ME450
Winter 2023 Semester
Final Design Report

Section 005

Team 27: Design and Implementation of Water Cup Stabilizer

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EXECUTIVE SUMMARY

The Covid-19 pandemic has led to a rise in the demand for delivery robots. However, current delivery robots are not good at stabilizing liquid, which can lead to spills and destabilization of robots due to fluid inertia during transportation. Current benchmarkings focus on stabilizers either for solid objects or large amounts of fluid transported by tanks or trucks, both inapplicable to liquid food stabilization. Our objective is to design a fluid stabilizer for food delivery robots to prevent spills and destabilization, build a prototype and perform simulations of actual delivery conditions to verify our design.

Our updated iterative design model utilizes the ME450 design framework and Cross's model as a backbone while making some important modifications, including the addition of iterations of designs and specifications at the stage of engineering analysis and parallel development of physical prototype and control algorithm. During problem definition, we identified 13 stakeholders. All primary stakeholders are related to our project through economic, safety, and social contextual factors, which will be our focus for later stages. We also identified six mandatory requirements (lightweight, capacity, scalability, stability, robustness, and controllability) and six desired requirements (low cost, durability, easy to set up, universal compatibility, low maintenance, and easy to use) with their corresponding specifications.

During concept exploration, we decomposed our device into four components (mount, linkage, actuator, platform) and utilized pugh charts for evaluation. Engineering analysis was performed for each requirement in order to determine specific material and parameter selections. The final selected concepts are screws as mount (optimal for universal compatibility requirement), truss as linkage (optimal for capacity requirement), a 3-DOF servo system coupled with one accelerometer and three two-bar links as actuator (optimal for stability, robustness, and controllability requirements), and a circular plate with four movable locks and one rubber band as platform (optimal for scalability and easy to use requirements). The four main components, mount, linkage, actuator (plate and two-bar links), and platform, were 3D printed using SLA. All other components were purchased online. During operations, the acceleration is measured and then converted to desired rotational and prismatic motions of linkage arms, then the platform is tilted to remain parallel to the liquid surface throughout the transportation.

Verification tests, including theoretical proof, computer simulation, or physical testing, were performed for each requirement. Most test results demonstrated good compliance of our design to the engineering specifications. For easy to set up, the test result, 6 min, was a little longer than the specified upper bound of 5 min. However, we are confident that the setup time could be largely reduced after mass production. A validation plan utilizing market-based testing was proposed but not performed due to time constraint.

Toward the end of the report, design critiques and potential risks were discussed for the sake of further optimization, the current setting had its strengths and weaknesses, as well as room for improvement in both system level and detailed level. Hardware implementation and control system design, despite being verified, can be realized in a more efficient manner. The team's reflection discussed possible design impact to the identified stakeholders and how the team power dynamics motivated us to make progress on the project. Arguments of inclusivity and ethical considerations played an significant role in the workflow. Finally, we made a list of recommendations that can be helpful for peer reference and future optimization. Potential risks mentioned in previous sections were discussed and possible technical solutions were provided.

REVISED ABSTRACT

When a food delivery robot is transporting liquid, there are some potential risks of spilling and disturbance because of fluid inertia. Therefore, it is necessary to improve delivery robot's performance on fluid stabilization to reduce these risks. Our project aims to design a control algorithm and implement a mechatronic device to stabilize fluid objects for food delivery robots. The mechatronic device is expected to be capable of counteracting the disturbance under the application environment.

1. PROJECT INTRODUCTION AND BACKGROUND

Fundamental Problem

The Covid-19 breakout created the need for social distancing as the infected population kept increasing and many countries released their policies against the pandemic. More shoppings therefore started to be conducted online. According to the International Trade Administration, the share of e-retail sales in total global retail sales had a big jump from 13.6% in 2019 to 18% in 2020, triggering a larger demand in delivery services [1]. Besides the increase in e-commerce, Covid also aggravated labor shortage. The average fraction of companies reporting at least one shortage from 2020 to 2022 was over four times higher than that from 2000 to 2020 [2]. In order to help with labor shortage and fulfill the large demand in delivery services, a huge increase in the global delivery robot market begins with an anticipated compound annual growth rate of 17.8% from 2021 to 2028 [3]. One important sector of this market is the food industry. From the customers' side, according to a report from Fabric in April 2020, approximately 52% of all U.S. customers had shopped online for food recently [4]. From the suppliers' side, many companies have started to use or develop their own delivery robots. Domino's Pizza partnered with TERAKI GmbH, a German AI company, to deliver pizzas using their robots on sidewalks in Berlin [5]. Kura Revolving Sushi Bar, a Japanese restaurant, is now using robots for delivery of drinks in almost all of its restaurants in North America.

