Enhancing the accessibility and usability of motion capture technology: design and development of indoor MoCap hardware system

by Cheng Chang

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Abstract

Motion capture technology (MoCap) is a revolutionary method to translate real-world subjects' movements into digital content across various industries, including robotics, medical devices, gaming, and biomechanics. This paper investigates how to make MoCap more accessible and usable to a broader and more diverse audience. Endorsing a user-centric design and development approach, the researchers defined the problem statement as wider acceptance and adoptions of the MoCap technology. Subsequently, a comprehensive market research and real-world MoCap guided how researchers would brainstorm solutions. After carefully considering factors such as camera angles, pole styles, height, light conditions, etc., researched also incorporated various related sensors, such as vibration meters and distance sensors, to generate the functional prototypes and test their ideas. Compared with traditional motion capture devices, the resulting MoCap system demonstrates an easier way to deploy MoCap and a steadier system under consistent vibrations. This improved accessibility and stability allows not only scientists and researchers but also sports coaches, doctors, or students to use MoCap effectively. In conclusion, this research contributes to bring MoCap technology a wider adoption and more practical applications. Meanwhile, the system's structural stability, manufacturing method, intergration with other sensors, and reliance on Sony RX0 cameras with resolution and frame limitation can be optimized in the future to meet an even broader user need.

Thesis Supervisor: Brian W. Anthony

Title: Principal Research Scientist of Mechanical Engineering

Acknowledgements

This project cannot be brought into realization without the support and helps from my thesis supervisor Professor Brian Anthony, Motion Capture teammates – Hadeel Abdo and Pierre Lonni, M.Eng. 2023 cohort, MIT Maker Works, my families, and friends. I would love to express my deepest gratitude to them for their valuable contributions to help me complete this project.

I would like to first thank my teammates Hadeel Abdo and Pierre Lonni for their dedication, commitment, and constructive insights. Throughout our journey together, we’ve had disagreements and debates over academic topics, but I firmly believe those make the final prototype more successful and comprehensive. I am honored to work with such a talented, passionate, and fun group.

Next, I would like to thank my thesis supervisor, Professor Brian Anthony. I am deeply grateful for his guidance and trust through the process. Brian has provided the team with opportunities to make independent decisions and explore freely while offering educational feedbacks and support. His mentorship is a source of our motivation to accomplish this project.

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Introduction

1.1 MoCap Overview

Motion capture technology (MoCap) has been an evolutionary way for people to understand human movements. Its sophisticated process establishes a bridge between the physical and virtual world by capturing, tracking, analyzing, and replicating real-world motions, including human body movements, facial expression, and even animals' motions. There are mainly three kinds of MoCap technology: marker-based, marker-less, and inertia-based. Marker-based MoCap relied on attaching reflective makers to the subject's body for precise motion tracking. It captures motion based on the tracking information from the markers, such as reflective spheres, shining diodes, or infrared markers (Khan, Zoller, Farid, & Grzegorzek, 2020). Benefited from advancements in computer visions, machine learning, and other technologies, marker-less tracking does not reply on reflective markers. Instead, it uses deep-learning models to identify the movements of body segments (Wade, Needham, McGuigan, & Bilzon, 2022). Under some cases, color-based marker-less tracking filters out the color users want to track. Inertia-based MoCap relies on the relative orientation and position of a proximal and distal sensor, such as accelerometers, gyroscopes, and magnetometers, to track joints positions (Hindle, Keogh, & Lorimer, 2021).

1.2 Physics Behind MoCap

The entire workflow of MoCap can be summarized into Figure 1 (Sigal, 2012).

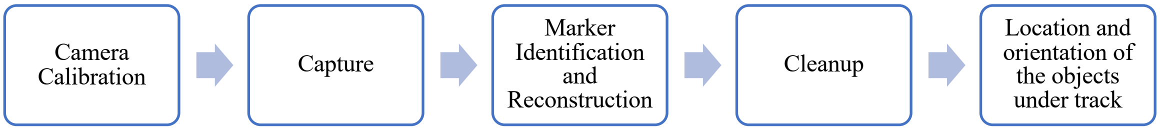


Figure 1: MoCap Pipeline

The first step in MoCap is to set up and calibrate cameras. For maker based MoCap replying on reflective markers, a calibration wand (Figure 2) is usually used to calibrate the cameras and the space. When using the wand, the user walks over the space while waving the wand in a Sin curve to cover as much space as possible for the calibration. After taking the video footage, the MoCap system identify markers and reconstruct it 3D with triangulation. Triangulation is a fundamental concept in MoCap where multiple reference points are taken to determine the spatial positions of an objective in real life. In maker-based motion tracking systems, distances and angles between infrared cameras and the markers are captured and calculated to determine the three-dimensional positions. This process is triangulation. Marker-less motion tracking uses computer vision and deep leaning techniques to analyze video footages and identify key points, such as the joints and limbs, to capture motions. After marker identification and reconstruction, the software reduces the noise, merges trajectories, and fills any missing holes from the footage. In the end, the system outputs the location and orientations of the objects under MoCap.

Figure 2: Calibration wand

1.3 Current Challenges and Problem Statement

Nowadays, various industries are using MoCap technology. According to a group of research scientists led by Matteo Menolotto, 1682 studies can be identified as industry-related research since 2015. The 1682 studies are mainly targeted and applied in health and safety, construction, industrial processes, robotics, and automotive (Menolotto, Komaris, Tedesco, O'Flynn, & Walsh, 2020). All these industries have a high barrier to enter and applying MoCap technology takes expertise and efforts. For example, to set up a Qualisys MoCap system, based on user interviews conducted (Section 2.4.2), it needs at least 2 hours from one or two. Ro capture video footage, the equipment and operational cost of MoCap is also really high. Currently, the most outstanding products in the market, such as Qualisys and Optitrack, costs at least 2000$ per camera. The budget can easily goes over 20000$ for the entire MoCap system. Section 2.4.1 later compares various products in the current marker. The operation and maintenance cost are also very high for the MoCap products. The cost barrier is an issue for small-scale companies or labs (Sharma, Verma, Kumar, & Sharma, 2019). How to make MoCap more accessible, usable, and versatile to a broader audience is the challenge this paper attempts to provide a solution for.

Research and Information Collection

2.1 Overview

Product design and development is a crucial step in technology innovation. It ensures the product can meet user needs and expectations. Some steps of product design and development process include ideation, designing, prototyping, testing, and launching (Iheanachor, Umukoro, & David-West, 2020). In motion capture, a well-planned and executed product design and development process can increase the effectiveness, accuracy, and precision of the resulted MoCap system. Thoughtful design can also result in easier hardware and software integration, higher versatility, and better user experience. In this motion capture hardware project demonstrated by this paper, researchers defined the design challenge and problem statement first, operated market research to identity potential competitions, interviewed potential users to learn more about user needs, brainstormed and finalized ideas, made functional prototypes, and performed related experiments to improve the designs.

