From Lab to Life: Bridging Gaps in Motion Capture to Increase Public Usability through Integrated Hardware and Software Solutions

by

Pierre Lonni

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ABSTRACT

This Master's thesis delves into the initial stages of the Lab-In-A-Box (LabX) project, an initiative within MIT's Center for Clinical and Translational Research (CCTR). LabX is dedicated to simplifying the incorporation of Motion Capture (MoCap) technology into home environments. The project's primary aim is to create portable and accurate MoCap systems, utilizing less intrusive technology (such as RADAR signals instead of traditional IR or visible light) for capturing motion of individuals in their everyday lives. This approach seeks to revolutionize MoCap's applicability, making it more accessible and user-friendly for public use.

The central focus of this research is the development of a portable and stable sensor rig, which is crucial to LabX's mission. Designed for precise data capture, the rig emphasizes ease of deployment and versatility, ensuring that it can be effectively used in various settings outside of specialized laboratories.

In addressing the challenges presented by traditional MoCap systems, the thesis details the hardware development process, focusing around the creation of the project's sensor rig, and incorporating sensor fusion technology. This enhancement allows simultaneous data capture at different locations, emphasizing stability and portability for versatile application in various public settings.

The thesis extends its focus to LabX's overarching goal of enhancing MoCap's public accessibility through integrated hardware and software solutions. A holistic approach is emphasized, encompassing sensor fusion and machine learning components. This integration aims to bridge gaps in traditional setups and render MoCap technology more inclusive and widely applicable.

This research significantly contributes to advancing user-friendly MoCap technology, signifying a transition from controlled laboratory environments to real-world applications. The incorporation of hardware, sensor fusion, and machine learning solutions in LabX establishes a foundation for future advancements, ultimately enriching public interaction with motion capture and seamlessly integrating it into everyday life.

Thesis supervisor: Brian Anthony
Title: Principal Research Scientist

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This thesis represents not just my efforts, but the support, guidance, and collaboration of many incredible individuals who have significantly contributed to my journey.

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To my family, particularly my mother, Christine Scagnetti, my sister, Pauline Lonni, my grandparents, Christiane ’Mimi’ and Séverin ’Titi’ Scagnetti, and my aunt and uncle, Sophie and Marc Meyer, I owe a deep sense of gratitude. Their unfaltering support and encouragement throughout my studies have been my foundation and strength. Their belief in my potential has been a constant source of motivation and resilience during the most challenging times.

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Finally, I am grateful to the Gadzarts community for their role in my journey. Their support and the opportunities they provided have been crucial in my development as an engineer and in paving my path to MIT.

This thesis is a reflection of the collective effort, encouragement, and support of each one of these individuals, and for that, I am eternally grateful.

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1 Introduction

Motion Capture (MoCap) technology has revolutionized various industries, from entertainment and gaming to healthcare and sports analysis. However, the widespread adoption of MoCap systems by the public remains limited due to the complexity of traditional setups, which often involve intricate hardware installations and software configurations. This Master's thesis introduces an innovative framework poised to bridge this gap by integrating market analysis, user interviews, sensor fusion technology, and machine learning algorithms.

It introduces an innovative framework within the context of the Lab-In-A-Box (LabX) project, a pivotal initiative at the Massachusetts Institute of Technology's Center for Clinical and Translational Research (CCTR). LabX is committed to simplifying the integration of MoCap technology into home environments, focusing on creating portable, accurate MoCap systems that minimize intrusiveness to maximize adoption. This comprehensive approach aims to lay the foundation for a user-friendly and easily deployable MoCap system, fostering inclusivity in public spaces.

The research presented in this thesis delves into both hardware and software aspects, addressing challenges spanning system design to the post-processing of human movement data. The hardware design centers around developing a sensor rig capable of capturing diverse data types at distinct locations, all at the same time. This sensor fusion strategy enhances the richness and accuracy of motion capture data, ensuring robust and adaptable performance in dynamic public environments. With considerations for portability and ease of setup, the design aligns with the overarching objective of making MoCap technology accessible in various public settings.

In tandem with hardware advancements, the software synchronization and post-processing components of the framework are crafted to streamline user interaction and enhance public adoptability. Offering a scalable solution for deploying MoCap technology in diverse public settings, this facet eliminates the need for complex infrastructure, contributing to the system's overall accessibility.

In conclusion, this Master's thesis contributes to the democratization of MoCap technology, presenting a holistic framework that addresses some challenges of hardware design, software synchronization, and post-processing in the context of public accessibility. By fostering a user-friendly and easily deployable MoCap ecosystem, this research paves the way for innovative applications in public spaces, ultimately enriching human experiences and interactions.

1.1 Motion Capture Technology

In the dynamic landscape of digital innovation, MoCap technology emerges as a pivotal and rapidly advancing tool, transcending its early entertainment industry roots to impact various scientific and practical domains. The present state of MoCap is characterized by remarkable technological progress, widening its scope of application and enhancing its capabilities in terms of accuracy and efficiency.

Originally popularized in the realms of film and video gaming for creating realistic animations, as presented in figure 1.1, MoCap technology has evolved substantially. This evolution is fueled by the integration of cutting-edge technologies such as artificial intelligence and machine learning, which have significantly improved the precision and range of motion capture systems. While contemporary MoCap systems have advanced in capturing more subtle and complex movements, they still present significant challenges in terms of portability and user-friendliness. Despite improvements, these systems often require complex setup procedures and specialized expertise to operate effectively, limiting their accessibility and practicality in various fields. This ongoing difficulty highlights a critical need for further innovation in MoCap technology, particularly in enhancing its portability and usability, to truly democratize its benefits across diverse applications.

Figure 1.1: Example of Motion Capture in Animation, at the House of Moves studio. This system has 72 infrared cameras surrounding the capture space and each performer has to wear a special suit with numerous reflectors [1].

One of the most notable areas where MoCap has made a significant impact is the medical field. Here, it serves as a critical tool in the convergence of technology and healthcare, offering innovative methods for diagnosis, treatment, and rehabilitation, as illustrated in figure 1.2. In clinical environments, MoCap provides vital insights into human biomechanics, enabling medical professionals to analyze movements such as gait and posture with an unprecedented level of detail. This is particularly valuable for diagnosing movement-related disorders, planning surgical interventions, and tracking the progress of rehabilitation therapies. MoCap's integration into medical practice not only enhances patient care but also fosters the development of personalized medicine approaches.

Figure 1.2: Example of Medical Use of Motion Capture. This allows analysis of all aspects of gait and movement and provides physical performance testing, including quantitative strength testing, kinematic and kinetic measurements, and mobility assessments [2].

1.2 Expanding the Scope of Motion Capture: The MIT-Sekisui House Collaboration

The evolution of motion capture technology, while remarkable, has encountered notable challenges, particularly in terms of portability and usability. This highlights the pressing need for innovation that not only refines the technology but also makes it more accessible and practical for broader applications. Addressing this need, a partnership [3] between the Massachusetts Institute of Technology (MIT) [4] and Sekisui House [5] has formed, as illustrated by figure 1.3. This partnership represents a critical development in the field of MoCap, driven by a shared commitment to enhancing living and aging experiences through technology.

Sekisui House, a leading Japanese firm known for its innovative approach to residential construction, has a vested interest in integrating advanced technologies into homes. With a reputation for building sustainable and comfortable living spaces, Sekisui House is exploring how MoCap technology can be utilized to improve home health monitoring and elder care. The company recognizes the potential of MoCap systems in monitoring and analyzing the movements and behaviors of residents, which can be vital in ensuring their safety and well-being, especially for the elderly.

This collaboration with MIT focuses on developing MoCap systems that are not only precise and sophisticated in tracking and analyzing human movement but are also practical and deployable in home environments. The project aims to create MoCap solutions that can be easily integrated into everyday living spaces without the invasive setup of traditional systems. This aligns with the broader vision of making MoCap technology more accessible and beneficial in residential settings.

This MIT-Sekisui House collaboration is characterized by several key research themes within the domain of motion capture technology. The themes that this thesis focuses on include:

- **Advancements in Motion Tracking Hardware and Analysis Algorithms**: Focusing on improving the precision and capabilities of MoCap systems, this theme is central to capturing and interpreting human movements with enhanced detail and sophistication.
- **Creation of Novel Sensors and Sensing Systems**: Involving the development of advanced sensors, this theme aims to provide more nuanced monitoring of human activities through technology seamlessly integrated into various environments.

The focus of this thesis is intertwined with these themes of the MIT-Sekisui House collaboration. It concentrates on enhancing motion tracking and analysis algorithms, as well as developing novel sensors and sensing systems. This dual focus is aimed at advancing MoCap technology in terms of both its analytical capabilities and its practical application in diverse environments. By addressing these themes, the thesis seeks to contribute significantly to overcoming the current limitations of MoCap systems, enhancing their precision, usability, and integration into everyday settings. This endeavor reflects a commitment to not just advancing the technology but also making it more accessible and beneficial across various applications.

In conclusion, the collaborative work of MIT and Sekisui House not only exemplifies innovation in MoCap technology but also sets a vital basis for this thesis. By aligning with the previous research endeavors, particularly in motion tracking and sensor development, this thesis contributes to the broader goal of democratizing MoCap technology. It presents a holistic framework that addresses the challenges of hardware design, software synchronization, and post-processing, all within the context of enhancing public accessibility and usability. This research thus paves the way for innovative applications in public spaces, ultimately enriching human experiences and interactions with technology.

Figure 1.3: Brian W. Anthony visits Japan for new collaboration between MIT and Sekisui house on Home Health Monitoring System [6].

1.3 Teammates Contribution

This thesis represents a segment of a collaborative research effort, a venture undertaken alongside the author's esteemed colleagues, Cheng Chang and Hadeel Abdo. Our collective endeavor aimed to explore and advance the field of motion capture technology, each contributing unique insights and expertise to a shared research framework. While the work presented herein is distinctly the author's, it is important to acknowledge that it was developed within the context of this collaborative group dynamic.

Cheng's involvement, which concluded in August, was crucial in the initial phases of the project. Her thesis, titled *'Enhancing the accessibility and usability of motion capture technology: design and development of indoor MoCap hardware system'*, encompassed key activities such as conducting user interviews, performing market analysis, engaging in system design ideation, and the development of a first prototype, a wooden rig. These initial efforts laid the foundations for the direction and scope of our joint research.

Hadeel Abdo's work, presented in her thesis titled *'Design and Development of a Mobile Motion Capture Suite for Advancing Technology Adoption'*, further extended the breadth of our project. She participated in user interviews and market analysis, alongside contributing to system design ideation. Her notable focus on sensor synchronization and motion capture data analysis added substantial depth and technical insights to our collective understanding.

In his role, Pierre Lonni, the author, engaged in various facets of this project. His contributions included assistance in user interviews, market analysis, and system design ideation. Beyond these shared tasks, he specifically focused on the development of a metal sensor rig, creating a machine learning algorithm for processing radar data into MoCap data, and the integration and synchronization of camera systems. These endeavors represent the core of his individual thesis work.

While there has been an overlap in certain aspects of the research, particularly in its initial stages, it is crucial to emphasize that the thesis presented here is a product of the author's personal intellectual effort. The collaborative elements of the group's work, such as the user interviews and market analysis, have been adapted and recontextualized to support the author's unique analytical perspective and findings. Thus, this thesis, authored by Pierre Lonni, stands as a testament to his distinct contributions within the group's research, ensuring its originality and authenticity.

1.4 Thesis Outline

This thesis, exploring the advancement of MoCap technology, unfolds through several interconnected chapters. The Introduction sets the stage, outlining the thesis's goals and the significance of MoCap advancements. Market Analysis and User Research delve into the current state of MoCap technology and user requirements, providing context for the project's objectives. The Hardware Design and Fabrication chapter documents the development of the MoCap system's structural hardware, detailing the design and manufacturing processes of the sensor rig.

In Sensor Fusion Technology and Software Development, the integration of sensors into the system and the development of software tools are discussed, highlighting the system's operational aspects. The Machine Learning Development chapter examines the use of machine learning for interpreting RADAR data in MoCap applications. Future Work suggests directions for further research and potential improvements in MoCap technology. This thesis concludes by summarizing the findings, contributions, and the broader impact on the MIT-Sekisui House project and the field of MoCap.

2 Market Analysis & User Research

2.1 Use Cases of MoCap

Building upon the comprehensive framework introduced in this thesis, which aims to enhance the public usability of MoCap technology through integrated hardware and software solutions, it becomes crucial to understand the diverse use cases of MoCap. These use cases not only highlight the versatility of MoCap technology but also inform the design considerations for system development, such as capture speed, accuracy, capture volume, and specific user requirements. The primary use cases identified for this thesis include medical applications, sports, performance arts, industrial settings, and educational platforms.

Medical Applications: Diagnosis and Rehabilitation

In the medical field, MoCap technology serves as a critical tool for diagnosis and rehabilitation. It offers detailed biomechanical analysis of patient movements, essential for diagnosing movement-related disorders and planning surgical interventions. In rehabilitation, MoCap's precise motion analysis is invaluable in tracking patient progress and tailoring rehabilitation programs. The emphasis in this domain is on accuracy and sensitivity of data capture, ensuring that subtle movements and progress can be quantitatively assessed.

Sports: Performance Analysis and Movement Optimization

Sports performance analysis and movement optimization is another significant use case. Here, MoCap technology aids in enhancing athletes' performance efficiency and reducing injury risks. It provides detailed insights into biomechanics, enabling the optimization of training programs and techniques, as showcased in figure 2.1. This use case prioritizes aspects like capture speed and the ability to analyze dynamic, high-speed movements within a sizeable capture volume.

Industrial Settings: Worker Movement and Fatigue Analysis

In industrial settings, particularly in factories, MoCap technology is increasingly used for worker movement and fatigue analysis. This application focuses on monitoring and analyzing workers' physical activities to improve workplace safety and efficiency. Key parameters

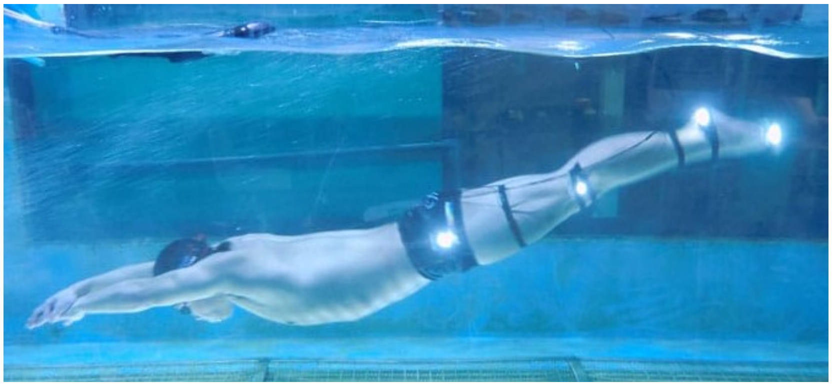


Figure 2.1: A motion capture system with LED lights in a circulate water channel. The study allowed researcher to better understand the fluid dynamics around a swimmer's body [7].

include the ability to accurately capture repetitive motions over extended periods and the robustness of the system to operate in various industrial environments.

Educational Platforms: Enhancing Learning through MoCap

MoCap technology also serves as an innovative educational platform, particularly in subjects like physical education, dance, and sports training. It provides students with real-time visual feedback on their movements, enhancing the learning experience. The focus in educational applications is on the system's ease of use, clarity of data presentation, and the ability to provide real-time feedback.

Performance Analysis in Dance and Music

Although less central to the thesis's primary focus, performance analysis in dance and music is an important application of MoCap technology. It enables the detailed study of movement patterns, timing, and coordination in artistic performances, as shown in the example of figure 2.2. Key parameters include motion fluidity, synchronization, and the ability to capture a full range of artistic expressions within varied spatial constraints.

The exploration of these use cases – medical applications, sports, industrial settings, educational platforms, and performance arts – underlines the broad applicability of MoCap technology. Each use case brings unique requirements and challenges, informing the system design to meet varied needs. Understanding these diverse applications is essential in creating a MoCap system that is user-friendly, easily deployable, and versatile enough to adapt to different contexts.

Figure 2.2: Dancer Kaelyn Dunnell dances in MIT's Immersion Lab with multiple motion-tracking markers on her body [8].

2.2 Existing MoCap Systems

An essential aspect of understanding the current state and future potential of MoCap technology involves an examination of existing systems. These systems range significantly in complexity, scalability, and application, from high-end, fixed MoCap rigs like Qualisys or OptiTrack products to more accessible, mobile solutions like smartphone-based mono camera systems. This section provides an overview of these varied systems, highlighting their distinctive features and applications.

2.2.1 High-End Fixed MoCap Rigs

At one end of the spectrum are high-end, fixed MoCap rigs such as those developed by Qualisys [9] and OptiTrack [10]. These systems are known for their precision and reliability, often used in professional settings like film production, advanced biomechanics analysis, and medical research.

This type of MoCap system is characterized by its use of infrared (IR) light technology. It typically involves a network of cameras installed around a capture area, which emit IR light. Reflective markers placed on the subject's body reflect this light back to the cameras. The system then uses the spatial data from these reflections to accurately reconstruct the subject's movement in three-dimensional space.

- **Qualisys** systems, for instance, offer high accuracy and are capable of capturing subtle movements, making them ideal for biomechanical research and clinical gait analysis. They typically involve multiple cameras installed around a designated capture area, tracking numerous infrared markers placed on the subject's body.

