innovation in the offshore industry. As a result, they set high standards to provide high-quality services and equipment. To “dare to pioneer” allows them to stay ahead of competitors, meet specific clients’ requirements, and improve their efficiency and operational performance.

Figure 4: First Compact Auto-Welding

FIRING LINE

Allseas is known for its speed in laying offshore pipelines. Two widely used pipelay methods are S-lay and J-lay, with the name referring the shape of the pipe as it goes to the ocean floor. The focus is on the S-lay method seen in Fig. 5 is deemed faster and more efficient for a larger range of water depths due to the horizontal firing line along the length of the ship (Allseas Engineering 2020).

The firing line is a production street of equipment and crew that weld the end of each pipe together into one continuous string. Each station performs an individual task, and when all tasks are done, the pipe is moved along. All stations try to be as fast as possible to keep up with the other stations and meet their operational speed quota. They all rely on one another to get the job done.

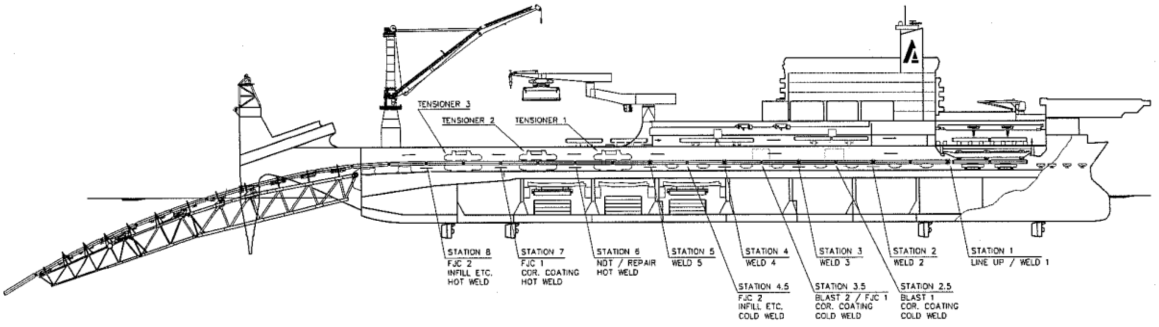

Figure 5: Firing Layout (detailed overview in Appendix 2)

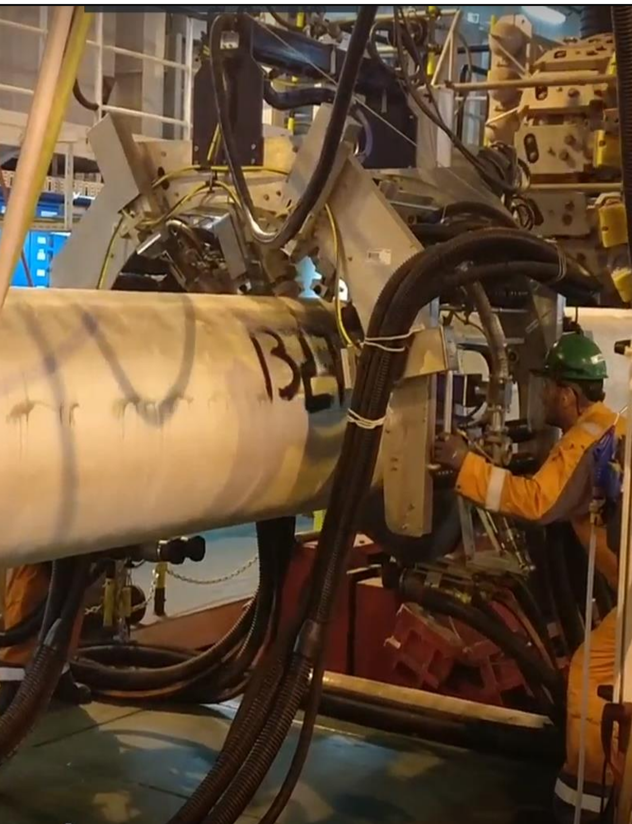

Figure 6: Two Operators Manually Handle FJC Machine

AUTOMATION

This thesis focuses on field joint coating (FJC) machine automation due to current reliance on manual labor. Currently, handling is dictated by the speed and placement of the two operators. As they handle each side of the machine on opposing sides of the pipe (Fig. 6) their coordination could lead to inconsistent movement and sway mitigation. While full automation presents several risks such as feasibility in dynamic environments, and time required to ensure safety, semi-automation allows a steppingstone to mitigate current problems (Appendix 2).

Automation is defined as controlling systems by "electronic devices, reducing human intervention to a minimum" (Automation Definition & Meaning, 2020). This minimum is subjective to the task, with a scale that determines what functions are allocated to the operator or the machine. The focus of this thesis is on Level 1 (Frohm 2008), which highly relies on the operator in the loop.

OPERATOR CONTROL

This thesis aims to shift focus back to operator control via human machine interfaces (HMI). The intention is to optimize machine performance through force feedback assistance for the operator. With rapid advancements in manufacturing automation, the human is still in the loop of these semi-automated processes, especially when transitioning from manual labour to automated machinery. Machine performance is traditionally prioritized, setting the role of HMI on a lower rung. This mindset yields room for human error and operator safety issues due to lack of machine control from inadequate or unspecialized HMI. Furthermore, the solutions that mitigate these issues in stable environments cannot be directly applied to offshore applications (further explained in Chapter 2). Hence, force feedback assistance could negate these differences and risks, specifically by adding telepresence for dynamic machine control.

FUNCTION ALLOCATION

The theory of Allocation of Functions, as described by Bouzekri et al. (2019) refers to "determining the distribution of work between humans and machines early during the design phase." It involves identifying tasks that should be performed by human operators and those handled by the machine systems. An inadequate allocation to the human operator can result in "underload and boredom, leading to decreased performance" while an excessive allocation can cause "cognitive, perceptive, or motoric overload" (Bouzekri et al 2019). Finding this balance can decrease stress that leads to error and in turn optimize machine performance and ensure operator engagement. Therefore, defining the FJC use case for force feedback is crucial for optimal allocation of tasks between the operator and the semi-autonomous system.

VISION CENTERED DESIGN

KEY INSIGHT: As manual tasks transition to automated ones, the task allocation (and forces felt performing them) adapt to new automation level.

1.3 SUBJECT & SCOPE
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FIELD JOINT COATING (FJC)

The subject is the fleet of field joint coating machines in the firing line. The field joint is a 50ccm-100cm long cutback section at the ends where the pipe is not coated. Before the pipeline can enter the water, the field joint is coated in the firing line on the vessel to prevent corrosion. Depending on the type of coating necessary, certain machines are needed for preparation and post processing of the coats.

This results in array of machines present in the FJC stations (Fig 8). Machines vary in weight from 300-900kg and inner diameters of 8”-60” depending on pipe size and function. While the type of coat may differ, the handling and placement of the machines on the field joint is identical.

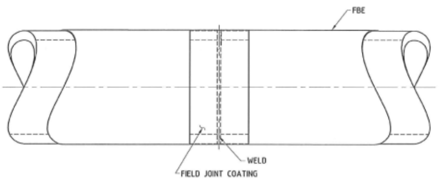

Figure 7: Field Joint Coating

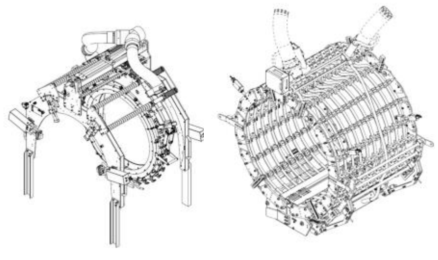

Figure 8: Example of FJC Machines

HANDLING

The scope is limited to the handling of the FJC machines. All the machines are handled with the same mechanical components (Fig. 9). The machines are suspended from an overhead trolley. The two operators grab handles on each side of the machine and manually maneuver on top of the pipe (more in Chapter 2). In literature, the three steps are to position, lower, and orient the machine onto the field joint (Allseas Engineering, 2020). After coating, the handling process is reversed for removal. The machine coating is automatic. However, to check if the machine is performing properly, manual reliance can lead to unsafe habits. Even with safety measures, accidents happen, such as an operator finger caught in the machine which accounts for 29% of Allseas injuries (Allseas Engineering, 2020).

USER CENTERED DESIGN

KEY INSIGHT: What habits are developed by the operators to maintain speed and control? What functions are neglected?

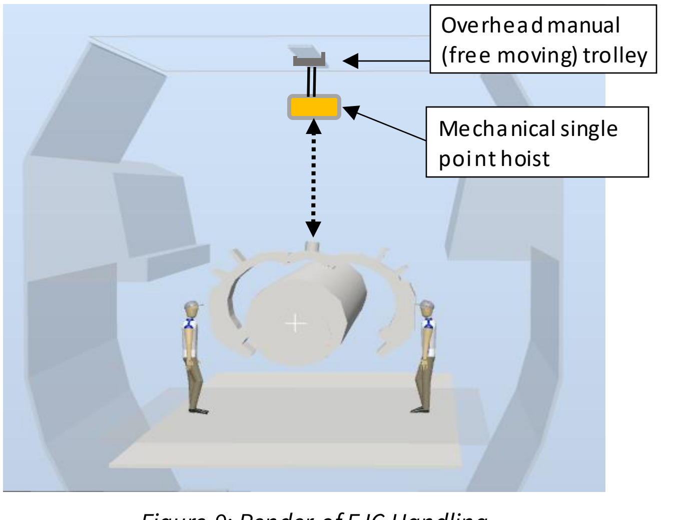

Figure 9: Render of FJC Handling

TELEOPERATION

The scope is further limited by the assumption that the trolley is motorized and teleoperated. As seen in Allseas FJC Handling Studies (2022) and academic literature, this is known as Automation Level 1: Manual Teleoperation (Frohm 2008). Other levels are explored by Allseas, but this level is chosen to study haptics potential that could be applied to other offshore applications. Teleoperation allows remote operation of dangerous inaccessible machinery. Due to its inherent need to provide feedback of machine performance to the distanced user, teleoperation serves as an ideal testing ground for force feedback. While force feedback and haptic interfaces are studied in teleoperation systems, their application to offshore systems is yet to be explored. This thesis aim is to test if this telepresence technology excites the firing line work floor while tailoring tasks for efficient performance.

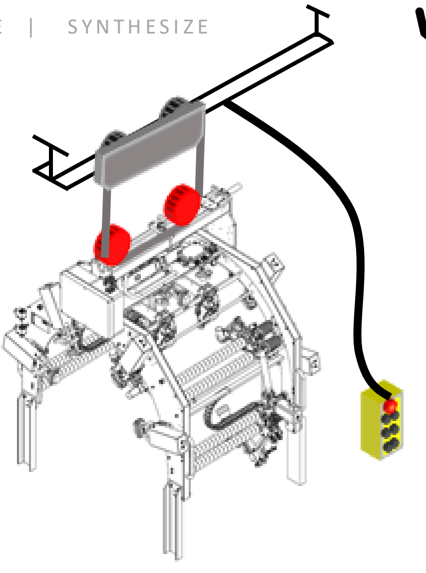

Figure 10: Allseas Design

Furthermore, it address the challenges posed by the unpredictable and dynamic nature of FJC machine environment.

KEY INSIGHT ***Haptics can aid operators by providing force feedback of machine function or movement.***

KEY INSIGHT ***Machines are designed for precision and repetition. Yet, humans are more flexible and adaptable to dynamic situations (Mukherjee et al., 2022).***

STAKEHOLDERS

The key stakeholders are the Allseas FJC operators and engineers who design for them (Appendix 1). Their philosophy is to develop & design equipment in-house to remain ahead of competition (Appendix 1 Competitor Analysis) and independent from contractors. Adjacent stakeholders are the future haptic designers at TU Delft. The field of haptics, specifically force feedback, is still largely unexplored, with most efforts directed to hardware and control loop analysis, rather than industry application or operator use. Thus, this project focuses on the users to evaluate increased operator engagement and performance in conjunction with mechanical principles to test the functionality of force feedback for Allseas applications.

Figure 11: Allseas Operators and Engineers Offshore

1.4 INITIAL REQUIREMENTS

1.4 INITIAL REQUIREMENTS

The assignment includes initial conditions or requirements for the deliverable and later identified teleoperated FJC use case. These conditions further limit the scope yet allow for more in depth design of the force feedback test set up. The overall requirements of efficiency and usability derive from Allseas R&D requirements. The realism requirements derive from Haptic Mechanical Design Theory (Delft Haptics Lab 2020).

TEST SET UP

The handheld, tabletop manipulator is limited to one degree of freedom for feasibility and focus on haptic design for the use case.

A simulation of the coating machine is used instead of real machines due to feasibility and sufficient realism for the teleoperated task. The focus of the research is on HMI and feedback interaction for task performance. The machine parameters such as weight, size, equations of motions, etc. are implemented to allow a source for machine force feedback to the user. The user perception of these forces for task performance are studied with these conditions.

EFFICIENCY

Time - The speed of the operation must be as fast or faster than current time to handle. Estimated from operators to be 10s (Appendix 2).

Physical Effort – The physical effort must be greatly reduced by employing a single operator and handling with only one hand.

Mental Effort – The mental effort or cognitive load should be reduced with assistance via physical feedback. Yet, the user must be more engaged with haptics than without.

Latency – There must be < 10ms delay between the user input and machine output, especially with haptics.

USABILITY

Intuition – The feedback chosen must be natural to the user and their expectations. The limitation is that this can be subjective based on experience, so testing the right users is essential.

Prevent Error – The system must be easy to operate and implement in Allseas infrastructure. The feedback must be assistive that it reduces operator and thus machine error.

REALISM

Reconstructing Reality – The level of feedback reconstruction must be sufficiently realistic for more natural feedback.

Simulating Reality – The model simulation must represent the physics and envisioned teleoperation task.

Enhance Reality – Force feedback must enhance HMI control by adding communication, gamification or engagement.

1.5 RESEARCH QUESTIONS

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The research questions are developed as the project continued. The high, mid, and low-level questions correspond to each chapter. To start research, the high-level questions are addressed. During research, the mid-level questions guided the development process. The final proof of concept test set up evaluation is conducted by answering the low-level questions. All questions are intended to learn how to design with and for force feedback in the offshore environment.

RELEVANT TERMINOLOGY

Haptic Feedback – General term for feedback using the sense of touch

Force Feedback – A type of haptic feedback that generates movement in a user device based on machine forces

Teleoperation – Remote user control of the machine

HMI – Human Machine Interface or the devices that operators interact with to control machines

Manipulator – An HMI that controls movement of a machine

HIGH-LEVEL

To Research

RQ1: What are the potential use cases for force feedback in offshore operations?

RQ2: How should the force feedback design guidelines be adapted for offshore HMI context?

MID-LEVEL

To Develop

RQ3: What sensory information can be enhanced, simulated, or reconstructed through force feedback in offshore use case?

RQ4: What physical aspects of haptic manipulators are most influential on user expectations of HMI control for anti-sway?

RQ5: What types of force feedback technology can communicate the forces acting on the machines to the operator?

LOW-LEVEL

To Validate

RQ6: Do users perceive lower workload (NASA-TLX) of entire task with or without force feedback?

RQ7: Do users take less time to learn & complete the task?

RQ8: Do users perceive the force feedback in the way the design intended?

02 RESEARCH

02 RESEARCH

Part 1 of this chapter delves into the research of FJC handling. Information is gathered through Allseas literature, FJC operator and engineer interviews, and FJC fabrication site observation. Insight analysis defines potential use cases for haptic exploration. Part 2 of this chapter explores haptic feedback regarding how human sense and perception determine the type of feedback required for the task. Force feedback design is explored though current applications, interfaces, and technology. Through haptic user interviews and expert insights, conclusions are drawn to start the development phase.

RESEARCH PART 1

2.1 FJC HANDLING
2.1 FJC HANDLING

FJC handling is a fully manual process. The main three steps mentioned in Chapter 1 are lower, position, and orient. Each of these steps include various physical stimuli, such as bumper force, axial alignment, grip of the handles and more. All these physical forces create built perceptions and expectations of task operation. Reliance on the physical forces felt from the machine is extremely important to the operators. Years of experience and training builds this reliance on senses, therefore feeling present and in control during the chaotic and dynamic offshore environment is essential.

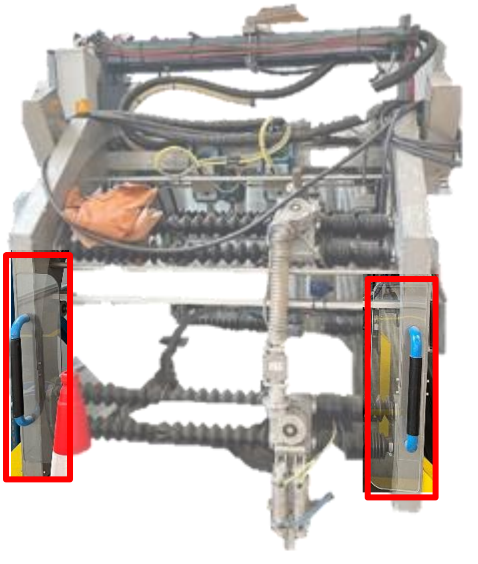


Figure 12: Handles To Grip and Maneuver FBE Coating Machine

Figure 13: FJC Machines Heijningen

FJC ENVIRONMENT

In the firing line, the FJC operators need to be aware of many tasks, operational standards, and safety all at once. Constantly moving, sweating, staying stable, and working in a cramped environment could lead to error and injury if teleoperation is not implemented in a safe and intuitively controlled manner. Wires and chains are sometimes in the operator's way or cause extra weight that they must pull with. Furthermore, the ships unpredictable movement causes machine momentum. Currently, the operators are physically holding the machine to prevent extra movement. As mentioned in Chapter 1, they must coordinate not only with other stations, but also with many operators within their own. Furthermore, they must always know when and which machine must be used as soon as possible to meet client time requirements (Allseas Engineering, 2020).

2.2 FJC INTERVIEWS

2.2 FJC INTERVIEWS

Interviews with engineers shed light on FJC equipment design, potential for automation, and experience operating. The main goal is to define use cases where haptic feedback be implemented to aid operation.

FJC ENGINEER

Research Question: *What is your view on the changes and steps toward automation of FJC machines?*

This FJC engineer works with other departments and coordinates between onshore and offshore. He believes the office can explore a lot of useful technology, however "practice must show whether something actually works." Furthermore, the offshore operators who directly use the equipment "often refine the system, making it more efficient." He has an affinity for keeping the human in the loop for FJC handling, stating that "full automation wouldn't work, the human needs to be involved" due to the nature of the environment and the optimal machine performance relies on those who operate it.

Figure 14: FJC Maneuver Practice

AUTOMATION ENGINEER

Research Question: *What are the challenges and goals for FJC handling automation?*

The engineers are biased toward making machine handling fully automated. This is mainly due to operator mistakes taking 1-2 hours to fix, which is a long delay. However, he would "rather have consistency even if it takes longer so we can plan the next automated section."

Automation contains a lot of limitations with maintenance, downtime of failure, and complexity of stationary structure in dynamic environment. This requires additional motion platforms, etc (Appendix 3).

Most importantly, he believes "All stations working together will be the most efficient." This means that the placement on the pipe must be quick and uniform for every field joint.

R&D ENGINEER

Research Question: *What unique considerations should be considered when designing equipment for the firing line?*

This R&D engineer has years of offshore experience and notices a "distance between what is designed in office and how the user approaches them."

Operators are skeptical of new methods initially and trust their experience and routines they created. However, if they eventually get used to it, they "accept that it makes their life easier or gets the task done faster."

"When offshore in the firing line, operators are going full speed and effort the entire time." This causes bumper pads of the machine to wear quickly when aligning on the pipe.

FJC OPERATOR

Two interviews are conducted on-site at Heijningen, Allseas fabrication unit. Observation of the process and how the users interacted with the machines allowed for richer insight on nuisances and habits operators adopted outside of what they consciously recognized. Below are summaries of the main insights.

In the firing line, the machine always hovers over the pipe since the field joint is in a different place when the pipe moves. When the pipe is stopped, the operators quickly grab the handle and drag it to the joint.

Alignment on field joint is primarily done by eye. The operators on each side of the machine agree to align the machine from the left or right boundary. This requires coordination with the other operator who is not visible from the other side of the pipe.

Speed is essential, they "always try to keep up with other stations." However, when mistakes are made, the error takes a long time to fix and is "*very frustrating. You feel stressed and mad at yourself for keeping the rest of the stations behind*."

Operators create their own routines. One common practice is to handle, step back, and use the control panel to start coating. They trust themselves more than the machines, relying on their physical touch to adjust and maintain operation. However, when hours of speed and effort create fatigue, it leads to sloppy habits. The main injury that occurs is when operators "put their hands inside of the machine part that rotates, then they lose a finger!" (FJC Operator, 8 Years offshore).

In addition, swaying of ship/waves acts on machines has an impact on operation.
"Oh yeah, it's crazy on board. The machines sway so much sometimes we have to tie them down" (Lead FJC Coordinator, 10 years offshore).

Lastly, when asked on their views of automation they are not opposed to it if it is helpful and they "can still feel in control, then I am for it." The operator trusts himself in manual control since if there is an issue, he can go fix it immediately. However, the parts that are automated are extremely helpful, even though they took time to get used to.

ADDITIONAL INSIGHT: CURRENT OFFSHORE HMI

Current offshore interfaces consist of unintuitive, randomly coloured buttons with no distinction other than the peeling label (Fig. 15). To use these at the required speed takes practice and training. After the machine is handled, the operators are no longer watching the machine. Their eyes focus on setting parameters per machine and joint. These universal control panels are not customized to these operations and take focus away from the task at hand, especially without feedback if the correct button is pressed (Appendix 4).

Figure 15: Universal Control Panel Heijningen

INTERVIEWS CONCLUSIONS

The interviews with people from four different but relevant backgrounds for the design of FJC teleoperation provided the following insights and developed conclusions.

The FJC operator spoke of the nature of offshore work and how technology improvements also bring difficulties. The FJC engineer believes that the human should not be taken out of the equation. Conversely, the automation engineer sees a clear end goal in fully automating the firing line processes but is aware of the rocky path required. In the middle is the R&D engineer who is responsible for designing the equipment which is becoming more and more automated, intended for the operators who must incorporate the changes into their workflow.

The varied interview responses demonstrate the incongruency between the engineers and operators. This creates two solution spaces of the functionality: the intended use from the designer and the practically realised use of the operator. To balance the desires of the engineers and operators, haptic feedback could allow for further automation while preserving operator control and acceptance.