2.2 Identify Design Challenge

As stated in Section 2.3, there are several current challenges of motion capture technology in the market: high entry barrier, time and effort consuming setup, and low versatility. This article demonstrates a product which challenges the current setup method and use method of MoCap. The design aims at improving users' experiences by alleviating the burden of setup and using MoCap technology. To understand the challenge more thoroughly, the researchers started with a visit to the MIT Immersion Lab for a live Optitrack demo.

2.3 Real-world Experiences with Motion Tracking

2.3.1 MIT Immersion Lab Visits

To better understand the current MoCap technology, the research group followed a live demo of the Qualisys calibration process in MIT Immersion Lab. Immersion Lab is an open research space that focuses on immersive technologies. It is equipped with a complete set of Optitrack motion tracking system. In the Immersion Lab, researchers helped with the re-calibration process. Some key points were learned from the visit:

1. IR cameras pointed down to avoid marker occlusion.
2. Camera cabling should be an issue to take under consideration. Currently, all the cameras in Optitrack system connect with each other in series. For each camera, there are at least two cables: one for the power and one for the signal.
3. The calibration process takes about 45~60 seconds waving the wand and covering the space with approximately 5 minutes of software calibration. After calibration, the user also needs to identify key joint points to each marker.

The visit was the research group's first encounter with the most updated motion capture technology. Even with the most updated technology, there were still room for faster deployment and easier access. The visit set a foundation for brainstorming and helped the research group to identify potential shortcomings of the user experience when dealing with the most advanced MoCap technology.

2.3.2 Color-based motion tracking

The research group also tried some open-sourced online software about MoCap. One program the researcher focused on is a color-based video analysis MATLAB code developed by MIT course 2.671 Measurement and Instrumentation. It is a program where it analyzes video clips and quantify motion trajectory as a function of time. Since the code focuses on 2D motion analysis, all the object motion should be perpendicular to the camera axis. The research group analyzed a neon green can kicked in the plane perpendicular to the camera axis.

After adjusting the color's saturation, hue, and vividity the researcher wants to focus on, the program slices the video into frames and track the center of gravity of the object under track. In the end, the program outputs the trajectory as shown in Figure 3.

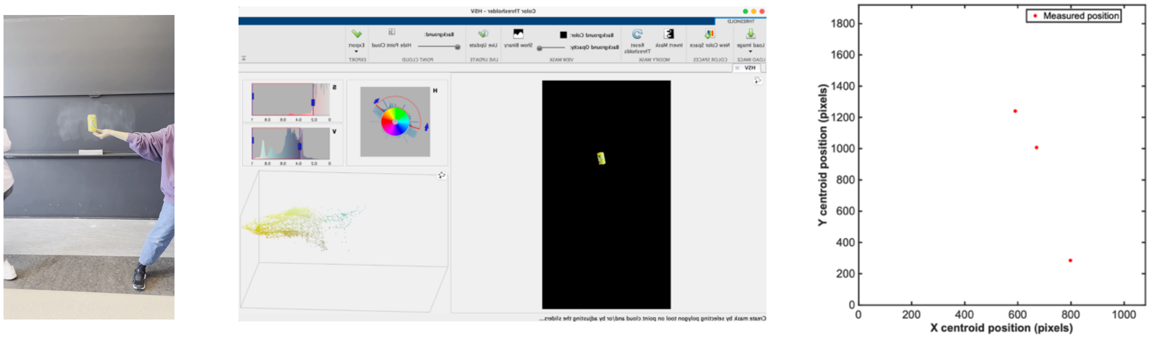


Figure 3: Color-based Marker-less MoCap Trial

The figure on the left shows how the can is kicked. It was kicked downwards in a plane vertical to the camera axis. The can is chosen because of the bright neon-green color. The color is unique in the testing scenario and easy to track with. The figure in the middle shows the interface of color thresholder which filters out the color under track using the Hue Saturation Value (HSV) scale. The top left corner shows the parameters this algorithm uses: H for color hue, S for saturation, and V for brightness values. With the right adjustment of HSV, the algorithm picks up the neon-green color of the can under track and everything else which is not under track are shown in black. The figure on the right shows the MoCap result, the trajectory of the can. Since the can was kicked too fast, only three datapoints were captured.

From this video collection experience, the learnings are:

1. Occlusion should be avoided. Occlusion occurs when the object under tracking is blocked or flies out of the frame.
2. Lighting can be a significant factor in motion tracking. When capturing data, stable and sufficient indoor light should be applied.

2.4 Further Studies and Final Mission Statement

2.4.1 Market Research

Motion capture technology has been under great demand in various industries, such as robotics, gaming, sports, medical devices, and so on. In the current marker-based motion capture market, companies, such as Optitrack (Optitrack), Qualisys (Qualisys), and Vicon (Vicon) are the most outstanding companies. For maker-less motion tracking, Theia3D (Theia3D) offers a revolutionary solution powered by artificial intelligence. Big tech companies, such as Microsoft, makes inertia-based motion tracking consumer electronic devices. Table 1 shows a cross-over comparison between different products and their parameters including different features, ease of use, scalability, precision, and cost.

	Features	Ease of use	Scalability	Precision	Cost
Optitrack	Marker-based, mounted to fixed frames	<10mins calibration, >2h installation	Can sync up to 8 prime color cameras	<0.2mm (>10000sqft)	8 cameras ~$25k
Azure Kinect	Marker-less vision tracking	Windows compatible	Need external software	At 2m, +/- 6mm (center of frames), 30mm (edge of frame)	~$500 for a new kit
Vicon	Marker-based, mounted to fixed frames	>2h installation	Up to 12	~0.02mm	~$50k for low end 10 cameras
Perception Neuron	Inertia based	Portable			
Sony RX0 ii and control	Marker-less	<10mins setup	Up to 100 cameras can be synchronized,	~mm	~800$ combined

box (SONY)			but need external software for more than 2 camera calibrations		

Table 1: Market Research

This table summarizes the market research conducted by the research group. Since the focus is mainly maker-based or marker-less MoCap, inertia-based products were eliminated.

Market research helped the research group get more familiar with the pros and cons of current products. Based on the market research, the research group tends to put the Sony cameras to their prototype as a trail later.

2.4.2 User Interviews

After the market research, the research group conducted 5 rounds of at least 30-minute interviews to understand more about user needs and the potential improvements they can make to the current MoCap systems. Interview questions can be viewed in Appendix 1. In the interviews, we asked users about how motion tracking is related with their work, their MoCap setup, how and when to calibrate, and whether the system drifts mechanically which would result in a need to re-calibrate. One potential improvement the research group found out is add redundancy at the same position vertically. Right now, most MoCap systems only have one camera at each location vertically, such as Figure 4 (MIT Immersion Lab, n.d.).

Figure 4: MIT Immersion Lab Camera Setup

In Figure 4, all the cameras point down above human heights to capture most of the motions. Some of the interviewees pointed out the above-the-head setup may cause occlusion. For example, when someone tries to do some floor motions, trackers at lower levels may be blocked. As a result, redundancy at vertical levels, which means having multiple cameras at different heights will be helpful. Only two interviewees set up the MoCap systems by themselves, which take at least 2 hours to set up a system which covers around 30 square meters. Most of them also use the software provided with the hardware camera systems. As a result, researchers make conclusions as the following:

1. Including more cameras at different heights can help to capture a wider range of motions.
2. Current MoCap technology has a high facility requirement. An empty space with stable structure around 6ft above the ground for cameras to mounted on is recommended.
3. Re-calibration can guarantee a more accurate results, but re-calibration takes extra time and efforts, which may result a discontinuity to project timeline.
4. To better integrate with the indoor environment, it is also valuable to think about the using cases at homes, offices, or classroom.