One critical problem for current food delivery robots is that they are not very good at stabilizing food, especially those with liquid. Unexpected dynamics in transportation would lead to spills. More importantly, fluid inertia makes the loading platform difficult to stabilize. Current work in stabilization focused on the use of multi-wheeled systems and suspension shock absorption structures to reduce disturbance from outside, especially from road conditions [6]. However, considering common placements of food on delivery robots, either on shelves like PuduBot or in cabins like Starship's robots, the inertia of fluid during transportation will create an extra disturbance originating from the inside of robots, which the current stabilization systems may not be able to deal with. This disturbance may destabilize robots, leading to robot malfunction. Possible environmental, social, economic, and safety issues caused by spills and destabilization are listed in Table 1.1 on Pg. 3.

Table 1.1. Environmental, social, economic, and safety issues related to spills and destabilization

	Spills	**Destabilization**
Environmental Issues	Waste of Resources	-
Social Issues	Decrease in Customer Satisfaction	
Economic Issues	Cleaning Cost	Robot Maintenance Cost
Safety Issues	Slip, Fall, Scald	Crash into Surroundings

Benchmarking

Many products have been developed to improve stabilization. For example, the gimbal stabilizer for cameras and phones uses a motion sensor to track movements and an algorithm to control its pivots and counteract any unwanted movements, including yaw, pitch and roll, in order to ensure stable and clean footage. The gimbal stabilizer also has adjustable mounts that can adapt to many different types or sizes of devices [7]. The gimbal's high adaptivity to different devices and ability to counteract unwanted movements are informative to our design. However, this stabilization technique is limited to rigid bodies. In case of food delivery, the gimbal stabilizer is unable to deal with motions of fluid inside the container or counteract the disturbance from fluid inertia.

Another benchmarking specifically targeting vibrations is Liftware Steady, an electronic stabilizing handle designed for people with Parkinson's disease or severe tremors. It is portable, with a dimension of 1.96 ✕ 3.94 inches and a weight of 3.8 ounces, adaptive to many different utensil attachments, and effective in reducing up to 70% of hand tremors [8][9]. The handle's good portable feature and technique for reducing vibrations are informative to our design. However, hand tremors are small amplitude, high frequency vibrations, while the disturbances a food delivery robot may encounter are vibrations with a large amplitude or nonperiodic dynamics like collisions. Therefore, the stabilization that Liftware Steady provides is not suitable for use on delivery robots.

For fluid transportation, the Liquid Surge Stabilizer works very well in stabilizing movements of liquid in partially loaded tanks. It is constructed of three rings with flow restriction pores, very easy to assemble and disassemble without need of any additional hardwares. During transportation, Liquid Surge Stabilizers are placed in the liquid to minimize its movement and prevent waves that may affect balance of the tank [10]. The stabilizer's easy-to-setup feature and the idea of reducing fluid inertia effect through flow restriction are informative to our design. However, this device is purely mechanical and passive control for fluid stabilization. It also requires direct contact with the fluid, which would not be applicable for food.

Objectives and Goals

In order to provide better stabilization for food delivery robots and prevent issues in Table 1, our mentor Xingze Dai, senior in Mechanical Engineering at University of Michigan, brought up the project Design and Implementation of Water Cup Stabilizer sponsored by the Mechanical Engineering Department of University of Michigan. Our major goal is to design a fluid stabilizer based on a programmable gimbal platform for delivery robots working in a complex. Intermediate objectives include performing simulations to verify the control algorithm, building and testing a prototype under equivalently configured delivery situations. A successful outcome consists of two parts: an algorithm that is capable and achievable of stabilizing disturbance in simulation, and a mechatronic assembly that can stabilize liquid objects through testing.