- **OptiTrack** provides similar high-quality capture capabilities, widely used in animation and game development. These systems are recognized for their ease of use and robust tracking abilities, even in larger capture volumes.

Such fixed MoCap systems, while offering unparalleled data quality and accuracy, come with limitations in terms of cost, portability, and setup complexity. They require a controlled environment and are typically beyond the reach of non-professional or occasional users due to their significant investment in hardware and space.

2.2.2 Accessible Mobile Solutions: Smartphone-Based Mono Camera Systems

At the other end of the spectrum are the more recent developments in MoCap technology, which leverage the ubiquity and computing power of smartphones. Smartphone-based mono camera systems, like Move.ai [11] or Plask [12], represent a leap towards democratizing MoCap technology.

They use advanced artificial intelligence (AI) algorithms to analyze video footage captured by a phone's camera, as senn in figure 2.3a. These algorithms are capable of identifying and tracking human body movements from the video, translating them into digital motion data. These algorithms are the backbone of 'marker-less tracking', where IR light and reflectors are discarded and visible-light video is used to track the movements.

- **Smartphone-Based Systems** use advanced algorithms to analyze video footage captured by a phone's camera, extracting motion data without the need for specialized hardware or multiple camera setups. These systems are designed for accessibility and ease of use, allowing users to capture and analyze motion data with minimal setup.

While these mobile solutions allow for motion capture without the need for specialized hardware or multiple camera setups, making MoCap technology more accessible and user-friendly, they often come with potential trade-offs in accuracy and data depth when compared to their high-end counterparts. The mono camera setup, for instance, may struggle with occlusion and complex three-dimensional movements.

2.2.3 Intermediate Solutions: MoCap Suits

MoCap suits, such as those produced by Rokoko [13] and XSens [14], fill an important niche between fixed high-end systems and mobile solutions. These suits utilize Inertial Measurement Units (IMUs), which are sensors capable of detecting movement and orientation based on acceleration and rotational rates. Embedded with multiple IMUs across various body parts, these suits can accurately capture motion data by interpreting the sensor readings, as seen in figure 2.3b. This technology allows for a significant degree of motion tracking accuracy while offering the advantage of portability.

- **Rokoko's MoCap Smartsuits** are known for their ease of use and flexibility. Users can wear these suits in various environments without the need for a fixed setup, making them suitable for on-site motion capture in fields like animation, game development, and sports training.
- **XSens Systems** provide similar benefits, with advanced sensor technology embedded in suits for full-body motion tracking. XSens suits are often used in scientific research, sports biomechanics, and film production for their accuracy and the ability to capture complex movements in real-time.

Both Rokoko and XSens MoCap suits fill an important niche in the market by combining a higher level of precision than most mobile solutions with greater flexibility and ease of deployment than fixed MoCap rigs. However, these systems still face challenges such as the need for wearing a suit, which may not always be feasible or comfortable in all application settings, and the potential for sensor errors, data inaccuracies or drift due to external factors like environmental conditions.

(a)

(b)

Figure 2.3: Examples of more accessible MoCap systems: (a) demonstration of the Move.ai application [15], where it is demonstrated that MoCap is made possible no matter the environment, and isn't restricted to human movement (as it can also track a ball); (b) example of the Rokoko Smartsuit [16], used here for outdoors motion tracking thanks to its lack of use of vision to track motion.

2.2.4 Bridging the Gap: Specialized and Mobile Systems

Acknowledging the strengths and limitations of existing MoCap systems, from high-end rigs and MoCap suits to mobile solutions, underscores a clear market gap for specialized yet mobile systems. This project, as part of the Lab-In-A-Box (LabX) initiative, aims to address this gap. The objective is to develop a MoCap system that merges the precision and data depth of high-end and suit-based systems with the portability and user-friendliness of mobile technologies.

The envisioned system is designed to be technically sophisticated for specialized applications, such as detailed biomechanical analysis, while remaining practical and deployable in diverse environments. This hybrid solution aims to offer the accuracy and reliability required for professional use cases without the constraints of fixed installations or the need to wear specialized suits. By achieving this balance, the project aims to expand the accessibility and applicability of MoCap technology, making it a versatile tool for various fields beyond its current domains.

2.3 User Interviews

As a last step to understanding the practical applications and limitations of current motion capture technology, several interviews were conducted with experts in the field. Each interview provided unique insights that are crucial for the development of an advanced and user-friendly MoCap system.

2.3.1 Interview with J.B., CEO of Reboot Motion

J.B.'s insights were particularly valuable in understanding the biomechanics study aspect of MoCap. Reboot Motion [17], under his leadership, focuses on a momentum-based approach to biomechanics, which is crucial for comparing athletes' movements. They prioritize analysis over mere data collection, offering a platform of reporting, data, and education, focusing on assisting coaches rather than replacing them with technology.

In terms of hardware, J.B. discussed using an optical camera system for capturing motion, mentioning systems like *Kinatrax* [18] and *Hawkeye* [19]. He highlighted the challenges of setting up such systems in stadiums, including the extensive time, cost, and effort required. Portable solutions, he suggested, should not compromise on accuracy. He also mentioned the potential of smartphone-based systems like *Uplift* [20], which use iOS devices, although they face challenges in camera setup and internet connectivity.

For Reboot Motion's own single-camera solution, J.B. emphasized the need for high frame rate and shutter speed videos. Different sports require varying frame rates, with baseball needing over 200fps, while basketball shooting might require 30-60fps. He discussed the importance of a modular system where additional cameras can enhance redundancy and accuracy.

2.3.2 Interview with P.N., Research Scientist

P.N. from MIT's Immersion Lab uses MoCap for detailed biomechanics research, such as tracking muscle lengths. He requires high precision, ideally 1mm or better. P.N. pointed out the limitations of his current system, including resolution issues and the spatial constraints due to the placement of cameras.

He discussed the process of calibration, which takes about half an hour and is done every few months. Continuous calibration is critical due to environmental factors like building vibrations. P.N. is the one who suggested the concept of "MoCap in a box," a system combining various technologies, such as RADAR, IR cameras, high-speed cameras, etc, for a comprehensive motion capture solution.

2.3.3 Interview with D.C., Graduate Researcher

D.C.'s use of MoCap for studying yoga movements offers unique insights. He mentioned the need for high accuracy in calibration for effective motion analysis. The limitations he discussed included issues with force plates, camera placement affecting data collection in certain poses due to occlusion, and calibration issues due to environmental factors like sunlight.

Dan emphasized the importance of visible light cameras alongside IR cameras for post-processing verification. He also highlighted the need he encountered for frequent recalibration, every two hours, to maintain accuracy, especially in not-controlled environments.

2.3.4 Interview with J.R., Research Fellow

J.R.'s work on markerless tracking sheds light on the challenges and potential of this technology. She discussed using MoCap for research on human movement and coordination. The accuracy of markerless systems like the one she was developing using Sony's camera system was a point of concern, with cm-scale accuracy compared to the mm-scale accuracy required, and that current MoCap systems can offer.

J.R. pointed out practical challenges, such as the need for re-calibration when the cameras are moved, especially in outdoor settings. She also highlighted the limitations of current software and the potential for automation in the calibration process.

2.3.5 Key Insights from Expert Perspectives

These interviews with experts in the field of motion capture have been instrumental in highlighting the multifaceted challenges and opportunities for the development of a new MoCap system. These insights emphasize the necessity for systems that offer high accuracy and flexibility across various settings. Key themes such as the need for modular and portable systems, and the challenges posed by calibration and environmental interference emerged prominently.

These discussions underscore a comprehensive understanding of the current landscape and the future potential of MoCap technology. Consequently, there is a clear emphasis on developing a system that harmoniously balances the precision of fixed rigs with the accessibility of mobile solutions, setting the stage for a potential revolution in the field of MoCap technology. This synthesis of diverse viewpoints and experiences from industry leaders and researchers is pivotal in guiding the creation of an advanced, user-centric MoCap system.

3 Hardware Design & Fabrication

This section delves into the hardware design and fabrication process that forms the core of the MoCap system development. This phase of the project is the culmination of research and ideation, drawing on the valuable insights gained from comprehensive literature review, market analysis, and in-depth user interviews. These preliminary stages provided a rich foundation of knowledge, enabling a better understanding of the current landscape of MoCap technology, its challenges, and the specific needs and preferences of users across various domains.

Building on this foundation, a process of conceptualizing various designs for the MoCap system began. The aim was to create hardware that not only addresses the identified gaps in existing technologies but also aligns with the evolving demands of MoCap applications in diverse settings, without loosing the LabX's project main focus of in-house MoCap. The design process involved brainstorming sessions, iterative prototyping, and continuous feedback loops, ensuring that each design choice was informed by both the theoretical and practical aspects of MoCap technology.

This chapter presents the journey from initial concepts to the final design of the sensor rig. It gives a detailed explanation of the design considerations that guided design choices, the challenges encountered during the fabrication process, and how these hurdles were overcome to develop an effective system. This narrative not only sheds light on the technical aspects of hardware development but also reflects the innovative spirit and problem-solving approach that underpins this project.

3.1 FReDPARRC Analysis

In the initial phase of this design project, the FReDPARRC method was employed, a systematic ideation and brainstorming framework developed by MIT Professor of Mechanical Engineering, A. Slocum [21]. Standing for Functional Requirements, Design Parameters, Analysis, References, Risks, and Counter-measures (as highlighted in figure 3.1), this approach provides a structured and comprehensive way to explore and define the key aspects of the MoCap system design.

This section of the thesis briefly outlines the components of the FReDPARRC analysis as applied to the MoCap system. The process began with identifying the Functional Requirements - the essential capabilities and functionalities that the MoCap system must achieve. Design Parameters were then established, guiding the design decisions to align with the project's objectives.

An Analysis was planned to evaluate the practicality and potential impact of these parameters, integrating insights from a range of References, including market research, literature reviews, and feedback from user interviews. These steps ensured that the design choices were informed and relevant to the current state of MoCap technology and its applications.

The potential Risks that could affect the project's successful completion were also assessed, alongside the Counter-measures to mitigate these risks. This comprehensive analysis ensures that the design process is well-rounded, addressing the complex nature of developing a sophisticated MoCap system.

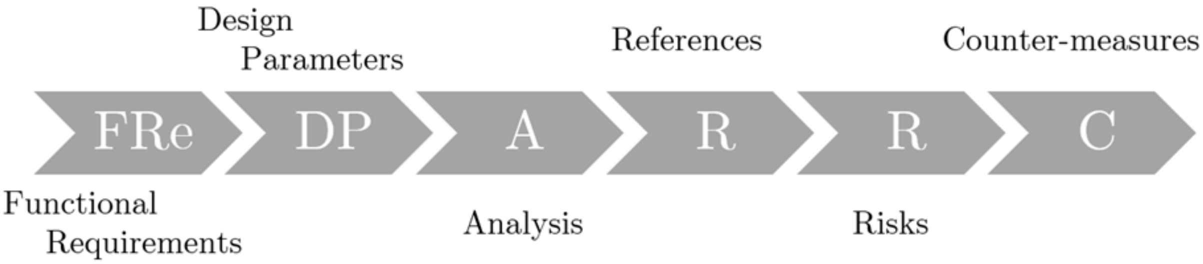


Figure 3.1: The FReDPARRC method's flow chart, showing the order of the different ideation phases, as explained in Prof. Slocum's book '*FUNdaMENTALS of Design*' [21].

While the FReDPARRC framework generated a multitude of ideas and potential directions for the MoCap system, this thesis focuses specifically on the hardware and mechanical design aspects. Other ideas, though valuable, fall outside the scope of this work but could be explored in future projects or research.

For a detailed account of the discussions and deliberations that took place during the FReDPARRC process, readers are referred to the appendix (A). This section provides an overview of the thought process and considerations that shaped the early stages of the MoCap system's design, setting the foundation for the detailed exploration of hardware and mechanical design aspects in the subsequent chapters of this thesis.

3.1.1 Functional Requirements

The Functional Requirements for the motion capture system are centered on ensuring transportability, modularity, precision measurement, ease of setup, data processing capabilities, and the synchronization of data captures. The system must be lightweight, compact, and easily transportable in terms of weight, volume, and shape. Modularity is critical, with the design aiming to accommodate various sensor types, including standard cameras, RADARs, acoustic sensors, and accelerometers. It should support power supply, control, and data acquisition from these sensors.

Precision in measurement is essential, focusing on frequency, image definition, allowable drift, and error budgeting. The system must be user-friendly, enabling easy setup, deployment, and minimal breakdowns. Data storage and processing require flexibility for real-time or delayed processing, online or offline. Synchronization of data captures involves aligning temporal, spatial, and different data types. Lastly, the system should be capable of monitoring human movement with the required frame rate depending on the movement type.

3.1.2 Design Parameters

The Design Parameters for the MoCap system include selecting appropriate sensors and their attachments, ensuring efficient data communication and storage, and determining power supply needs. The materials for housing or stand construction and specific machine elements are also crucial considerations to meet the functional requirements. The design must facilitate seamless communication with the main unit and other units, and incorporate effective data processing capabilities. These parameters are fundamental in translating the functional requirements into a tangible, operational system.

3.1.3 Analysis

The Analysis phase involves a detailed examination of several key aspects of the system's performance. Vibration analysis of the sensor rig ensures stability and accuracy. Spatial drift analysis of sensors is conducted to maintain precision in data capture. The number of compatible sensors is evaluated to ensure system versatility. Synchronization accuracy and temporal drift are analyzed to guarantee the reliability of data captures over time. Lastly, motion capture accuracy is scrutinized to ensure the system meets the required standards for different applications.

3.1.4 References

References for this project include specific sensors incorporated into the system design, types of tripods suitable for stable setup, and an exploration of existing MoCap systems available at MIT's CCTR and Immersion lab. Multimodular data systems are reviewed for insights into efficient data handling. Additionally, marker-less tracking technologies are examined as potential references for innovative tracking solutions.

3.1.5 Risks

Identified Risks in the project include the potential for the system to fall over or move excessively, issues with power supply or data collection, challenges in cable management and device collision, privacy concerns, data loss or corruption, complexity in usage, inappropriate weight distribution, sensor interference, and visual obstruction. Each of these risks poses a threat to the system's functionality and user experience.

3.1.6 Counter-measures

To mitigate the identified risks, Counter-measures are devised. These include designing a highly stable system or even securing it to a wall, robust solutions for power supply and data collection, smart cable management or wireless configurations, ensuring HIPAA-compliant data collection, providing intuitive setup instructions and automation, easy system calibration and validation, and incorporating error messages for visual obstructions. These counter-measures are crucial for ensuring the system's reliability, user-friendliness, and compliance with privacy and safety standards.

3.2 Design Iterations

Throughout the development of the motion capture system, a series of design iterations were undertaken to optimize the system for efficiency, adaptability, and user experience. Each iteration addressed key aspects such as sensor variability, vibration dampening, modularity, and cable management, enhancing the system's overall functionality and meeting the functional requirements.

3.2.1 Sensor Variability

One of the primary design challenges was ensuring compatibility with a wide range of sensors, especially large full-frame cameras commonly used in professional MoCap setups. The attachment system was thus designed with universal 1/4-20 UNC threads, a standard mount size in the camera industry, ensuring compatibility with most camera models. This feature allows users from various professional backgrounds to easily integrate their existing equipment with this system.

Additionally, understanding the need for quick adaptability in dynamic capture or research scenarios, a quick-release plate was incorporated into the design, as shown in figure

3.3. This plate enables users to switch sensors rapidly, significantly reducing downtime between different configurations and allowing for a more seamless operation. This adaptability is crucial in environments where time is a constraint and precision is paramount. This quick-release plate is assembled to the rig thanks to an Arca-Swiss quick release system, a type of standard attachment for cameras whose dimensions are shown in figure 3.2, allowing users to use other Arca-Swiss systems on the rig for greater adaptability.

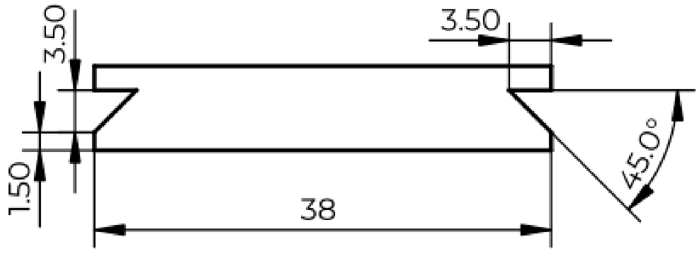


Figure 3.2: The Arca-Swiss Quick Release System's profile, a widely used standard in the photography industry for attaching and detaching cameras from tripods quickly and securely.