User interviews provided the research group with valuable first-hand user feedbacks. Based on the interviews, the research group was able to finalize their mission statement and proceed with designing and prototyping.

2.4.3 Final Mission Statement

To conclude the research and information collection stage, the research team is motivated to change the fact that high-end MoCap currently only exists within large-scale companies, research labs, and prominent institutes. The research team is dedicated to promote MoCap technology to a larger audience: doctors and nurses should be able to utilize MoCap in their office to better study patients' motions; teachers can deploy MoCap in the classroom to assist their teaching; future house owners can embed MoCap to their homes to detect falls from gaits. To sum up, the design and development goal is to make a versatile, modular, and functional MoCap hardware system for fast and easy deployment.

Brainstorm, Design, and Prototyping

3.1 Hardware Brainstorming

Now with sufficient amount of learning and study about user needs of a MoCap system, the research group divided the entire design task into three parts for brainstorming: calibration, mechanical drift, and pole hardware designs. Calibration has the most developed technology currently and is one of the most important steps in MoCap. If there is a system which can detect mechanical drift and tells the user when to recalibrate, the research group believes that such system could increase the efficiency of using MoCap. The research group also decides to spend efforts on re-designing the camera poles because the group believes that a new and well-thought structure can make the user experience more pleasant. For each part, at least 2 factors were under considerations with their own variations. The following three figures (Figure 5, 6, and 7) explained the thought process layer-by-layer. These figures illustrate how brainstorming was accomplished for camera pole designs, drift detections, and calibration. Researchers use an idea tree diagram method to navigate through their ideas.

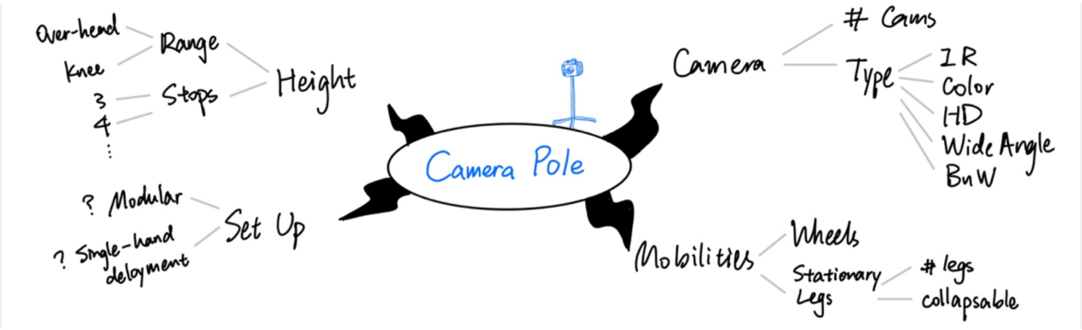


Figure 5: Brainstorm Idea Tree of Camera Poles

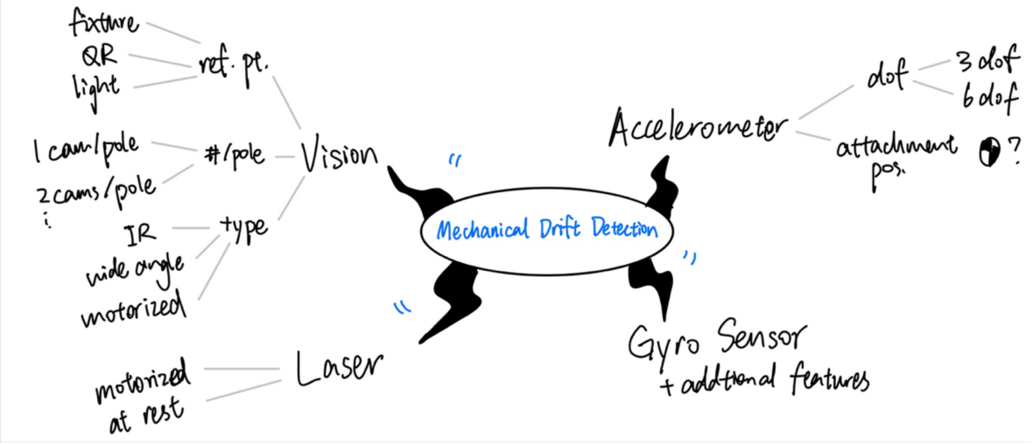


Figure 6: Brainstorm Idea Tree of Mechanical Drift Detection

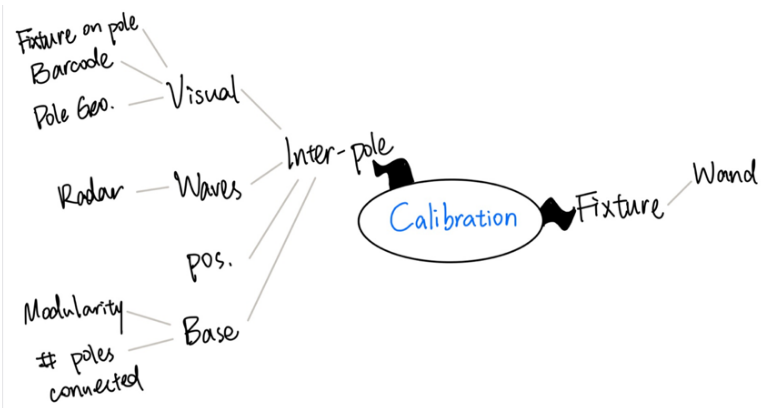


Figure 7: Brainstorm Idea Trees

The brainstorming gave out a lot of variations so that the researchers made a design matrix to decide what features to include in the first prototype.

Number of Cameras			**Wires**			**Markers**		
Value	Importance	Feasibility	Value	Importance	Feasibility	Value	Importance	Feasibility
1	-	:)	yes	+	:)	no	+++	:)
2	+	:)	no	++	:(	reflective	+	:|
3	++	:|				color	-	:)
4	+++	:|						

Number of Poles			**Height of Poles**			**Types of Mounts**		
Value	Importance	Feasibility	Value	Importance	Feasibility	Value	Importance	Feasibility
1	-	-	knee level	++	:)	tripod	++	:)
2	+	:)	waist level	++	:)	embed in the wall	+	:|
3	++	:|	eye level	++	:)	on wheels	++	:|
4	+++	:|	over head	++	:)	joints	+++	:|

Table 2: Design Matrix

A design matrix showing how decisions were made about number of cameras, wiring, type of markers, number of poles, height of poles, and type of mounts. Each condition has different values, and each individual value's importance and feasibility are rated. When rating importance, a minus sigh "-" means that the design has no significance to the project, and a plus sign "+" means the design can be significant to the project's performance. In the feasibility rating scales, a minus sign "-" is followed by a minus sign in the importance column, which means the design choice is abandoned because of the low impact on the project. A smiley face

":)" means the researchers are confident about making this design into real life. A mutual face ":|" means researchers need additional support and information but still feel the plausibility. A sad face ":(" means researchers do not feel the possibility of continuing the design choice in the given time span.