Designing a haptic feedback device involves comprehending the forces exerted by tools to create a perception of trust, acceptance, and intuitive control. Operators remain in the loop of semi-automated processes, and they tend to trust their own input more than relying on full automation. Haptic feedback allows for automation steps of the firing line machines while providing the forces acted upon the machine, making operators feel more present and informed. By incorporating haptic feedback, the device strikes a balance between automation and human involvement, enhancing the overall user experience and efficiency.

The firing line environment is also fast-paced overstimulating. So, it’s important to make a clear but engaging user experience that encourages the operator to focus on the task at hand. Ultimately the user decides how it will be used, the designer can only steer interaction to an intended use.

From the interviews across multiple disciplines, it’s clearly necessary to take a multidisciplinary approach to designing a feedback device to meet machine requirements and user needs.

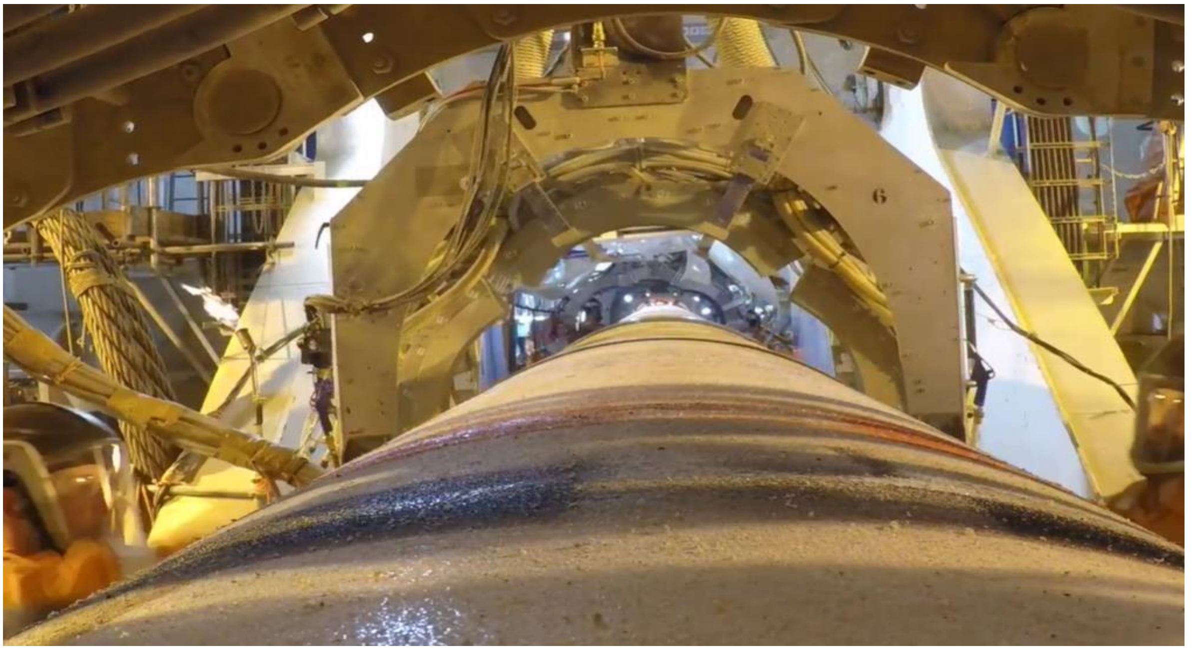


Figure 16: FJC Machine and Two Operators Offshore

2.3 POTENTIAL USE CASES
2.3 POTENTIAL USE CASES

IDENTIFIED USE CASES

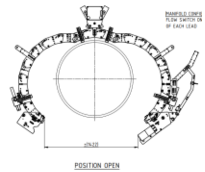
In the context of FJC, there are a few physical phenomena and operational movements which are interesting for force feedback.

For a focused force feedback experience, it is best to narrow to one force phenomena to be transmitted to the user. In this case, the force will either be inertia driven (i.e., due to the movement of the FJC machine), or impact driven (due to collision with another object) (Fig. 17).

For an inertia force feedback, the placement of the FJC machine is correlated to the sway of the machine while it is controlled by the trolley.

Placement of the pipe in the *x*, *y*, or *z* would all be feasible, as there will be inertia from the pipe moving, and all directions are necessary to the function of the FJC machine.

For an impact driven load, the FJC machine bumping on the pipe could also be useful for the operator, however impact forces are choppy and could interrupt the flow of the operator as well as damage the machine.



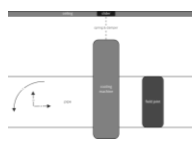
PLACEMENT Z-AXIS ONTO PIPE

FJ ALIGNMENT

BUMPER FORCE

BUMPER AXIAL ALIGNMENT

PLACEMENT Y-AXIS



PLACEMENT X-AXIS

Figure 17: Use Cases

Coordinate system:
x-axis is longitudinally along the pipe
y-axis is in the transverse direction
z-axis is vertical.

ADDITIONAL INSIGHT: OTHER OFFSHORE USE CASES

Additional use cases outside of the scope of the project appeared through research and exploration. These include the ROV department for deep sea machine manoeuvring, pipelay crane operation, and steering of the ship itself. While this test set up is not designed directly for these applications, it is interesting to consider the benefits of force feedback for other offshore projects. This proof-of-concept test set up can act as a demonstrator for force feedback potential in offshore control in general.

PART 1 CONCLUSIONS

CONCLUSIONS

RQ1 What are the potential use cases for force feedback in offshore applications?

Potential applications are categorized as inertia or impact based, since these are currently the most significant direct physical feedback

The firing line stations heavily rely on one another. Hence the movement and placement of FJC seems to be one manual bottleneck.

Offshore HMI is currently disconnected from task. Force feedback can enhance them by providing machine presence at a distance for various teleoperations offshore.

Haptics lies in between manual and automation, inheriting benefits and limitations of each.

RQ2 How should the haptic feedback design process be adapted for offshore HMI context?

To design for haptics in offshore HMI, there is a need to understand the operation as a whole, from engineers to operators.

The goal of the feedback needs to be identified in terms of which machine force and why. For example, machine weight movement to optimize speed.

While the office engineers believes in automation, operators have a different acceptance threshold and trust in their manual practice.

Engineer and operators have different expectations and perceptions of handling. Both agree that the feeling of control is necessary for operator and task performance.

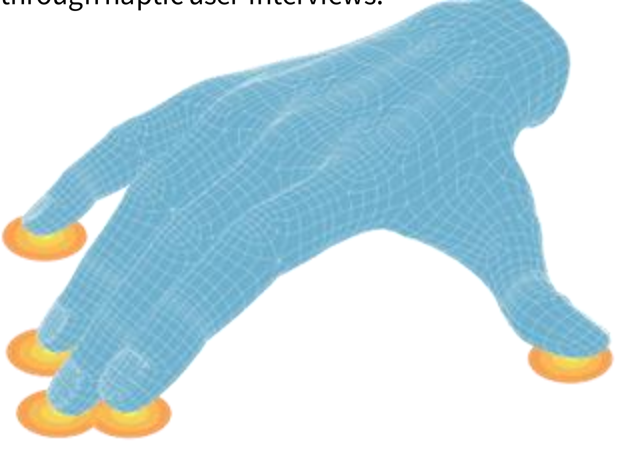
RESEARCH PART 2

2.4 HAPTIC FEEDBACK

2.4 HAPTIC FEEDBACK

Haptic feedback relies on the sense of touch and movement. In order to design feedback that aids the operator, in this case giving the operator a feeling of control and intuitive force feedback, understanding how humans sense and perceive touch and movement is necessary.

This research section aims to explore the significance of haptics as a crucial role in human interaction, highlighting the potential for force feedback assistance in a multisensory environment, like the firing line. Haptic feedback is categorized into two types, derived from human sense of touch and movement. The focus on kinesthetic or force feedback is relevant for heavy machinery movement. However, elements of active tactile implementation are also studied since every interaction includes both forms of haptics. How humans actively perceive these haptic sense modalities is studied through haptic user interviews.



HUMAN SENSORY SYSTEM

The human sensory system is inherent to our interaction with the environment, involving constant sensory engagement and cognitive perception. Every interaction with a physical object is a multi-sensory experience, however the input of information is unequally distributed amongst them. This combination creates a hierarchy of perceptive reliance of three sensory modalities: sight, hearing, and touch.

Sight and hearing are often emphasized in current daily interactions. However, this mainly attests to the information that users consciously perceive, and are guided to perceive, due to designed interactions and familiar feedback cues.

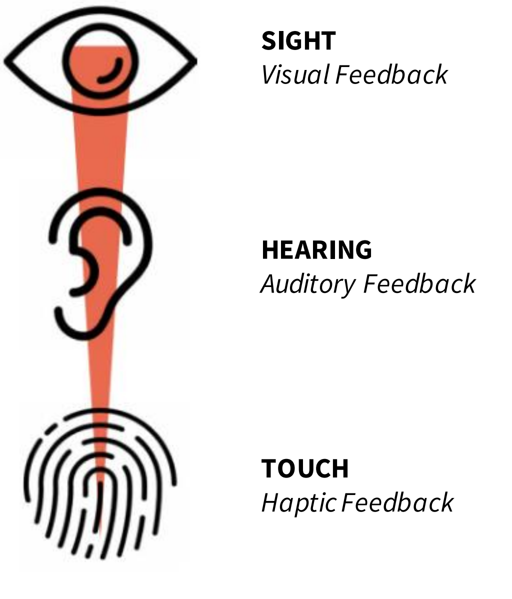


Figure 18: Hierarchy of Sensory Input

PERCEPTION OF SENSES

Perception is awareness of the senses. Vision is seen as the dominant modality, yet this is because users are conditioned to rely on it. In the age of rapid digitalization and entertainment, products and their designed feedback are directed towards visual displays, text, or graphics. From billboard ads to smartphones, people constantly use and are aware of sight. However, research shows that the "accepted hierarchy of human senses (sight, hearing, touch, taste and smell) is not universally true across all cultures" (Martin, 2018). Cultures that place value on their musical heritage can communicate more efficiently on describing sounds, even when non-musicians were tested. Researchers conclude that the hierarchy of sensory perception relies on user experience and context. For FJC operators, their reliance on physical touch and felt machine movement is the dominant modality. They perceive touch as control, as they trust in their movements more than an automated machine.

REACTION TIME

While the speed of visual response is suitable in most cases, there is only so much information humans can visually perceive. Especially when conflicting information is present, touch generates a faster reaction time "in both humans and monkeys, the response to tactile stimuli was faster than visual stimuli" (Godlove et al., 2014). In more dangerous or fast paced environments, physical nerves allow for faster interpretation while other senses are being used for other inputs. While touch has the fastest reaction time (Fig #), the focus of this thesis is force feedback. This relies on movement, which is takes longer for human muscle contraction than nerve endings. Yet, when precise judgement is required, the response modality that dominates is movement, where different weights, shapes, and especially forces of object colliding can be felt (White, 2012). Touch and movement are the only sense that is reciprocal, where the object someone moves inherits their forces as well.

For the times on the right, sensory input relates to the time it takes a stimulus to reach the brain, while reaction time is of sensory input to action (Kemp et al., 1973). These times are from multiple studies such as M, U. (n.d) and Jain et al. (2015).

	Sensory Input	Reaction Time
Touch	>1 msec	155 msec
Hearing	10 msec	160 msec
Sight	40 msec	200 msec

TACTILE VS. KINESTHETIC

Touch and movement translate to tactile and kinesthetic feedback. Using tactile or kinaesthetic senses, people either passively or actively touch an object. The combination of these results in different feedback and device uses (Appendix 4). For the FJC application, the focus is on active kinesthetic feedback due to the immense forces produced by the machine. For more intuitive control and natural feedback of machine movement, the weight and position of the machine should be felt. The resulting forces categorize the HMI as an active kinesthetic manipulator.

Fig. 19 Tactile Feedback

Tactile devices stimulate the skin, usually through a display. These displays aim to recreate texture, vibration or temperature felt through skin receptors (Stanford 2020).

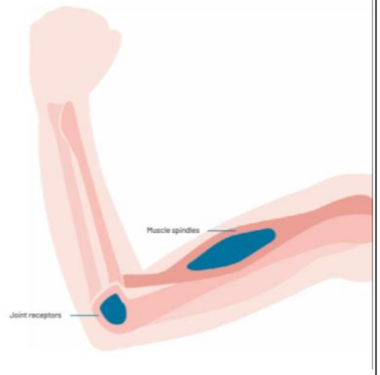


Fig. 20 Kinesthetic Feedback

Kinesthetic devices produce a force or motion based on the size, weight, or contact of the manipulated object. This activates receptors in muscles and tendons (Stanford 2020).

2.5 USER INTERVIEWS
2.5 USER INTERVIEWS

Discussions are had with 5 tactile display users and 3 general kinesthetic device users. The goal is to understand their experience and perception of active tactile and active kinesthetic feedback. This provides insight on how haptic technology is integrated to create a desired experience.

ACTIVE TACTILE FEEDBACK

Research Question: Which tactile feedback properties feel acceptable or intuitive? How do you describe the experience?

Commonly found in smartphones, active tactile feedback gives the user the feeling of interacting with something mechanical, when they are not. Users expressed that it “feels like you are pressing a button when even though you are not.” For some, they become so used to the feedback that they “can’t type without haptics.” However, if the haptics are not performing well, users discussed that “the feedback can’t keep up with my typing speed” and they would “rather have no haptics than bad haptics.”

Figure 21 Apple’s ‘Taptic’ Engine

ACTIVE KINESTHETIC FEEDBACK

Research Questions: How do you perceive the force feedback experience? What sensory information is enhanced, simulated, or reconstructed through force feedback?

Active kinesthetic feedback is used to simulate more physical interactions. For example, it is present in modern video game hardware like the PS5 controller, where there is variable resistance in the finger triggers. This allows the user to “feel present because the controller changes resistance based on finger force and gun type” (Fig 22).

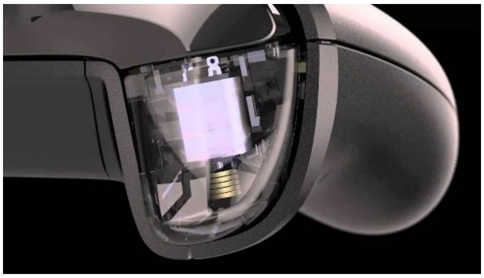


Figure 22: PS5 Adaptive Triggers

In racing simulators, environmental loads like friction on the road and wind on the car can be shared to the driver via a steering wheel. As a Formula Student Driver remarks, “the simulator wheel gives me the force and resistance needed for me to feel what my real steering wheel should have” (Fig 23).

Figure 23: Racing Force Feedback Wheel

ANALYSIS

What became evident from the interviews of users of both active tactile feedback and active kinesthetic feedback, is that clarity and seamlessness is key when it comes to the effectiveness of haptic feedback. In haptic terminology, this relates to transparency, or the difference between the real and designed feedback. Latency should not be noticeable, and the forces should not feel too artificial. When haptic feedback is implemented well, or meeting prior expectations, users from both tactile and kinesthetic haptic devices have more engaging experiences.

Active tactile haptics is more of an addition to the experience, where something like typing on a phone feels a bit more tangible and mechanical, but the haptics are not at the forefront of the user experience. Active kinesthetic haptics on the other hand has higher situational awareness on how the user is interacting with the device. For example, changing the resistance while turning a racing simulator steering wheel due to environmental factors effects the ability of the user to steer the wheel since they are fighting the force in the wheel. At the cost of the wheel being harder to turn, it gives the user information about what environmental forces the car is experiencing, allowing them to compensate accordingly.

To aid clarity in haptics, the device should be designed for the desired feedback. With this, it helps to create a focused experience. To narrow down on a single force phenomena to be fed back to the user. Otherwise, it can be distracting if the user experiences something they aren't expecting. The magnitude of the feedback force is also important as there is a window in which the senses are optimally engaged. If the feedback is too much, it will disrupt the ability of the user to complete the task.

Attention must be paid to the relationship between how the senses are engaged and what forces are modelled. A multimodal experience, paring haptics and visuals, can be a powerful tool if it is designed to improve the quality of the information exchange with the user, rather than overwhelm and confuse the user.

2.6 HAPTIC FEEDBACK HMI
2.6 HAPTIC FEEDBACK HMI

Haptic feedback HMI is first studied to understand the design process for creating feedback. Force feedback is typically studied in research, but there are some industry applications. HMI for force feedback take on a different form, feel, and function based on their task (Fig. 24). Characterized with more resistance, control, and designed experience.

While general HMI can be interchangeable due to their simplistic manoeuvrability, more specialized tasks need specific designs and interactions. Their shape, form, ergonomics, stroke, grip, etc must be designed with the context of the task in mind. The user must be involved in the process, because of their experience and methods to perform the task. Existing perception and expectations are carried from old contexts to new HMI. Therefore, understanding user perception is necessary.

The focus is on a type of force feedback HMI called manipulators, master devices that control a follower that moves objects or interacts with a remote environment.

Behind each interface embodiment is the technology and respective control systems. The desired context dependent feedback is created by programming and connecting hardware. The design and optimization of these systems are challenging and can make or break the experience. Most of force feedback is implemented only in research, without advanced open-source design methodologies other than final products or technology.

GENERAL CONTROLLERS TO SPECIFIC MANIPULATORS

While some applications can accept general controllers, to get the most potential from haptics, force feedback user interfaces must be specifically designed for the task and operator. Feedback design goes hand in hand with the embodiment. A surgeon can't operate with a steering wheel nor can a formula driver race with a surgery instrument. The specific feedback needs to equally match its unique application, embodiment and ergonomics for the designed effects to be felt.

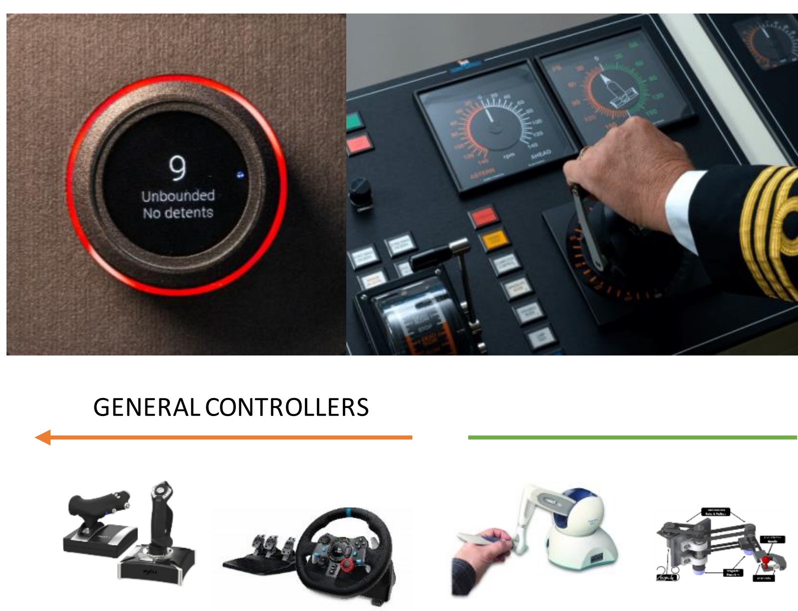


Figure 24: Spectrum of Manipulators

FORCE FEEDBACK APPLICATIONS

The physical aspects of a haptic manipulator influence user expectations, which differ per industry application. In surgical procedures that require small and precise movements, highly sensitive and accurate HMI devices are developed to ensure optimal control and precision. Size and weight of haptic manipulators affect the experience and feedback distribution. Surgery devices should be designed to be compact and lightweight, allowing for those precise movements and minimizing user fatigue during prolonged usage. Conversely, in modern aircrafts, control loading systems are employed to provide pilots with a sense of the forces applied to control surfaces, enabling quick adaptability and safety. Ergonomic design elements, such as the shape of the handgrip and the placement of buttons provide intuitive and comfortable user interactions. When it comes to teleoperation, where direct physical contact is lost, perceiving the appropriate actions becomes challenging. This creates a need to produce relevant muscle memory and consistency, despite the absence of direct contact. Incorporating the correct force for feedback into HMI systems can match those perceptions and mimic muscle memory to bridge that gap, thereby enhancing user handling expectations in haptic manipulators.

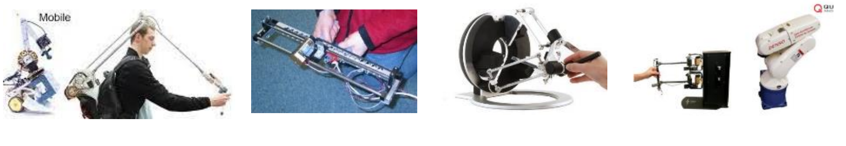
EMBODIMENT EXPECATIONS

The embodiment expectations are influenced by its shape, feel, and function. These factors guide user interactions and align with the cognitive nature of their tasks. Early in the cognitive process, haptic perception is shaped by expectations and predefined assumptions (Breitschaft et al., 2019). The theory of hierarchical predictive coding underscores the significance of expectations in perception, where sensory input validates existing assumptions about the external world (Clark, 2013). By minimizing the difference between the input and assumed perception, this can optimize human interaction with the device. Design features such as shape, curvature, and surface characteristics significantly influence perceived functionality (Carbon, 2013). These design "signifiers" contribute to self-explanatory interaction design, triggering semantic associations and leveraging users' prior knowledge to support manipulation with force feedback.

HAPTIC RESOLUTION & HUMAN PERCEPTION THRESHOLDS

Haptic resolution is the ability to discern differences in weight and forces, due to human perceptual system thresholds. Humans can detect these differences with a threshold around 6%, enabling the distinction between objects with slightly different weights (Jones 2018). For example, changes in the angle of the upper arm are easier to recognize than slight bends of the finger. Device movement or user hand placement can influence feedback distribution and effectiveness.

SPECIALIZED MANIPULATORS



2.7 EXPERT INTERVIEWS

2.7 EXPERT INTERVIEWS

HAPTICS LAB EXPERT

Research Question: How does the process for designing haptic feedback look like?

On the technical details, the Haptics Lab expert explained the options with regards to input and output: “Main elements are the four-channel system. Position-position, position-force, force-position, and force-force.”

From a design point of view, the expert agreed that it would be mutually beneficial to bridge the gap between mechanical engineering and industrial design.

Research Question: How helpful and in what way do you believe force feedback will be for this Allseas use case?