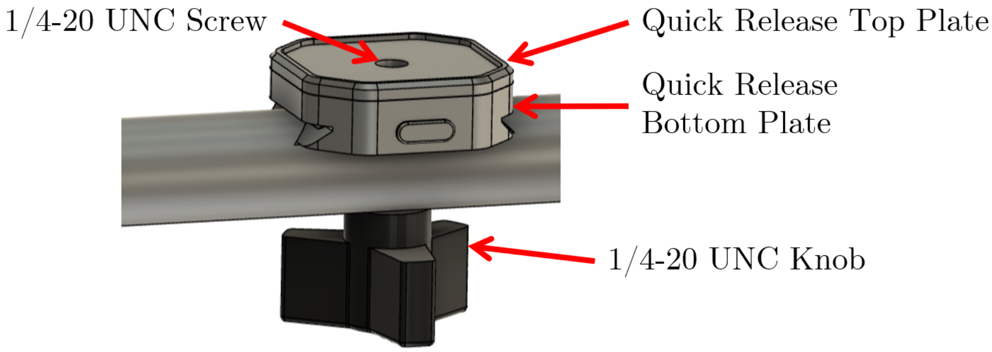


Figure 3.3: The attachment has been designed with a quick-release plate to facilitate sensor change, and all the threads are 1/4-20 UNC as it is the photography material's standard.

3.2.2 Vibration Dampening

Accurate motion capture requires a stable platform, free from vibrations that could distort data. To address this, the system's base is equipped with rubber casters, shown in figure 3.4, whose material properties have vibration-absorbing qualities. This base ensures that even minor tremors or surface irregularities do not impact the data quality. The rubber base is retractable, providing the added functionality of using wheels for easy mobility. This feature is particularly beneficial in larger studio or field settings where the system needs to be moved frequently.

Figure 3.4: This element is used to reduce the vibrations experiences by the sensor during data capture (left position), while allowing good mobility thanks to the wheel (right position).

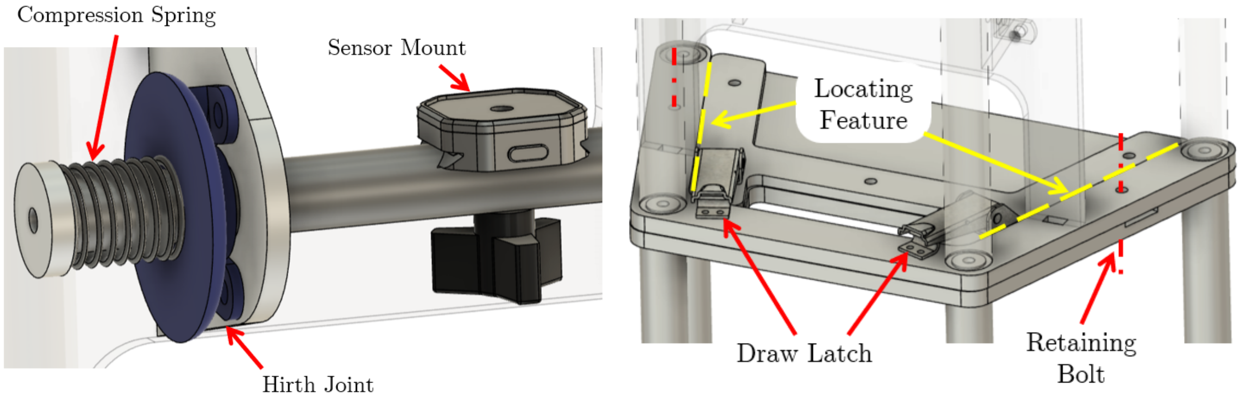
In addition to the base design, the vertical structure of the rig features large hollow tubes. These tubes, owing to their geometry, naturally dampen vibrations, adding another layer of stability. Furthermore, the incorporation of springs at the base of each sensor mount, as seen on figure 3.5a, adds to the rig's ability to absorb and mitigate any inadvertent movements, ensuring the integrity of the captured data.

3.2.3 Modularity

Modularity was a key focus in the design to cater to diverse capture and research requirements. The system includes a Hirth joint mechanism for each sensor mount, allowing for robust adjustments in sensor orientation. This flexibility is crucial for capturing motion from various angles and heights, accommodating different subject sizes and movement types.

The rig's stackable compartments are a novel feature, allowing users to modify the height and position of sensors easily. The user can choose whichever configuration is necessary, easily stacking multiple compartments thanks to a locating feature that eases their positioning between each other, and latches and bolts which are used to secure the assembly, as highlighted in figure 3.5b. This modularity is particularly beneficial for customizing the setup for specific applications, be it in a controlled studio environment or a dynamic outdoor setting. The ease of interchanging these compartments between rigs makes the system highly versatile.

The base compartment of the system is designed with ample space to house additional sensor hardware, such as switches, routers, and power supplies. This spacious design ensures



(a)

(b)

Figure 3.5: Details of some of the assembly features developped for this design: (a) A detail of the sensor mount, where the compression spring adds a layer of dampening effect, and the Hirth joint allows the selection of the sensor's rotation while keeping it robust to vibrations; (b) A detail of the positioning and retaining features between two compartments.

that all necessary equipment can be integrated into a single, cohesive unit, simplifying the setup and reducing the need for external hardware.

3.2.4 Cable Management

Effective cable management is crucial for maintaining a tidy and safe working environment, especially when the product is designed for a more general audience. As shown in figure 3.6, the design includes carefully placed holes in the back of each compartment, allowing for a streamlined routing of cables between compartments and to the base unit. This feature not only improves the aesthetic appeal of the setup but also minimizes the risk of cable entanglement or tripping hazards, which is particularly important in busy studio environments.

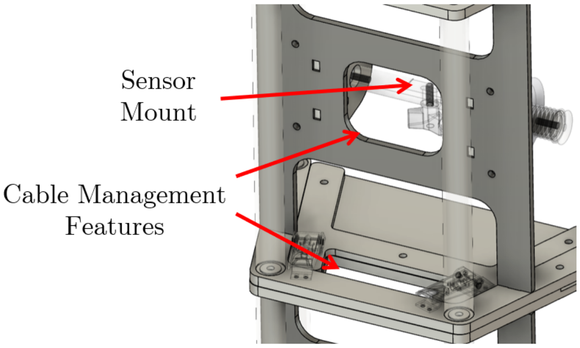


Figure 3.6: Holes have been carefully placed to allow for good and easy cable management, a primary concern in sensors systems like this.

Additionally, a dedicated hole in the middle plate of each compartment facilitates direct and easy connection of the sensors. This design consideration simplifies the setup process, making it more user-friendly and reducing the time required for installation and calibration.

3.2.5 Overall Design

These design iterations, driven by a deep understanding of user needs and technical requirements, have resulted in a MoCap system shown in figure 3.7, that is versatile, user-friendly, and suitable for a wide range of motion capture applications, from medical analysis to academic research.

Figure 3.7: Front & Back view of the system's CAD. This example is composed of the base compartment, two sensor compartments and an empty compartment for height adjustment.

3.3 Fabrication & Learnings

The fabrication of the MoCap system was an intricate and enlightening process that involved various manufacturing techniques. This section delves into each step of the fabrication, highlighting the methods used and the valuable insights gained.

3.3.1 Bill of Materials

The fabrication of the MoCap system began with the development of a comprehensive Bill of Materials (BOM). A BOM is essentially a detailed inventory of materials, components, and assemblies required to build a product. It serves as a critical blueprint for manufacturing, ensuring that every necessary item is accounted for and available at the right stage of the production process. For this project, the creation of an accurate and well-organized BOM was crucial for streamlining the fabrication process and managing resources efficiently.

Aluminium was chosen as the primary material for its combination of strength and lightweight properties, which were essential for ensuring the MoCap system's portability and durability. The use of aluminium struck the right balance between ease of handling and structural integrity, making it an ideal choice for a system designed for frequent transportation and setup.

In terms of fasteners, a deliberate decision was made to standardize on just two types of threads across the entire design. This standardization greatly simplified the assembly process (and ultimately the maintenance process), reducing the complexity and potential for errors during construction. While this approach meant that some parts of the system were fitted with bolts stronger than what was strictly necessary, it provided a uniformity that was advantageous for both assembly and potential future servicing.

This streamlined approach to material and component selection was a key factor in the successful fabrication of the MoCap system. By carefully considering each item in the BOM and its role in the overall design, the production process became efficient and effective. The complete Bill of Materials, detailing every component used in the construction of the MoCap system, can be found in the appendix B. This document provides an in-depth view of the range and types of materials selected, offering insights into the thoughtful planning and resource management that underpinned the fabrication phase of the project.

3.3.2 Material Blanking and Rough Shaping

The initial phase of fabricating the MoCap system involved initial cutting of the components, a process crucial for setting the foundation of the subsequent, more precise manufacturing steps. This stage primarily utilized waterjetting, employing the 'Omax 2652 JetMachining Center', a sophisticated tool adept at handling the complexities of cutting intricate designs from sheet metal. The 'Omax Layout' software played a critical role in this phase, allowing for the optimization of cutting patterns and material usage. The waterjet cutter was particularly effective for its precision and ability to cut through aluminium sheets without inducing thermal distortions, a common issue with other cutting methods such as laser or plasma cutting.

In addition to waterjetting, a band saw was used for cutting parts to their rough dimensions. This method was especially useful for larger components or when quick, preliminary cuts were required before more detailed shaping. The band saw's versatility in handling various material types and sizes made it an integral part of the initial fabrication process. The initial rough fabrication set the stage for the fine-tuning and precision work that followed, ensuring that the basic shapes and sizes of the components were ready for the next steps.

3.3.3 Precision Machining and Detailed Component Refinement

After the initial material shaping, the MoCap system fabrication progressed into the precision machining phase. This critical stage was conducted using a 'Prototrak SMX Bridgeport 2 Axis' mill, a choice driven by the need for higher accuracy and finer detail than what was achievable through waterjetting. The machining process was pivotal for creating intricate features, notably the Arca-Swiss profile, which was integral to the sensor attachment mechanism of the system. Given the complexity and required precision of this feature, a dovetail endmill was utilized. This tool was specifically calibrated for working with the hard steel shaft, ensuring the profile was machined to exact specifications.

Additionally, machining played a crucial role in refining components that had blind holes or required more accuracy. These aspects were beyond the capabilities of waterjetting and demanded the precision that only machining could provide. This process was instrumental in ensuring that each component met the stringent dimensions and tolerances necessary for seamless assembly and optimal functionality of the system.

The detailed drawings and specifications used for the machining process are included in the appendix C. These documents provide a comprehensive view of the intricate designs and precise measurements that were essential to this phase of fabrication.

3.3.4 System Assembly and Structural Welding

The final step in the fabrication process was the assembly and welding of the MoCap system's components. Given the challenges associated with welding aluminium, this task was outsourced to skilled professionals. Their expertise was vital in ensuring strong and stable joints, a necessity for the system's structural integrity. Welding was particularly important for securing the tubes at the ends of the structure, where threaded rods and bolts alone, designed as the initial component to secure the tubes, could not provide the required rigidity.

The assembly process involved meticulously putting together the machined and waterjet-cut components, ensuring that every piece fit perfectly as per the design specifications.

Attention to detail during this phase was crucial to avoid any misalignments or errors that could impact the system's performance. The combination of precise machining, careful assembly, and expert welding resulted in a robust and reliable MoCap system, capable of withstanding regular use and transportation.

3.3.5 Fabrication Insights and Progression

The fabrication of the MoCap system was a multi-staged process that combined various manufacturing techniques, each crucial to the project's progression. This journey began with the initial rough fabrication, where basic component shapes were formed using waterjetting and band saw cutting. This phase laid the groundwork for the more detailed work that followed.

In the precision machining phase, the 'Prototrak SMX Bridgeport 2 Axis' mill was utilized to refine components to their exact specifications. This stage was essential for achieving the high levels of accuracy required for the system's components, particularly for intricate features like the Arca-Swiss profile.

The final assembly and welding phase brought together all the machined parts. Given the complexities involved in welding aluminium, this stage was crucial for ensuring the structural integrity and stability of the system. Outsourcing this task to skilled professionals ensured high-quality welds that were essential for the system's durability.

Each fabrication phase played a significant role in transitioning from the initial design to a functional MoCap system. The process not only highlighted the importance of adaptability and precision in manufacturing but also provided valuable insights into working with diverse materials and techniques. The progression through these phases demonstrated the meticulous planning and execution needed to create a complex and high-quality motion capture system.

3.4 Final Prototype

The culmination of the MoCap system's design and fabrication process is embodied in the final prototype. This prototype consists of a base compartment and a sensor compartment, assembled together to demonstrate the system's functionality and design features.

The following figures offer a comprehensive view of the assembled prototype and its individual compartments, illustrating how the various design and fabrication elements discussed throughout the thesis have materialized into this final product.

3.4.1 Assembled Prototype Views

Figure 3.8a to 3.8e present different perspectives of the assembled prototype, showcasing the integration of the base and sensor compartments. These images highlight the system's overall design, reflecting the modularity, adaptability, and robustness that were key objectives of the project.

(a) (b) (c) (d) (e)

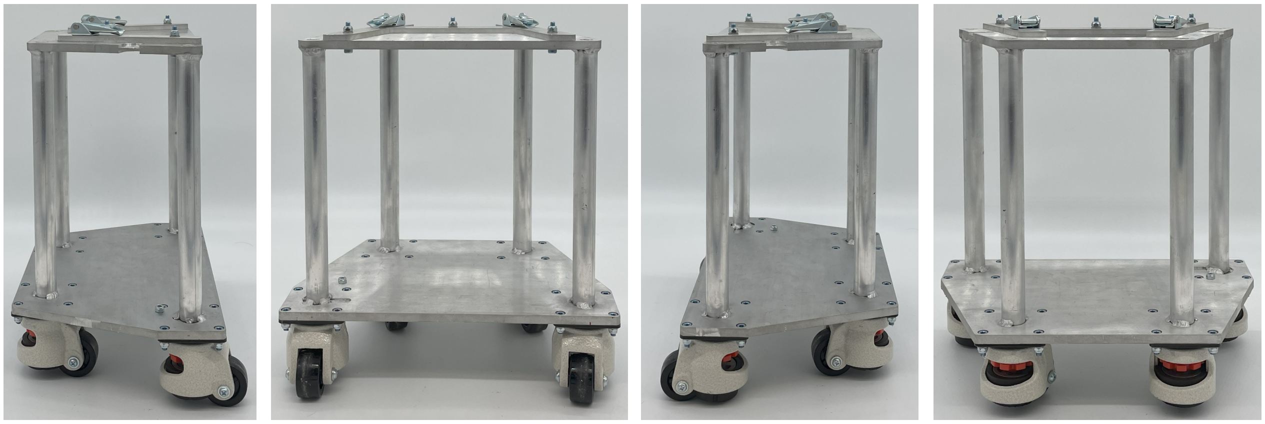
Figure 3.8: Pictures of the assembled prototype under numerous views: (a) Left view; (b) Front view; (c) Isometric view; (d) Right view; (e) Back view.

3.4.2 Base Compartment Views

Figures 3.9a to 3.9d focus on the base compartment, a crucial element of the prototype providing stability and housing space for essential components. These views underscore the compartment's design considerations for portability and structural integrity.

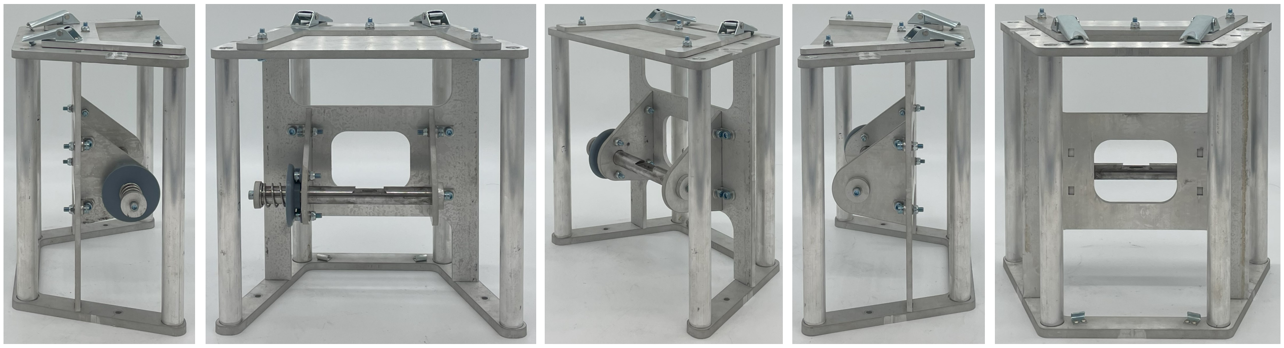
3.4.3 Sensor Compartment Views

The sensor compartment is highlighted in figures 3.10a to 3.10e, demonstrating the compartment's modularity and adaptability features. These images illustrate how the compartment can accommodate various sensors and adjust to different motion capture scenarios, while showxasing a robust structure.



(a) (b) (c) (d)

Figure 3.9: Pictures of the prototype's base compartment under numerous views: (a) Left view; (b) Front view; (c) Right view; (d) Back view.