3.2 Sensor choices

Since after the user interviews (Section 2.4.2), the research group realized the need to take user scenarios into considerations. Various sensors were chosen, including vibration sensors, distance sensors, temperature, humidity, and CO2 concentration sensors. Given the time span of this project, distance and vibration meters were purchased at first. Both of the distance and vibration sensors were chosen as plug-and-use types given the short time frame left in the project.

Figure 8.1: Distance Sensor

Figure 8.2: Vibration Sensor

These figures (Figure 8.1 and 8.2) show the distance and vibration sensors chosen for this project. The figure on the left shows the plug-and-use distance sensor from Terabee. It is a time-of-flight distance sensor. The figure on the right shows the vibration meter from WITMOTION. The vibration meter is capable of recording acceleration, angular velocity, and angle at three axials.

3.3 Design Iterations

Given the design task is about versatile and easy-to-use motion capture system, a decision to make modular compartments with the user's choice to plug in color cameras, IR cameras, vibration sensors, distance sensors, or other electronics devices. The first design was a stackable block design as shown in Figure 9. It was the first modular design illustrated in Fusion 360.

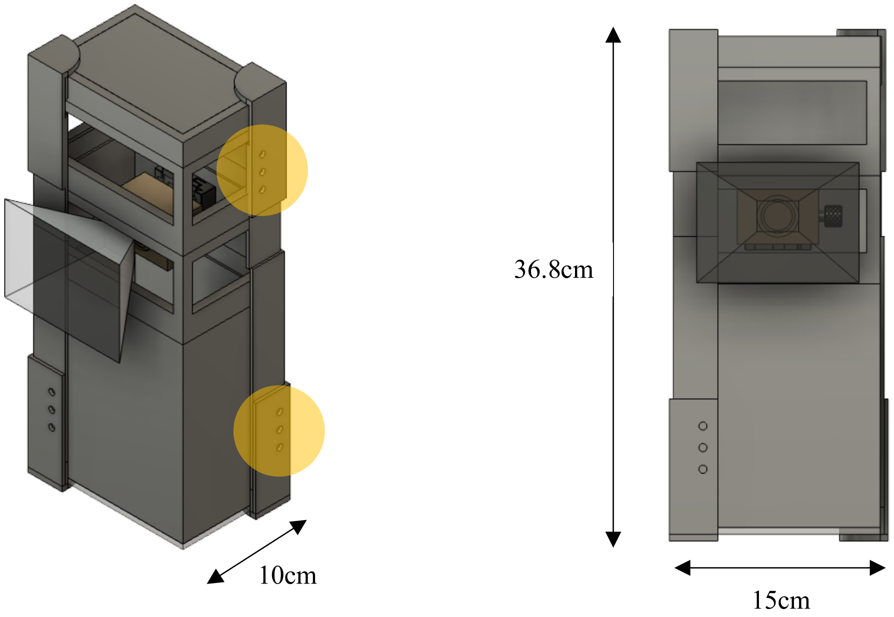


Figure 9: First CAD Design

The first design iteration is a stackable block design. Stackable block design was the first CAD prototype. The figure on the left is an isometric view of the model, and the figure on the right is a front view. The diagonal brackets are designed to secure the movements of blocks stacking up.

At the top and bottom of brackets, there are three holes (highlight in yellow) designed for users to change heights.

This model is modular, capable of change heights, and not too many cables will be exposed to air. However, the height change is only limited to three different modes. To change any other compartment, the user needs to remove the diagonal brackets. The inconvenience quickly brought the researcher a realization to move on to the next design.

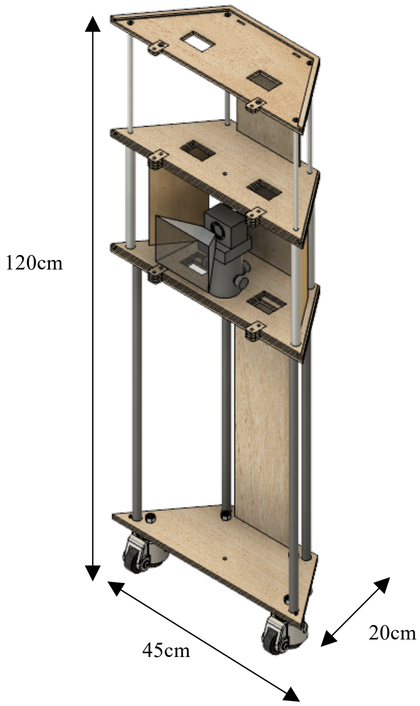


Figure 10.1: Isometric View of Trapezoid Design Assembly

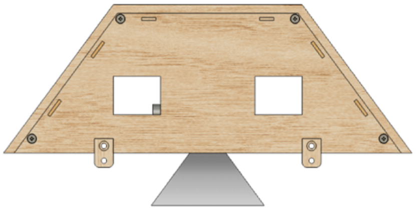


Figure 10.2: Top View of Trapezoid Design

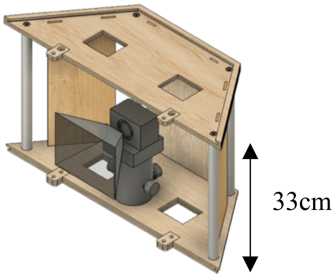


Figure 10.3: Isometric View of a Single Compartment in Trapezoid Design

Figure 10: Trapezoid Design

All other compartments are similar: they have the same trapezoid shape and stackable.

The second design is a trapezoid design as shown in Figure 10. The trapezoid's legs are parallel with SONY camera's field of views. It is a visual confirmation for the users to learn how wide the camera frame captures.

Vibration in MoCap is always a concern so certain features are design here to prevent as much vibration as possible while still making the using experience easy and pleasant. First, all compartments are locked in with each other with a slide-in feature as shown in the following Figure 11. To better illustrate the structure, the top lid is demonstrated with a 50% opacity. As shown in this figure, every individual compartment can slide in to the other one, where vertical vibration can be minimized because of the underhung structure. Additional tabs (highlight in yellow) allow M4 bolts and nuts to go through in the end to provide some extra structural security and vibration proof. In figure 11, countersink features for the head of the bolt to rest on can also be reviewed.