The expert validated the usefulness of the anti-sway use case (see Chapter 3). The dynamic forces of a pendulum-like object swinging are interesting from a haptics perspective, as reducing sway with traditional manual controls is something only highly experienced crane operators can succeed at consistently.

CONTROL ENGINEERS

Research Question: What elements of the feedback loop will influence the transmission?

The control engineers affirmed that if the model and equations of motions are properly designed and built, the most influential parameters will be latency and gains. Latency should be minimized and unnoticeable or else the feeling of control will suffer. With gains, it is a balancing act to have the right amount of input and output gains. The input gains effect how sensitive the model will be to the user’s input, and the output gains will directly change the magnitude of feedback the user will experience.

Research Question: How necessary is it to run a real time simulation?

Control engineers stated that it is “essential to have a real-time simulation.” In order to simulate teleoperation of a machine, the user needs to be experiencing the physically accurate time scale. Especially with a naturally moving system like a pendulum. Simulink is recommended due to its widely known real-time application and hardware in the loop connection.

ANALYSIS

The interviews with technical experts provided both practical knowledge for the necessary building blocks of a haptic feedback device, but also an interesting discussion on design. The haptics lab expert confirmed the need for designers to be involved in haptics, and that the haptic feedback field would benefit from the considerations made by designers with regards to user experience and expectations.

The controls engineer fueled this argument by regarding latency and gains as the most influential parameters for the haptic feedback device, as these parameters directly affect the user experience. If latency is too noticeable, the user will not feel immersed in the task and the feedback will not feel natural. Control gains set the magnitude of the user's interaction with the device and simulation. Furthermore, most force feedback systems restrict the movement of the user by means of some mechanical input, such as an electric motor. This coupled with rapid virtual prototyping such as MATLAB Simulink should aid in the test set up proof of concept hardware in the loop development (Fig. 25).

These interviews motivated the need for a force feedback test setup. A practical approach, rather than just theoretical, is advantageous for the design process as the choices made with the feedback will be as a result of real user experience rather than predicted theoretical values from research.

As with typical manual control systems, the input is dictated by the user, but the difference with force feedback is that the human is directly affected by the output in the same mechanism which is used to deliver the input. Thus, the human is very much in the loop which makes it a complex interaction to model, as the human is less predictable than the mechanical and electrical components of a typical controls system. With the practical design approach, the theoretical model of a human (in mechanical engineering literature) is replaced by a real life human, and the system is analyzed via user tests with a force feedback test setup.

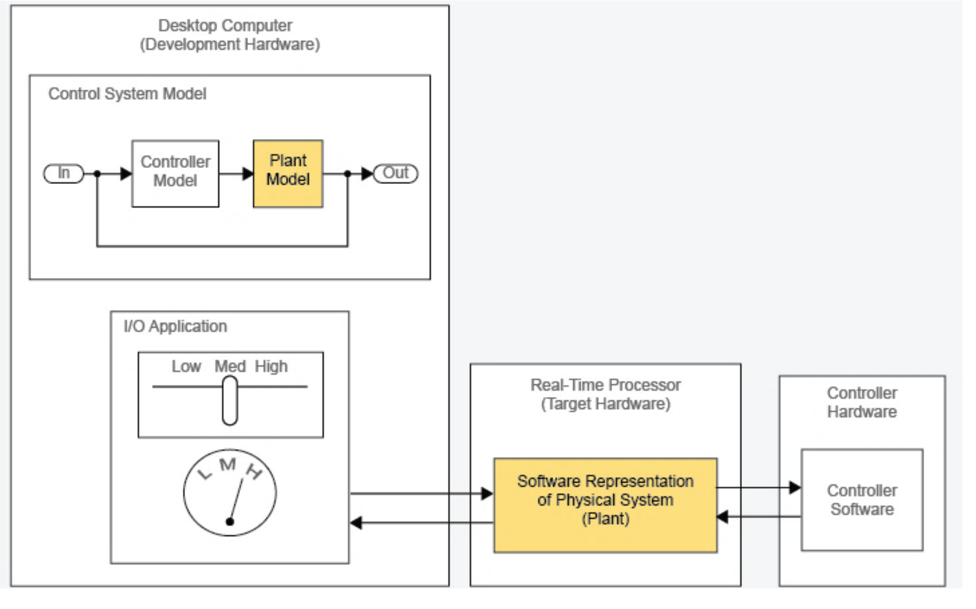
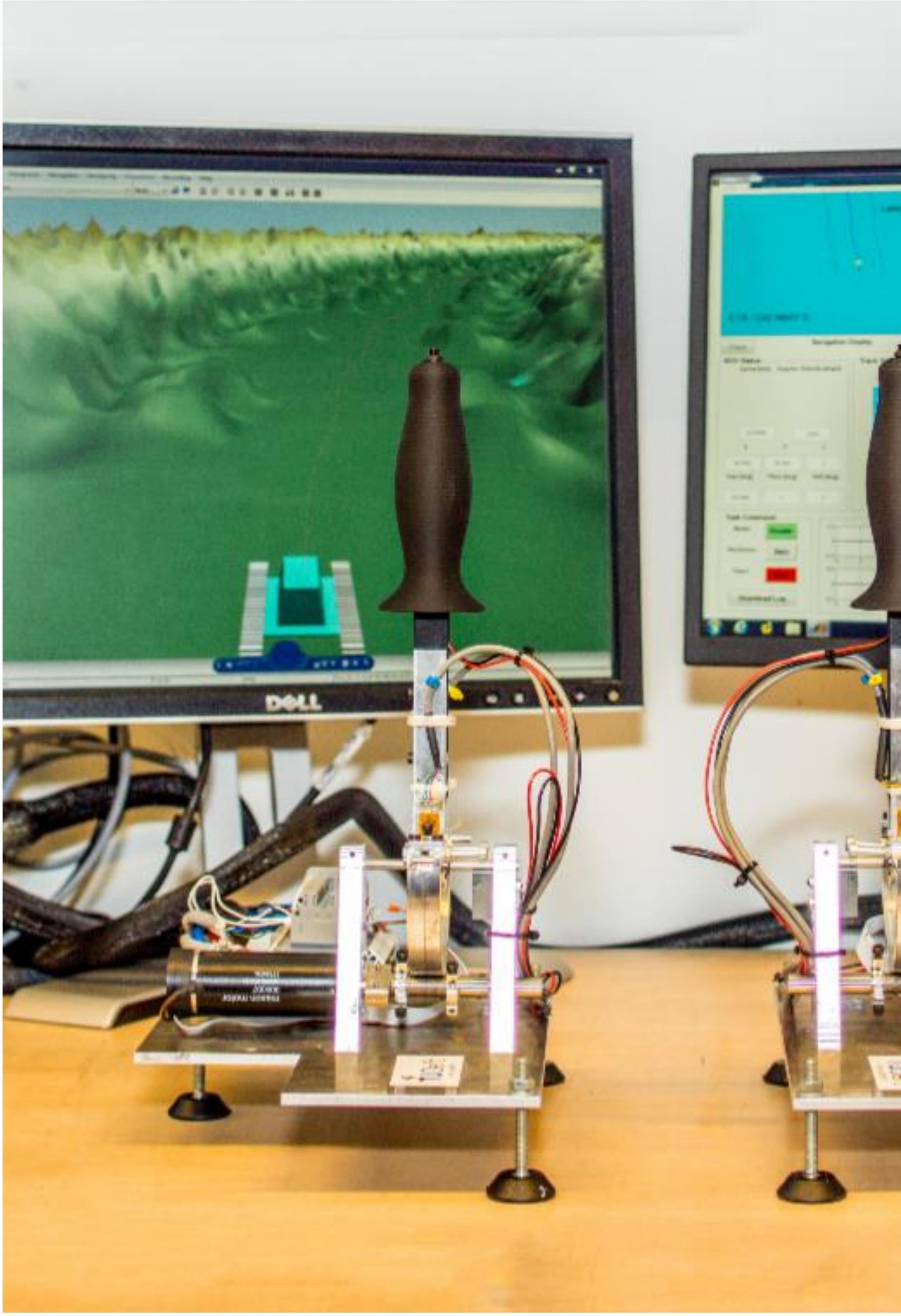


Figure 25: MATLAB Hardware In the Loop Diagram

PART 2 CONCLUSIONS



CONCLUSIONS

RQ3: What sensory information can be enhanced, simulated or reconstructed through force feedback for the offshore use case?

Feedback mechanisms, like rotary to linear force conversion or torque-increasing gears create different feedback experiences.

Different haptic cues should be based on user experience to be understood effectively. For example, more simple feedback in a chaotic environment can aid the operator rather than causing confusion or distraction.

Haptics integrated in multimodal environments can help balance sensory thresholds. The transparency level determines how reconstructed the forces should be.

Feedback must be delivered quickly for fast and continuous interpretation. Context factors like task environment, and target group can create meaningful haptic experiences.

RQ4: What physical aspects of haptic manipulators are most influential on user expectations?

The DOF, ergonomics, and limb movements from haptic manipulators impact its feedback mechanisms and user cognition of the task.

Understanding the cognitive and perceptual aspects of human interaction with the manipulator is essential in tailoring haptic feedback to user expectations effectively.

The design and manipulation of stimuli (material, weight, etc) can cue, invite, or dissociate certain responses.

The combined expertise of designers and mechanical engineers provide multidisciplinary perspectives to understand haptic technology's terminology, benefits, and limitations.

03 DEVELOP

03 DEVELOP

This chapter delves into the development of the proof-of-concept force feedback test set up system. First is use case selection and anti-sway exploration. Next is ideation of the simulated task, the feedback based on physics of the FJC, and the handheld manipulator. The simulation creates the force feedback felt in the designed manipulator and the hardware implements them. From ideation, initial concepts are created for user testing. The results are analysed for iteration and final concept development with haptic prototyping. The final concept is presented with relevant design choices, ready for user evaluation.

3.1 USE CASE SELECTION

3.1 USE CASE SELECTION

DECISION MATRIX

To determine the use case, a decision matrix is utilized. The categories were assistive haptic control, where it would guide the user to the correct placement or alignment. Repulsive haptic control would generate a contact force, or preemptive contact force. Accuracy in this sense means which is required for accurate coating. Dynamics is the use case being subject to the ship and environmental dynamics (Fig. 26). As see below, the most interesting aspect is that all use cases are affected by the dynamics of the ship. This brought about a new use case that is applicable to the six identified use cases, as well as any offshore application.

	PLACEMENT Z-AXIS	PLACEMENT X-AXIS	PLACEMENT Y-AXIS	BUMPER AXIAL ALIGNMENT	BUMPER FORCE	FILED JOINT ALIGNMENT
ASSITIVE	✓	✓	✓	✗	✗	✓
REPULSIVE	✗	✗	✗	✓	✓	✗
ACCURACY	✗	✓	✗	✓	✓	✓
DYNAMICS	✓	✓	✓	✓	✓	✓

ANTI-SWAY

All use cases are subjected to the sway and dynamics of the ocean. The operators might have sea legs, but the machines don't. Having them physically compensate while trying to be fast and controlled on every use case is extremely difficult and leads to dangerous situations. Therefore, the new use case that is most relevant for offshore applications is mitigating the sway of the FJC machines.

Figure 26: Ship Subject to Environment Loads

3.2 ANTI-SWAY EXPLORATION

3.2 ANTI-SWAY EXPLORATION

For all use cases, the machine is subject to the offshore dynamic environment. The sway of these machines cannot be mitigated in the same way as static contexts. The momentum of the machine can cause alignment issues and affect quality of coating. Furthermore, it can cause damage to the machine if remotely operated improperly. This creates an opportunity for force feedback to be implemented as an assistance for stabilization.

Oscillations are typically hard to understand unless felt. While possible to stabilize them visually, the user must interpret very quickly in this setting which can take years of experience. Hence, most onshore anti-sway optimizes control systems inside the trolley rather than using a human controller. As noted, humans are more flexible in dynamic environments, which is why the human operator remains in offshore applications. This sections aims to give more control to the human operator by understanding their perception of controlling sway and dealing with unpredictable machine swing.

Putting literature into practice, the embodiment and use of industrial teleoperated manipulators do not cognitively match the task at hand. This incongruency can be further exacerbated when applying haptics. Both need to be considered to provide the desired experience, in this case creating the feeling the control and efficiency to the operators. Especially without distracting or frustrating them.

PAYLOAD SENSITIVITY

Crane operation and its payload sensitivity closely resembles that of teleoperated FJC machines. On construction sites where the cranes are used, dynamic environmental factors like “changing wind loads, can also lead to payload sway ” (Fang 2018). However, on a ship the wind loads are combined with that of the waves, exacerbating the dynamics. If the FJC operators are no longer in the firing line to physically mitigate the movement, “the payload is sensitive to acceleration and deceleration, causing unwanted motions like load sways and bouncing.“ (Abdullahi 2018).

While this is the extreme case, even the overhead trolley systems on land are not completely effective. Most automatic anti-sway systems “are designed for single-pendulum cranes…where payload oscillation follow a more linear and modellable movement” (Zhang 2020). The trolley calculates and adjusts the movements based on fixed, pre-defined paths. Since the field joint is in a different location every time, and the sway can be in various directions, this approach can be applied, but is limited. For example, most of these controls simply limit the speed and are completely automatic. For FJC operation speed is essential, and the operators need to be in control in case there is error where the machine is placed.

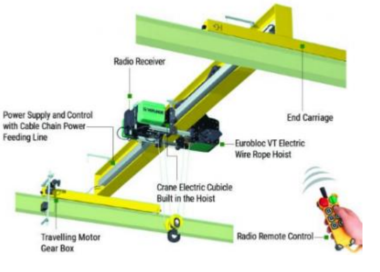


Figure 27: Overhead Trolley Control

COGNITIVE DISCONNECT

For teleoperating FJC, overhead trolley is assumed to be motorized. However, there is a disconnect between the user input and the machine operation. As mentioned previously, the trolley automatically reduces the sway. This reliance on automated machinery at a distant location "breaks the loop between the operators motor planning and perceived feedback" causing an inability to effectively integrate perceptual information with execution of voluntary behaviors (Finney, 2013). The operator is left confused and fighting their own actions since they are controlling a device that is not displaying its decisions. The control is now given solely to the machine. In conjunction, is the unintuitive HMI with only buttons to control the trolley. Despite advances in automatic sway technology, there is a need to create a more "natural sensorimotor coordination in complex crane operations, especially in now days industries almost all cranes are controlled by human operators" (Zhang 2020). There is no trust in the devices seen in Fig. 28 as they indirectly control the sway through the trolley, with extreme reliance on visual feedback. The current device in office (Fig 29) is extremely difficult to operate for large hands covered in gloves. Even with improved ergonomic and more intuitive designs, users found this teleoperation exhausting and frustrating (Ref. Chapter 4). Users validated this disconnect and lack of trust and control (Fig. 30).

Figure 28: Overhead Trolley With Controller

Figure 29: Allseas Current Handheld HMI

CONCLUSIONS

There is a vast amount of research on optimizing trolley automatic anti-sway, yet they still rely on user input. This input is quite limited and lacks control or feedback on the machine operation. To integrate haptics, shared control or assistive feedback could allow for more information or trust in in the machine. This could fix the cognitive disconnect, and put focus on the single task, rather than splitting the operators focus. More ergonomic controls and intuitive feedback can mitigate sway in dynamic environments. The simulation needs to include the parameters to make the swing accurate, and the feedback must match what the user expects to feel (angle, velocity, weight, etc).

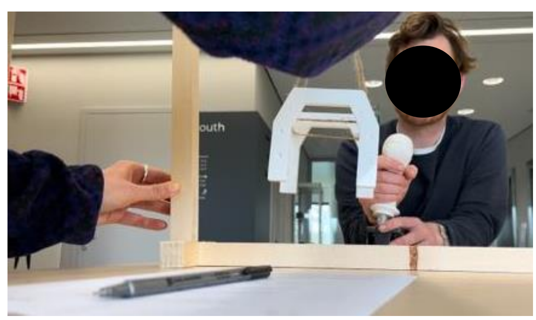


Figure 30: Example of User Test Control

"I am trying to make the machine not go out of control, but it's hard not to look at the trolley." – Test User

3.3 IDEATION

3.3 IDEATION

First round of idea generation encompassed all three solution spaces (simulation, feedback, and manipulator) in a mind map (Fig. 31). This fueled different possibilities, but the scope is reduced by returning to the initial requirements of the assignment. Once the system is understood, each space was ideated in isolation. The design process was iterative, and the three spaces are dependent on one another, so when one solution as developed, it was checked for compatibility with the others before moving forward.

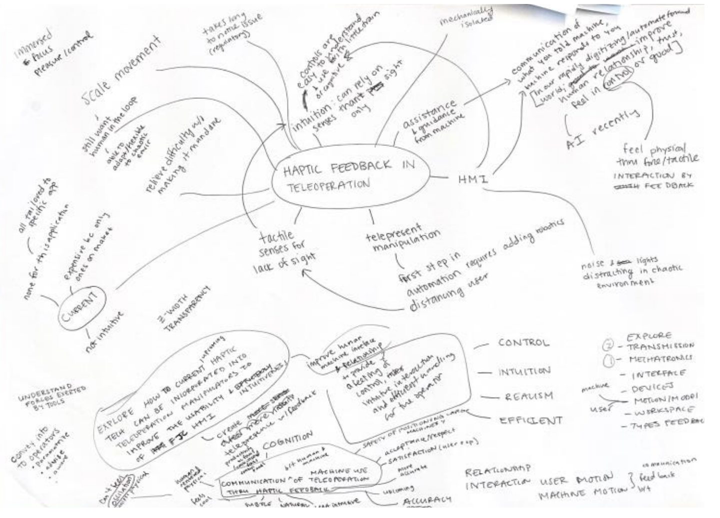


Figure 31: System Mind Map

SIMULATION

The simulation recreates the FJC machine dynamics and allows for rapid iterations of the control system and feedback parameters. The physical parameters such as machine weight, trolley distance, etc. are kept constant. The visual correlates to the chosen physics model and its equations of motion. After ideation, literature, and discussion with colleagues, a single pendulum is the basis of dynamics model for FJC predicted behavior (Fig 32 and Appendix 6-7). The degrees of freedom, or moving parts, are determined as the payload swing (1 DOF) and the horizontal overhead trolley (1 DOF). Before developing the simulation, this physics model and task associated with it is tested with users (3.4).

FEEDBACK

After definition of FJC dynamics, the machine output feedback must be chosen based on the equation of motions. The physics model and reference to literature such as Farkhatdinov and Ryu (2008) gave insight on which elements to design for. Since the use case is sway, the parameters of the machines swing (rotational) will be the feedback. However, the user controls the trolley movement linearly. Ideation for intuitive feedback for conflicting movements is conducted resulting in three forms. However, force feedback must be felt in order to understand and design for it (explored in 3.6). Lastly, intention of the feedback is ideated on, such as assisted control or error prevention.

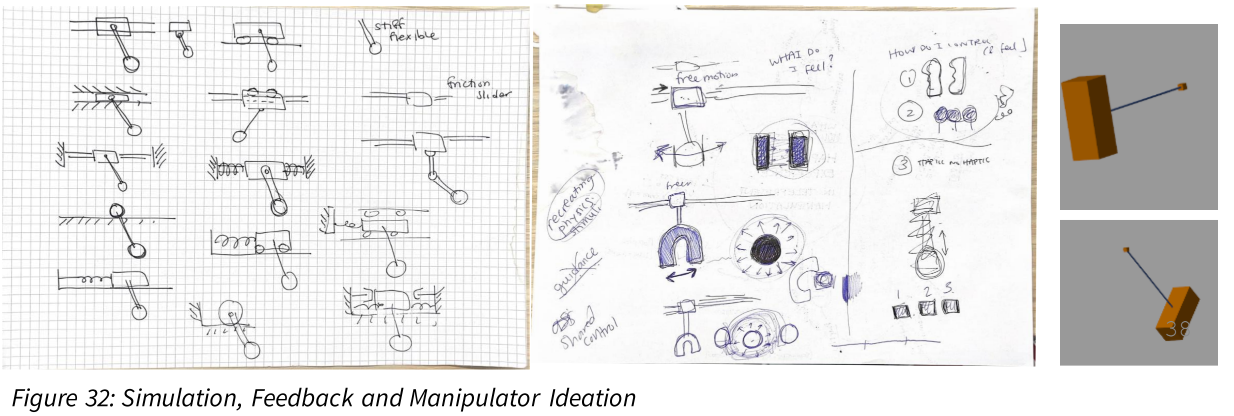


Figure 32: Simulation, Feedback and Manipulator Ideation

Figure 33: Force Feedback Technology

ADDITION RESEARCH: HAPTIC TECHNOLOGY

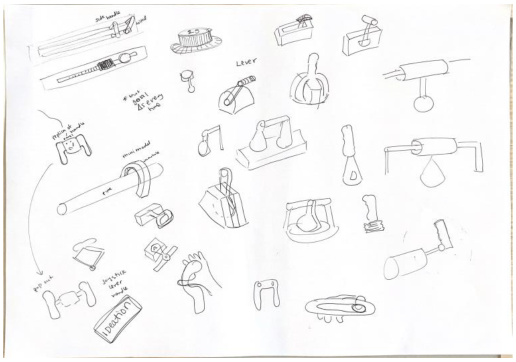
Despite limited knowledge of the design process, the existing technology and mechanisms are readily available for implementation. Haptic perception relies on sensory signals derived from mechanical interactions, encompassing contact forces, torques, object and limb movement, and object mass or weight. To achieve effective haptic feedback, different types of technologies are utilized. Each are tailored to specific applications and integrated with the form to create diverse experiences.

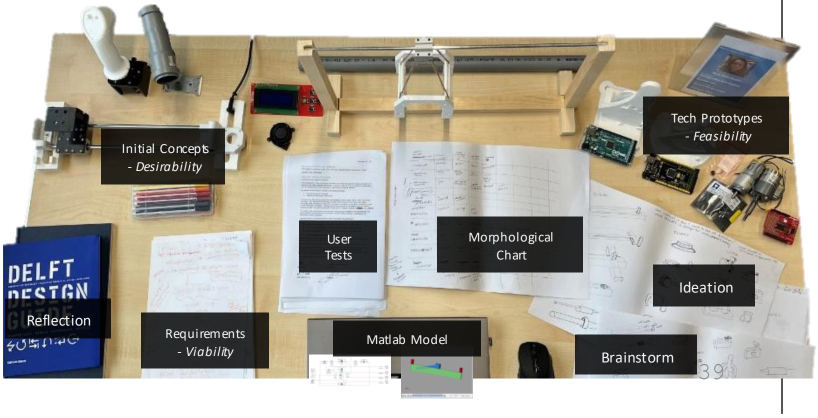
Force feedback requires the presence of actuators, drivers, and transmission mechanisms. Actuators must be capable of moving the manipulator to a certain degree. The force applied should be substantial enough, yet intuitive for users. The design must ensure that users do not feel the transmissions of the device itself, allowing for seamless interaction. Additionally, sensor accuracy and low latency are needed to incite an immediate and intuitive reflex from users, reducing the need for interpretation.