With help from the librarian, we have found a series of engineering standards that we need to follow in the development of our product from the Art, Architecture & Engineering Library of University of Michigan. In particular, for CAD design of the physical system, we would follow ASME Y14.5 standard: Dimensioning and Tolerancing to ensure our design is understandable to other engineers and/or manufacturers without any confusion [11]. For the powertrain, we would follow IEEE 2847-2021 for more efficient DC power transmission and communication to loads and IEC 61508 for functional safety related to our programmable electronic system [12][13]. For the physical strength of our product, we would follow ASTM E606 and E466 for fatigue testing [14][15].

2. DESIGN PROCESS

Considering the complexity of this project, the design process we are employing is beyond simple processes such as activity-based or solution-based. For a complicated project with significant design uncertainties, our team is conducting this project using a combined model of concentric stages, activities and solution spaces as shown in Figure 2.1d[16]. We have considered simple problem oriented design processes and stage based models, however, these models are too fundamental to and may not satisfy our needs along the way. If we decided to employ the pure stage based model, it would not be able to capture all the detailed activities in each stage. On the other hand, we decided to employ the pure activity based model, then we would lose the chance to track project progress from broader visions.

Figure 2.1. Multiple combined design process samples. C represents the iterative model and D represents the concentric model[16].

The same story happened with the problem/solution based processes, we proposed a new product while not entirely ruling out the possibility of reverse engineering the benchmarking products for inspirations. The above indicates that we need a more sophisticated model to structure our design process, after careful consideration and selection, the concentric stage-activity-solution space model becomes the most promising one because it incorporates all the advantages of simple models while introducing flexible and comprehensive components. So far, one particularly helpful model we have been studying is the one with iterative activities in every stage as shown in Figure 2.1c[16]. This model is also a combination of stage-based and activity-based models and it introduces repetitive activities and allows frequent censoring and revising which would be helpful for the consistency and coherence of the entire project. Based on the textbook iterative model, we optimize this model to another level which becomes the updated iterative model. In the concentric model, not all activities are necessarily repetitive, however, the iteration has been optimized such that important activities are kept for all stages while some activities are specific to respective stages. This adjustment will save a lot of time by cutting down redundant tasks while maintaining proper rigorousness and desired advantages of the iterative model.

The iterative model we were using is actually very similar to the ME450 design framework as shown in Figure 2.2[17], the key stages in this project are problem definition, concept exploration and solution development and verification. These three stages correspond to the three phases in our project schedule.

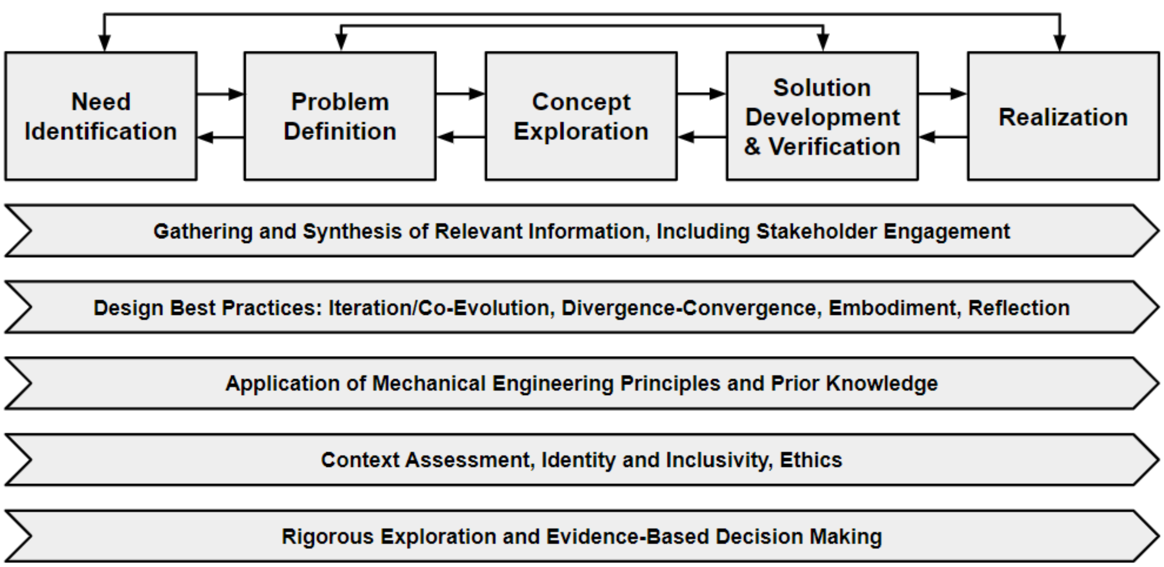


Figure 2.2 ME450 Design Process Framework. Square boxes indicate different design stages and 5 ribbon-shaped text boxes represent various activities associated with all stages.