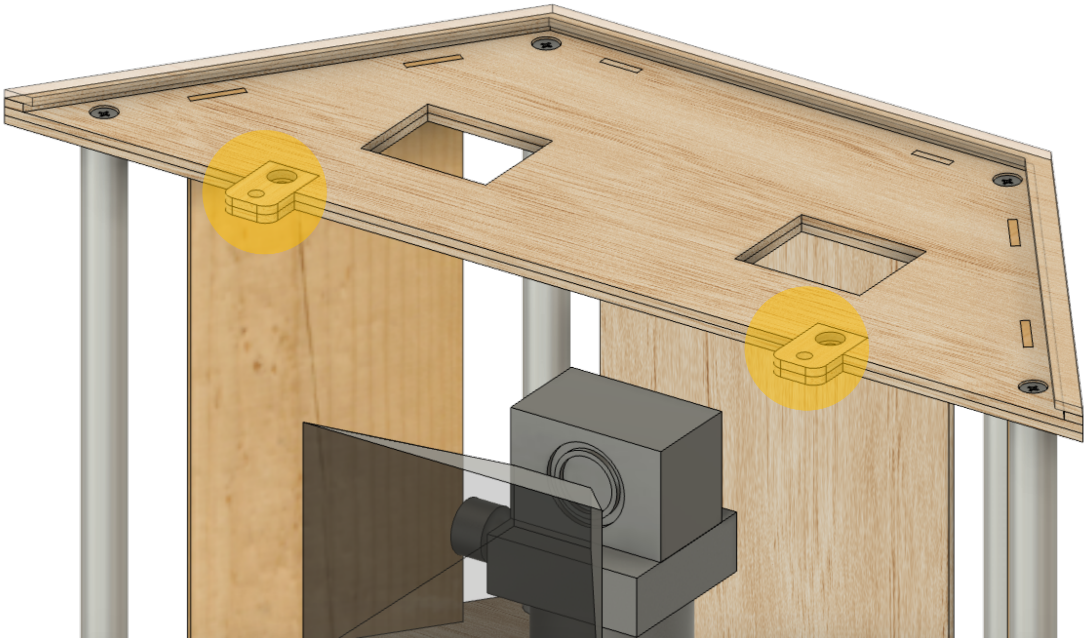


Figure 11: Close-up of a Single Compartment in Trapezoid Design (Isometric View in Figure 10.3)

A close-up view of the compartment's slide-in structures and tabs (highlight in yellow). These two features prevent vibrations at xyz directions as much as possible while the user experience can still be simplistic and enjoyable.

3.4 Prototyping and Assembly

Plywood is chosen as the primary structure material for this initial stage of prototyping because of the following reasons. First, at the beginning stage, there are always a lot of design iterations. Plywood is easy to manufacture with a short lead time, which makes the material very compatible for design changes. Second, with the help of laser cutting, there will be less tolerance stack up errors and less tolerance concerns. With the cost point lower than metals, wooden plywood panels were laser-cutted and metal supporting structures were lathed for the final prototype. Some major prototyping steps include laser-cutting the panels, glue panels, machining shafts as supports, and assembly. Assembly is fairly easy to understand and execute for this prototype. The researcher spends less than 30mins for one individual compartment. A complete assembly SOP is included in Appendix 3. If higher production volume is desired, an alignment fixture to make sure all the laser cut pieces are aligned is recommended in the future.

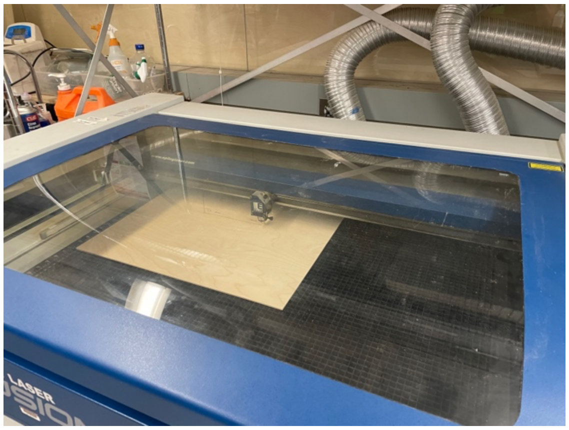


Figure 12: Prototyping – Laser Cutting

Figure 13: Prototyping – Curing

3.5 Final Prototype and User Scenarios

The final wooden prototype is shown in Figure 14. Additional weight bags are added for better weight distribution and balance. There are two user scenarios as shown in Figure 14, which also provides a real-world reference with human. The human in the figure is 5’7 tall.

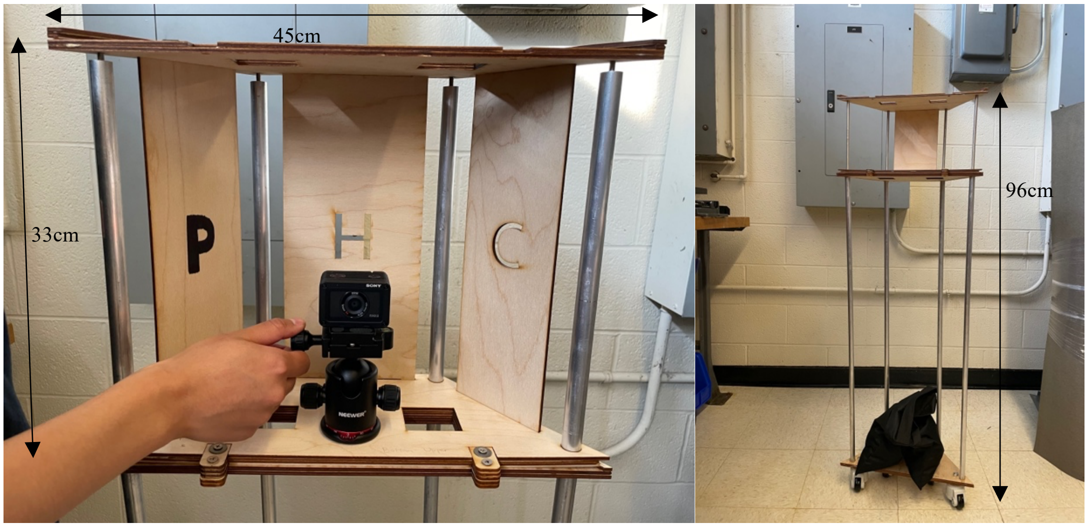


Figure 14: Final Prototype Look

The figure at the left is a close-up view of one compartment. The figure at right shows what it looks like when one compartment is stacked up to the base with a weight bag.

Figure 15: User Scenarios

These two figures show the two using scenarios of this MoCap system. The first picture shows the first case where the entire system will be used. Multiple compartments will be stacked to the base. The figure on the right shows the second case where only one single compartment will be used and put on existing furniture at home.

Test Trails and Experiment Results

4.1 Objectives

Given the tight time frame of this test, the test goal is to compare the single compartment use case to a tripod. The test is to validate if there are less drift comparing the single compartment design and the tripod design and if external vibration can be dampened by the single compartment design. Similar test methods can be applied to another user case where compartments are stacked up to the base.

4.2 Test Setup and Test Methods

Both the tripod and the single compartment is set up so that cameras are at the same height level. The two devices are placed right next to each other. The vibration meters used here are from WITMOTION as mentioned in Section 3.2. Three test cases were performed: walking around the two devices, jumping, and using a message gun to introduce some vibration to the system. Under all cases, all the vibration source is placed equal distance from either of the devices. Section 4.3 is a step-by-step instruction on how to replicate the test.

4.3 Test Steps

To replicate the test, repeat the following the steps:

1. Set up tripod and secure the camera. Put the prototype on the table. Ideally with a rubber mat to dampen the vibration. However, the test ran in August did not use a rubber mat. Make sure the cameras at the tripod and the prototype are at the same height (Figure 16).