MANIPULATOR

For the handheld manipulator, current manipulator embodiments are explored for inspiration (Appendix 6-7) Iindustrial contexts remains relatively limited and often fragmented as they are still in research phases. There is a reliance on general forms, which might be from lack of available products. For example, one study reuses two surgery pen manipulators to operate a crane, which works but is not optimal for the task (Zhu 2022). This manipulator embodiment can be confusing and unfit for efficient user operation. While elements of these forms might be useful for the task, iteration or redesign could make them better suited for the task. Understanding why these forms are still used can bring insight on what elements to bring to the next design phases. After brainstorm, cluster, and using a morphological chart, three basic forms are created in conjunction with the payload swing use case (Appendix 6-7). The intention is to control the trolley, but still incorporate that the goal is to mitigate sway through relevant embodiment design.

In understanding haptic interactions, the human body can be modeled as a mass-spring-damper system, where muscles, bones, and neurons play essential roles. Human users can actively control the stiffness of their muscles, contributing to the perception of haptic feedback and making it an integral part of the design process. The most relevant muscle movement should be tested.





3.4 CONCEPT USER TEST

3.4 CONCEPT USER TEST

The goal of this test is to find ways to improve three common manipulator embodiments to fit the anti-sway use case and designed task. Specifically, the purpose is to discover which elements of the form and arm movement is most intuitive and provided more control for the users. Three common embodiments for teleoperation manipulation are developed with some iterations to fit the task of controlling a trolley with FJC load sway. This test addresses the cognitive load theory and evaluates the disconnect between user input and machine output through the HMI design (like the button of trolley). The set up is seen in Fig. 34.

I will control the sliding trolley and excite the machine, which is physically built to match the dynamics of a single pendulum. The user will try to mitigate the swing by controlling the trolley using each embodiment. After each embodiment is used, the user answers how intuitive the control was. The test questions and data can be seen in Appendix 8. A pilot test is conducted with industrial designer peers before testing with the real users in the office. The Allseas office personal are the target users. The various departments will provide insight from different levels of experience and expectations, but still, that of the offshore context.

CONCEPT EMBODIMENTS

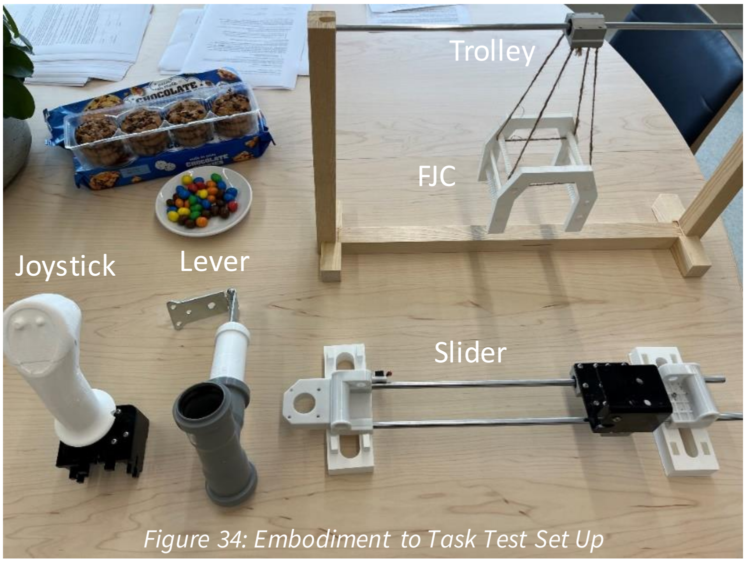


Figure 34: Embodiment to Task Test Set Up

Below are embodiment descriptions and hypothesis for the test. There is no force feedback in these forms.

Slider: common in less industrial applications like light switches, sound boards, and other adjustable mechanisms.

Hypothesis: The slider can be intuitive in terms of the linear movement and large range of motion. However, the slider will be least intuitive for sway cognition.

Joystick: most common form, used in aircrafts, gaming, and many other applications due to its general shape and grip.

Hypothesis: Joystick will be the favourite grip and handle. However, it will not be the most intuitive for the task due to limited range of motion.

Lever: usually situated vertically, hence this interaction is side to side to fit the task. The movement of the arm is wider, and the grip is also large enough to feel control.

Hypothesis: Lever will be more intuitive for the task since more stroke follows the linear motion more. Lever is less common so it might take some time to get used to.

USER TEST RESULTS

The results on the right show that the joystick is scored as most the most intuitive (Appendix 8). However, it's important to note that the joystick is rated higher because familiarity, but users remark how it has less range of motion for this application.

With more resistance, the lever would be easier to control and intuitive. One user states, "If know centre or there was some resistance, I would prefer this stroke and arm movement." Therefore, a combination of both embodiment properties could yield more intuitive control.

One user verified "not having feedback sucks, especially because taking eyes off the trolley/machine to look at the controller feels dangerous." This validates the cognitive disconnect explored earlier.

INTUITIVE USE SCORES

	Joystick	Lever	Slider
Mean	3.8	3.5	2
Median	4	3	2
Sum	52	47	36

ADDITIONAL INSIGHT

Various users provided insight on crane operator controls, state that "operators will smash through everything, breaking generic joysticks and prioritize speed." Not only does this mean the embodiment has to be robust, but also it is useful to design the embodiment in a way that guides the user to interact a certain way. From observing user motions, it can be assumed that the speed of the operator can also attest to frustration. The frustration derives from the machine not operating in the expected way, such as a delay from the device input. This also could be from the user expecting the device to meet the expectations of its embodiment. Al imitation of the test is that I was controlling the trolley, so there is still some disconnect between user input and machine output. Lastly, people want the device for their own HIL test set up to see what their simulations would feel like, generating buzz in the office.

Figure 35: User Test Interactions

3.5 CONCEPT DEVELOPMENT
3.5 CONCEPT DEVELOPMENT

The concept development includes three solution spaces, the simulation design, feedback design, and manipulator design. The simulation and manipulator are physical manifestations that are guided by the feedback design. Therefore, the methods for simulation and manipulator are described, with feedback design integrated as the main goal and directing the development.

SIMULATION DESIGN METHOD

The V-method is a common control and system engineering method. Within each stage is an iteration and testing loop. In this case Arduino code, motor hardware, and simulation are tested in isolation as well as with the system. Debugging and finding error and optimization piece by piece is necessary.

Design of the model and control loop creates a blueprint and foundation for how to build on the system. Starting simple is key. The first iteration is just the trolley, then attachment, then load. Once one element is figured out, the rest is easier to build upon, which is the characteristic nature of virtual prototyping and building a model. While various literature on simulation without hardware and haptics, they provide necessary information such as Fig 36 from as Farkhatdinov and Ryu (2008).

Real time simulation is chosen, due to its accuracy and need for user input to directly affect machine output. MATLAB Simulink is chosen due to Allseas familiarity with the software as well as the known connection for real time HIL testing.

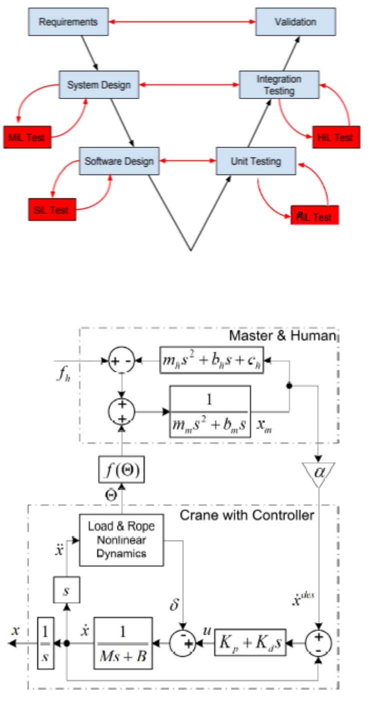
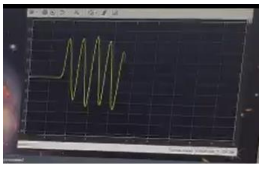


Figure 36: V-Method & Model

VIRTUAL PROTOTYPING

Virtual prototyping allows for rapid iteration and model adjustments for simulation of the desired experience. This falls under the Simulation category of haptic theory, since it is reconstructing the FJC forces for this envisioned teleoperation future. The physics model does not stay in isolation. The human input needs to be considered and modelled as well, with a controller, which is what converts the input into a force (Fig. 37). The Vanderbilt Simulink model is used as a basis for set up and learning how connect to hardware but is completely reconstructed to fit the FJC pendulum model (Appendix 9). The equations of motions are derived, and three types of force feedback are taken from the machine movement, specifically the sway angle, angular velocity, and a combination of both (Appendix 9). The most difficult step is connecting the hardware to the software. Much patience, time, and debugging is needed. Furthermore, trying different elements of feedback from the equations of motions only works with the hardware connected. Different forces from the same model can feel very intuitive or really distract the user.



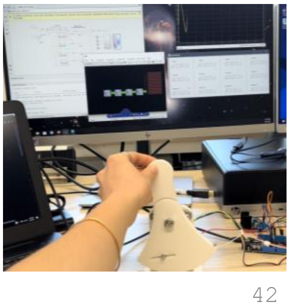


Figure 37: Testing Device Input

MANIPULATOR DESIGN METHOD

The “Frankenstein Method” is about building piece by piece, testing each in isolation as well as in the system. Each piece must be designed with the intention of working with the others, but the validation of each component working individually brings greater understanding of how to optimize the performance. Hands on testing is the only way to understand how the mechanisms feel and the transmission of the feedback. The reliance on our sense of touch is vital to understand how different mechanisms can influence the feedback. Only after exploring and testing can the perception, expectations, and overall desired experience can be created. A/B testing and rapid prototyping is essential to feel the transmission of the mechanical components and ensure they do not interfere with the resistance, friction, or other elements that could ruin the haptic feedback. To understand the basic of HIL haptic design, the Stanford, Rice, Vanderbilt, and ETH University haptics kits were studied (Appendix 10). Their design and technology are outdated (2012) are only for educational and research purposes hence they are heavily redesigned. Mechanical optimization and lecture slides from the TU Delft haptics lab are also referenced in the design process. From left to right, Fig. 38 depicts this process.

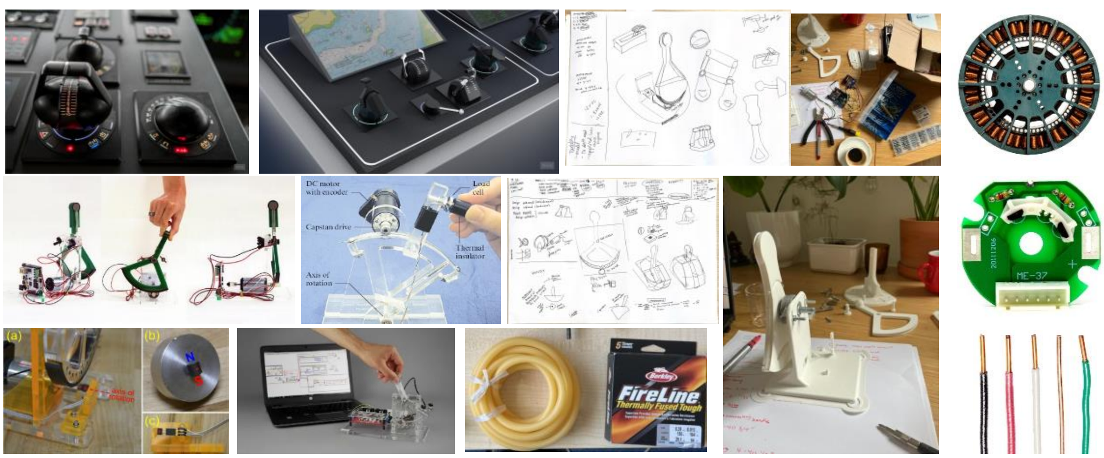


Figure 38: Inspiration, Research, Sketching, Iteration Process

MANIPULATOR PROTOTYPING

First, inspiration is drawn in mood boards as well as embodiments and control mechanisms that fit the anti-sway use case, and the desired intuitive feedback movement. The simulation and task design is constantly referenced to make sure the rotation, stroke, and shape of the embodiment matched the task. Trolley position or velocity control must be intuitive, as well as the machine sway feedback movement in the device. The device must also work equally without teleoperation, so there is the choice to turn or reduce the haptics if necessary.

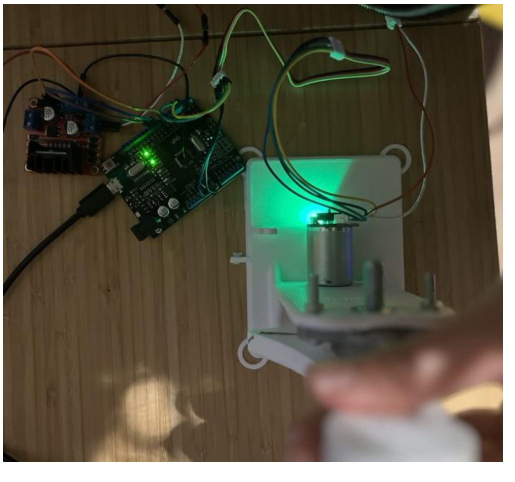


Figure 39: Hardware Testing

INITIAL USER FEEDBACK

To identify and fix initial bugs and optimize the proof-of-concept test set up performance, the Rapid Iterative Testing and Evaluation is conducted before testing with target users (RITE, n.d.). Figure 40 depicts the approach. This iterative feedback testing is useful for force feedback, since it is a new technology for most people. Furthermore, haptics needs to be felt in order to tailor its interaction to the task. Five users were asked to excite and stabilize the simulation. Each user had feedback which was adopted in the next iteration. The validation of the improvement is if the next user does not see the issue or notice the change as the issue.

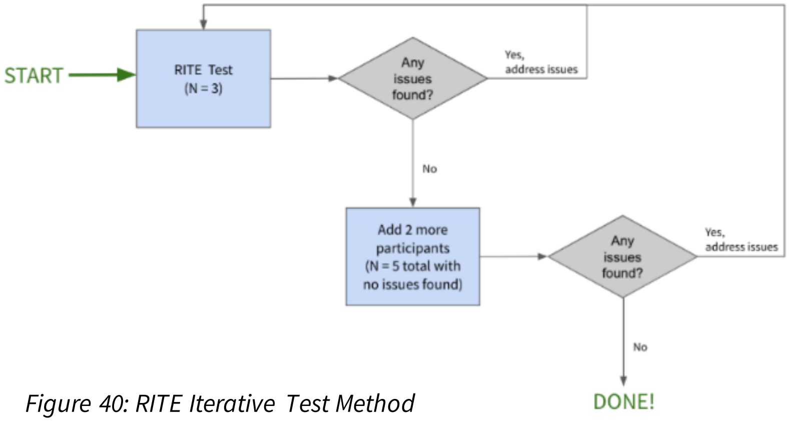


Figure 40: RITE Iterative Test Method

SIMULATION USE CASE & FEEDBACK INSIGHTS

This method allowed for rapid iteration and validation of each design choice.

First note was the model visual, making it clear that it is an FJC machine and that the trolley friction is reduced to have more realistic movement. Different colors differentiated the pieces which allowed for less interpretation and more focus on the feedback. From three feedback types (Appendix 9) the mid level transparency is chosen, which is based on the angular velocity of machine. Furthermore, users wanted assistance, so the force resisting the direction of control, so the user was clued where to go.

Lastly an excite button was added to have uniform start sway.

Figure 41: RITE Test With User

MANIPULATOR INSIGHTS

Paddle shape and design was edited to have a cut out on the top, for change of ergonomic grip for the future. These parts were 3d printed and connected with bearings and screws. A power supply is added which added consistent motor movement due to regulated power vs. batteries. This increased the voltage to 7.5V which then needed feedback gain adjustments. This more powerful feedback made the device base require a solid board to weigh it down. An instruction manual is added as well (Appendix 11-12).

To minimize latency and smooth transmission, the motor gearbox is removed. More RPM allows for a wider range of movement while still providing the necessary resistance.

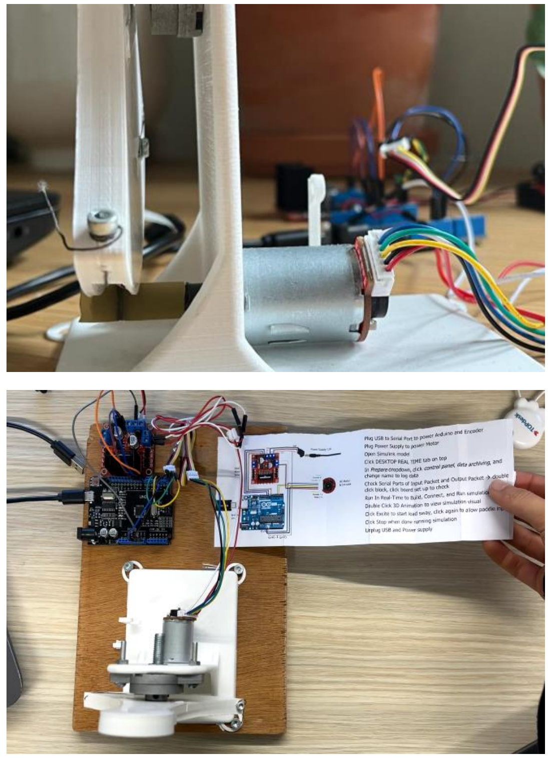


Figure 42: Iteration and Rebuild

LIMITATIONS GOING INTO FINAL CONCEPT

Figure 43: In House Construction

The test set up is a proof of concept for force feedback in offshore application. Furthermore, it is an exploration on feedback types, use cases, and design implementation of HMI. Therefore, this is not a final design of what should be implemented on board. Most importantly, the purpose is to understand and incorporate the user perspective and how that affects the force feedback design process.

This feedback is only for one degree of freedom manipulator and in only one element of the use case. There are no outside environmental factors influencing the physical model. Lastly, the simulation reconstructs the FJC but in an envisioned setting. As a simulation, it is not accurate to the real machine movement and is limited by the parameters that are set.

3.6 FINAL CONCEPT
3.6 FINAL CONCEPT

The final concept is Paddy, the fully functional teleoperation with force feedback test set up. The name is shorthand for the paddle shape. Paddy includes the simulation and visual, feedback technology, and manipulator embodiment. The three solution spaces with design choices are described.

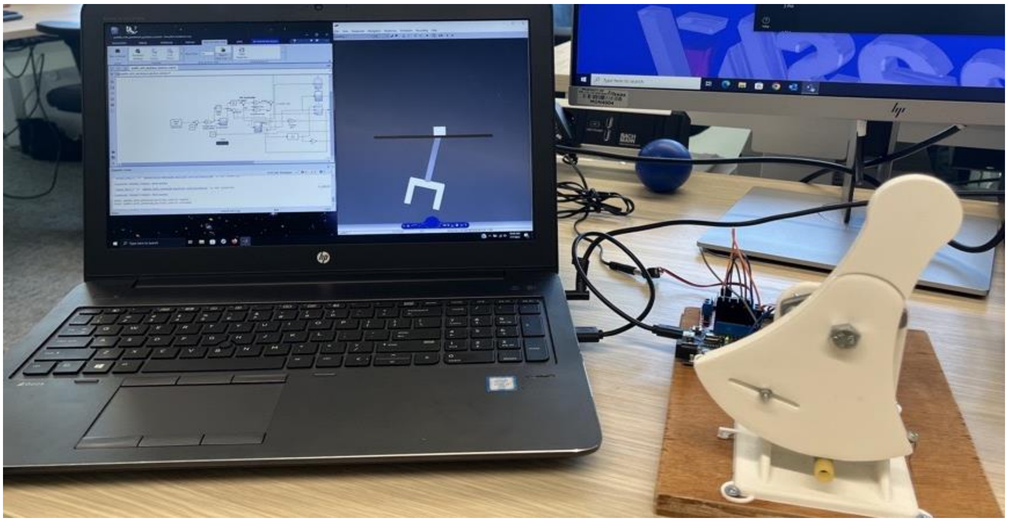


Figure 44: Test Set Up With Simulink Simulation (left) and Manipulator with Hardware (right)

SIMULATION

Processor Coding
Arduino code converts encoder position to bytes for the software to read. Provides motor control and encoder input readings.

Real-Time Software
Simulink model creates EOM and calculates angular velocity feedback. Peer tested gains for intuitive force strength in assistance.

Task Visual
Trolley & FJC Visual moves with paddle input. Resembles and follows the physics with minimal latency

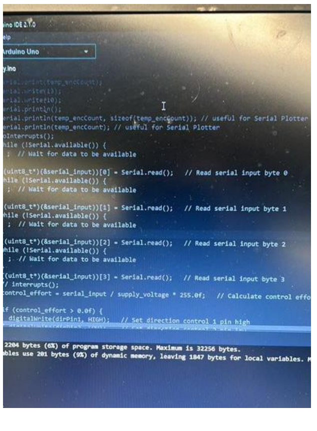


Figure 45: Arduino Code

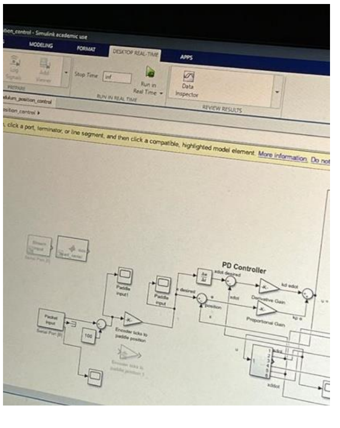


Figure 46: Simulink Model

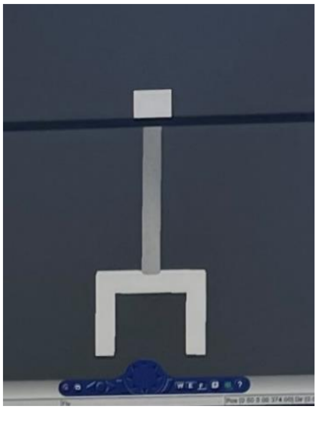


Figure 47: Simulink Visual

FEEDBACK MECHANISMS

Processor
Arduino & Motor Driver allows for iterative prototyping and open-source code for proof of concept. Need to understand voltage amps and power supplies, plus circuitry.