This ME450 design framework also has the concentric and iterative property that matches our desired model. This is particularly important because we would like to have the option of making modifications in prior phases if we have spotted any crucial deficiency. The ME450 design framework also listed common activities among all stages and we have been using those to guide our design process. For example, we have been using "gathering and synthesis of relevant information" to construct the stakeholder map and will also apply this technique for future design phases. Other activities such as "application of mechanical engineering principles and prior knowledge", "Context assessment" and "Rigorous exploration and evidence-based decision making" are serving as our primary line of action. All of the common activities are woven into our design process and have great significance on our progress and decisions along the way. A more accurate schematic of our iterative model is shown in Figure 2.3 below.

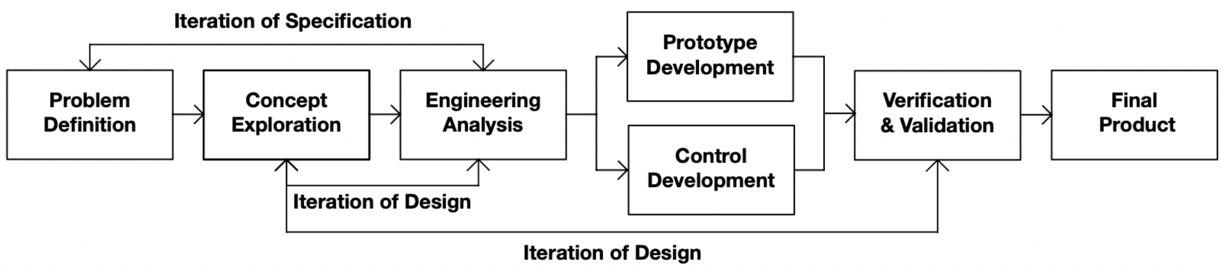


Figure 2.3 Team 27 Design Process Schematic

Another similarity between our model and the ME450 framework is that additional activities are encouraged beyond the common ones, for example, for concept exploration phase specifically, we would like to have an intense brainstorming/debating activity in order to propagate thinking outside the box and challenge existing concepts. Moreover, our specific design process included iteration of engineering requirements and specifications based on feedback and increased awareness of our progress. To sum up, the optimized model we are employing is very much the same as the ME450 design process framework which has iterative stages, concentric phases, common activities and stage-specific activities. All of these properties allow us to design systematically, reflect efficiently and work effectively.

During the conceptual generation phase, we utilized the iterative model to navigate through the entire process. Our teammates have gathered relevant information from various sources, conducted divergent thinking techniques, applied technical knowledge, explored the inclusivity and ethics, and made evidence-based decisions to ensure we have a variety of solution concepts and systematic progression for concept downselection.

3. DESIGN CONTEXT

We identified 14 stakeholders and categorized them based on three different metrics, primary, secondary, and tertiary groups, ecosystem roles, and driving contexts as shown in Figure 3.1