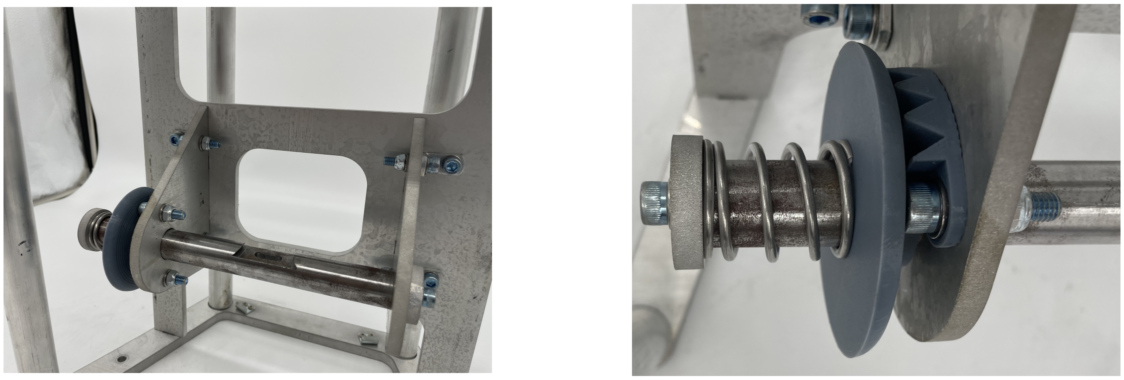


(a) (b) (c) (d) (e)

Figure 3.10: Pictures of the prototype's sensor compartment under numerous views: (a) Left view; (b) Front view; (c) Isometric view; (d) Right view; (e) Back view.

3.4.4 Sensor Mount and Hirth Joint Details

Figure 3.11a and 3.11b provide close-up views of the sensor mount and Hirth joint from the sensor compartment. These images showcase the innovative design elements that enhance the prototype's functionality, such as the Arca-Swiss profile and the Hirth joint for sensor orientation, which improve the overall vibration dampening and adaptability of the system.



(a)

(b)

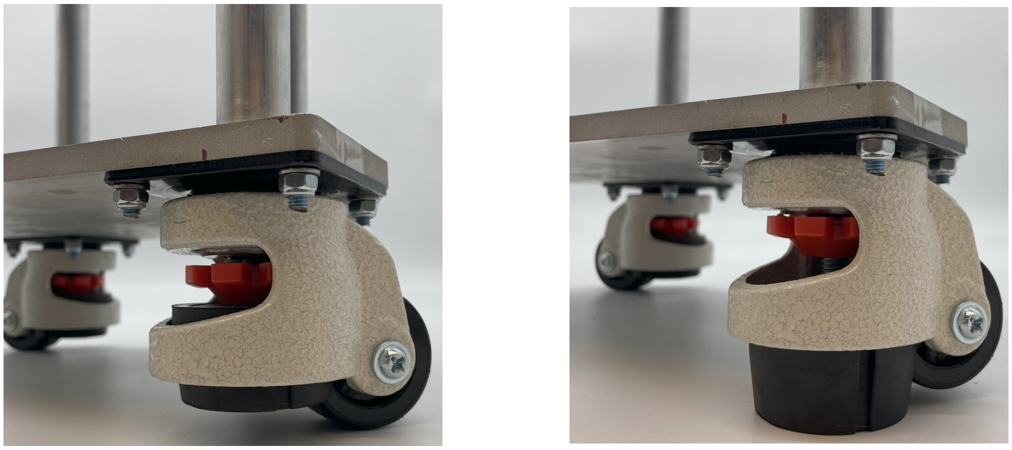
Figure 3.11: Pictures of some parts of the sensor mount's components: (a) A detail of the overall sensor mount, where the Arca-Swiss cut and cable management hole can be seen; (b) A detail of the 3-D printed Hirth joint and spring, allowing for orientation selection and improving overall vibrations dampening.

3.4.5 Retractable Caster Details

Finally, figures 3.12a and 3.12b demonstrate the functionality of the retractable casters mounted on the base compartment. These images illustrate the system's mobility and stability features, crucial for easy transportation and effective vibration dampening during operation.

3.5 Vibration Analysis

A vibration analysis has been carried out to analyze the capability of the prototype and its dedicated components to dampen vibrations compared to standard structures like a table or a tripod. This analysis is crucial to validate the effectiveness of the prototype in maintaining stability during motion capture operations, and reducing spatial drift of the sensors.

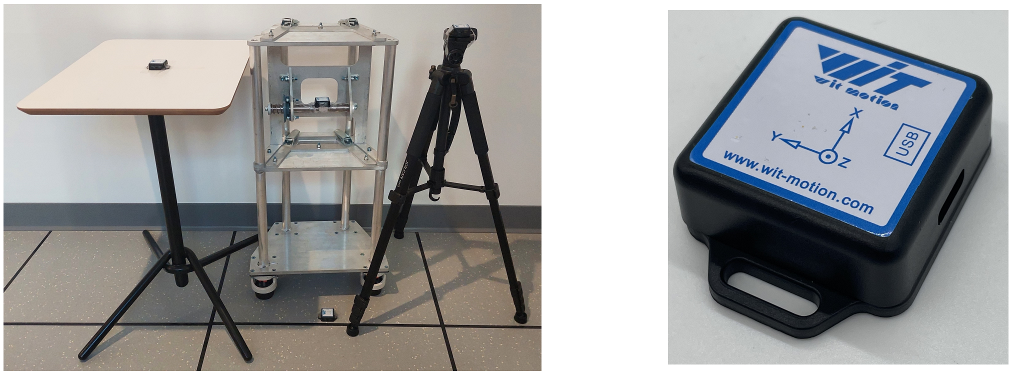


(a) (b)

Figure 3.12: Pictures of the retractable casters mounted on the base compartment: (a) Retracted caster, allowing the wheel to be used for easy transportation of the sensor rig; (b) Extended caster, making the rig more stable and dampening vibrations thanks to the rubber base.

3.5.1 Experiment Setup and Data Acquisition

To conduct this experiment, an accelerometer was placed on different structures – the floor (used as the vibration baseline), a standard table, a conventional tripod, and the prototype – to measure and compare vibration levels, as seen in figure 3.13a. The setup aimed to replicate real-world conditions where these structures might be used for sensing, and to an extent, motion capture.



(a) (b)

Figure 3.13: Pictures of the experiment carried out to analyze the structure's capability to dampen vibrations: (a) A sensor has been placed on each element from which vibration data is acquires: the floor, a table, a tripod, and the prototype; (b) Picture of the accelerometer used for the experiment [22].

The accelerometers used were 9 Axis (Acceleration + Gyro + Magnetometer + Angle

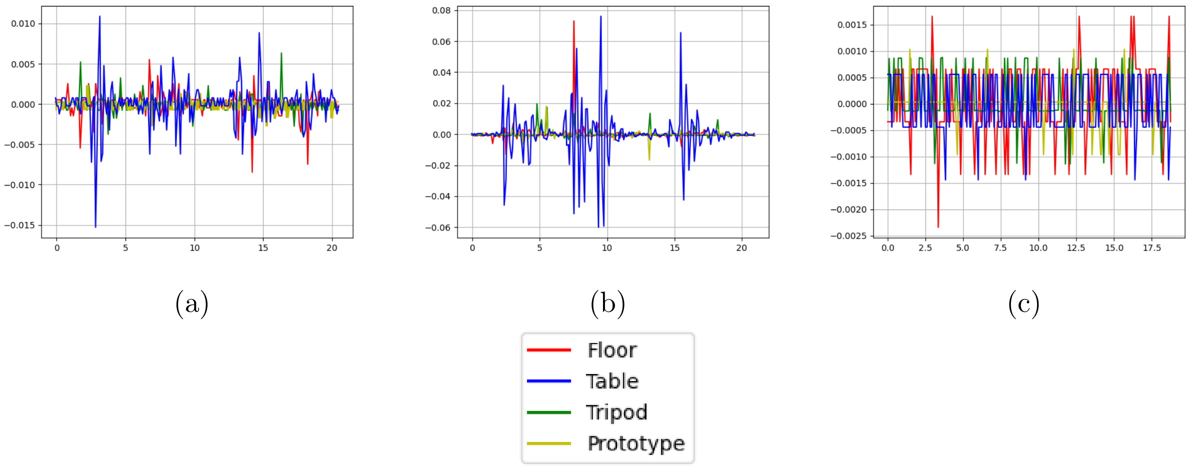
Inclinometer) Gyroscopes [22], as seen in figure 3.13b, fixed on the different structures. The accelerometer data from each structure was recorded at the same time, for the same vibrations (consisting of people walking, stomping, and jumping around the sensors), and under the same conditions to ensure consistency in the measurements. This setup provided a baseline for understanding the inherent vibration-dampening capabilities of each structure.

3.5.2 Data Processing

The vibration data collected for this study was processed using Python. The details of the code used for this analysis can be found in the appendix D. The data processing included several key steps:

- **Normalization**: To account for variations in sensor orientation across different structures, the norm of the accelerometer data was computed. This calculation considers the 3-D components of acceleration, providing a uniform measure of vibration intensity regardless of sensor tilt.
- **Baseline Correction**: Each dataset's mean was subtracted from the individual data points. This step helps to correct potential gravitational calibration discrepancies, facilitating more accurate comparisons between data from different sensors.
- **Synchronization**: The data from various sensors were synchronized based on their timestamps. This ensures that the comparison of data points is conducted at equivalent time points across all sensors. In the analysis, the initial timestamp of one of the sensors was used as a reference to align all datasets.
- **Statistical Analysis**: The resulting raw data was directly utilized in statistical analysis to maintain the fidelity of the vibration signals. This approach allows for an unaltered representation of the vibration patterns, which can be crucial in certain analyses.

The data obtained from these steps is presented in figure 3.14 and provides initial insights into the effectiveness of the different structures in dampening vibrations. Observations from the figure reveal varied performance across the tested structures: while the table often exacerbates vibrations, the tripod consistently shows positive results, moderately reducing vibrations in all scenarios. In contrast, the prototype demonstrates a more notable ability to effectively dampen vibrations, indicating its superior design in managing such disturbances.



(a) (b) (c)

Figure 3.14: The charts display processed sensor data from various experimental runs, including walking, jumping, and remaining still next to the setup. The data, correlated with the sensors identified in the legend, showcase distinct vibration behaviors across the structures. While the table often intensifies vibrations, the tripod demonstrates a consistently moderate effectiveness in dampening vibrations. In contrast, the prototype exhibits a superior ability in consistently reducing vibrations effectively. These observations highlight the relative stability and effectiveness of each structure in managing vibrations, with the prototype standing out as the most effective solution.

3.5.3 Results and Interpretation

The vibration analysis experiment yielded significant insights by comparing the standard deviation of acceleration across different structures against a baseline measurement from the floor, as presented in table 3.1. This comparative approach enabled a quantitative assessment of each structure's ability to dampen vibrations. Here's a detailed interpretation of the results:

- **Table**: The analysis showed that the table amplified vibration levels, increasing them by +82.5% relative to the floor. This finding suggests that using a standard table as a sensor base can actually intensify vibrations. Such an increase could potentially compromise the accuracy and integrity of data captured, especially in precision-dependent motion capture applications.

- **Tripod**: The tripod's performance in reducing vibrations was not as effective as expected. It showed a decrease in vibration levels by -40.4% compared to the floor. This result indicates that while tripods are typically associated with stability, their capacity to dampen vibrations is not optimal. For motion capture setups demanding high stability, tripods may not be the best choice.

- **Prototype (MoCap System)**: The prototype exhibited impressive vibration-dampening capabilities, reducing vibration levels by -63.7% in comparison to the floor baseline. This significant reduction in vibrations confirms the prototype's effectiveness in providing a stable platform for motion capture. The design and material choices in the prototype effectively minimized vibrations, ensuring more stable and accurate data capture.

These findings clearly demonstrate the prototype's superior performance in vibration reduction, an essential attribute for high-quality motion capture systems. The success of the prototype in outperforming conventional setups like tables and tripods validates the design objectives and emphasizes the crucial role of thoughtful engineering in developing specialized motion capture equipment. The results reinforce the prototype's suitability for applications where precision and stability are paramount.

	Standard deviation's difference from the baseline (the floor's signal's standard deviation)		
	Table	**Tripod**	**Prototype**
Walking 1		Corrupted Data	
Walking 2	+77.46%	-29.65%	-57.00%
Walking 3	+199.86%	-38.93%	-45.38%
Walking 4	+105.71%	-20.56%	-71.57%
Jumping 1	+180.62%	-48.67%	-62.47%
Jumping 2	+138.27%	-60.40%	-75.26%
Jumping 3	+175.29%	-23.61%	-79.41%
Jumping 4	+128.45%	-65.31%	-80.32%
Still 1	-21.05%	-38.94%	-60.85%
Still 2	-27.88%	-65.93%	-59.14%
Still 3	-21.79%	-30.44%	-49.77%
Still 4	-27.26%	-22.11%	-58.96%
Average	+82.52%	-40.41%	-63.65%

Table 3.1: This table presents the results from the vibration analysis experiment, comparing the standard deviation's difference from the baseline (the floor's signal's standard deviation) across various tests. It includes data for different scenarios such as walking, jumping, and remaining still, for each of the three compared structures: Table, Tripod, and Prototype. The percentages indicate the increase or decrease in vibration levels relative to the baseline. Notably, the table generally increased vibration levels, the tripod moderately reduced them, and the prototype showed a significant reduction in vibrations. These results provide a quantitative measure of each structure's effectiveness in vibration dampening, with the prototype demonstrating superior performance.

4 Sensor Fusion Technology & Software Development

This chapter delves into the vital aspect of integrating sensor fusion technology and advanced software development in MoCap systems. The seamless amalgamation of varied sensors and software is crucial for the creation of a MoCap system that is not only versatile but also precise and adaptable across different settings.

The chapter is structured into key sections, each focusing on an integral component of the system's technological ecosystem. The exploration begins with an examination of the platform, ROS2, an essential framework that facilitates the integration of diverse sensors into a cohesive system. Following this, the focus shifts to the selection of cameras, a critical hardware component, ensuring they allow easy development to enhance the system. In the realm of software development, the chapter delves into the nuances of developping software that can effectively implement the sensors in the system. Finally, the chapter culminates with a look at synchronization experimentation, a process pivotal to ensuring that the data from various sensors are accurately aligned in time.

This comprehensive approach to sensor fusion and software development is not just about technical integration. It reflects a broader narrative of responding to market needs and user feedback, as identified in earlier chapters. This alignment of hardware innovation with software sophistication exemplifies the project's commitment to pushing the boundaries of MoCap technology.

4.1 ROS2: The Backbone of Sensor Integration

In the development of the MoCap system, the selection of ROS2 (Robot Operating System 2) as the core framework for sensor integration was based on its distinguished capabilities and widespread acceptance in the field of robotics and camera vision. The decision to integrate ROS2 was driven by several key considerations:

- **Facilitates Seamless Sensor Communication**: ROS2 excels in enabling communication among various sensors. This is essential in MoCap technology where data synchronization and integration from multiple sources is critical. ROS2's architecture allows for efficient data exchange and processing across different sensor types, ensuring cohesive system operation.

- **Wide Adoption in the Community**: The extensive use of ROS2 in the robotics community means abundant resources and support are available. This widespread adoption leads to a robust and well-tested framework, with solutions and best practices readily accessible. It also increases the likelihood of finding pre-existing libraries or community contributions for sensors lacking official ROS2 support.

- **Flexibility and Scalability**: ROS2's modular design offers remarkable flexibility, allowing for the integration of a wide range of sensors and devices. This adaptability is crucial for a project aiming to blend various sensor technologies. The scalability of ROS2 ensures that the system can evolve, accommodating future technological advancements and additional sensor types.

- **Community-Sourced Development and Support**: The active ROS2 community provides a wealth of shared knowledge, troubleshooting support, and ongoing development, contributing to the system's continuous improvement and relevance.

By leveraging the strengths of ROS2, the MoCap system can achieve a high level of sensor integration, communication efficiency, and operational reliability. ROS2 thus forms the backbone of the system, enabling the advanced sensor fusion required to meet the project's ambitious goals in motion capture technology.

4.2 Camera Selection: Opting for Raspberry Pi's HQ Camera

The selection of the camera for the MoCap system was a crucial decision, and after thorough consideration, the Raspberry Pi's High-Quality (HQ) Camera seen in figure 4.1 was chosen for its integration into the system. This choice was driven by several key factors that align with the project's objectives:

- **Ease of Development**: The Raspberry Pi platform is known for its user-friendly interface and robust community support, making it an excellent choice for development purposes. This ease of development is vital in a project where rapid prototyping and iterative testing are essential.

- **Popularity and Reproducibility**: The Raspberry Pi's HQ Camera is widely used in various applications, from hobbyist projects to professional setups. Its popularity ensures that this MoCap system can be easily reproduced and modified by others, fostering a community-driven approach to development and innovation.

- **Preliminary Work Suitability**: While the frame rate of the Raspberry Pi's HQ Camera may not be the highest on the market, it is sufficiently adequate for preliminary work and development stages. This allows for effective testing and refinement of the MoCap system without the need for high-end, expensive camera equipment.
- **High-Quality Sensor**: The camera boasts a 12.3-megapixel sensor, providing high-resolution images that are crucial for detailed motion capture. The quality of the sensor ensures that the captured data is precise and reliable, a non-negotiable aspect in motion capture technology.
- **Versatility of the Raspberry Pi**: The Raspberry Pi itself is a versatile and powerful tool, and its integration with the HQ Camera adds to the system's overall flexibility. This versatility makes the development process more generalizable and adaptable to various motion capture scenarios.

Figure 4.1: Raspberry Pi 4 module with an HQ camera attachment on a specific case which eases mounting of the set-up.

The integration of the Raspberry Pi's HQ Camera into the MoCap system represents a balance between quality, ease of use, and cost-effectiveness. This decision is a testament to the project's commitment to creating a motion capture system that is not only high in quality but also accessible and adaptable to a wide range of users and applications.