Actuator
12V DC Motor without gearbox for less resistance other than feedback. Power of motor makes significant difference in actuation.

Sensor
Absolute encoder made with hall sensors and magnet already mounted onto dc motor. Must put in original position each time.

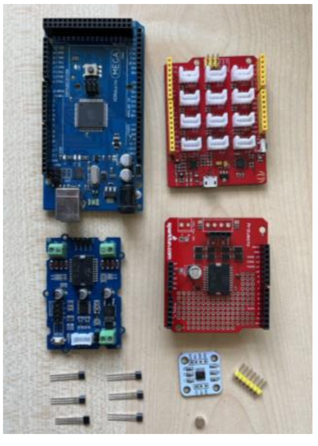


Figure 48: Arduino & Driver

Figure 49: DC Motors

Figure 50: Absolute Encoder

MANIPULATOR

Transmission
Capstan wire reduces friction and slip. Adjustable wire tension. User can't feel effects of rotation of motor shaft

Embodiment
Paddle shape and rotation mimics the trolley top & pendulum load. Bearing allows for smooth rotation.

Drive
Motor Shaft cover smoothly delivering force to user. Allow more RPM of motor allows more range of motion

Figure 51: Capstan Wire

Figure 52: Embodiment

Figure 53: Drive Iteration

DEVELOP CONCLUSIONS

CONCLUSIONS

RQ5: What types of haptic technology can communicate the forces acted on the machines to the operator?

Technology is accessible, but limited availability of devices, design choices, or documentation.

Before ideation, need to understand which forces from the use case should be implemented. Then design the type of experience to create with the technology.

Consider the transmission components used or when forces are translated or combined as to not take away from feedback experience.

Haptic cues through varying resistance and stiffness convey machine states and obstacles. Typically accomplished via actuator, sensor and microprocessor.

Insights on The Development, Design, and Prototyping Process

A simple model is sufficient for certain task, such as anti-sway, while other models should be fleshed out before testing.

Hands-on prototyping is necessary to design effective manipulator and feedback mechanisms.

Continuous evaluation leads to improved manipulator performance and feedback. When evaluating, first step is to block other inputs i.e. test one form of DOF of the force before adding another.

The meaning of haptics emerges after integration with other modalities and data, in this case the visual simulation, sound of motor, manipulator material, etc.

Small changes to the physical design and mechanisms immediately affect how the forces are experienced.

Prototyping connects all the design solution spaces together in one test set up. Each piece should be tested in isolation as well as in the system.

04 VALIDATE

04 VALIDATE

This chapter delves into validation the force feedback test set up. The test purpose supported by several hypothesis is formed to inform future development and validate the current test set up. The methods are discussed and tested with a pilot test to check for error and create or more robust official user test. The results are statistically calculated and discussed. Lastly, conclusions are drawn based on the findings and analysis.

4.1 TEST PURPOSE
4.1 TEST PURPOSE

The purpose of the test is to evaluate the user's perceived usefulness, workload, and acceptance of teleoperation with and without force feedback. This test will also evaluate the design process of the test set up, through discussion on certain design choices. As discussed in Chapter 3, how to design with and for force feedback is not well documented and exists only in niche industries or with haptic researchers. The use case will also be analysed by the target group based on their prior experience with FJC machines, pipelay, automation, or similar crane operation.

DESIGNED EXPERIMENT

The designed experiment is to test anti-sway of field joint coating machines with teleoperation via the Paddy manipulator and simulation. These machines are suspended from an overhead trolley which dictates its position. The task is to control the position of the trolley in order to mitigate the sway of the machine until it is stabilized. There is a practice period, then the first trial is performed three times. Then NASA TLX scale (five questions) and the UMUX-LITE scale (two questions) are answered. This is repeated with the second trial. After the trials, they will answer four discussion questions.

Figure 54: Office Test Set Up

HYPOTHESIS

1. Users mitigating the sway with Paddy will perceive the task as easier with force feedback than without.
2. Users mitigating the sway with Paddy will have lower perceived workload of the task when using force feedback than without.
3. Users mitigating the sway with Paddy will finish the task faster when using force feedback than without.
4. Users will favour force feedback when asked which feedback is more intuitive, gives more user control, and which more enjoyed.

4.2 USER TEST PLAN

4.2 USER TEST PLAN

METHODS

To test the hypothesis and gather data, various methods are employed. Before the task, the users answer three prior experience questions (HIL, video games, FJC operation, and crane operation) using the Likert scale. Out of the twelve Allseas personnel tested, six start with Trial A, visual only, and other six start with Trial B, to get more unbiased results. Each trial consists of a practice run for familiarity and then three attempts. Then the perceived usefulness and usability are asked on the UMUX LITE 7-point scale. The perceived workload is asked on the NASA TLX 21-point scale. Then the next trial is tested, and scale is filled out again for comparison. After the entire test, perceived acceptance is asked through discussion questions based on the Van der Laan scale. For all attempts, MATLAB records the excite button (that excites the machine uniformly to each user), user input, machine output and time of each. This allows for calculation of machine stabilization time and number of reversals. Lastly, a picture is taken of how the user holds the device to analyse how hand placement affects feedback distribution. (Full test in Appendix 13).

PARTICIPANTS

Participants are recruited from various Allseas departments (R&D, Naval, Pipelay, Controls) to get perspective from all the people who would further develop this device. Also, they were chosen based on varied experience to see the comparison between users with and without experience with FJC or anti-sway controls.

PILOT TEST

A pilot test with seven users from Allseas and industrial design peers provided promising initial results for haptics and allowed for a test iteration to acquire more robust results.

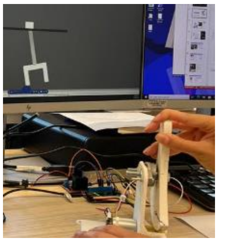


Figure 55: Pilot Test

LIMITATIONS

Limitations include the target group. While most of them have some prior experience with the intended use case and FJC machines, they are not full time FJC operators. Therefore, the assumptions and conclusions made are limited to the subjectivity of those tested. However, real operators are not necessary for this initial stage to prove the concept. The R&D engineers will be the developers of this device and their insight on equipment design for offshore applications will suffice. Additionally, by testing with various departments, these users collaborate with different operators, yielding insight on similar anti-sway controllers like crane operators. For the intention of proving the concept of haptics for offshore use cases, these participants and their insights are enough to validate the first stage.

The excitement of the machine is exaggerated to analyse the force feedback. While the physics are correct, the amount of sway is in an extreme situation. The test focuses more on the user's perception of the force feedback, and its relevance in initial stages of the force feedback design process. This is not a final or even mid stage prototype that needs complete accuracy. Lastly, there are no other environmental or contextual factors in the simulation. Therefore, no complete conclusions on offshore environment applications can be claimed without further tests.

4.3 QUANTITATIVE RESULT & ANALYSIS
4.3 QUANTITATIVE RESULT & ANALYSIS

The quantitative results and analysis of the test are shown for perceived acceptance, perceived workload, and stabilization time. The mean, median, p-values and significance are shown for the resulting data. For UMUX-LITE, there is a standardized calculation and SUS evaluation (Admin, 2023). The Key shows visual only vs. visual with force feedback (FF).

PERCEIVED ACCEPTANCE

The perceived acceptance, described via UMUX-LITE and SUS results from the users, are displayed in Figures 56 and 57. The questions asked are if the device, Paddy, meets their requirements, and is easy to use.

Between visual and force feedback, there is a slight difference, by 8% and 7%, favoring the force feedback case. For reference, the averages are also shown for the how the user felt the device met requirements and was easy to use. To calculate the P-values, normality of the data is first checked to determine the method to be used (Appendix 14). For meeting requirements, the mean and median are significantly favorable for force feedback (p-value < 0.05) , while for ease of use there is not much difference. These results imply that the force feedback device is favorable for the user with regards to meeting the requirements for completing the task. However, for ease-of-use, more testing with a larger sample size will provide more clarity.

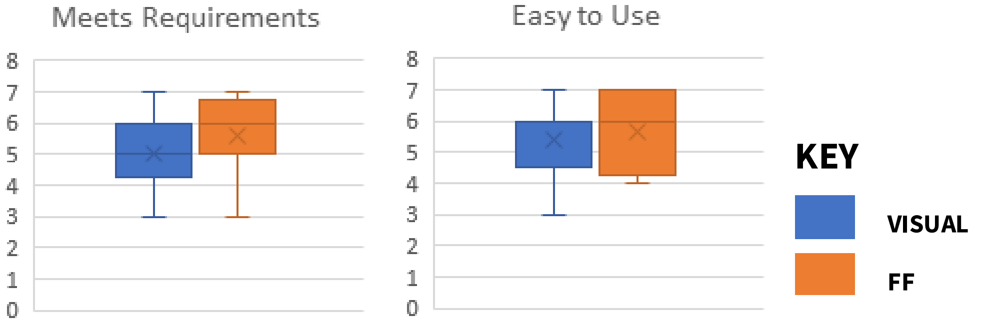


Figure 56: UMUX-LITE Scores

TRIALS	UMUX -LITE	SUS	REQ MEAN (MEDIAN)	EASY MEAN (MEDIAN)
Visual	86.81	68.5	5 (5)	5.42(6)
FF	93.76	73.01	5.59 (6)	5.67 (6)
% Difference	+8%	+7%	+12% (+20%)	+5% (0%)
P-Value	-	-	0.014	0.286

Figure 57: UMUX-Lite Evaluation

PERCIEVED WORKLOAD

The NASA Task Load Index (TLX) test is used to quantify the perceived workload the users have while using the device during the test. Figure 59 summarizes these results, with averages of the responses and statistical significance. Overall, the TLX results showed a normal distribution (Appendix 14), thus paired t-tests are used to quantify significance. For mental demand, the results are similar between the feedback options. This is logical since processing the visual feedback takes most of the mental load, which is present in both tests. For physical demand, it is not surprising that force feedback scores higher with significance. This implies that the feedback force impacts the user and is important to fine tune.

For the performance ratings, the scale is such that higher results mean the user felt less successful. For this, there is a significant difference between the cases with only visual feedback and those with force feedback. The users felt more successful at completing the task when force feedback was present. With visual feedback only, the users will overcompensate and not have a good feel for how much they should push against the sway. This point is also supported by the frustration metric, where users felt more frustrated with the visual feedback only case. However, without major significance, these results are only implications and require testing with a larger sample size.

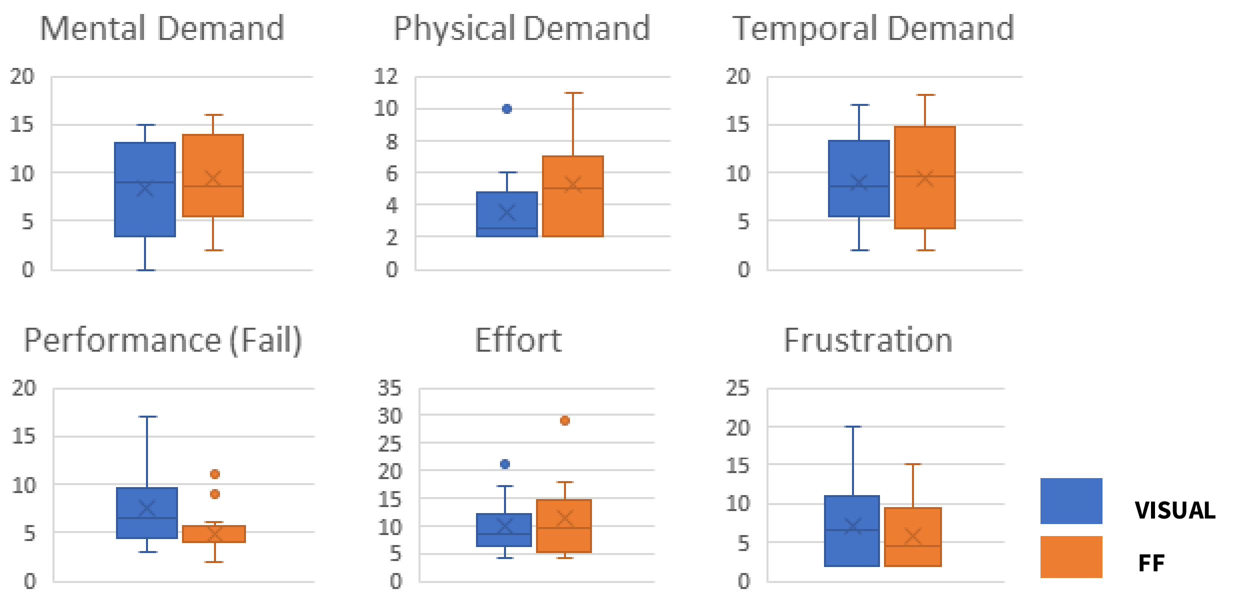


Figure 58: Workload Results

VARIABLE	P-VAL	SIG	VISUAL MEAN (MEDIAN)	FF MEAN (MEDIAN)
Mental Demand	0.354	No	9 (9.5)	9.34 (8.5)
Physical Demand	0.035	Yes	3.59 (2.5)	5.25 (5)
Temporal Demand	0.189	No	8.92 (8.5)	9.42 (9.5)
Performance (Failure)	0.024	Yes	7.5 (6.5)	4.92 (4)
Effort	0.158	No	10 (8.5)	11.25 (9.5)
Frustration	0.234	No	7 (6.5)	5.75 (4.5)

Figure 59: Workload Statistics

STABILIZATION TIME

The stabilization time is calculated as the time from the start of the test, when the pendulum is most excited and the user gains control of the trolley, until the end of the test, when they manage to stop the pendulum motion from swinging (within 1 degree of the natural laying position).

From the data of the twelve users, the mean, median, and standard deviation are calculated for stabilization times. The two data sets do not represent a normal distribution (Appendix 14), so to test for significance the non-parametric Mann-Whitney U-test is used to determine the P-values (Figure 61). With haptic feedback, both the mean and median of stabilization time are lower, by 15% and 23%, respectively. This suggests that haptic feedback could lead to a faster reduction in sway. However, a larger sample size is necessary to confirm this.

The standard deviation is lower for the force feedback case by 17%. The standard deviation provides insight on the variability of the results, thus the haptic feedback tests had more consistent stabilization times as compared to the tests with only visual feedback.

The P-Values for the time statistics are not less than 0.05 so thus there is not statistical significance between the results. However, there is still a difference in the results, as showed by the mean, median, and standard deviation. It indicates that the tests are similar in that they are both the same simulation of a swaying machine, with the only difference being the inclusion of force feedback.

Figure 60 shows examples of the data, where position (in degrees) is on the vertical axis, and time (in seconds) on the horizontal. Most users did well by counteracting the machine position with their input in the first 5 seconds, however the people with longer times showed to keep moving the paddle and changing their input after it was necessary.

Lastly, its noted that those who started with haptics had a shorter learning period for visual. Conversely, those who started with visual had a lot longer learning period. This can imply that force feedback brings more situational awareness, hence faster times or optimized performance.

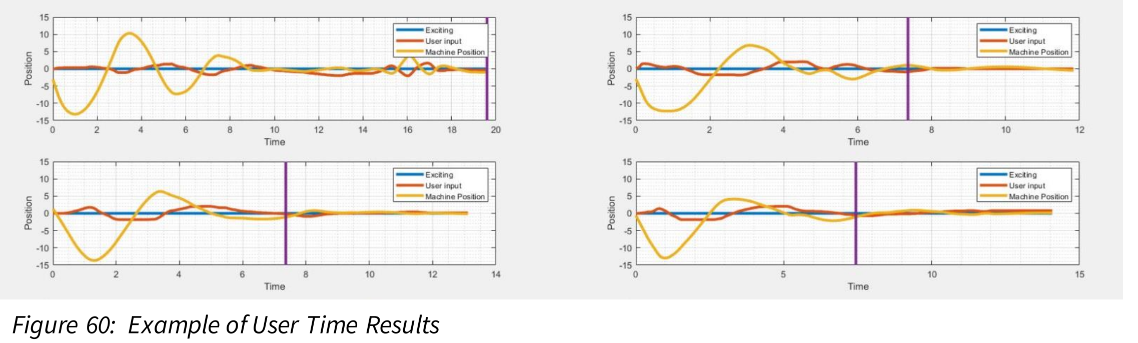


Figure 60: Example of User Time Results

TRIALS	MEAN (seconds)	MEDIAN (seconds)	STD. DEV (seconds)	P-VAL	SIG
Visual	13.9	11.3	9.4	0.246	No
FF	11.8	8.7	7.8		
% Difference	-15%	-23%	-17%	-	-

Figure 61: Time Statistics

4.4 QUALITATIVE RESULT & ANALYSIS
4.4 QUALITATIVE RESULT & ANALYSIS

Qualitative analysis derives from post-test discussion questions. Thematic analysis is used to identify themes as in “topics, ideas and patterns of meaning that come up repeatedly” (Caulfield, 2023). User quotes are selected that best represent the identified thematic answer. The users are asked if visual or force feedback is more intuitive, provides more control, and gives more enjoyment or engagement. The pictures of user handling is also analysed.

KEY

VISUAL

FF

INTUITIVE

Force feedback is considered more intuitive by most users. Users stated that “now they know the behaviour” and that it was an “extra dimension confirming what you see.” These users believed that they responded quicker to the forces because it was a natural response to the assistance. However, some users thought the feedback was unintuitive wishing it was flipped to be error prevention rather than assistance. These users felt that the force feedback “is fighting me, like it was different to what I thought of the visual.” This could be a next test iteration with the feedback reversed (error prevention). While not validated, it is noted that two users returned to test with the reversed feedback and found it much more intuitive.

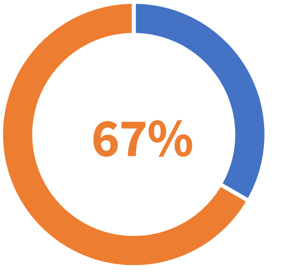


Figure 62: Intuitive Stats

CONTROL

The feeling of control is more split, with force feedback only slightly favored. The users who felt in control with force feedback believe it “really felt like I was in connection with the machine” and they “knew what I was doing all the time rather than guesswork.” Some users who were torn thought “I felt more control with larger swings, but I wanted more linear feedback for the small angles.” The variation in forces should be tested, as well as which forces feel more control for those with operator experience. These users tended to feel more control with the visual, based on already knowing how the pendulum load works. They didn’t “want something resisting me, I wasn’t used to it at first.” Others thought the feedback just needed to be of a different dimension, like the angle itself instead of velocity. Again, an unofficial test with two users made them feel more in control with angle feedback and linear gains.

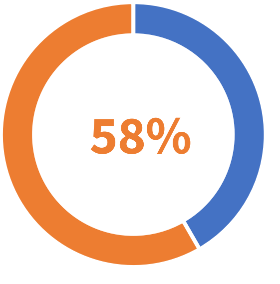


Figure 63: Control Stats

ENJOYMENT

For almost all users, force feedback is more enjoyable and engaging. For some force feedback felt “more realistic with the motor” and “more alive, like I should be paying attention to something happening, in a good way.” Other users enjoyed the visuals “because it was more challenging and gamified” which is not necessarily positive for operator control when heavy machine loads are swaying. Those users tended to have faster times which could be due to their video game experience and lack of offshore FJC or crane experience.

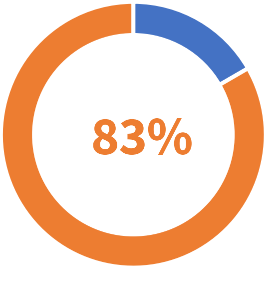


Figure 64: Enjoyment Stats

EMBODIMENT EFFECTIVENESS

Most users found that the embodiment and arm movement is “fit to do the task” and “met my expectations, except that the motor was stronger than I thought for this little one!” Ergonomics are the only comment for improvement of shape. However, part of the test was to not have any large use cues as to see where the users hold the device. Specifically, it was to see how the users felt the force feedback based on where they held it. These pictures are compared with their other answers to further asses the effectiveness. For example, the in Fig. 65, where the user holds the bottom, the user took 51.6s to stabilize with visuals, yet 13.6s with haptics. This was the most drastic difference of scores, which could be accounted for feeling the motor and feedback much more. Conversely, those who tried to grip fully sometimes did not feel the haptics as strongly. While it is not quantitatively proven and based in subjectivity, there seem to be some correlation between hand placement and effectiveness of this force feedback.

Figure 65: Various User Hand Placement

ADDITIONAL INSIGHT

Users provided additional insight on where they believed the force feedback would help the operators of other offshore applications. As mentioned in Chapter 2 of potential use cases, the sway application would be very helpful in pipe transfer crane sway (PTC). Specifically, for the operator to feel how to compensate for it or how gently to lift. Others believed that it could keep operators alert in case of emergency, especially if the force feedback was switched from assistive mode to error prevention. Deep sea mining operators would benefit from how deep they are going and steer control. For ROV specifically, feeling the forces of tightening a screw or how hard to push an object. Overall, users confirmed that force feedback effectively clues the muscles of machine movement for teleoperation. However, while almost half the users had crane operation or similar experience, none of them were FJC operators so further testing and evaluation is needed.

VALIDATE CONCLUSIONS

CONCLUSIONS

RQ6: Do users perceive lower workload (NASA-TLX) of entire task with or without haptic feedback?

Physical demand is significantly increased with force feedback. This result is not surprising, since the user needs to fight the forces in the manipulator. However, it implies that the feedback should be carefully optimized as to not diminish its effectiveness.

Performance is improved with force feedback according to the results. Furthermore, users experience a more successful feeling when completing the task. Additionally, efficiency is important for company and business success.

RQ7: Do users take less time to learn & complete the task?

Force feedback trials on average are faster than with only visuals.

If the user had force feedback trial first, then the difference between visual and force feedback task times are shorter. Vise versa produced longer times.

There is a learning period for each task, hence multiple trials are necessary.

Those with prior relevant experience had a harder time accepting the force feedback initially. If adjusted to their liking, there is more trust.

RQ8: Do users perceive the feedback in the way the design intended?