Figure 16: Test Setup

2. Turn on both vibration meter at the tripod and at the prototype. Place them flat as Figure 8.2. Let the sensors collect data for about 20 seconds. Try minimizing the surrounding this period of time. This is to offset any measurement error the sensor might have.

3. Perform the test cases: walking around the two devices, jumping, and introduce external vibrations using a message gun. Make sure under each cases, the vibration source is at the same distance away from both cameras. In the vibration case, place a message gun with the highest output firmly against the wooden ground floor to create vibration (Figure 17).

Figure 17: Vibration Test

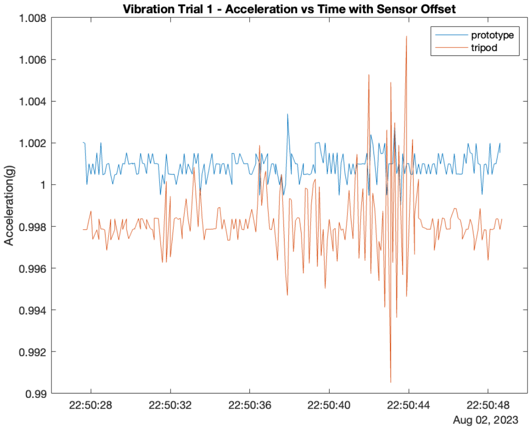
4. Record data while performing the test. When the test is done, send the data to MALTAB code for further analysis.

4.4 Results and Analysis

The recorded data is in text files and opened in MATLAB for plotting. Total acceleration is chosen to be plotted because a lower total acceleration implies a more stable system. After offsetting the sensor, total acceleration versus time graphs were plotted for each case to compare the two devices. However, under the walking cases, significant datapoints are not enough to plot total acceleration versus time for neither device. As a result, only jumping and vibration cases were studied in the end. The results are figures are shown in the following figures (Figure 18 and 19). MATLAB code can be found in Appendix 2.

Figure 18: Acceleration VS Time For the Jumping Testing Case After Offset

The first spike (all spikes are highlighted in yellow) happens right before 23:01:04 where the total acceleration of tripod reached 0.95g while the wooden prototype's total acceleration is 0.96g. The second groups of spikes happen around 23:01:06 where the wooden prototype seems to have a much lower acceleration compare with the tripod. The third spike is only prominent for the wooden prototype not the tripod. This trial suggests that the wooden prototype is slightly worse than the tripod under sudden external changes.



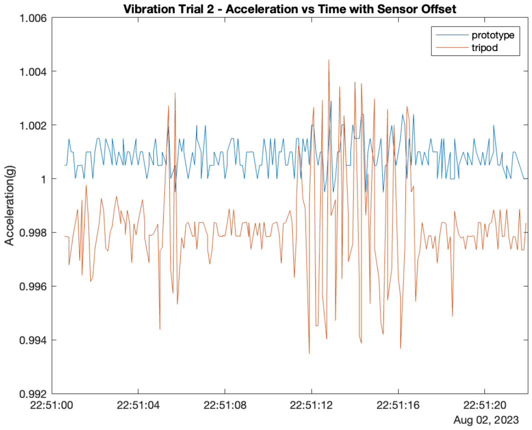


Figure 19.1: Trial 1 of Acceleration VS Time For the Vibration Testing Case After Offset (On the left)

Figure 19.2: Trial 2 of Acceleration VS Time For the Vibration Testing Case After Offset (On the right)

Both these pictures are from the vibration trails. Trial 1 and 2 are under the same test conditions. It is clear from the plots that under same-frequency vibration, the wooden prototype dampens the external vibration more since the acceleration values fluctuates less.

The plots show a trend where the wooden prototype undergoes a lightly higher total acceleration compared with the tripod. Under sudden changes, both the wooden prototype and tripod perform similarly. However, wooden prototype can dampen the vibration more than the tripod when the external vibration is consistent. This is beneficial for long-time MoCap use and less re-calibration. Under the vibrating cases, the wooden prototype's total acceleration fluctuates less than the tripod. This may be caused by the weight different between the wooden prototype and the tripod. Since the wooden prototype's base is made of three layers of plywood glued with each other, the base is not perfectly flat, which causes extra vibration. Where the wooden prototype is placed also affects the results. The floor where the test is performed on is made from wood, which should have more vibration compared with a concrete floor.

Conclusions and Future Work

5.1 Conclusions

In conclusion, the single compartment user case of the wooden prototype sacrifices stability slightly but innovates the way how MoCap can be applied to a boarder audience and embedded in future homes. To improve the wooden prototype's stability so that MoCap can have a higher accuracy, there are several ways which will be explained in the following Section 5.2.

5.2 Recommended Future Work

Based on the test results, there are a lot of future work can be done to improve the current hardware system:

1. Add rubber mat features to the bottom of each compartment as anti-slippery precaution methods.
2. If higher production volume is desired, an alignment fixture to ensure that all the laser cut pieces are aligned can be helpful.
3. Change the material to metal, such as aluminum or stainless steel. Heavier weight and flatter surface can reduce vibrations.

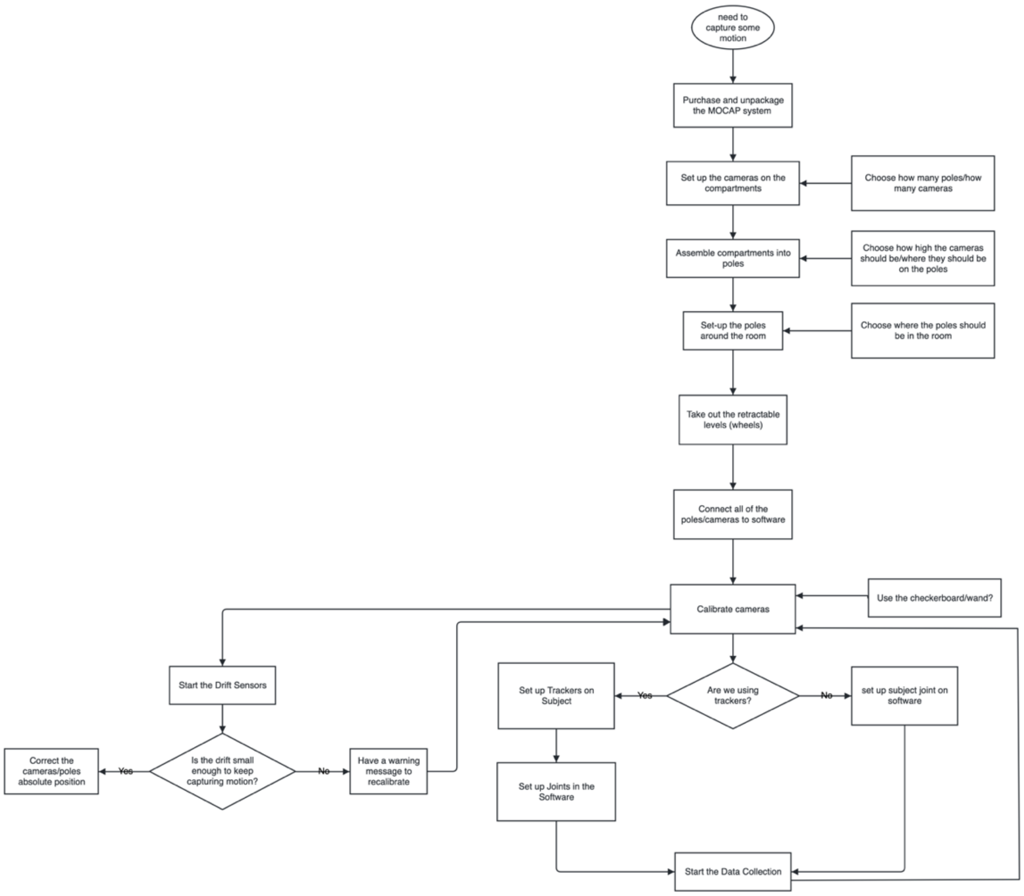


Figure 20: Workflow Chart of the MoCap System

Given the workflow of a MoCap system, there are also multiple potential future improvements:

1. Combine imagine process and distance sensor to the testing trails. Not only vibration should be recorded but also the change in distance. With the help of visual pictures or distance sensors, the mechanical drift should be quantified. A threshold can be determined if a large amount of data can be recorded and analyzed. In the end, the goal will be to tell the user when to re-calibrate the system to save time and efforts of calibration.
2. Add other home sensors, such as distance sensors, temperature sensors, humidity sensors, and CO2 sensors, for a more comprehensive system.
3. Research on how to MoCap wirelessly so that cabling issue can be resolved.

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Appendices

1. Interview Questions

- General questions
  - Hello, how are you? Thank you for taking the interview.
  - What do you use motion tracking for?
  - What kind of accuracy do you need?
  - Does your system have any limitations for what you do?
  - What software do you use?
- Poles
  - What are the typical spatial constraints in your application (height and floor surface)?
  - How do you typically mount the cameras (tripods, wall/ceiling, etc)?
  - How many different camera positions do you use?
  - What's the field of view of the cameras?
  - What's the cameras' frame rate? Resolution?
  - Are the cameras color/black and white/infrared? Why?
  - Do all the cameras do the same thing?
  - How much redundancy is there? Why?
  - How are the cameras synchronized? Synchronization errors?
- Calibration
  - How long does it take to calibrate?
  - What is the accuracy after calibration?
  - Why do you use the wand/the fixture?
  - Is it automatic or do you have to manually set-it up on the software?
  - How easy is it to do?
  - What could be made easier/quicker?
- Drift
  - How long does it take to see drift? At what rate does it happen?
  - How does the drift manifest itself? Can you see it directly or is it only during data analysis?

- Is there any automatic compensation?
- Does the software detect drift automatically?
- How often do you usually recalibrate?
- Does it depend on the number of cameras used?