4.3 Software Development for MoCap System

The development of the software infrastructure for the MoCap system was a critical component of this project. The goal was to create a system that was both powerful and user-friendly, ensuring seamless integration and operation of various sensors. This section delves into the key decisions and implementations made in the software development process.

The choice of operating system was fundamental to the system's functionality. Linux Ubuntu 22.04.3 was selected due to its stability, broad support base, and compatibility with ROS2 Humble Hawksbill, the chosen version of the Robot Operating System 2. This combination provided a robust and efficient environment for software development, offering both flexibility and reliability.

The MoCap system's hardware setup included three Raspberry Pi units, each playing a distinct role in the data capture and processing workflow. Two of these units were equipped with Raspberry Pi High-Quality (HQ) Cameras and ran on Ubuntu Server. Designated as 'slave' sensors, their primary function was image capture. The Ubuntu Server was apt for this role, as it efficiently handles the backend processes without the need for a graphical interface.

The third Raspberry Pi served as the 'master' sensor. It was installed with Ubuntu Desktop, allowing for the direct visualization and storage of the captured images. This setup was essential for real-time data monitoring and processing, a critical aspect for effective motion capture.

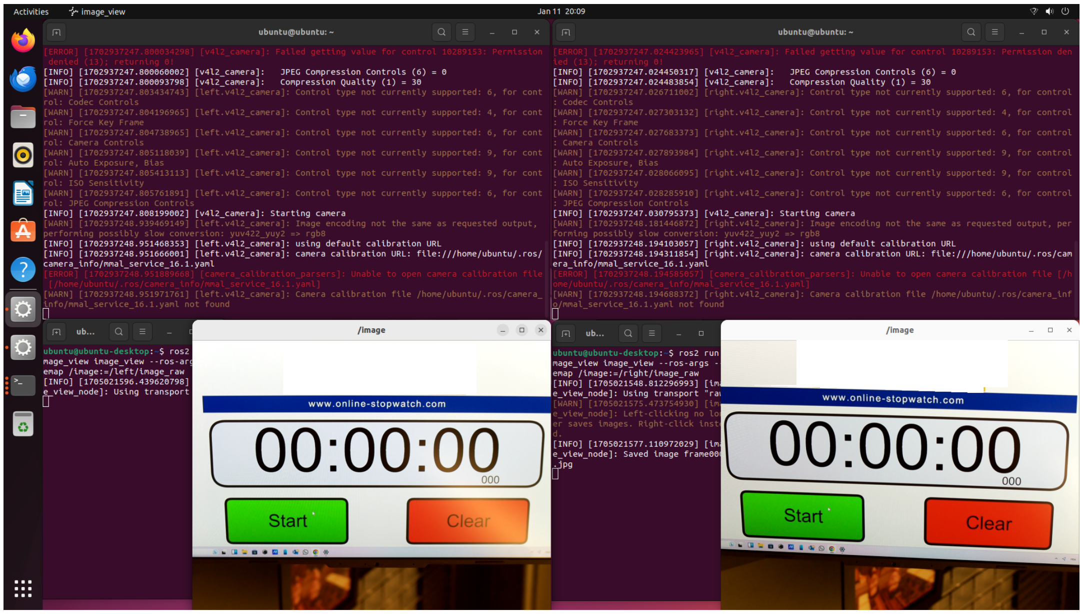
To aid in the replication and setup of the system, detailed instructions for installing Ubuntu and ROS2 on the Raspberry Pi units were provided in the appendix E. This documentation aimed to streamline the setup process, making it accessible for users with varying levels of technical expertise.

Furthermore, comprehensive guidelines for capturing and processing data using the Raspberry Pi units and ROS2 were outlined in the appendix F. These instructions were designed to ensure efficient management of the MoCap system's sensors and data flow, providing a clear and structured approach to operating the system, and allowing the user to have a multi-view visualization as seen in figure 4.2.

In summary, the software development for the MoCap system was marked by careful selection of operating systems and strategic utilization of ROS2. This approach not only facilitated the integration of various sensors but also ensured that the system was capable of handling complex data processing tasks with ease, making it a robust and user-friendly tool for motion capture applications.

4.4 Synchronization Experimentation

A crucial aspect of the MoCap system's functionality is the synchronization of data across multiple sensors. This section discusses the experimental approach undertaken to evaluate the synchronization capabilities of the system, ensuring precise and concurrent data capture from different sensors.



```
[ERROR] [1702937247.800034298] [v4l2_camera]: Failed getting value for control 10289153: Permission
 denied (13); returning 0!
[INFO] [1702937247.800060002] [v4l2_camera]:   JPEG Compression Controls (6) = 0
[INFO] [1702937247.800093798] [v4l2_camera]:   Compression Quality (1) = 30
[WARN] [1702937247.803434743] [left.v4l2_camera]: Control type not currently supported: 6, for cont
rol: Codec Controls
[WARN] [1702937247.804196965] [left.v4l2_camera]: Control type not currently supported: 4, for cont
rol: Force Key Frame
[WARN] [1702937247.804738965] [left.v4l2_camera]: Control type not currently supported: 6, for cont
rol: Camera Controls
[WARN] [1702937247.805118039] [left.v4l2_camera]: Control type not currently supported: 9, for cont
rol: Auto Exposure, Bias
[WARN] [1702937247.805413113] [left.v4l2_camera]: Control type not currently supported: 9, for cont
rol: ISO Sensitivity
[WARN] [1702937247.805761891] [left.v4l2_camera]: Control type not currently supported: 6, for cont
rol: JPEG Compression Controls
[INFO] [1702937247.808199002] [v4l2_camera]: Starting camera
[WARN] [1702937248.939469149] [left.v4l2_camera]: Image encoding not the same as requested output,
performing possibly slow conversion: yuv422_yuy2 => rgb8
[INFO] [1702937248.951468353] [left.v4l2_camera]: using default calibration URL
[INFO] [1702937248.951666001] [left.v4l2_camera]: camera calibration URL: file:///home/ubuntu/.ros/
camera_info/mmal_service_16.1.yaml
[ERROR] [1702937248.951889668] [camera_calibration_parsers]: Unable to open camera calibration file
 [/home/ubuntu/.ros/camera_info/mmal_service_16.1.yaml]
[WARN] [1702937248.951971761] [left.v4l2_camera]: Camera calibration file /home/ubuntu/.ros/camera_
info/mmal_service_16.1.yaml not found
```

```
[ERROR] [1702937247.024423965] [v4l2_camera]: Failed getting value for control 10289153: Permission den
ied (13); returning 0!
[INFO] [1702937247.024450317] [v4l2_camera]:   JPEG Compression Controls (6) = 0
[INFO] [1702937247.024483854] [v4l2_camera]:   Compression Quality (1) = 30
[WARN] [1702937247.026711002] [right.v4l2_camera]: Control type not currently supported: 6, for control
: Codec Controls
[WARN] [1702937247.027303132] [right.v4l2_camera]: Control type not currently supported: 4, for control
: Force Key Frame
[WARN] [1702937247.027683373] [right.v4l2_camera]: Control type not currently supported: 6, for control
: Camera Controls
[WARN] [1702937247.027893984] [right.v4l2_camera]: Control type not currently supported: 9, for control
: Auto Exposure, Bias
[WARN] [1702937247.028066095] [right.v4l2_camera]: Control type not currently supported: 9, for control
: ISO Sensitivity
[WARN] [1702937247.028285910] [right.v4l2_camera]: Control type not currently supported: 6, for control
: JPEG Compression Controls
[INFO] [1702937247.030795373] [v4l2_camera]: Starting camera
[WARN] [1702937248.181446872] [right.v4l2_camera]: Image encoding not the same as requested output, per
forming possibly slow conversion: yuv422_yuy2 => rgb8
[INFO] [1702937248.194103057] [right.v4l2_camera]: using default calibration URL
[INFO] [1702937248.194311854] [right.v4l2_camera]: camera calibration URL: file:///home/ubuntu/.ros/cam
era_info/mmal_service_16.1.yaml
[ERROR] [1702937248.194585057] [camera_calibration_parsers]: Unable to open camera calibration file [/h
ome/ubuntu/.ros/camera_info/mmal_service_16.1.yaml]
[WARN] [1702937248.194688372] [right.v4l2_camera]: Camera calibration file /home/ubuntu/.ros/camera_inf
o/mmal_service_16.1.yaml not found
```

```
ubuntu@ubuntu-desktop:~$ ros2
mage_view image_view --ros-arg
emap /image:=/left/image_raw
[INFO] [1705021596.439620798]
e_view_node]: Using transport
```

```
ubuntu@ubuntu-desktop:~$ ros2 run
mage_view image_view --ros-args -
emap /image:=/right/image_raw
[INFO] [1705021548.812296993] [im
e_view_node]: Using transport "ra
[WARN] [1705021575.473754930] [im
e_view_node]: Left-clicking no lo
er saves images. Right-click inst
d.
[INFO] [1705021577.110972029] [im
e_view_node]: Saved image frame00
.jpg
```

Figure 4.2: This screenshot shows the master's desktop view, where the two slaves' view are visualized, and can be recorded. The two terminals on the top are remotely connected to the slave units through an SSH connection and send them the command line to start publishing picture messages. The two terminals on the bottom receive those ROS2 messages and display them (one terminal per slave unit).

4.4.1 Experimental Setup

The experiment was designed to test the synchronization between two slave Raspberry Pi units equipped with HQ cameras. These units were tasked with capturing images of a screen displaying a precision timer. The setup, seen in figure 4.3, was aimed at simulating a real-world scenario where multiple cameras capture a synchronized sequence of events.

The master Raspberry Pi unit played a key role in orchestrating this experiment. It was responsible for receiving and compiling the images transmitted by the slave units. By doing so, the master unit provided a centralized point of analysis, enabling the assessment of synchronization accuracy across the slave sensors.

4.4.2 Data Acquisition and Analysis

The data acquisition process involved simultaneously capturing picture feeds from the slave units, all triggered by the master machine. This simultaneous triggering was crucial to assess the degree of synchronization between the slave units.

Once the data was captured, a manual comparison was conducted to evaluate the synchronization precision. This analysis involved comparing the timestamps on the images

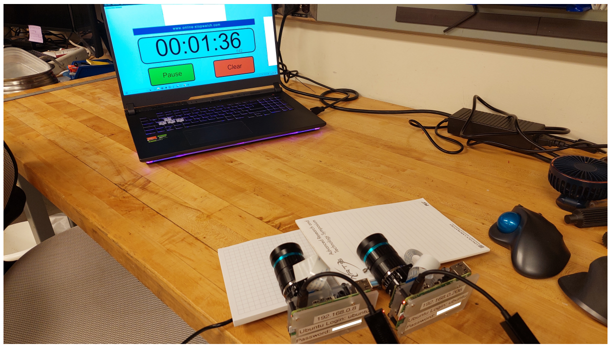


Figure 4.3: This picture shows the synchronization experiment's setup, where two slave Raspberry Pi units observe a timer, and the master Raspberry Pi unit (out of the picture) remotely receives the corresponding images and saves them.

captured by the slave units, as indicated by the precision timer displayed on the screen. The focus was on measuring the time difference between the corresponding frames captured by each slave unit.

4.4.3 Results and Implications

The results from the synchronization experiment highlighted significant challenges in achieving the desired level of precision for the MoCap system. The average time discrepancy between the images captured by the slave Raspberry Pi units was 61 milliseconds. This average discrepancy translates to an effective frame rate of approximately 16 frames per second (fps), notably lower than the target of 30 fps, which equates to a frame every 33 milliseconds. Moreover, the maximum time discrepancy observed in the experiment was 196 milliseconds. This further emphasizes the need for enhanced synchronization capabilities. Such a high discrepancy poses a challenge, especially in applications where precise timing and coordination between multiple sensors are critical.

These findings suggest that while the system can acquire data from multiple sensors, there is a considerable gap to bridge to achieve the tight synchronization necessary for accurate motion analysis. The current level of synchronization, although functional, falls short of the standards required for precision-sensitive motion capture tasks.

Addressing these synchronization challenges will be a key area of focus in future developments. Enhancing the system's synchronization capabilities will not only improve its accuracy and reliability but also expand its applicability in demanding motion analysis scenarios. The insights gained from this experiment are invaluable for guiding the next steps in refining the system's design and software integration to achieve a higher frame rate and more precise data capture.

5 Leveraging RADAR in MoCap with Machine Learning

5.1 Background: RADAR Data in Motion Analysis

In the realm of MoCap, RADAR systems emerge as powerful tools capable of capturing complex motion data while preserving privacy. Unlike traditional camera-based systems, RADAR data does not reveal identifiable human features, thus offering a non-intrusive and privacy-centric approach to motion analysis. This chapter delves into the challenges and opportunities of integrating RADAR technology with machine learning to enhance MoCap capabilities. RADAR systems, as highlighted in the research by Gurbuz et al. (2019) [23], offer a compelling alternative to traditional camera-based MoCap, capturing complex motion data without compromising individual privacy. This feature makes RADAR particularly suitable for environments where privacy is a crucial concern, such as in healthcare settings or personal spaces.

However, the use of RADAR in MoCap presents unique challenges. RADAR data tends to be dense, noisy, and less intuitively interpretable compared to visual data from cameras. Machine learning algorithms, renowned for their ability to process and analyze complex datasets, are well-suited to address these challenges. They can effectively extract meaningful patterns and insights from RADAR signals, enhancing the MoCap system's capabilities.

This chapter focuses on the development and implementation of a machine learning framework tailored for interpreting RADAR data in MoCap applications. It outlines the experimental setup for data collection, the process of transforming RADAR signals into usable data, and the machine learning model's architecture and training. This exploration underscores the synergy between RADAR technology and machine learning, expanding the scope of motion capture to advance the collaborative work between MIT and Sekisui House as explained in section 1.2.

5.2 Data Collection and Preprocessing for Machine Learning Integration

In developing a machine learning model capable of interpreting RADAR data for MoCap applications, we utilized data sourced from an independent study by MIT researcher Daniel Coopeland. This section outlines the process of data collection, preparation, and the approach taken to simulate RADAR data which we will take for the model's creation.

5.2.1 Participant Recruitment and Study Protocol

The study recruited 16 diverse participants, aged 18-31, with varying yoga experience levels. Selection criteria were based on physical capability to perform yoga poses, ensuring a diverse motion data set. Conducted under the approval of the Institutional Review Board (IRB), the study maintained ethical standards, including informed consent from all participants.

5.2.2 Controlled Data Collection Environment

Data collection was executed in a laboratory setting equipped with a state-of-the-art MoCap system and a 4-Channel 24GHz Analog Devices FMCW RADAR. The MoCap system, with its 14 infrared cameras set around the room and 18 reflective markers attached on top of the participant's joints, captured detailed motion data, while the strategically placed RADAR system provided complementary motion capture.

5.2.3 Yoga Poses and Motion Capturing Procedure

Participants performed 13 yoga poses in a predetermined sequence, covering both static and transitional movements. This variety in poses ensured the capture of a wide range of human motions, essential for a comprehensive data set useful in machine learning.

5.2.4 Data Synchronization and Processing

The MoCap data, including spatial 3-D coordinates and velocities of markers, was meticulously synchronized with the RADAR data. This synchronization was vital to align the datasets temporally, ensuring accurate data for analysis. Advanced filtering methods were employed to refine the data sets, preparing them for integration with machine learning algorithms.

5.2.5 Simulating RADAR Data with RadarSimX

A key aspect of the data preprocessing involved simulating RADAR data using RadarSimX [24], an open-source RADAR simulator. This simulator, tuned to the settings of the 4Tx/2Rx MIMO DemoRad Analog Devices RADAR, was used to generate Range Doppler Maps (RDMs) from the MoCap data. The simulator's capability to replicate various RADAR positions added a dimension of realism and complexity to the simulated RADAR data.

Each motion capture sequence was broken down into individual poses and transitions, and the corresponding position and velocity data of the MoCap markers were input into RadarSimX. The simulator produced time-series RDMs, capturing the nuanced RADAR signatures of each movement. This data augmentation approach, generating 8 RDMs per transition due to the MIMO architecture, added valuable noise and variability to the dataset, enhancing its suitability for machine learning applications.

This approach to simulating RADAR data provided us with a rich and realistic dataset, pivotal for training our machine learning model to generate accurate MoCap data from RADAR inputs. The resulting dataset, a fusion of refined MoCap and simulated RADAR data, forms the foundation for our subsequent machine learning development.

5.3 Developing a Machine Learning Model for MoCap Generation

In the pursuit of enhancing MoCap technology with privacy-preserving features, this project embarks on developing a machine learning model capable of interpreting RADAR data to generate MoCap data. Unlike traditional visual systems, RADAR offers a unique means of capturing motion without compromising individual privacy. This project explores the integration of RADAR with machine learning to create a system that respects privacy while delivering accurate motion capture data.

5.3.1 Challenges of Interpreting RADAR Data

RADAR data, known for its density and noise, presents a significant challenge in extracting clear motion information. An example of the data used in this section can be seen in figure 5.1. To tackle this complexity, we turn to the capabilities of machine learning, especially neural networks. These networks excel at processing and making sense of complex and noisy datasets, which is crucial in translating RADAR signals into meaningful motion data.