Forces can be customized to preference of novice vs. experienced operators

How and where the user holds the device affects how strong or how intuitive the forces feel

Embodiment creates expectation of the task and what is being controlled

05 SYNTHESIZE

05 SYNTHESIZE

Final Conclusions
Allseas Recommendations
Force Feedback Design
Reflection

This chapter delves into the final conclusions of the thesis. Recommendations for Allseas future test set up and force feedback implementation are analysed. Then the force feedback design guidelines curated from this thesis process are stated. Where these guidelines and where force feedback could be applied in various fields is synthesized. Lastly, a reflection on this project concludes this last chapter.

5.1 FINAL CONCLUSIONS

5.1 FINAL CONCLUSIONS

FJC ANTI-SWAY USE CASE

The anti-sway use case has proven highly relevant and effective in addressing the research questions and fulfilling the specified requirements for FJC (Field Joint Coating) offshore teleoperation. The implementation of force feedback technology allows for accurate replication of the sway sensation caused by the weight of the FJC machines, enhancing their handling during operations. The study consults FJC offshore operators on their own experience and intuition for problem-solving, highlighting the need for mechanisms to capture and access this valuable expertise. By integrating haptics to reintroduce intuitive forces, a vital connection between human expertise and automation is established, potentially leading to improved operational efficiency and safety. The positive response from Allseas users with prior experience further underscores the practical applicability of this approach across various industrial contexts. Future research should consider the acceptance of new technologies alongside existing practices, fostering advancements in FJC operations and human-machine interactions.

FORCE FEEDBACK TEST SET UP

The implementation of force feedback technology for a 1 DOF manipulator and 2 DOF simulation demonstrated promising results in terms of efficiency, usability, and realism. The system met most of the requirements, showing response times under 10 seconds, real-time operation without noticeable delay, and reduced mental effort with an engaging interface. Participants felt moderately in control due to the good device embodiment, although the feedback optimization could enhance the control feeling further. Force feedback proved to be assistive in preventing errors, but some users experienced a trade-off between control and acceptance. The research highlighted the significance of a force feedback test setup to accurately design for forces and suggested the inclusion of statistical data for substantiating findings. Further testing with statistical analysis are warranted to realize the full potential of the force feedback for anti-sway use case. Overall, this study lays the groundwork for designing future advancements and optimization in teleoperation for machine handling, benefiting various offshore applications.

FUTURE TESTING

Future testing of the proof-of-concept test set up requires some adjustments and more users. Evaluating the ergonomic grip's placement and exploring potential gains or motor adjustments will optimize user comfort and control. Expanding degrees of freedom and parameters in the model will increase system versatility and realism. Adding environmental factors like ship motions can further increase the realism of the simulation and test the ability of the test setup to handle more difficult scenarios. Adapting reverse feedback to trigger only with incorrect user input can potentially reduce errors. Exploring the adoption of sway angle instead of angular velocity offers insights into force feedback cues for improved teleoperation handling. Testing blindfolded, reverse feedback, and sway angle was done with two participants which shows encouraging initial results, necessitating more users for conclusive outcomes. Lastly, integrating a more accurate way of determining stabilization time within MATLAB will enhance the overall results and effectiveness of the system.

5.2 ALLSEAS RECOMMENDATIONS

5.2 ALLSEAS RECOMMENDATIONS

TEST SET-UP ITERATION

For the next iteration of the test setup for Allseas, several key recommendations can significantly enhance the teleoperation handling experience. Firstly, implementing a more wholistic simulation with additional parameters will provide a more realistic and comprehensive testing environment, enabling a thorough evaluation of the force feedback teleoperation system's capabilities. Secondly, exploring velocity control as an alternative to position control can improve system responsiveness and user interaction, potentially leading to more intuitive and precise operations.

Additionally, the full FJC placement process should be considered (not only the anti-sway case) in the simulations. In conjunction, manipulator design should ensure aligned ergonomic design to optimize user comfort and control during teleoperation tasks. The effectiveness of the teleoperation can also be tested at further distances from the FJC operations, i.e., outside of the firing line.
To facilitate a smoother transition for operators, the next iteration should include a learning period to adapt to the new reality of teleoperation. Furthermore, exploring the feasibility of implementing direct drive mechanisms may be beneficial for mechanical robustness, particularly well-suited for tasks with limited movement requirements, such as small angle adjustments.

Considering the potential benefits of incorporating additional degrees of freedom, experimenting with haptics in multiple axes or providing different haptic feedback for various elements of the task can further refine the system's performance and user experience. Moreover, setting up the human-machine interface with additional buttons for other controls can streamline operations, allowing operators to focus on the task at hand without unnecessary distractions.

OTHER OFFSHORE USE CASES

Integrating force feedback in various Allseas applications can aid in HMI operations. For the pipe handling crane (PHC), force feedback can enhance safety and precision during lifting operations, providing real-time force information for optimal control.

In ship control, particularly dynamic positioning (DP) and assessing thruster load capabilities, force feedback can establish a connection between operators on the bridge and the forces experienced by the ship. This immersive feedback can improve control and manoeuvrability, ultimately enhancing the ship's performance.

For training in crane or field joint coating (FJC) operations, force feedback can provide trainees with a realistic experience, helping them develop essential skills and improving overall training effectiveness.

In maintenance tasks carried out from remote locations, force feedback enables technicians to feel the physical resistance of their actions, such as screw insertion or operating robotic systems. This feedback enhances precision and efficiency during remote maintenance operations. Moreover, in pipeline inspection, force feedback offers operators information to detect anomalies and irregularities more accurately. Motion compensation other than sway can be analysed such as objects sliding or turning. This can significantly improve the quality and reliability of inspection processes.

5.3 FORCE FEEDBACK DESIGN
5.3 FORCE FEEDBACK DESIGN

DESIGN GUIDELINES

A list of design guidelines for force feedback manipulators are developed based on the design and development of Paddy .

Intentional Integration: Force feedback is not add-on feature. Design force feedback as an integral part of the system from the beginning of the development process. to ensure its seamless incorporation.

Clear Purpose: Determine the specific reasons for implementing force feedback, ensuring that its inclusion serves a distinct purpose and enhances user interactions intentionally.

Niche Consideration: Recognize that force feedback devices cater to specific niche applications and tailor the design accordingly to suit the target users' requirements.

Identify Task & Use Case: Identify the specific task or application where force feedback is needed to enhance user experience and improve task performance. Outline scenarios and interactions to ensure force feedback aligns with user needs and desired machine or performance outcomes.

Define Sensory Thresholds: Determine the force levels to be conveyed to users, setting realistic thresholds for accurate force feedback that enhance the user's perception and engagement. Haptics can be most effective in some multi-modal experiences if touch or movement is prevalent.

Choose Feedback Type & Technology: Based on the use case and user requirements, select the most appropriate force feedback type (force cues, assistance, resistance, etc.). Research and explore various force feedback technologies available to find the most suitable solution.

Integrate Embodiment: Decide on the most effective way to integrate the force feedback technology into the user interface or device, considering physical form, placement, and ergonomic considerations to ensure a seamless and desired user experience.

Collaborative Prototyping: Utilize a rapid and iterative prototyping approach to gather user feedback throughout the design process. Promote collaboration among team members with different skill sets, including engineers, designers, and domain experts.

Virtual Validation: Utilize virtual prototyping tools and simulations to evaluate the force feedback system's performance in conjunction with building the manipulator. Ensure early validation and refinement to optimize the design.

User-Centric Testing: Involve users throughout the design process, starting from the early stages. Gather user feedback to tailor the force feedback system to meet user needs and preferences effectively. Decide level of transparency, and strength of gains relevant for intuitive feedback.

OTHER APPLICATIONS

Force feedback could potentially enhance HMI, task performance, and user safety in the following other applications.

In dangerous situations like bomb diffusion and heavy machine maintenance, force feedback can provide operators with force cues, allowing them to accurately navigate intricate forces in real-time, reducing errors, and enhancing their effectiveness in critical tasks.

For designers using CAD systems, incorporating force feedback can add a new dimension to the design process, enabling them to feel the forces exerted by virtual objects and improving the accuracy and intuitiveness of their designs.

In the domain of prosthetics for amputees or individuals with disabilities, force feedback can revolutionize the field, providing users with a sense of force that closely simulates natural sensations, ultimately enhancing the functionality and usability of prosthetic limbs.

Even in recreational activities like remote control cars and toys, force feedback can elevate the play experience, making it more engaging and immersive, enhancing the sense of force and control over the toy's movement.

In construction and manual tasks like lifting furniture or placing objects far away, force feedback can assist operators in perceiving and responding to the forces involved, optimizing their control and reducing the risk of accidents, leading to safer and more efficient operations.

5.4 REFLECTION
5.4 REFLECTION

My main goal for this thesis was to design, develop, and test a proof-of-concept test set up for Allseas teleoperated FJC handling. A lot of weeknights and weekends made this achievable. The complexities of a force feedback system were more than I imagined. Typically, I strive for a challenge, but the intense research and exploration factor to understand how to feasibly make this system was an unknown but necessary step.

I not only excelled in my Arduino skills, but also MATLAB, Simulink real time models, and control loop. Furthermore, my exploration of force feedback technology and rapid prototyping increased my confidence in electronics and hardware in the loop configuration.

Force feedback is something I always considered only in gaming as an additional feature. I learned that this is far from the case. Industrial applications of force feedback can make operations more efficient, make operators feel more present, and bring more control between human-machine interaction. As someone who has a hands-on approach to designing and interacting with my environment, understanding how to make force feedback intuitive is fundamental to using this telepresence technology.

Offshore applications, especially machines on such a large scale, were an extremely interesting and new field for me. It is hard to imagine these applications without seeing them first hand. Furthermore, offshore applications are not so common in the industrial engineering faculty, specifically product design. This can be said for force feedback as well, as its origins stem from mechanical engineering research. As a designer with a mechanical engineering background, I constantly strive to bridge the gaps between these fields. I especially see force feedback HMI as a subject that can benefit from this collaboration and am glad to have the opportunity to contribute to it.

REFERENCES

REFERENCES

Allseas Engineering. (2022) FJC Feasibility Study. Unpublished internal company document.

Anton, J. (2006). Probing Question: If a blind person gained sight, could they recognize objects previously touched? Penn State University. Retrieved May 14, 2023, from https://www.psu.edu/news/research/story/probing-question-if-blind-person-gained-sight-could-they-recognize-objects/

Automation Definition & Meaning Dictionary.com. (2020). In Dictionary.com. https://www.dictionary.com/browse/automation

Bouzekri, E., Canny, A., Martinie, C., Palanque, P., & Gris, C. (2019). Using Task Descriptions with Explicit Representation of Allocation of Functions, Authority and Responsibility to Design and Assess Automation. In Springer eBooks (pp. 36–56). https://doi.org/10.1007/978-3-030-05297-3_3

Breitschaft, S. J., Clarke, S., & Carbon, C. (2019). A theoretical framework of haptic processing in automotive user interfaces and its implications on design and engineering. Frontiers in Psychology, 10. https://doi.org/10.3389/fpsyg.2019.01470

Carbon, C.-C., & Jakesch, M. (2013). A model for haptic aesthetic processing and its implications for design. Proc. IEEE, 101, 2123–2133. https://doi.org/10.1109/JPROC.2012.2219831

Caulfield, J. (2023). How to do thematic analysis | Step-by-Step Guide & Examples. Scribbr. https://www.scribbr.com/methodology/thematic-analysis/

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behavioral and Brain Sciences, 36, 181–204. https://doi.org/10.1017/S0140525X12000477

Delft Haptics Lab, The Human Controller. (n.d.). Retrieved from https://delfthapticslab.nl/education/education/the-human-controller/

Farkhatdinov, I., & Ryu, J. (2008). A study on the role of force feedback for teleoperation of Industrial Overhead crane. In Springer eBooks (pp. 796–805). https://doi.org/10.1007/978-3-540-69057-3_101

Finney, Glen. (2015). Perceptual-Motor Dysfunction. Continuum (Minneapolis, Minn.), 21, 678-89. https://doi.org/10.1212/01.CON.0000466660.82284.69

Frohm, J., Lindström, V., Winroth, M., & Stahre, J. (2008). Levels of Automation in Manufacturing. Ergonomia - International Journal of Ergonomics and Human Factors, 30, 181-207.

Godin, D. (2014, June). Aspects of Research through Design: A Literature Review. DRS Digital Library. https://dl.designresearchsociety.org/drs-conference-papers/drs2014/researchpapers/85/?utm_source=dl.designresearchsociety.org%2Fdrs-conference-papers%2Fdrs2014%2Fresearchpapers%2F85&utm_medium=PDF&utm_campaign=PDFCoverPages

Godlove, J., Whaite, E. O., & Batista, A. P. (2014). Comparing temporal aspects of visual, tactile, and microstimulation feedback for motor control. Journal of Neural Engineering, 11(4), 046025. https://doi.org/10.1088/1741-2560/11/4/046025

Jain, A., Bansal, R., Kumar, A., & Singh, K. (2015). A comparative study of visual and auditory reaction times on the basis of gender and physical activity levels of medical first year students. International Journal of Applied and Basic Medical Research, 5(2), 124. https://doi.org/10.4103/2229-516x.157168

Jones, L. A. (2018). Haptics, The MIT Press essential knowledge series. The MIT Press, Cambridge, Massachusetts.

Martin, S. (2018, November). Is there a universal hierarchy of human senses? University of York. https://www.york.ac.uk/news-and-events/news/2018/research/is-there-a-universal-hierarchy-of-human-senses/

Mukherjee, D., Gupta, K., Chang, L. H., & Najjaran, H. (2022). A survey of Robot Learning Strategies for Human-Robot Collaboration in Industrial Settings. Robotics and Computer-Integrated Manufacturing, 73, 102231. https://doi.org/10.1016/j.rcim.2021.102231

Okamura, A. (n.d.). ME 327: Design and Control of Haptic Systems. Stanford University. Retrieved from https://web.stanford.edu/class/me327/

Plaisier, M. A., Kuling, I. A., Brenner, E., & Smeets, J. B. J. (2019). When does one decide how heavy an object feels while picking it up? Psychological Science, 30(6), 822–829. https://doi.org/10.1177/0956797619837981

Qi Zhu, Tianyu Zhou, Jing Du, Haptics-based force balance controller for tower crane payload sway controls, Automation in Construction, Volume 144, 2022, 104597, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2022.104597.

Rapid Iterative testing and Evaluation (RITE). (n.d.). GitLab. Retrieved from https://about.gitlab.com/handbook/product/ux/ux-research/rite/#elements-of-rite

Rodríguez, J., Velazquez, R., Del-Valle-Soto, C., Gutierrez, S., Varona, J., & Enríquez-Zárate, J. (2019). Active and passive haptic perception of shape: Passive haptics can support navigation. Electronics, 8(3), 355. https://doi.org/10.3390/electronics8030355

U., M. (n.d.). Reaction times to sound, light and touch - Human Homo sapiens - BNID 110800. Retrieved from https://bionumbers.hms.harvard.edu/bionumber.aspx?s=n&v=4&id=110800

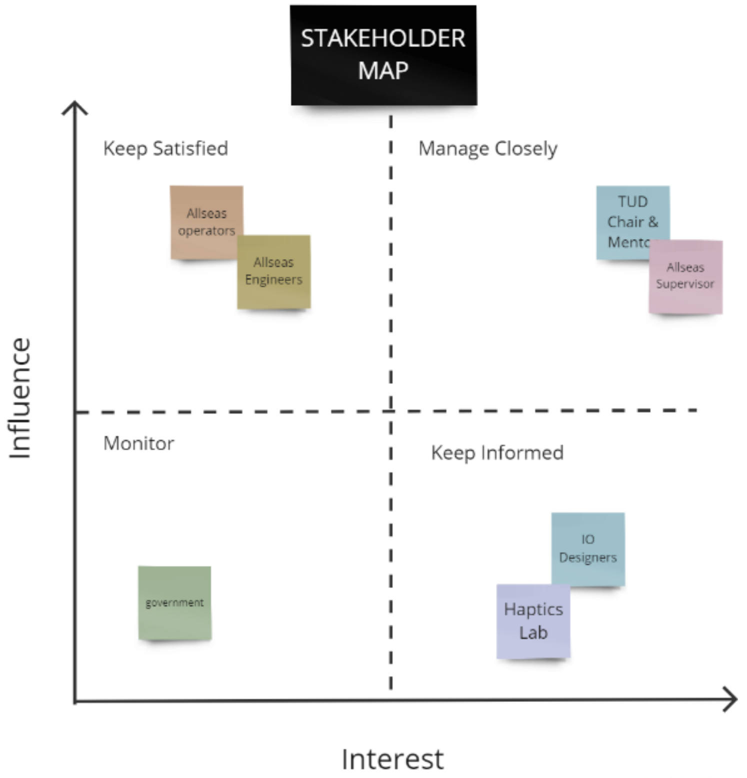
White, P. A. (2012). The experience of force: The role of haptic experience of forces in visual perception of object motion and interactions, mental simulation, and motion-related judgments. Psychological Bulletin, 138(4), 589–615. https://doi.org/10.1037/a0025587

Y. Fang, J. Chen, Y. K. Cho, K. Kim, S. Zhang, E. Perez (2018). Vision-based load sway monitoring to improve crane safety in blind lifts. J. Struct. Integr. Mainten., 3(4), 233-242.

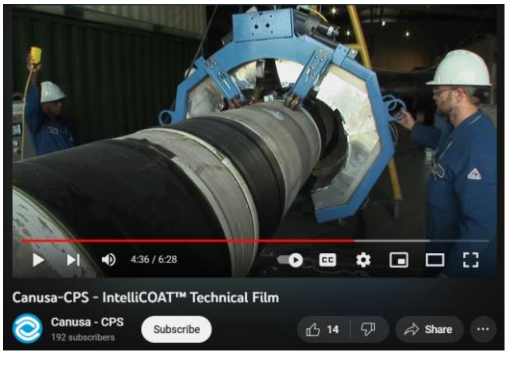
M. Zhang, Y. Zhang, B. Ji, C. Ma, X. Cheng (2020). Modeling and energy-based sway reduction control for tower crane systems with double-pendulum and spherical-pendulum effects. Measure.

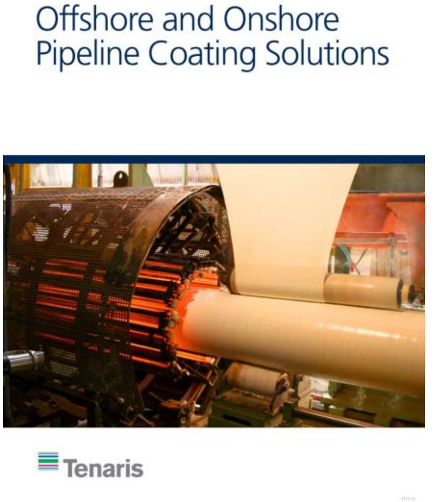
APPENDIX 1
APPENDIX 1

STAKEHOLDER MAP



COMPETITIVE ADVANTAGE



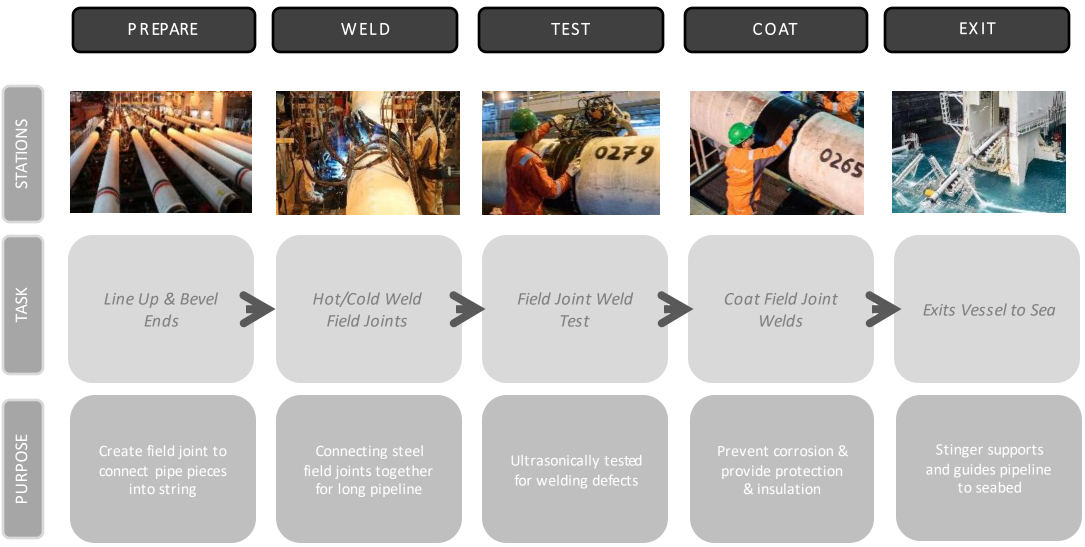


By examining practices and techniques of competitor offshore and onshore pipelay machines, valuable insights into industry standards, potential challenges, and innovative approaches employed by competitors. So far, the competitors are manually placing the machine, or have it roll on the pipe instead of an overhead trolley. This leads to complications in smooth handling and buckling issues of weight on the pipe.