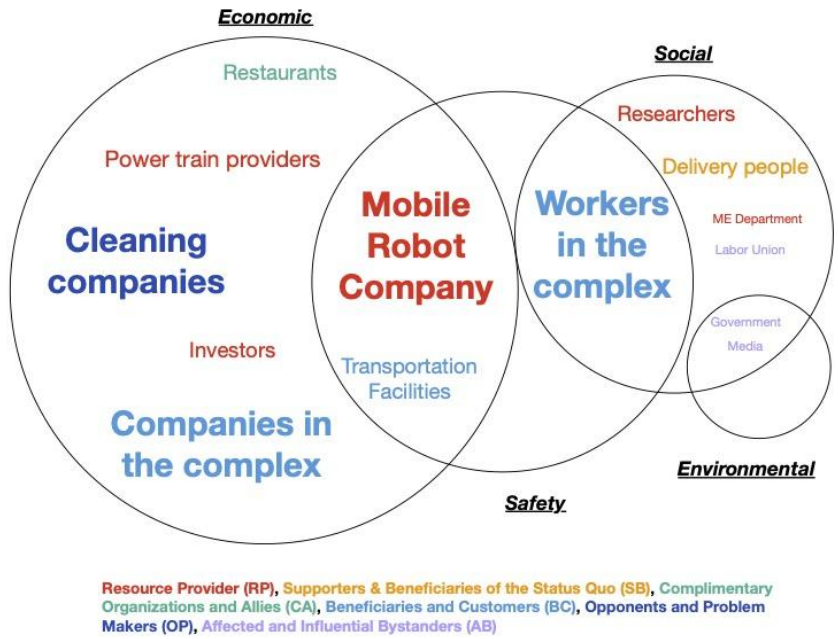


Figure 3.1. A stakeholder map with different font sizes indicating primary, secondary and tertiary stakeholders, colors indicating different ecosystem roles as labeled at the bottom, and circles indicating different driving contexts. The largest font size (bolded) represents primary stakeholders.

Primary Stakeholders

Primary stakeholders are directly impacted by the problem and/or the development of a solution. We identified four primary stakeholders: mobile robot companies (RP), workers in the complex (BC), companies in the complex (BC) and cleaning companies (OP).

For mobile robot companies, our project has positive impacts in both economic and social contexts. The fluid stabilizer will help enhance robots' ability to deliver liquid food safely and in good condition. According to El-Said and Hajri, this improvement in perceived usefulness (the technology's ability to perform as expected) would lead to increase in experience satisfaction, therefore not only attracting more customers and business opportunities but also enhancing the company's reputation and increasing the social acceptance of robot service [18].

For workers in the complex, our project has positive impacts in both safety and social contexts. Our fluid stabilizer would effectively prevent spills and destabilization of robots due to fluid inertia, thus reducing the risk of workers being scalded by hot liquid or hit by malfunctioning robots. With the implementation of fluid stabilizer, delivery robots become capable of delivering more kinds of food and providing better delivery services, creating more convenience for workers.

For companies in the complex, our project has a positive impact in the economic context. According to IBM's study, the cumulative time that office workers in New York spend waiting for and being stuck in an elevator in the past 12 months was about 16.6 years [19]. This huge waste of time in elevators makes all companies in office buildings incur the cost of wasted energy and loss of productivity. With better stabilization abilities, now instead of disjoint workers getting into elevators to pick up their food downstairs at the same time, robots can deliver food to workers in a more regulated manner, saving time and energy. Companies in the complex would therefore benefit economically from lower operating costs and increase in worker productivity.

For cleaning companies, our project has a negative impact in the economic context. With the implementation of fluid stabilizer, the possibility of spills will be largely reduced, leading to decrease in business opportunities for cleaning companies.

Secondary and Tertiary Stakeholders
Secondary stakeholders are part of the problem context but may not experience the problem themselves and/or may not be directly impacted by a solution. We identified six secondary stakeholders: restaurants (CA), delivery people (SB), powertrain providers (RP), investors (RP), researchers (RP) and transportation facilities (CB). Tertiary stakeholders are outside of the immediate problem context but may have the ability to the success or failure of a potential solution. We identified four tertiary stakeholders: ME department(RP), government (AB), labor union (AB), and media (AB).

Both investors and powertrain providers will experience positive economic impact from our project. Our fluid stabilizer is electronically powered and requires a complete set of powertrain including motors, gears and shafts, providing more business opportunities to powertrain providers. With the ability of improving stabilization, we expect that our product will attract many robot companies to purchase and implement their robots, bringing economic benefits to investors.

Researchers, another Resource Provider, cares most about helping solve potential environmental, social, economic, and safety issues related to delivery robots and will gain reputation from their designed solution, and therefore be positively influenced by our project in the social context. Since our mentor Xingze Dai is also part of the design team, he will belong to "Researchers" and would be most interested in the social context related to our project.