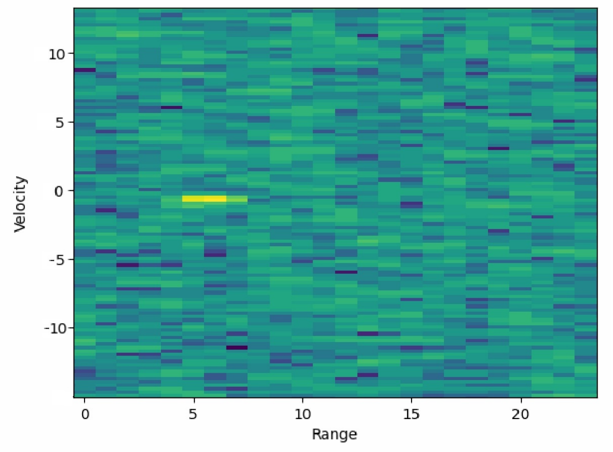


Figure 5.1: Example of a RADAR Range Doppler Map (RDM) that represents the intensity of the signal received based on the range (x-axis) and the velocity (y-axis). In this example, we can observe a stationary object approximately 6 meters away from the sensor.

5.3.2 Training the Model on Simulated RADAR Data

Our approach involves training a neural network model on simulated RADAR data. This data is derived from yoga movement motion capture sequences captured at MIT. The model architecture combines LSTM (Long Short-Term Memory) units and CNN (Convolutional Neural Network) layers, as seen in figure 5.2, to handle both the temporal dynamics and spatial characteristics of the RADAR signals. The ultimate goal is to enable the model to transform these signals into accurate three-dimensional coordinates of human joints, emulating traditional MoCap systems.

5.3.3 Results and Insights from Model Training

The initial results from training the machine learning model on simulated RADAR data highlighted a significant gap in achieving the desired level of MoCap accuracy. Despite a low mean absolute error validation loss of only 0.05 (equivalent to 5cm in meter-based data), the visual comparison of the original and generated MoCap data revealed notable inaccuracies, as illustrated in 5.3. The model could roughly approximate the overall posture and orientation of human figures, but it struggled to precisely replicate the detailed movements and exact coordinates found in the original MoCap data. This discrepancy emphasized the necessity of high-resolution RADAR data for capturing the subtleties of human motion more accurately.

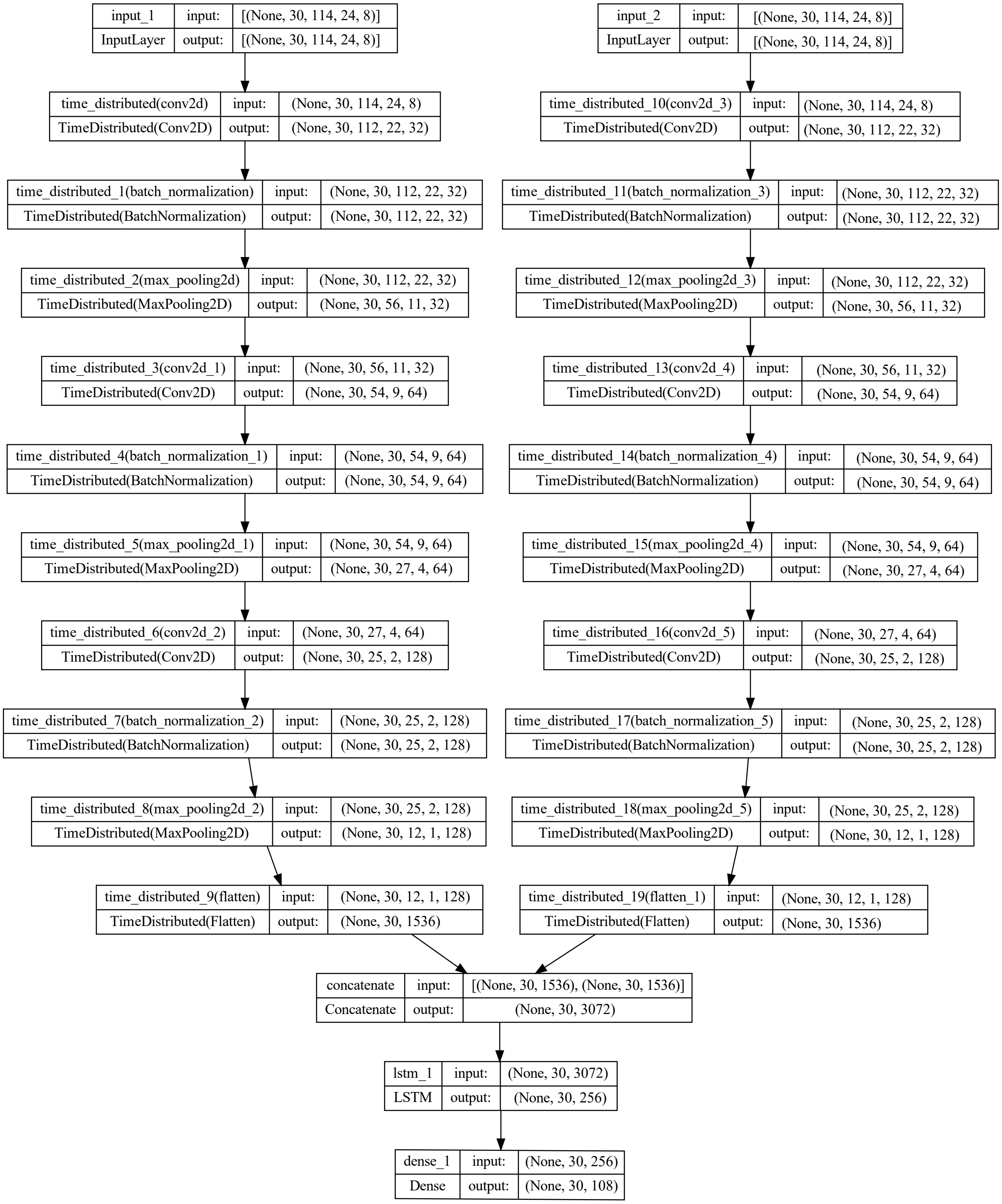


Figure 5.2: Architecture of the model, taking as input two RADARs' RDMs and outputting the 3-D coordinates of the different joints. A combination of LSTM units and CNN layers has been used to handle the tempral and spatial characteristics of motion capture.

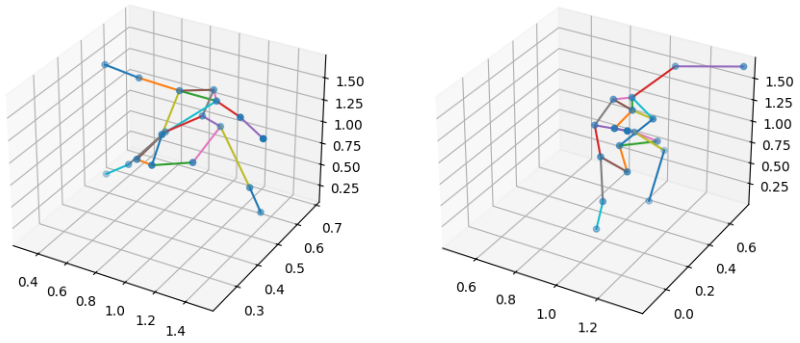


Figure 5.3: Visualization of the original MoCap data (left) and the generated MoCap data from the simulated RADAR data (right).

5.3.4 Future Directions and Potential Improvements

In response to these findings, the next steps involve refining the model by training it with higher-resolution RADAR data and expanding the dataset to include a more diverse range of movements. This approach is expected to enhance the model's ability to generalize across different motion scenarios, thereby improving its accuracy in generating MoCap data from RADAR inputs. By focusing on these improvements, we aim to not only advance the precision of the model but also to extend its applicability in privacy-sensitive motion capture scenarios.

These efforts highlight the promising integration of RADAR technology with machine learning to develop non-intrusive MoCap systems. By tackling the unique challenges posed by RADAR data, this research contributes to innovative motion analysis methods that prioritize individual privacy and open new avenues in the field of motion capture technology.

6 Future Work

The development of an advanced Motion Capture system has paved the way for new research avenues. This chapter outlines future directions for extending the work presented in this thesis.

6.1 Usability and User Experience

- **Interface Development**: Focusing on creating user-friendly interfaces that simplify interaction with the MoCap system. This includes designing software tools that enable users to easily capture, interpret, and analyze motion data, thereby enhancing the system's accessibility to a broader user base.
- **Extensive User Testing**: Implementing comprehensive user testing protocols across various settings, such as clinical environments, sports facilities, and entertainment industries, to gather valuable insights. Feedback from a diverse range of end-users, including healthcare professionals, athletes, and motion analysis experts, will be crucial in identifying practical needs and enhancing system utility.

6.2 Long-Term Sustainability and Scalability

- **Modular Design**: Prioritizing modularity in design to accommodate future technology upgrades and specific user requirements. This approach will enable customization of the system for various applications, ensuring long-term relevance and adaptability.
- **Sustainable Materials and Methods**: Investigating and employing cost-effective, eco-friendly materials and manufacturing methods. This approach aims to make the MoCap system more accessible and appealing by reducing production costs and environmental impact.

6.3 Sensor Fusion and System Integration

- **Diverse Sensor Integration**: Expanding the system's capabilities by incorporating a range of sensors, such as LIDAR or state-of-the-art RADAR. This integration aims to enhance the richness and accuracy of the data captured, offering a more comprehensive understanding of motion.

- **Advanced Synchronization**: Refining synchronization methods to achieve real-time, precise integration of data from various sensors. This will ensure the system's reliability and accuracy, especially important in dynamic environments where rapid movements occur.

6.4 Enhancing Data Resolution and Processing in Machine Learning Models

- **High-Resolution RADAR Data**: Prioritizing the acquisition and utilization of higher-resolution RADAR data to capture more detailed and accurate human movements. This will involve exploring advanced RADAR technologies and data processing techniques.
- **Sophisticated Algorithm Development**: Creating advanced machine learning algorithms for more efficient data synchronization, filtering, and noise reduction. These algorithms are expected to significantly enhance the accuracy and reliability of the generated MoCap data.

6.5 Application-Specific Development

- **Healthcare and Rehabilitation**: Customizing the MoCap system for specific applications in healthcare, such as patient movement analysis during rehabilitation, could lead to significant advancements in treatment methodologies and patient care.
- **Sports Performance**: Adapting the system to analyze and enhance athletic performance by providing detailed feedback on movements, techniques, and postures. This application could be particularly beneficial for coaching and training in various sports disciplines.

These outlined directions represent the initial steps towards achieving the broader goals of the MIT-Sekisui House collaboration. The intention is to integrate advanced MoCap technology into everyday life, enhancing our understanding and interaction with motion in various settings. The progress achieved in this thesis lays a solid foundation for continued research and innovation in MoCap technology.

7 Conclusion

Reflecting on this journey in advancing Motion Capture (MoCap) technology, this thesis marks an initial contribution to the LabX project within MIT's Center for Clinical and Translational Research (CCTR) and the MIT-Sekisui House collaboration. It showcases significant progress in making MoCap more accessible and practical for home environments.

Key developments include the design of a portable and stable sensor rig, vital for capturing accurate motion data in various settings. This rig, with its innovative sensor fusion capabilities and versatility, is a testament to the project's commitment to enhancing MoCap technology's user-friendliness. Additionally, the integration of RADAR signals for privacy-sensitive motion analysis represents a state-of-the-art approach, addressing privacy concerns often associated with traditional MoCap systems.

Throughout this thesis, a multifaceted approach was taken to tackle challenges in hardware design, software development, and machine learning integration for Motion Capture technology. This comprehensive effort has not only advanced the technical aspects of MoCap but also broadened its potential applications. The impact of this work extends from enhancing healthcare and rehabilitation practices to revolutionizing sports analysis and everyday activities at home.

As this research concludes, it sets the foundation for future advancements. The paths forged here lead towards a future where MoCap seamlessly integrates into our daily lives, enhancing our understanding of human motion and revolutionizing our interaction with technology. This thesis is more than just a technical achievement; it is a step towards enriching human experiences with advanced technology in a non-intrusive and user-centered manner.

In essence, the work presented in this thesis embodies the essence of innovation - blending technical prowess with practical application. It's a beacon for future research, pointing towards a world where advanced MoCap systems not only exist in laboratories but become an integral part of our homes and lives.

A FReDPARRC

A.1 Functional Requirements

The functional requirements for the motion capture (MoCap) system are critical in guiding its design and ensuring it meets the necessary standards for practical application. These requirements include:

- **Transportability**: The system should be easy to transport, which involves considerations of weight, volume, and shape. It should be compact enough for easy handling yet robust enough for safe transport.
- **Modularity with Sensors**: The design must accommodate the maximum size of various sensors, ensuring compatibility with standard cameras, RADARs, acoustic sensors, accelerometers, etc. It should also provide necessary support like power supply, control, and data acquisition.
- **Precision Measurement**: The system must deliver high-precision measurements, including frequency, image definition, allowable drift, and error budgeting. This is essential to ensure accurate and reliable data capture.
- **Ease of Setup and Deployment**: The system should be straightforward to set up, deploy, and start capturing data, with minimal risk of breakdowns.
- **Data Storage/Processing**: It should be capable of both real-time/delayed processing and online/offline data handling, according to the specific needs of the application.
- **Synchronization of Data Captures**: This involves aligning data temporally, spatially, and in terms of data type, ensuring cohesive and synchronized data collection.
- **Monitoring Human Movement**: The system should provide the required frame rate for capturing different types of human movements accurately.

A.2 Design Parameters

The design parameters for the MoCap system include:

- **Type of Sensors and Attachments**: Choosing appropriate sensors and designing corresponding attachments is crucial for capturing diverse data types.
- **Data Communication and Storage**: Establishing efficient and reliable methods for data transmission and storage.

- **Power Supplies**: Ensuring stable and adequate power supply for the system's operation.
- **Materials for Housing/Stand**: Selecting suitable materials that offer durability and stability.
- **Specific Machine Elements**: Identifying and integrating necessary machine components for the system.
- **Communication with Main Unit/Other Units**: Ensuring effective communication channels within the system.
- **Data Processing**: Developing capabilities for processing and analyzing the captured data.

A.3 Analysis

The analysis phase of the design includes:

- **Vibration Analysis of Sensor Rig**: Assessing the rig's stability and susceptibility to vibrations.
- **Spatial Drift Analysis of Sensors**: Evaluating the potential drift in sensor positioning over time.
- **Number of Compatible Sensors**: Determining the maximum number of sensors that can be integrated without compromising functionality.
- **Synchronization Accuracy and Temporal Drift**: Analyzing the precision of synchronization and potential temporal drift.
- **Motion Capture Accuracy**: Assessing the overall accuracy of the MoCap system.

A.4 References

The references for the MoCap system design include:

- **Specific Sensors Incorporated**: Details of the specific sensors used in the system.
- **Tripods**: Reference to the utilization of tripods for stabilizing systems.
- **CCTR/Immersion Lab**: Reference to the available MoCap systems at MIT for benchmarking.
- **Multimodular Data Systems**: Exploring existing multimodular data systems for insights.
- **Marker-less Tracking**: Incorporating principles and technologies from marker-less tracking systems.

A.5 Risks

Potential risks in the development and use of the MoCap system include:

- **Fall Over/Move Too Much**: Risk of the system becoming unstable or moving excessively.
- **Power/Data Collection Issues**: Challenges related to consistent power supply and efficient data collection.
- **Cable Management/Collision with Device**: Managing cables effectively to prevent entanglement or tripping hazards.
- **Privacy Concerns**: Addressing concerns related to data privacy and user consent.
- **Data Loss/Corruption**: Risk of losing or corrupting valuable data.
- **Complexity in Use**: The system being too complex for users to operate effectively.
- **Weight Balance (Too Heavy/Too Light)**: Ensuring the system is neither too heavy nor too light for its intended use.
- **Sensor Interference**: Potential interference between different sensors.
- **Visual Interference/Blocked**: Risks of the sensors' view being obstructed or interfered with.

A.6 Counter-measures

Counter-measures to address the identified risks include:

- **Stability/Attachment Solutions**: Ensuring the system is stable or can be securely attached to structures like walls.
- **Robust Power/Data Collection**: Implementing reliable systems for power supply and data collection.
- **Smart Cable Management/Wireless Options**: Implementing efficient cable management strategies or considering wireless solutions.
- **HIPAA-Compliant Data Collection**: Ensuring data collection and handling complies with HIPAA regulations for privacy [25].
- **Intuitive Setup and Automation**: Making the setup process intuitive and automated where possible.
- **Easy Calibration/Validation**: Simplifying calibration and validation processes for user convenience.
- **Error Alerts for Obstructions**: Incorporating error messages or alerts when sensors are blocked or obstructed.

B Bill Of Materials

Included in this appendix is the detailed Bill of Materials (BOM) that was compiled for the fabrication of one base compartment and one sensor compartment of the MoCap system. This BOM serves as a reference for understanding the specific materials and components required for constructing these essential parts of the system.

It is important to note that the URLs and sourcing information provided in the BOM may become outdated over time. However, the detailed descriptions and specific references included for each item are intended to assist the reader in identifying equivalent products, should the need arise. This approach ensures that even with changes in product availability or supplier updates, the BOM remains a valuable and usable resource for anyone looking to replicate or modify the design of the MoCap system.