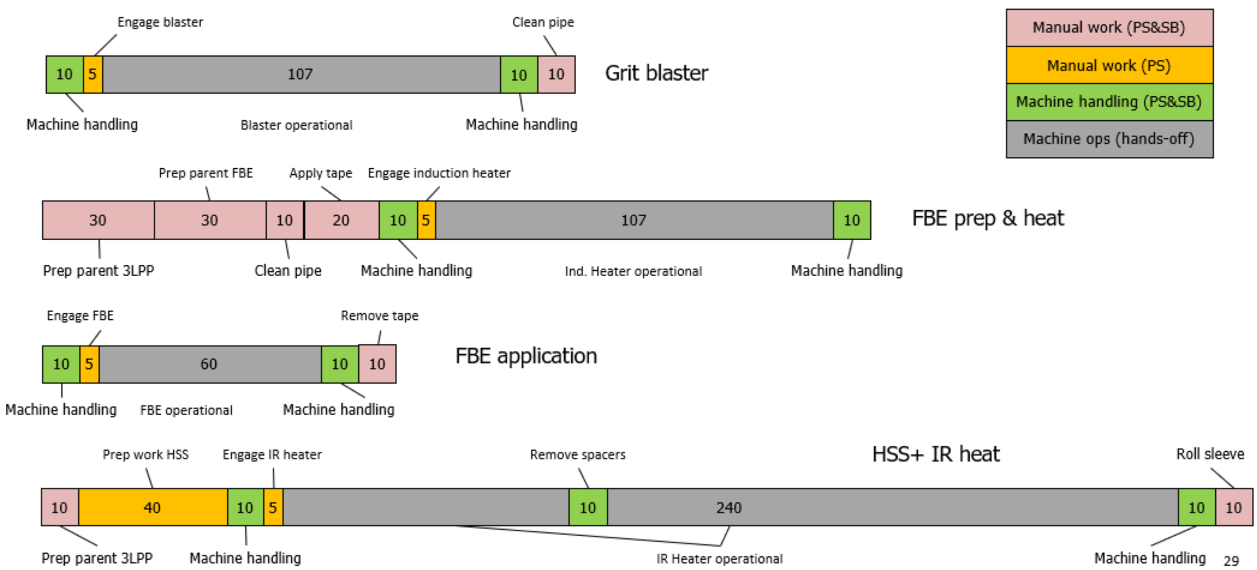
APPENDIX 2

APPENDIX 2

FIRING LINE PROCESS



FIRING LINE TIME BASED ON OPERATOR EXPERIENCE (ALLSEAS 2020)



APPENDIX 3

APPENDIX 3

RISKS OF FULL AUTOMATION (ALLSEAS 2022 & FROHM 2008)

Robustness

- Sensor reliability to handle every situation is difficult in this unpredictable, dynamic environment offshore
- Robot has to continually scan/view pipe and adjust would require a stiff foundation. However, if the robot moves with the pipe, the platforms are not stiff enough to
- Automate big obvious steps, miss out on manual details – all human actions must be replaced before going automatic
- Good at repetitive tasks but not analytical decision making – required for FJC

Safety

- fully automatic robots are required to have a fence around it with automatic shut off is pass fence – this removes crew nearby (so all tasks have to be autonomous due to small space, not enough room)
- What if a sensor is blocked, what if pipe stops and it cant find the joint

Acceptance

- Client has to trust this new machine and operation during PA
- Operators are skeptical of new methods, same for the last 30 years
- Communication man & machine

Finance

- Initial investment is steep, and maintenance is also expensive for costly parts
- Reliability is costly

Speed

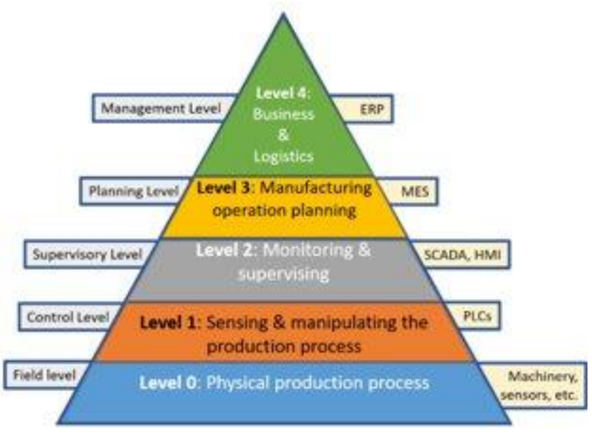
- Downtime in robot failure
- Introducing new takes time, money, effort for training, designing, testing etc.

LEVELS OF AUTOMATION

A further development of LoA in the context of Telerobotics control was developed by Milgram et al. (1995), see table 12, who defined LoA by considering the different roles a human operator can play in controlling telerobotics, including being a decision-maker and direct controller. As Milgram et al. point out; one of the key aspects that have to be considered is the role of the human operator in relation to other elements of the control system. This means that, for anything other than completely automated systems, it will resolve into a spectrum of different tasks for the human operator, ranging from *manual teleportation* to *autonomous robotics*.

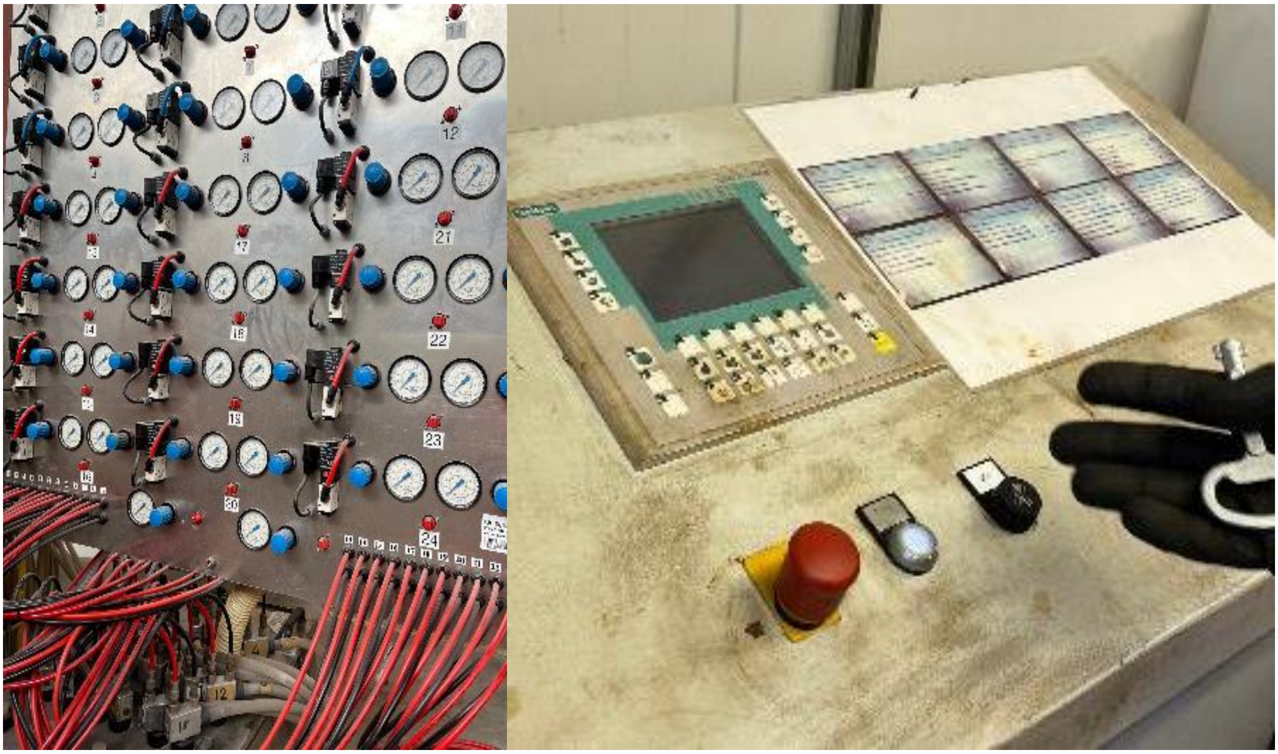
Table 12 Five levels of automation (Milgram et al. 1995)

Manual Teleoperation	The most basic operating mode, defines all situations in which the human operator is constrained to remain continuously in the control loop.
Telepresence	Typically, this involves some form of master-slave control system, where the human operator initiates all actions of the master arm.
Director / Agent Control	Director / Agent (D/A) control can be considered as a basic form of supervisory control, where the human operator acts as a director and the limited intelligence robot acts as her or his agent.
Supervisory Control	Supervisory control describes a wide range of options were the human operator can take on a variety of supervisory roles.
Autonomous Robotics	Fully autonomous teleoperations. The system work without remote control and the human has no part in controlling the system.



APPENDIX 4
APPENDIX 4

ALLSEAS CURRENT OFFSHORE HMI



FORCE FEEDBACK HMI MOODBOARD

APPENDIX 5
APPENDIX 5

PASSIVE FEEDBACK

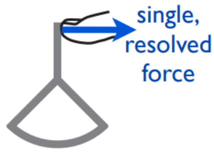
Focus on the sensation experienced

Uses very small forces of ques (like vibration) felt through nerves only (Stanford 2020)

ACTIVE FEEDBACK

Focus on the object

Sufficient force that it is used through your muscles (Stanford 2020)



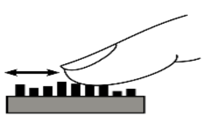
MATRIX OF FEEDBACK TYPES (Rodríguez et al., 2019)

ACTIVE

TACTILE

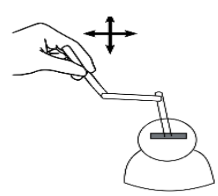
The user deliberately explores the touchable surface (typically with the fingertips or palms).

Their purposive actions lead to a fully free surface exploration. Skin is deformed or stimulated as the result of the exploration process



KINESTHETIC

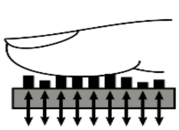
The user consciously applies forces and motion to the haptic device. The user gathers information from the reaction forces and motion



PASSIVE

TACTILE

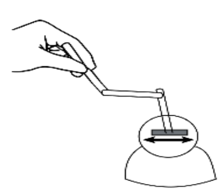
The user does not perform any motion while in contact with the touch stimulation device. The device changes its tactile properties to deform or stimulate the skin.



KINESTHETIC

The device imposes the information and guides the user's actions.

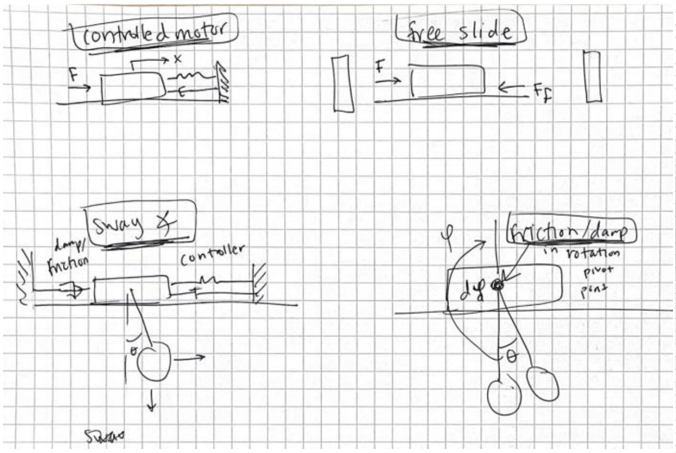
Cognitively, the user monitors the inflow of haptic data to build a mental representation of the information displayed.

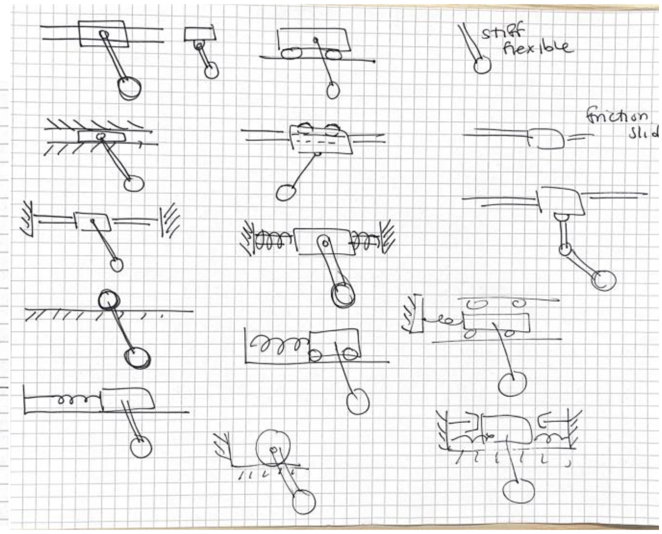


APPENDIX 6

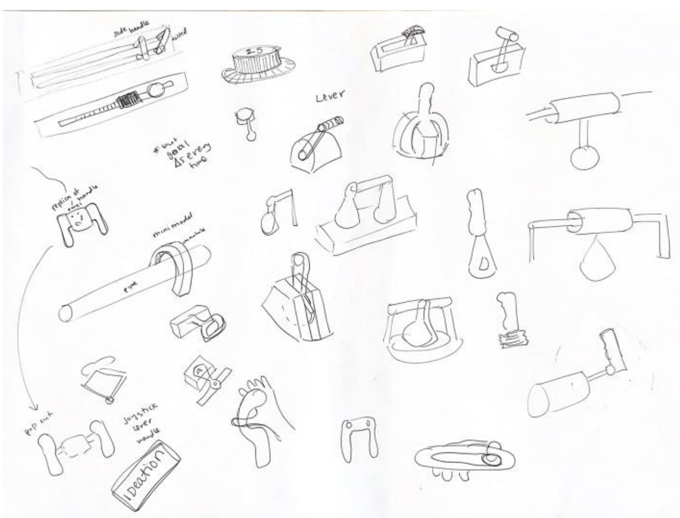
APPENDIX 6

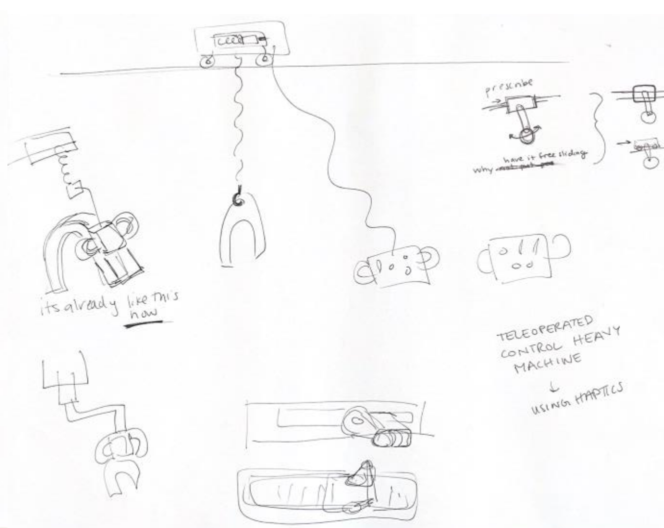
SIMULATION IDEATION & CLUSTER

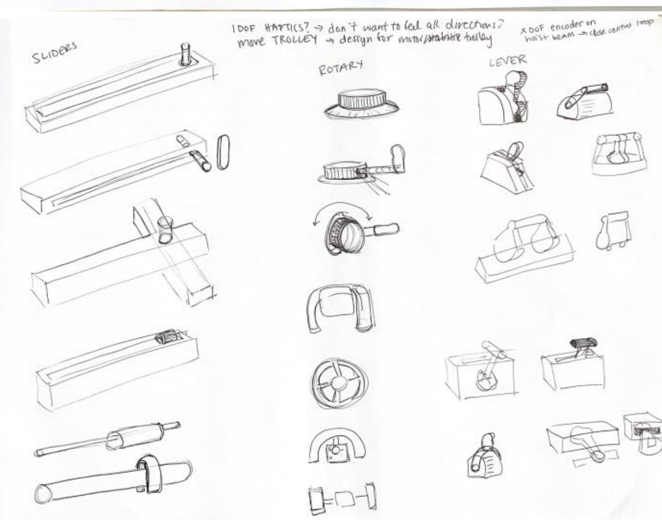


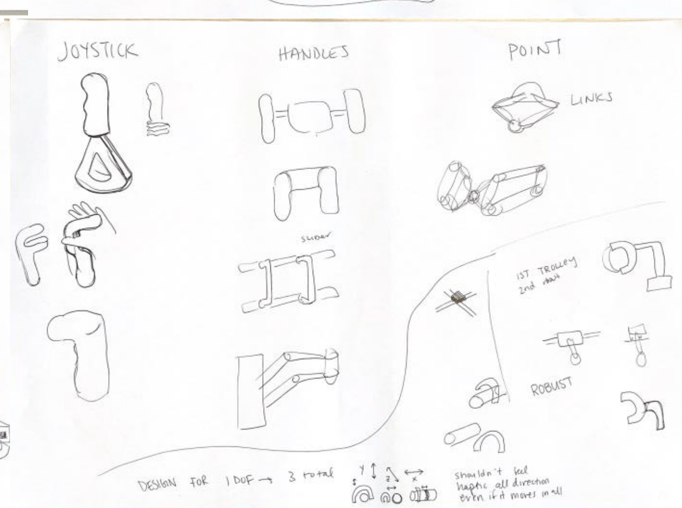


MANIPULATOR BRAINSTORM, IDEATION, CLUSTER

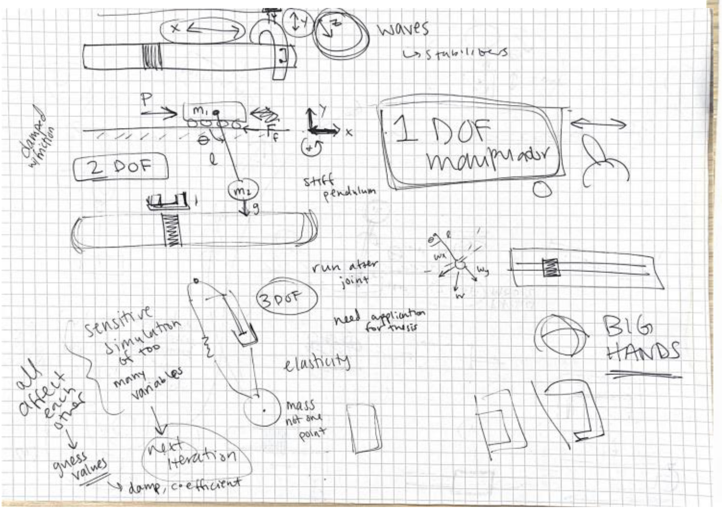


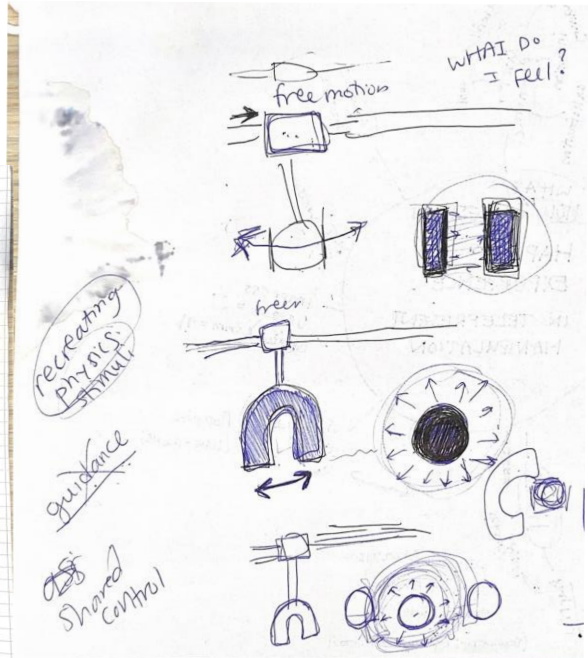




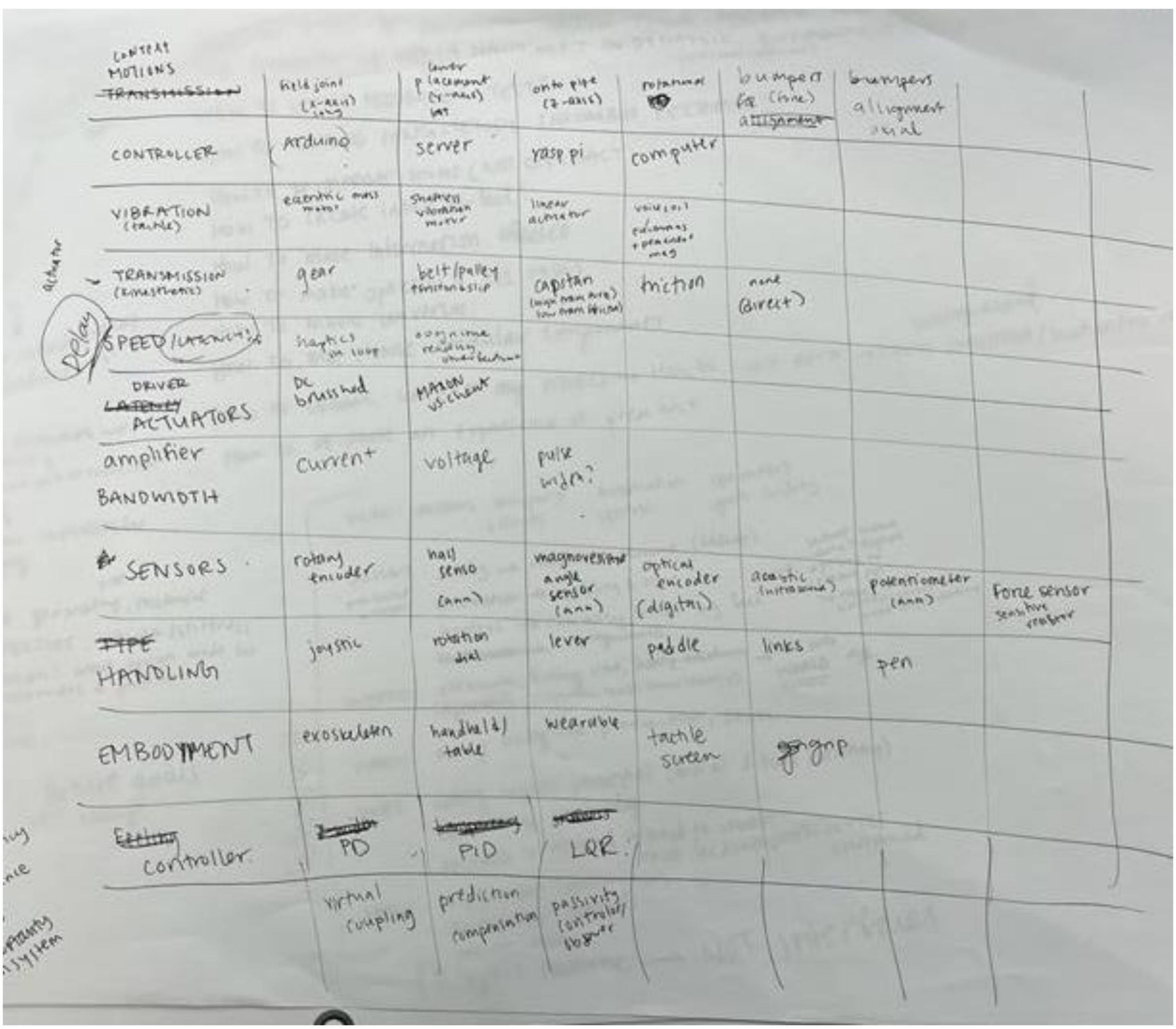


FEEDBACK IDEATION & CLUSTER





MORPHOLOGICAL CHART



APPENDIX 7
APPENDIX 7

FORCE FEEDBACK MANIPULATORS

Manipulators allow users to pick up, move, and place objects that re heavier than a single human can move. They consist of a handheld remote either portable or connected to device that can perform the task. In industrial applications, these are quite common, but without any force feedback or only in a general sense.