2. MATLAB Code to Analyze the Data

```
%% written by Cheng, use this to plot acceleration vs time with sensor offset

%% Offset
filename = 'TripodMeterOffset.txt';
T_tripodOffset = readtable(filename);
T_tripodOffset.Properties.VariableNames{1} = 'time';
T_tripodOffset.Properties.VariableNames{2} = 'acceleration';
T_tripodOffset.Properties.VariableNames{3} = 'ax';
T_tripodOffset.Properties.VariableNames{4} = 'ay';
T_tripodOffset.Properties.VariableNames{5} = 'az';
T_tripodOffset.Properties.VariableNames{12} = 'angular velocity';
T_tripodOffset.Properties.VariableNames{13} = 'wx';
T_tripodOffset.Properties.VariableNames{14} = 'wy';
T_tripodOffset.Properties.VariableNames{15} = 'wz';
T_tripodOffset.Properties.VariableNames{16} = 'angle';
T_tripodOffset.Properties.VariableNames{17} = 'anglex';
T_tripodOffset.Properties.VariableNames{18} = 'angley';
T_tripodOffset.Properties.VariableNames{19} = 'anglez';

axMean_tripod = mean(T_tripodOffset.ax);
ayMean_tripod = mean(T_tripodOffset.ay);
azMean_tripod = mean(T_tripodOffset.az);

axValue = 0;
ayValue = 0;
azValue = 1;

%offset prototype
filename = 'PrototypeMeterOffset.txt';
T_protoOffset = readtable(filename);
T_protoOffset.Properties.VariableNames{1} = 'time';
T_protoOffset.Properties.VariableNames{2} = 'acceleration';
T_protoOffset.Properties.VariableNames{3} = 'ax';
T_protoOffset.Properties.VariableNames{4} = 'ay';
T_protoOffset.Properties.VariableNames{5} = 'az';
T_protoOffset.Properties.VariableNames{12} = 'angular velocity';
T_protoOffset.Properties.VariableNames{13} = 'wx';
T_protoOffset.Properties.VariableNames{14} = 'wy';
T_protoOffset.Properties.VariableNames{15} = 'wz';
T_protoOffset.Properties.VariableNames{16} = 'angle';
T_protoOffset.Properties.VariableNames{17} = 'anglex';
T_protoOffset.Properties.VariableNames{18} = 'angley';
T_protoOffset.Properties.VariableNames{19} = 'anglez';

axMean_proto= mean(T_protoOffset.ax);
ayMean_proto = mean(T_protoOffset.ay);
azMean_proto = mean(T_protoOffset.az);
```

```
% plot for visualization
plot(T_tripodOffset.time, T_tripodOffset.ax)
hold on
plot(T_tripodOffset.time, T_tripodOffset.ay)
plot(T_tripodOffset.time, T_tripodOffset.az)
legend('ax','ay','az')
ylabel('Acceleration(g)')
title('Accelecration When Tripod is At Rest')
hold off

figure
plot(T_protoOffset.time, T_protoOffset.ax)
hold on
plot(T_protoOffset.time, T_protoOffset.ay)
plot(T_protoOffset.time, T_protoOffset.az)
legend('ax','ay','az')
ylabel('Acceleration(g)')
title('Accelecration When Prototype is At Rest')
hold off
figure


%% Jump Acceleration VS Time for Both Structures
clc
% tripod data
filename1 = 'tripod_jumping.txt';
T_tripodJump = readtable(filename1);
T_tripodJump.Properties.VariableNames{1} = 'time';
T_tripodJump.Properties.VariableNames{2} = 'acceleration';
T_tripodJump.Properties.VariableNames{3} = 'ax';
T_tripodJump.Properties.VariableNames{4} = 'ay';
T_tripodJump.Properties.VariableNames{5} = 'az';
T_tripodJump.Properties.VariableNames{12} = 'angular velocity';
T_tripodJump.Properties.VariableNames{13} = 'wx';
T_tripodJump.Properties.VariableNames{14} = 'wy';
T_tripodJump.Properties.VariableNames{15} = 'wz';
T_tripodJump.Properties.VariableNames{16} = 'angle';
T_tripodJump.Properties.VariableNames{17} = 'anglex';
T_tripodJump.Properties.VariableNames{18} = 'angley';
T_tripodJump.Properties.VariableNames{19} = 'anglez';

%prototype data
filename2 = 'prototype_jumping';
T_prototypeJump = readtable(filename2);
T_prototypeJump.Properties.VariableNames{1} = 'time';
T_prototypeJump.Properties.VariableNames{2} = 'acceleration';
T_prototypeJump.Properties.VariableNames{3} = 'ax';
T_prototypeJump.Properties.VariableNames{4} = 'ay';
T_prototypeJump.Properties.VariableNames{5} = 'az';
T_prototypeJump.Properties.VariableNames{12} = 'angular velocity';
T_prototypeJump.Properties.VariableNames{13} = 'wx';
T_prototypeJump.Properties.VariableNames{14} = 'wy';
T_prototypeJump.Properties.VariableNames{15} = 'wz';
T_prototypeJump.Properties.VariableNames{16} = 'angle';
T_prototypeJump.Properties.VariableNames{17} = 'anglex';
T_prototypeJump.Properties.VariableNames{18} = 'angley';
T_prototypeJump.Properties.VariableNames{19} = 'anglez';

%offset the meter
T_prototypeJump.ax = T_prototypeJump.ax - axMean_proto + axValue;
T_prototypeJump.ay = T_prototypeJump.ay - ayMean_proto + ayValue;
```

```
T_prototypeJump.az = T_prototypeJump.az - azMean_proto + azValue;
T_tripodJump.ax = T_tripodJump.ax - axMean_tripod + axValue;
T_tripodJump.ay = T_tripodJump.ay - ayMean_tripod + ayValue;
T_tripodJump.az = T_tripodJump.az - azMean_tripod + azValue;

%plotting
a_prototypeJump = sqrt(T_prototypeJump.ax.^2 + T_prototypeJump.ay.^2 +
T_prototypeJump.az.^2);
a_tripodJump = sqrt(T_tripodJump.ax.^2 + T_tripodJump.ay.^2 + T_tripodJump.az.^2);
plot(T_prototypeJump.time, a_prototypeJump)
title('Jumping - Acceleration vs Time with Sensor Offset')
ylabel('Acceleration(g)')
hold on
plot(T_tripodJump.time, a_tripodJump)
legend('prototype','tripod')
hold off
figure


%% Vibration (2 trails) for both structures and plots
clc
% tripod data
filename = 'tripod_vibration.txt';
T_tripodVibration = readtable(filename);
T_tripodVibration.Properties.VariableNames{1} = 'time';
T_tripodVibration.Properties.VariableNames{2} = 'acceleration';
T_tripodVibration.Properties.VariableNames{3} = 'ax';
T_tripodVibration.Properties.VariableNames{4} = 'ay';
T_tripodVibration.Properties.VariableNames{5} = 'az';
T_tripodVibration.Properties.VariableNames{12} = 'angular velocity';
T_tripodVibration.Properties.VariableNames{13} = 'wx';
T_tripodVibration.Properties.VariableNames{14} = 'wy';
T_tripodVibration.Properties.VariableNames{15} = 'wz';
T_tripodVibration.Properties.VariableNames{16} = 'angle';
T_tripodVibration.Properties.VariableNames{17} = 'anglex';
T_tripodVibration.Properties.VariableNames{18} = 'angley';
T_tripodVibration.Properties.VariableNames{19} = 'anglez';

% prototype data
filename = 'prototype_vibration.txt';
T_prototypeVibration = readtable(filename);
T_prototypeVibration.Properties.VariableNames{1} = 'time';
T_prototypeVibration.Properties.VariableNames{2} = 'acceleration';
T_prototypeVibration.Properties.VariableNames{3} = 'ax';
T_prototypeVibration.Properties.VariableNames{4} = 'ay';
T_prototypeVibration.Properties.VariableNames{5} = 'az';
T_prototypeVibration.Properties.VariableNames{12} = 'angular velocity';
T_prototypeVibration.Properties.VariableNames{13} = 'wx';
T_prototypeVibration.Properties.VariableNames{14} = 'wy';
T_prototypeVibration.Properties.VariableNames{15} = 'wz';
T_prototypeVibration.Properties.VariableNames{16} = 'angle';
T_prototypeVibration.Properties.VariableNames{17} = 'anglex';
T_prototypeVibration.Properties.VariableNames{18} = 'angley';
T_prototypeVibration.Properties.VariableNames{19} = 'anglez';

%offset the meter
T_prototypeVibration.ax = T_prototypeVibration.ax - axMean_proto + axValue;
T_prototypeVibration.ay = T_prototypeVibration.ay - ayMean_proto + ayValue;
T_prototypeVibration.az = T_prototypeVibration.az - azMean_proto + azValue;
T_tripodVibration.ax = T_tripodVibration.ax - axMean_tripod + axValue;
T_tripodVibration.ay = T_tripodVibration.ay - ayMean_tripod + ayValue;
```

```
T_tripodVibration.az = T_tripodVibration.az - azMean_tripod + azValue;

% plotting vibration trail 2
a_prototypeVib = sqrt(T_prototypeVibration.ax.^2 + T_prototypeVibration.ay.^2 + T_prototypeVibration.az.^2);
a_tripodVib = sqrt(T_tripodVibration.ax.^2 + T_tripodVibration.ay.^2 + T_tripodVibration.az.^2);
plot(T_prototypeVibration.time(1:210), a_prototypeVib(1:210)) % sparse the data for the same array length
title('Vibration Trial 1 - Acceleration vs Time with Sensor Offset')
hold on
plot(T_tripodVibration.time(1:210), a_tripodVib(1:210)) % sparse the data for the same array length
legend('prototype','tripod')
ylabel('Acceleration(g)')
hold off
figure

%% plotting vibration trail 2
plot(T_prototypeVibration.time(329:540), a_prototypeVib(329:540))
title('Vibration Trial 2 - Acceleration vs Time with Sensor Offset')
ylabel('Acceleration(g)')
hold on
plot(T_tripodVibration.time(329:540), a_tripodVib(329:540))
legend('prototype','tripod')
hold off
```

3. SOPs

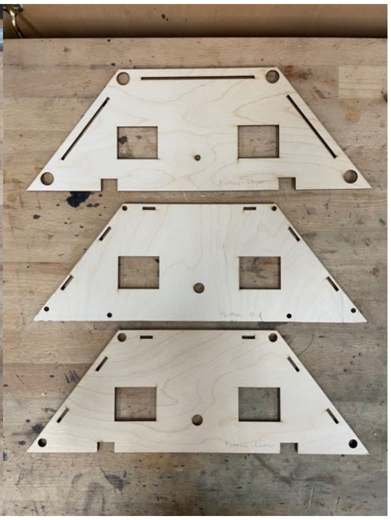
1. Lathe the shafts so that both ends of the shaft has a tapped hole 10mm long for M5X0.8

L12mm flat head bolts.

2. Laser cut all the wooden panels and identify each individual panels as shown in pictures.

Base bottom panels

Top panels.



Bottom panels

3. Glue and cure adjacent panels.

4. Screw shafts to the base.

5. Add back and side panels. Filing the edges may help for fitting.

6. Screw the top panels to shafts.

7. Glue and cure top edges.