Name	Reference	Quantity	URL
General Purpose			
M6 Screws, 25 mm Long (Pack of 50)	91502A169	1	mcmaster.com/91502A169/
M6 Screws, 30 mm Long (Pack of 50)	91502A170	1	mcmaster.com/91502A170/
#6 Screws, 1/4" Long (Pack of 50)	93310A144	1	mcmaster.com/93310A144/
M6 Locknut (Pack of 100)	90576A115	1	mcmaster.com/90576A115/
M6 Washers (Pack of 100)	93475A250	2	mcmaster.com/93475A250/
6061 Aluminium Round Tube (3 ft)	9056K36	3	mcmaster.com/9056K36-9056K363/
6061 Aluminum Sheets (0.375" thickness, 8"x24")	8975K372	1	mcmaster.com/8975K372-8975K607/
6061 Aluminum Sheets (0.375" thickness, 12"x48")	9246K475	1	mcmaster.com/9246K475/
6061 Aluminum Sheets (0.25" thickness, 12"x48")	9246K425	1	mcmaster.com/9246K425/
18-8 Stainless Steel Threaded Rod (M6 x 1 mm Thread Size, 1 M Long)	90024A070	3	mcmaster.com/90024A070/
Adjustable-Grip Draw Latch	1864A22	4	mcmaster.com/1864A22/
Base Compartment Specific			
Leveling Casters Retractable (Pack of 4)	60F - without ratchet	1	amazon.com/dp/B08PVFJ14B
M6 Screws, 18 mm Long (Pack of 50)	91502A166	1	mcmaster.com/91502A166/
Sensor Compartment Specific			
Steel Corner Bracket	1556A26	4	mcmaster.com/1556A26/
D-Profile Rotary Shaft	8632T386	1	mcmaster.com/8632T386/
Plastic Three Arm Knob	57715K55	1	mcmaster.com/57715K55/
Compression Springs (Pack of 2)	2006N367	1	mcmaster.com/2006N367/
Ulanzi Claw Quick Release System (Generation II)		1	ulanzi.com/products/ulanzi-claw-quick-release-system-generation-ii

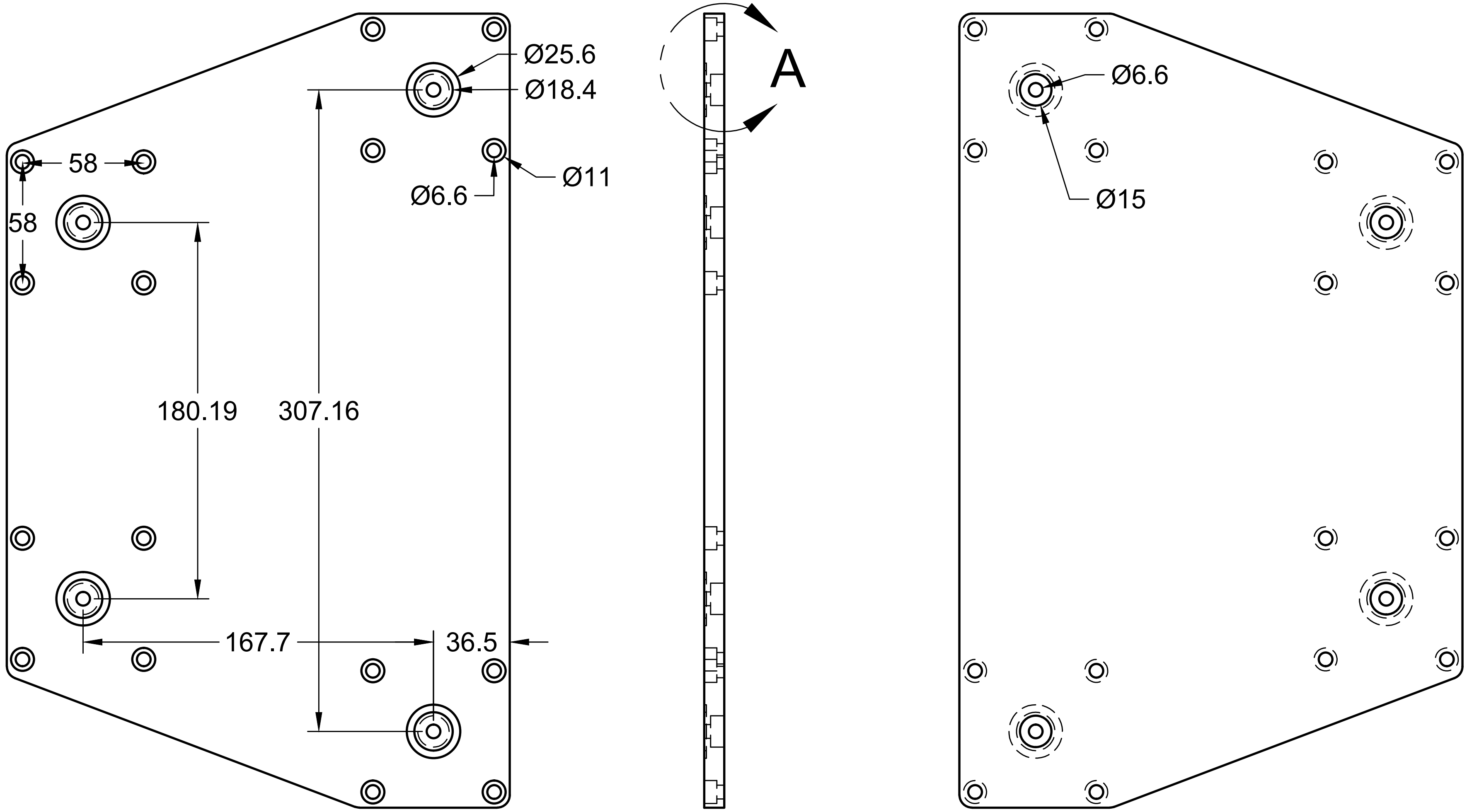
Table B.1: Bill of Materials for base and sensor compartments

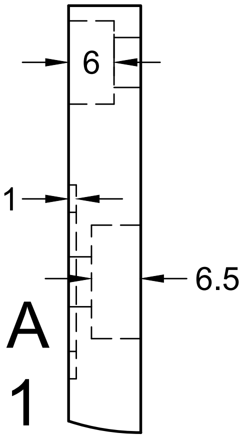
C Drawings

This appendix contains detailed drawings of the parts within the MoCap system that required precision milling. These drawings are critical as they provide the specifications and dimensions needed for machining the components accurately. These drawings are crucial for anyone looking to replicate or modify parts of the MoCap system. They offer a clear and detailed visual representation of the components, providing essential information for the machining process.

The decision to include only the milled parts in this section stems from the necessity of having exact drawings for CNC milling operations. These drawings serve as a guide for the machinist, detailing the specific dimensions and shapes required for each part. In contrast, components manufactured through other processes like waterjetting or band saw cutting did not require the same level of detailed representation for their fabrication.

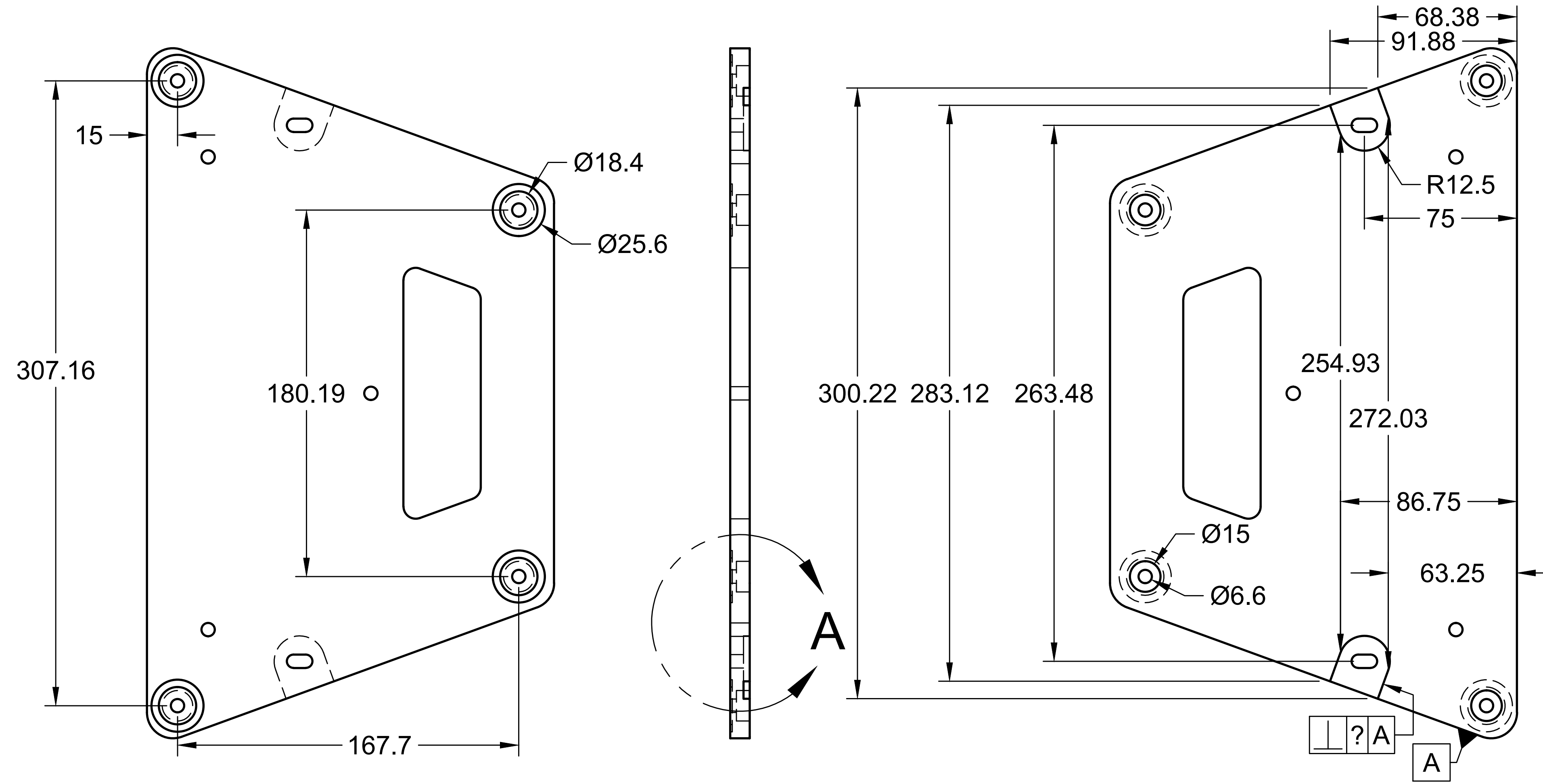
It's also important to mention that the dimensions provided in these drawings do not include tolerances. This omission is deliberate, as the prototype parts were fabricated using a CNC mill, which inherently provides a high degree of precision and consistency. The absence of specified tolerances in these drawings reflects the precision capabilities of CNC milling, ensuring that each part is produced accurately according to the dimensions provided.

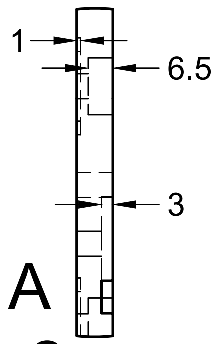




DETAIL A
SCALE 1

	PROJECT Sensor Rig - First Prototype			
	TITLE Base Compartment Bottom Plate			
APPROVED	SIZE A	CODE	DWG NO	REV 5
CHECKED				
DRAWN Pierre Lonni 02/08/2023	SCALE 1:3	WEIGHT	SHEET 1/1	