The choice of rate, position, or force feedback control is task-dependent and should be taken into consideration in the early planning stages.

Robert D. Christ, Robert L. WernliSr., in The ROV Manual (Second Edition), 2014 19.5.3 Force feedback control

SIMULATION MODEL DIAGRAMS

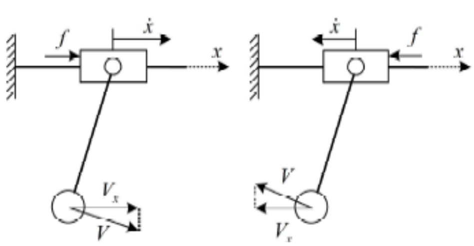
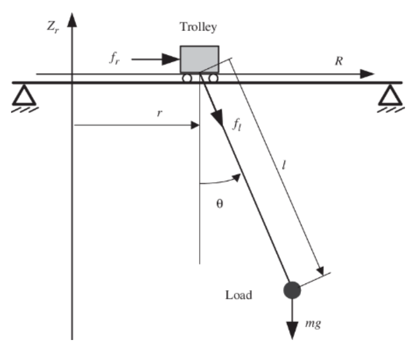
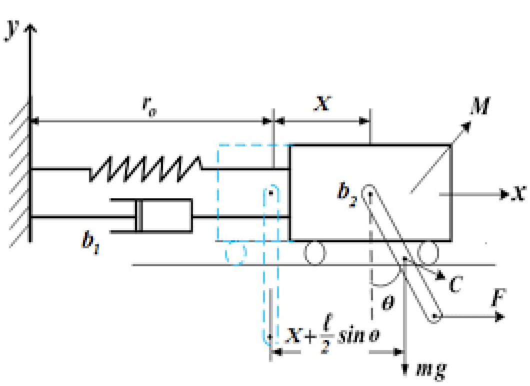
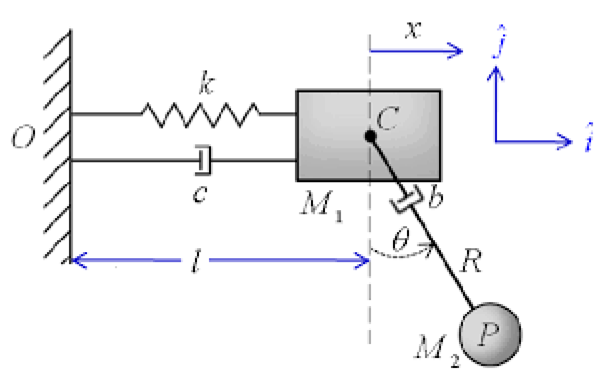


Fig. 5. Scheme for reducing load oscillations with force feedback, based on angular velocity



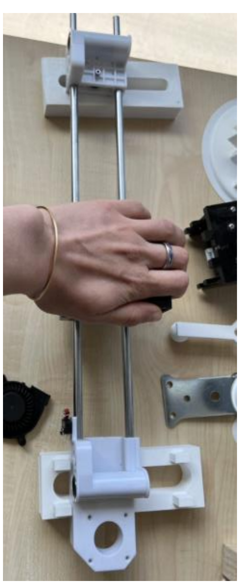




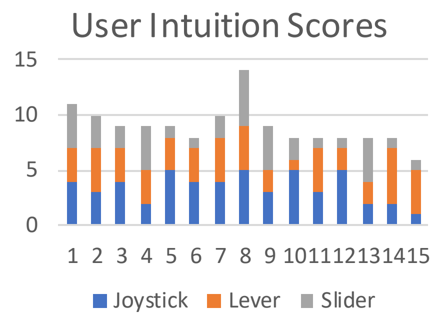
APPENDIX 8
APPENDIX 8

CONCEPT TEST QUESTIONS & RESULTS



How natural was the device movement to guide the trolley/offset the swing? Why?
1 2 3 4 5
What did you like about the control of this device for this operation?
What did you not like about the control of this device operation?
Which device was your favourite for this operation? Why?

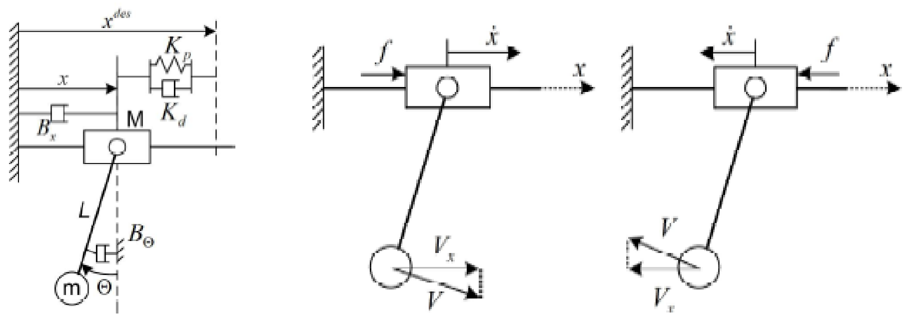


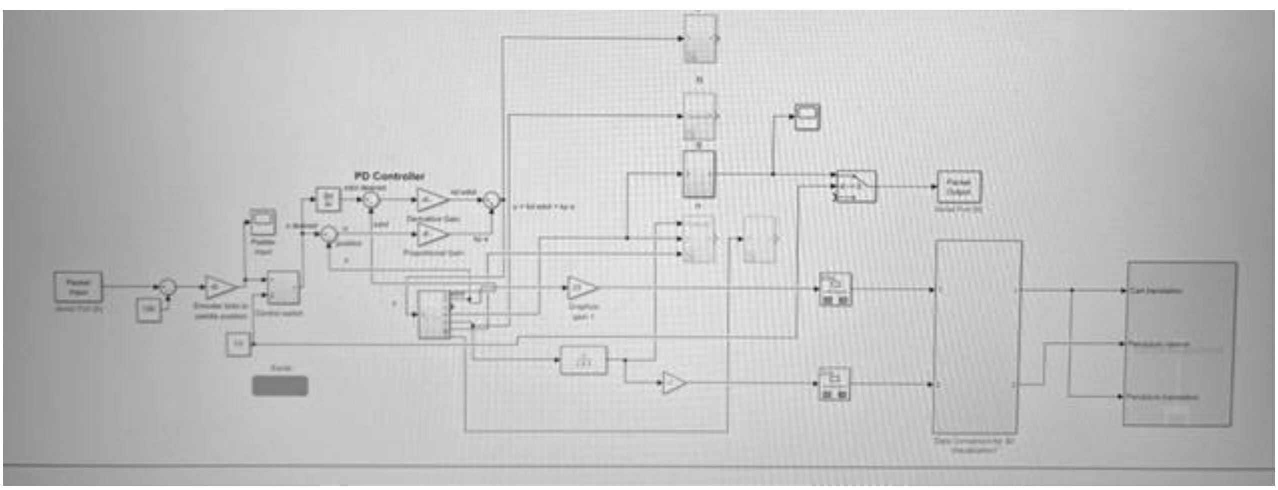
User	Joystick	Lever	Slider
1	4: more intuitive, more dimentionality, velocity control	3: weird, unfamiliar, velocity perfereed	4: difficult, but steady speed position to prevent swing
2	3: don't like the minor twist	4: nicer motion used to than twist	3: intutitive but don't like how far few, linar
3	4: simple motion and uses less brute force just fingers	3: more responsive and easier like that it is arm based not wrist based	2: position hard and not natural with haptics, slider linear and delay
4	2: way more effort due to sensitivity, over do heavy doesn't feel heavy but like the move back to neutral	3: visually natural, and integrating, manual position and control tendencies feel natural	4: really sturdy control and heavy needs it, most control natural translation visual but needs resistance
5	5: more natural and use to it more and minor movements are hard because how far am I pushing what is rest	3: linear positibvlity swings different from leveer frequency in hand than what is happening, if there was a middle and resistance would be higher	1: unnatural velocity based, when wanted to go back it kept going
6	4: feel in control, goes to middle is nice, but micro adjustments	3: easy with fingers	1: left going back negative would be better, but you have to use your whole arm
7	4: with training because its very sensitive and not as visual, tilitin gmotion not sure, needs pushback and resistance	4: focus more on the hand and can understand what doing better with more range	2: position same, use wrong, most visual
8	5: control that operators is used to, intuitive since familiar	4: les intuitive grip, but if you know limit than you can make it ergonomic	5 intutive equally but motor might be issue feedback
9	3: Less degrees would be better but then not as much movement, but more experienced	2: speed with this one, or if you know the 0	4: way easier same direction controling
10	5: intuitive connect natural frequency	1: hinge in wrong spot not intutive	2: not natural to control swing, speed
11	3: small movements less feeling of control, not analog with the task	4: correlation with linear movement is nice	0: control position and feel scale of position only
12	5: familiar, don't think just focus on movement or motion	2: weird, larger stroke, odd to twist arm	1: neutral middle would help, odd movement, if it was spring loaded maybe
13	2: difficult where the end is, worse, speed only, not poition	2: not intuitive, not know end motion, feels faster, rotational vs. linear cant get motion in translation	4, visual position know controller speed matches, intuitive
14	2: can break from operator crane	5: more linear and more range of motion	1
15	1: not intuitive	4: more control of swing	1

APPENDIX 9
APPENDIX 9

SIMULINK MODEL & EQUATIONS OF MOTION DERIVED FROM
Farkhatdinov and Ryu (2008) and Vanderbilt University

$$\begin{cases} (M+m)\ddot{x} + B\dot{x} + mL(\dot{\Theta}^2 \sin\Theta - \ddot{\Theta}\cos\Theta) = u \\ mL^2\ddot{\Theta} + b\dot{\Theta} - mL\ddot{x}\cos\Theta + mgL\sin\Theta = 0 \end{cases}$$



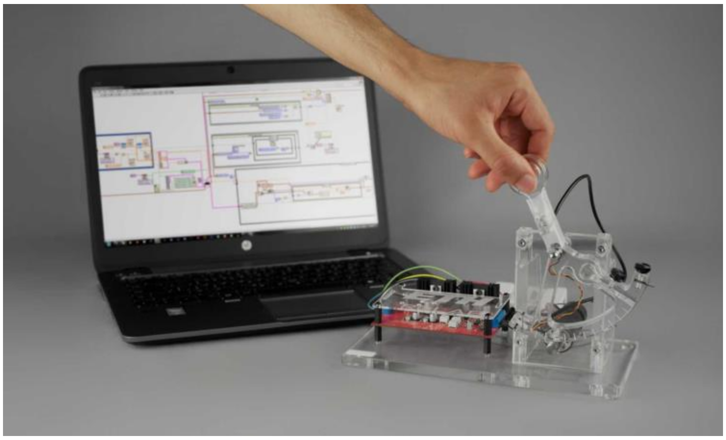


FORCE OUTPUT

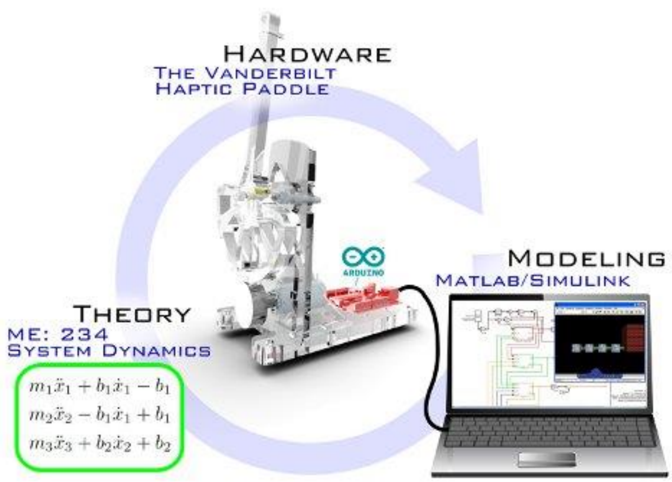
- F1 = k1(theta dot squared sin theta – theta double dot cos theta)
- F2 = k2 theta dot
- F3 = k4 theta

APPENDIX 10
APPENDIX 10

OPEN-SOURCE TEST SET UP REFERENCES



ETHZ Haptic Paddle. (n.d.). ETHZ Haptic Paddle – Rehabilitation Engineering Laboratory | ETH Zurich. https://relab.ethz.ch/downloads/open-hardware/haptic-paddle.html



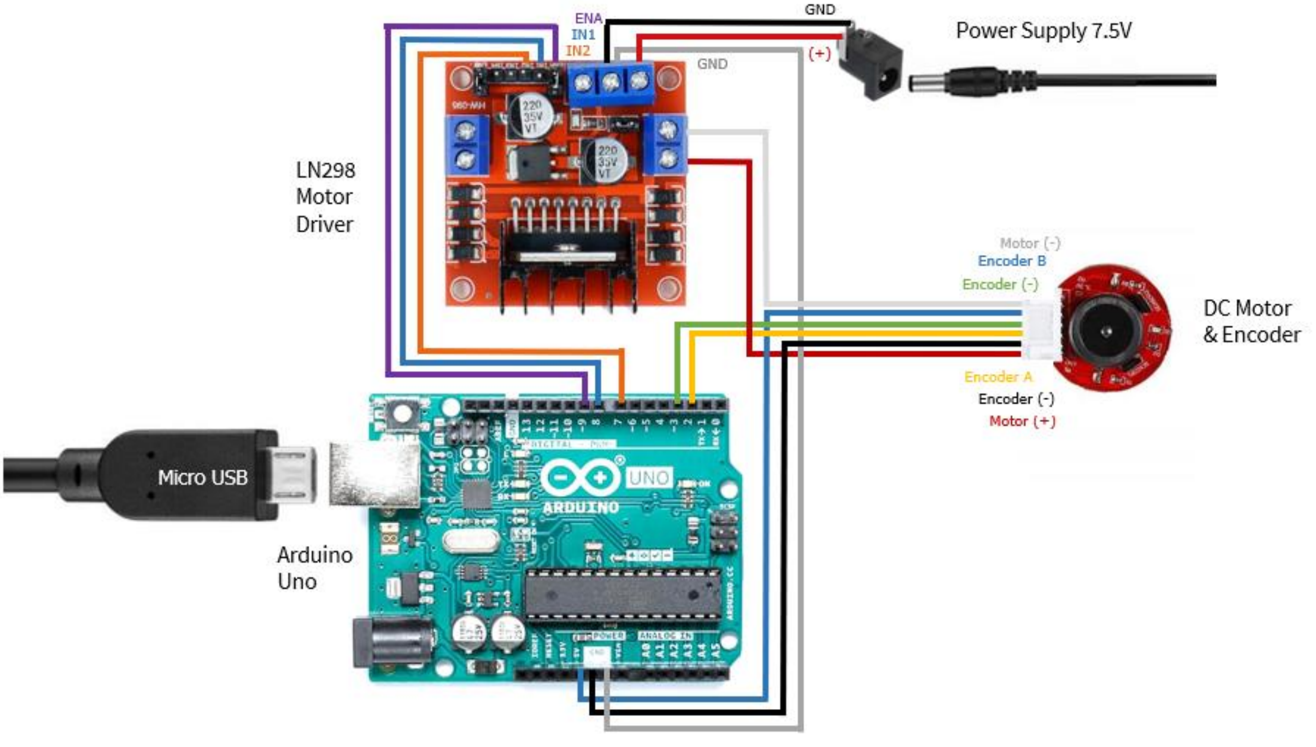
Vanderbilt Medical and Electromechanical Design Laboratory. (n.d.). https://research.vuse.vanderbilt.edu/MEDLab/haptic_paddle.html

Hapkit. (n.d.). https://hapkit.stanford.edu/index.html

Hands-on Haptics: The Haptic Paddle | MAHI Lab. (n.d.). https://mahilab.rice.edu/content/hands-haptics-haptic-paddle

APPENDIX 11
APPENDIX 11

CONNECTION GUIDE



PARTS

Electronics
LN298 Motor Driver
Arduino Uno
7.5V Power Supply
Micro USB Cable

Hardware
Bearing, Bearing Screw, 2 Support Screws, 2 Washers, 2 Nuts
Capstan Wire, 2 Screws, Nut, 2 Washers
Motor Shaft Print, Rubber
12V DC Motor with encoder, Motor screw, wires
Paddle 2 pieces, Paddle Structure
Wooden Base

Software
Arduino Code
Simulink File
MATLAB Processing File

APPENDIX 12
APPENDIX 12

HOW TO RUN PADDY

Plug USB to Serial Port to power Arduino and Encoder
Plug Power Supply to power Motor
Open Pendulum with Slider Position Control Simulink model
Make sure you are in DESKTOP REAL TIME tab on top
In Prepare dropdown, click control panel, data archiving, and change the user number to log data
Check Serial Ports of Input Packet and Output Packet → double click block, click board set up to check
TIP: plug the USB into the same port each time as to not have to check
Run In Real-Time to Build, Connect, and Run simulation. You can click the drop to do each individually.
TIP: if model is built once, then from then on you can just click Connect and Run to run faster
Double Click 3D Animation to view simulation visual
Click Excite to have the load swing, click again to allow paddle input
Click Stop when done running simulation
Unplug USB and Power supply

HOW TO REPLACE CAPSTAN DRIVE

Face the Paddle (not encoder)
Remove the Slider Center Screw and Right Corner Screw
Make a loop at the end of the Fishing Wire. Place loop on Slider center screw
Tighten the slider center screw, nuts, washers with wire in place
Run other end of wire through the left hole and under the paddle
Loop the wire 2 or 3 times counterclockwise around the rubber motor shaft
Bring wire up and through right hole
Wrap wire around screw and tighten in place
Adjust slider center screw to tighten wire if necessary

APPENDIX 13
APPENDIX 13

LIKERT SCALE PRE-TASK QUESTIONS

I have worked with hardware in the loop (joystick + simulation?)

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

I play video games frequently

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

I have hands-on experience with crane operation or similar load movement

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

I have hands-on offshore experience with FJC machines or similar firing line machines

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

UMUX-Lite

PADDY's capabilities meet my requirements.

0 1 2 3 4 5 6 7

PADDY is easy to use.

0 1 2 3 4 5 6 7

Post-Trial Questions

2. How **effective** is the embodiment for performing the task?
3. Which feedback form did you find more **intuitive**? Why?
4. Which feedback form do you feel more in **control**? Why?
5. Which feedback form did you **enjoy more**? Why?
6. Comments or Questions?

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

APPENDIX 14

APPENDIX 14

STATISTICAL METHODOLOGY

To test for statistical significance, the shape of the distributions first need to be checked for normality. For this, the Shapiro-Wilk test is used.

For the UMUX-lite tests, the distributions for "meeting the requirements" are normally distributed with Shapiro-Wilk p-values of 0.21 and 0.17 ($P>0.05$), thus the paired t-test is used. However, for "ease of use", the data is not normally distributed with Shapiro-Wilk p-values of 0.001 and 0.032 ($P<0.05$), thus the Mann-Whitney u-test is used.

For the NASA TLX tests, overall, the distribution showed to be normal, with Shapiro-Wilk p-values of around 0.20 ($P>0.05$). Thus, the paired t-tests are used.

For the stabilization time tests, the distributions were not normal, with a Shapiro-Wilk p-value of 0.00015 ($P<0.05$). Because of the non-normality, the paired t-test cannot be used, instead the Mann-Whitney u-test is used to test for significance.

		Settling Time							
		Haptics (seconds)				Visual (seconds)			
A/B	User	Practice	Trial1	Trial2	Trial3	Practice	Trial1	Trial2	Trial3
A-visual	1	14.08	14.08	10.48	5.76	32	11.36	7.12	9.04
B -haptics	2	14.32	7.36	7.36	7.44	10.46	7.2	9.28	10.72
A-visual	3	25.44	14	13.6	22	51.68	44.32	31.12	41.36
B -haptics	4	22.16	20.4	20.24	19.2	19.84	20.08	13.12	18.64
A-visual	5	3.84	8.24	6.24	4	7.36	5.6	3.92	7.36
A-visual	6	9.36	6.32	6.48	6.16	6.08	15.04	4.16	14.08
A-visual	7	8.08	4.24	6.4	5.2	6.48	6.08	8.64	19.04
B -haptics	8	20	25	25	11.2	16.88	19.52	18.56	16.64
A-visual	9	7.84	4.16	3.76	3.68	7.02	4.24	6.48	8.32
B -haptics	10	50	8.8	25.12	34.48	20.32	22.16	15.68	13.2
B -haptics	11	16.72	8.56	5.68	10.56	14.16	7.84	7.84	9.68
B -haptics	12	10.88	13.92	11.04	18.56	17.6	16.72	11.2	12.64

USER TEST DATA

Intro Questions				UMUX - lite				NASA-TLX											
HIL	Video games	Crane	FJC	Req	Easy	Req	Easy	Mental Demand		Physical Demand		Temporal Demand		Performance		Effort		Frustration	
agree	strongly agree - used to play more	neutral - followed and worked with them, tried it	agree	3	3	3	5	2	7	2	2	17	18	6	2	4	13	2	6
strongly disagree	neutral	disagree	agree	3	3	4	6	5	2	5	5	10	9	3	2	8	6	2	2
neutral	disagree	neutral	disagree	4	6	6	7	2	2	3	2	2	2	17	5	9	4	7	2
agree	strongly disagree	strongly agree	strongly disagree	5	6	6	6	5	5	2	7	7	7	4	4	5	5	2	2
neutral	disagree	agree	srongly disagree	5	6	5	6	14	14	4	7	5	5	4	4	8	9	2	2
disagree	agree	strongly disagree	strongly disagree	5	6	6	7	9	7	2	10	8	10	7	4	6	9	4	5
strongly disagree	strongly disagree	strongly disagree	strongly disagree	6	6	7	7	8	7	6	4	7	4	7	4	7	4	6	4
strongly disagree	neutral	disagree	strongly disagree	6	4	5	4	15	15	10	11	11	12	10	9	11	10	12	11
disagree	agree	strongly disagree	strongly disagree	6	6	7	4	11	13	2	6	15	15	8	11	17	18	8	10
disagree	agree	disagree	strongly disagree	5	6	5	4	10	14	2	2	9	14	12	4	12	15	12	15
strongly disagree	strongly disagree	strongly disagree	strongly disagree	5	6	6	5	12	16	3	5	14	15	6	6	12	13	7	8
strongly disagree	strongly disagree	strongly disagree	strongly disagree	7	7	7	7	15	10	2	2	2	2	6	4	21	29	20	2