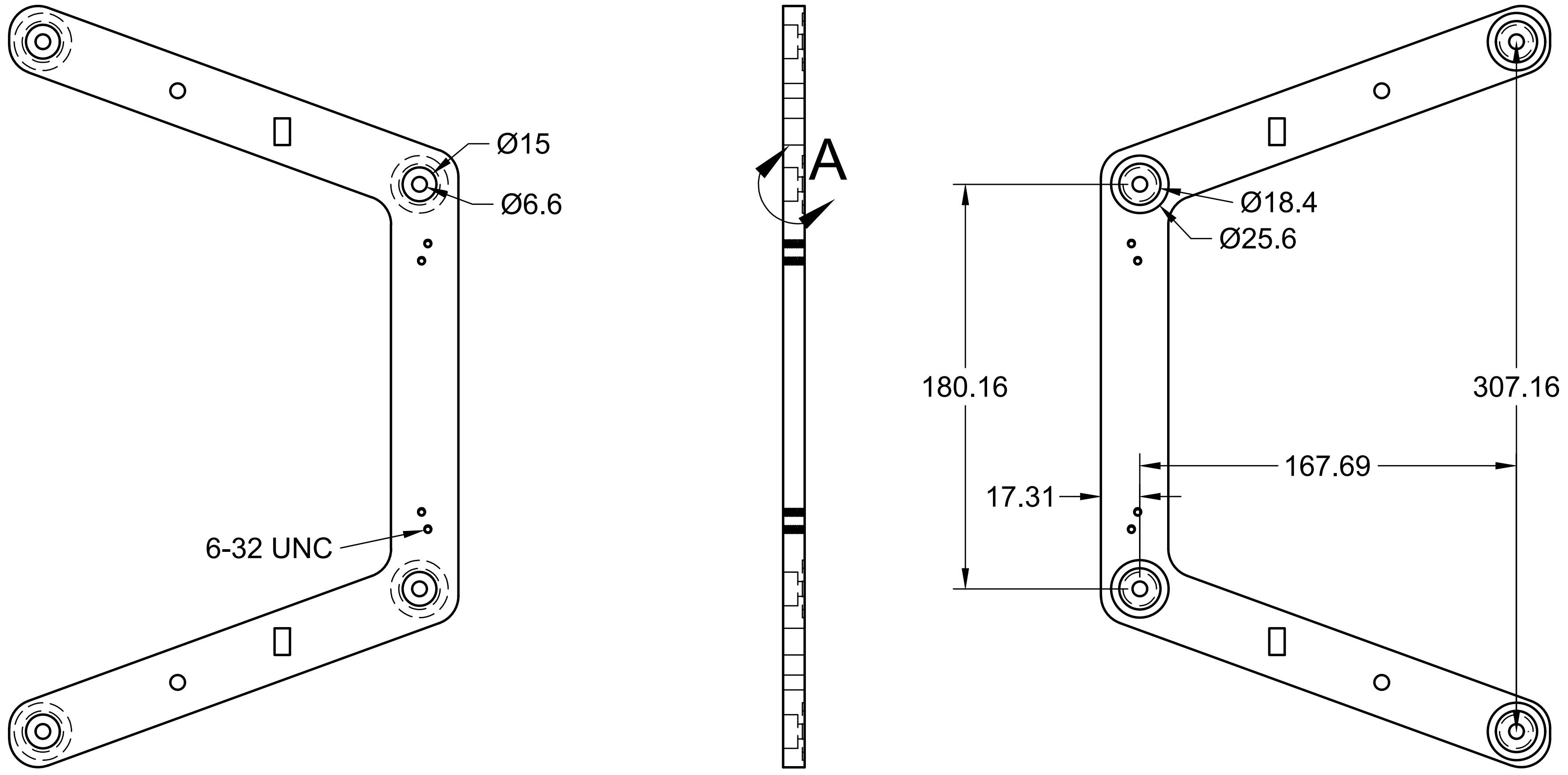
DETAIL A
SCALE 1:2

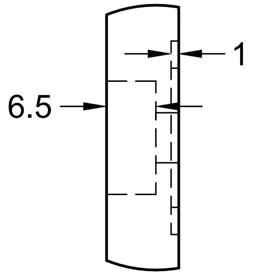
PROJECT
Sensor Rig - First Prototype

TITLE
Base Compartment
Top Plate

APPROVED
CHECKED
DRAWN Pierre Lonni 02/08/2023

SIZE A
CODE
DWG NO
REV 4
SCALE 1:3
WEIGHT
SHEET 1/1



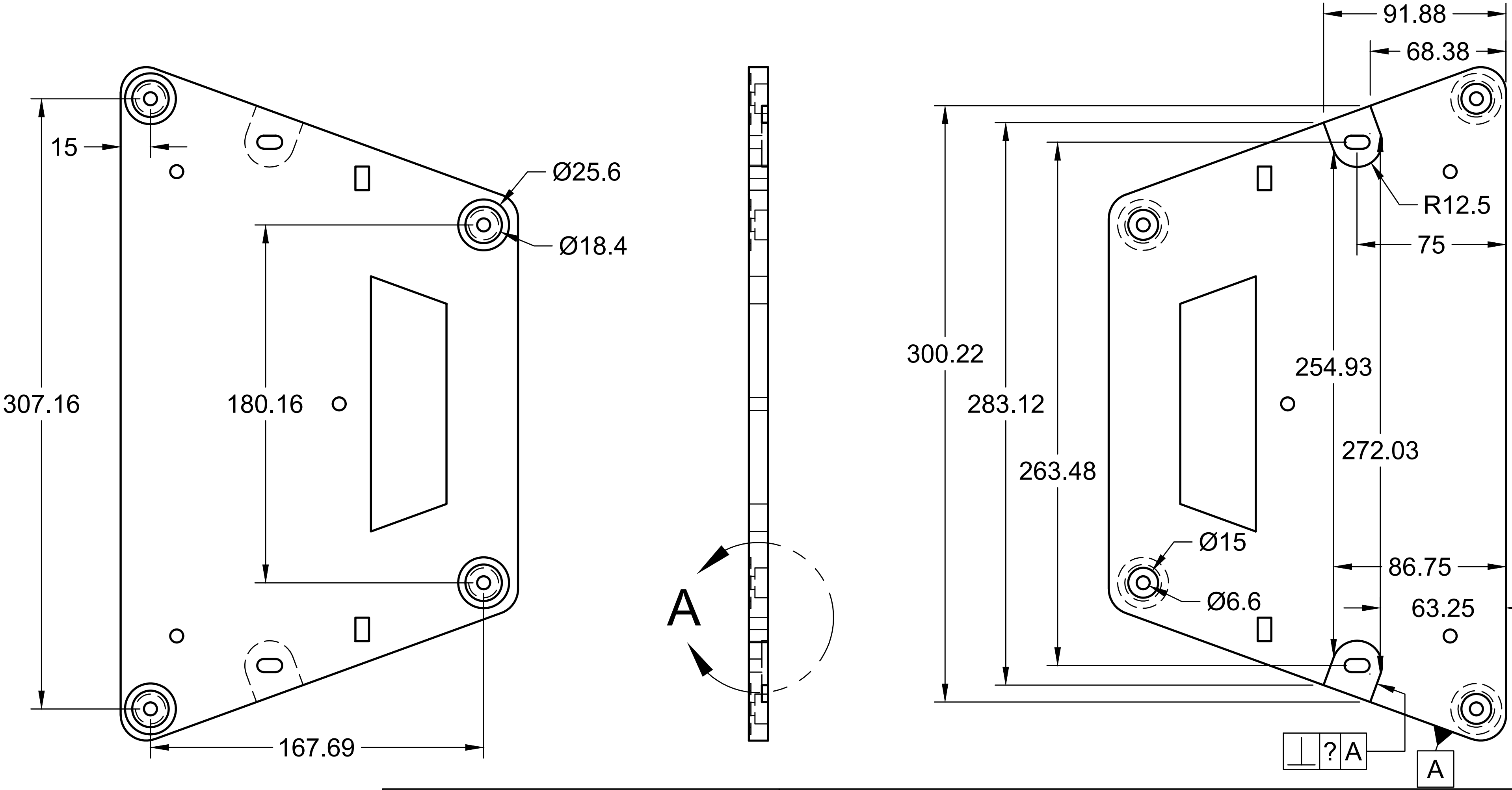


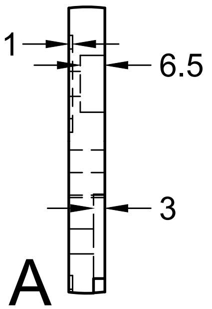
DETAIL A
SCALE 1

PROJECT
Sensor Rig - First Prototype

TITLE
Sensor Compartment
Bottom Plate

APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	A			5
DRAWN Pierre Lonni 02/08/2023	SCALE 1:3		WEIGHT	SHEET 1/1



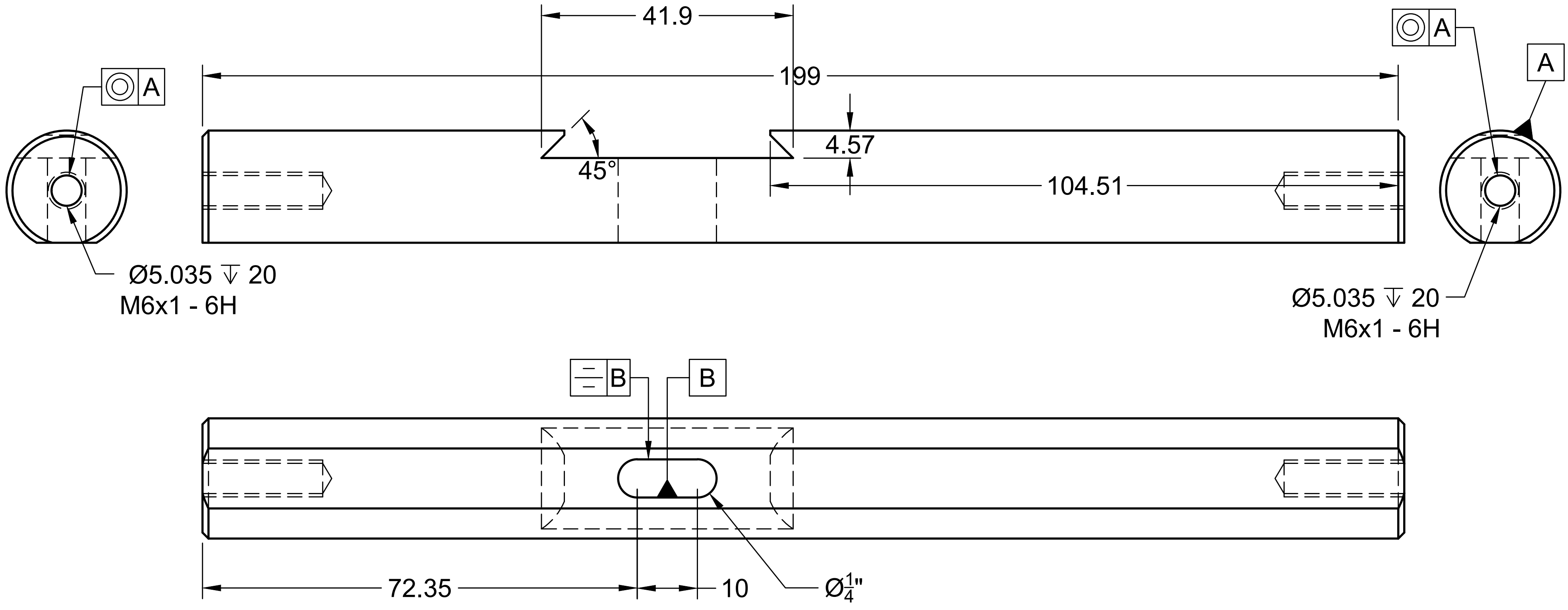


DETAIL A
SCALE 1:2

PROJECT
Sensor Rig - First Prototype

TITLE
Sensor Compartment
Top Plate

APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	A			5
DRAWN Pierre Lonni 02/08/2023	SCALE 1:3	WEIGHT		SHEET 1/1



PROJECT Sensor Rig - First Prototype				
TITLE Sensor Compartment Sensor Mount Shaft				
APPROVED	SIZE A	CODE	DWG NO	REV 3
CHECKED				
DRAWN Pierre Lonni 7/31/2023	SCALE 1:1		WEIGHT	SHEET 1/1

D Vibration Analysis Code

This appendix presents a Python script used for analyzing vibration data from different surfaces. This script integrates essential libraries like NumPy and Matplotlib for numerical computations and data visualization. It processes vibration measurements from various sensors, normalizes the data, synchronizes it based on timestamps, and visualizes the results. The script also includes functionality for exporting processed data into a CSV file for further analysis.

```python
import numpy as np
import matplotlib.pyplot as plt
import csv

def convert_time_to_seconds(string):
    """
    Convert a time string in the format 'HH:MM:SS.mmm' to seconds.
    """
    date_str, time_str = string.split(' ')
    hh, mm, ss, mmm = map(int, time_str.split(':'))
    return hh * 3600 + mm * 60 + ss + mmm * 0.001

# Constants and file names
file_name = "Still 4"

# Initializing lists for different devices
devices = {"WT901BLE68(C214D4D0B684)": [],
           "WT901BLE68(11D2175E7452)": [],
           "WT901BLE68(8558327A3A8B)": [],
           "WT901BLE68(2F90F41359E2)": []}

# Reading and parsing the data file
with open("./Vibration/"+ file_name +".txt", "r") as file:
    next(file)  # Skip the first line (header)
    for line in file:
        time_str, device_id, x, y, z, AsX, AsY, AsZ, AngleX, AngleY,
           AngleZ, HX, HY, HZ, Q0, Q1, Q2, Q3, Temperature, Version,
           Battery = line.strip().split('\t')
```

```
        if device_id in devices:
            devices[device_id].append([convert_time_to_seconds(time_str),
                                       float(x), float(y), float(z)])

# Data normalization
for device_id in devices:
    times, x_vals, y_vals, z_vals = zip(*devices[device_id])
    norms = [np.sqrt(x**2 + y**2 + z**2) for x, y, z in zip(x_vals, y_vals, z_vals)]
    mean_norm = np.mean(norms)
    norms = [norm - mean_norm for norm in norms]
    devices[device_id] = [list(times), norms]

# Data synchronization and plotting
initial_time = devices[next(iter(devices))][0][0]  # Assuming all devices start at the same time
plt.figure()
for device_id, (times, norms) in devices.items():
    times = [t - initial_time for t in times]
    if device_id == "WT901BLE68(C214D4D0B684)":
        plt.plot(times, norms, label=device_id, color='r')
    if device_id == "WT901BLE68(11D2175E7452)":
        plt.plot(times, norms, label=device_id, color='g')
    if device_id == "WT901BLE68(2F90F41359E2)":
        plt.plot(times, norms, label=device_id, color='b')
    if device_id == "WT901BLE68(8558327A3A8B)":
        plt.plot(times, norms, label=device_id, color='y')
plt.grid()
plt.show()

# Saving data to CSV
with open(file_name+".csv", 'w') as f:
    fc = csv.writer(f, lineterminator='\n')
    for device_id, (times, norms) in devices.items():
        fc.writerows([[device_id] + times, norms])

# Statistical calculations
```

```python
std_devs = {device_id: np.std(norms) for device_id, (_, norms) in devices.items()}
base_std = std_devs[next(iter(std_devs))]  # Assuming the first device as the baseline
for device_id, std in std_devs.items():
    if device_id == "WT901BLE68(C214D4D0B684)":
        print(f"Floor: {100 * (std - base_std) / base_std:.2f}% difference from floor") #Check that the baseline is indeed the floor (should have a difference of 0%)
    if device_id == "WT901BLE68(11D2175E7452)":
        print(f"Tripod: {100 * (std - base_std) / base_std:.2f}% difference from floor")
    if device_id == "WT901BLE68(2F90F41359E2)":
        print(f"Table: {100 * (std - base_std) / base_std:.2f}% difference from floor")
    if device_id == "WT901BLE68(8558327A3A8B)":
        print(f"Prototype: {100 * (std - base_std) / base_std:.2f}% difference from floor")
```

E Installation Instructions for ROS2 on Raspberry Pi with HQ Camera

E.1 Introduction

This short guide enumerates all the steps needed to install and use ROS on a Raspberry Pi to capture video data. The different hardware and software specifications are the following:

- Raspberry Pi 4 Model B
- Raspberry Pi High Quality Camera Module
- Ubuntu Desktop 22.04.3 LTS (Jammy Jellyfish)
- ROS2 Humble Hawksbill

E.2 Installation

E.2.1 Operating System

SD Card

To install the Ubuntu OS on your Raspberry Pi, you need to insert an SD Card in your computer and use the *Raspberry Pi Imager* software (that you can download at https://www.raspberrypi.com/software/). On the software, select the following options:

- Raspberry Pi Device: *Raspberry Pi 4*
- Operating System: *Other general-purpose OS* → *Ubuntu* → *Ubuntu Desktop 22.04.3 LTS (64-bit)*
- Storage: Your SD Card's name

Then you can click the "Next" button to write the OS on the SD card. Once the process is done, you can take the SD card and install it in your Raspberry Pi.

Set Up On Raspberry Pi

Now that the SD Card is inserted in the Raspberry Pi, you need to finalize the OS set-up. No particular instructions for that, just remember to update it at the end by typing the following commands in a terminal (that you can easily open with `Ctrl+Alt+T`).

- First check for updates with:

```
sudo apt update
```

- Then upgrade the upgradeable packages with:

```
sudo apt full-upgrade
```

E.2.2 Robot Operating System (ROS)

You will install ROS2 Humble Hawksbill version, which you can install with the instructions on the following website: https://docs.ros.org/en/humble/Installation/Ubuntu-Install-Debians.html. For a shorter tutorial, I'll include the steps we need here.

- Set locale

```
locale  # check for UTF-8

sudo apt update && sudo apt install locales
sudo locale-gen en_US en_US.UTF-8
sudo update-locale LC_ALL=en_US.UTF-8 LANG=en_US.UTF-8
export LANG=en_US.UTF-8

locale  # verify settings
```

- Ensure that the Ubuntu Universe repository is enabled

```
sudo apt install software-properties-common
sudo add-apt-repository universe
```

- Add the ROS 2 GPG key with apt

```
sudo apt update && sudo apt install curl -y
sudo curl -sSL https://raw.githubusercontent.com/ros/rosdistro/master/ros.key
   -o /usr/share/keyrings/ros-archive-keyring.gpg
```

- Add the repository to your sources list

```
echo "deb [arch=$(dpkg --print-architecture) signed-by=/usr/share/keyrings/ros
   -archive-keyring.gpg] http://packages.ros.org/ros2/ubuntu $(. /etc/os-
   release && echo $UBUNTU_CODENAME) main" | sudo tee /etc/apt/sources.list.d
   /ros2.list > /dev/null
```

- Update your apt repository caches after setting up the repositories

```
sudo apt update
```

- Ensure your system is up to date

```
sudo apt upgrade
```

- ROS 2 Desktop Install

```
sudo apt install ros-humble-desktop
```

- ROS 2 Development tools

```
sudo apt install ros-dev-tools
```

E.2.3 Camera View Packages

This setup is inspired by a Youtube video by *gaseoustortoise* that you can find at the following URL: https://www.youtube.com/watch?v=va7o7wzhEE4. Again, here's a shorter version of his tutorial.

- Installing camera libraries

```
sudo apt install libraspberrypi-bin v4l-utils ros-humble-v4l2-camera
```

- Installing image library

```
sudo apt install ros-humble-image-transport-plugins
```

- Checking group permissions

```
groups
```

  - If the `Video` group isn't in the list, add it with the following command.

```
sudo usermod -aG video *username*
```

  - Then reboot the OS.

```
reboot
```

- Installing `raspi-config` and enabling interfaces

```
sudo apt-get install raspi-config
```

- Enabling interfaces

```
sudo raspi-config
```

Now that you're in the `Raspberry Pi Software Configuration Tool`, go to `"3 Interface Options"` and enable `"I1 Legacy Camera"`, `"I4 SPI"` and `"I5 I2C"` (select `"Yes"` on the corresponding menus). After that, select `"Finish"` to exit the `Raspberry Pi Software Configuration Tool`.

- Verify that your camera is detected

```
vcgencmd get_camera
```

If your camera is detected, you should get:

```
supported=1 detected=1, libcamera interfaces=0
```

- On the device where you want to view the images, install the image-view library

```
sudo apt install ros–humble–image–view
```

E.3 Setting up ROS communication

E.3.1 Starting the ROS node

In the terminal that will output the images (on the device that has the camera), go through the following steps:

- Setup the ROS environment

```
source /opt/ros/humble/setup.bash
```

- Start the ROS node outputting raw image data

```
ros2 run v4l2_camera v4l2_camera_node ––ros–args –p image_size:="[640,480]" –p
    camera_frame_id:=camera_link_optical
```

E.3.2 Checking the data is published

In the terminal that will receive the images, go through the following steps:

- Setup the ROS environment

```
source /opt/ros/humble/setup.bash
```

- First option: visualize the video feed

```
ros2 run image_view image_view ––ros–args –r /image:=/image_raw
```

- Second option: see the raw images data

```
ros2 topic echo /image_raw
```

To exit any of those feeds, press on `Ctrl+C`.

F Instructions for ROS2 image capture on Raspberry Pi set-up

1. Power on the three Raspberry Pi (One ’master’ connected to a keyboard, a mouse and a screen, and two ’slaves’ equipped with an HQ Camera module).
2. On the master Raspberry Pi (the one without the camera module), login with the username and password.
3. Open 3 terminals on the master Raspberry Pi (one terminal per machine). You can use the shortcut `Ctrl+Alt+T` to open a terminal.
4. On two of the terminals, connect to the slave Raspberry Pis (the ones with a camera module) with: `ssh ubuntu@[IP address]` where the IP address can be found on the corresponding machine with the terminal command `ip a`.
5. On each terminal, setup ROS2 with the following command:

```
source /opt/ros/humble/setup.bash
```

6. On the slave terminals (controlling the slave Pis), start the camera feed with the following command and set a camera name to differentiate the different feeds:

```
ros2 run v4l2_camera v4l2_camera_node −−ros−args −p image_size:="[640,480]" −p
    camera_frame_id:=camera_link_optical −r __ns:=/[camera name]
```

7. On the ‘master’ terminal (controlling the master Pi), you can do multiple things:
    - Check the different messages it hears:

```
ros2 topic list
```

    - From that list, find the message corresponding to the images and replace `/image_raw` in the following commands with that/those name(s)
        - See the images you hear:

```
ros2 run image_view image_view −−ros−args −r /image:=/[camera name]/image_raw
```

        - Save the images you hear:

```
ros2 run image_view image_saver −−ros−args −r /image:=/[camera name]/image_raw
    −p filename_format:=[folder path]/[camera name]%04i.%s
```

        - See the images’ raw data (usually just to check if you receive them correctly):

```
ros2 topic echo /image_raw
```

8. To stop any feed outputted/received, you can use `Ctrl+C` in the corresponding console

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