Restaurants and transportation facilities will experience positive impact from our project in both safety and economic contexts. The fluid stabilizer would help reduce the possibility of spills and robot malfunctions due to destabilization, and provide a safer and more reliable delivery service. Besides, according to ARK, the cost of robot delivery per mile is at least 6 times less than the cost of human delivery [20]. With a safer and more reliable delivery service provided by our product, robot delivery can be largely implemented, thus saving more money for both restaurants and transportation facilities.

Both delivery people and the Labor Union will experience negative social impact from our project. According to research conducted by Prof. Acemoglu from MIT and Prof. Restrepo from Boston University, robots have a significant negative impact on jobs and wages in such a way that for every robot added per 1000 workers in the U.S., the average wage declines by 0.42%, and the employment-to-population ratio decreases by 0.2% [21]. With the help of our fluid stabilizer, robots will be able to take over more delivery jobs, causing an increase of the unemployment population. Moreover, due to the low cost associated with robot delivery, the wages for human delivery workers will continue to decrease as well.

Government and media are related to our project through both social and environmental contextual factors. As the use of delivery robots become more widespread, governments need to issue new regulations to deal with robots' interactions with pedestrians and impact on the local environment. Media would be interested in how the fluid stabilizer would influence people and the environment, and media coverage would again influence people's perception of our fluid stabilizer.

As our sponsor, the Mechanical Engineering Department of University of Michigan cares most about the social context since their essential intention of funding this project is to help educate Mechanical Engineering students to gain more practical experience and become better engineers in the future.

Stakeholder Engagement
Throughout the design process, we collaborated very closely with our mentor Xingze since he is also one of our team members. We also worked closely with our sponsor, the Mechanical Engineering Department of University of Michigan, through weekly meetings with course instructors and monthly updates with presentations and design review reports.

We did not conduct any interviews with other stakeholders, but we have performed careful observations on restaurants which implemented delivery robots and customers who received robot delivery services. We visited Kura Revolving Sushi Bar in both Novi and Troy, which had implemented delivery robots in particular for delivery of drinks since last year. According to our observations, when a delivery robot arrived at the designated table, the drinks were usually already spilled on the tray and around the cups. As customers, our hands would get dirty when transferring the cups from the robot to our table. The spills would also cause extra cleaning work for staff after each delivery, which is both effort and time-consuming. Considering that the flat and simple path in Kura has already brought such challenge for delivery robots, in a more crowded place like a complex which involves more moving objects like humans and requires more complicated motions like getting on or off elevators, it would be difficult for current delivery robots to complete fluid transportation without causing larger range of spills or even more serious accidents like crush into surroundings or pedestrians.

Inclusivity

Our device does not require too much force from users to secure or release a container, which ensures equal usage across customers with different genders and ages. The design for the mounting mechanism has a high universal compatibility that can adapt to different robots. And the design for the platform has a high scalability which can adapt to different sizes and shapes of containers. Since most robots are only capable of maneuvering on flat surfaces, for people living on higher floors without elevators, current delivery robots would not be able to climb up stairs and complete the delivery. In this case, our fluid stabilizer would still be helpful as a hand-held device for human carriers to better stabilize liquid food when climbing up or down stairs.

Sustainability

As explained in the Project Introduction and Background section, our device would make a significant progress in stabilizing fluid for delivery robots which currently still remains as an unsolved problem (or at least no solutions were widely used in the society). Since the fluid stabilizer does not emit any pollutants during operation, if we use mostly recyclable materials to build the body and renewable energy stored in batteries to power the system, the fluid stabilizer should not lead to any undesirable environmental consequences in its lifecycle. In addition, if we can control the cost of purchase in a reasonable amount, our design would also be self-sustaining in the market due to the increasing demand for delivery robots. Besides, because the device requires a robot, or other transportation mechanism, as a carrier and is only useful in liquid delivery, we do not expect to see an overconsumption in the market.

Intellectual Property

Since we are a student-led project team and no companies or organizations will be involved in the development of our product, our four team members would together own the potential intellectual property of the final product. At this stage, we do not anticipate to patent our final design, but we would research on previously patented designs with similar functionalities and use them as learning materials for our own design. Currently, we have searched in the European Patent Office for “stabilization” and “tremor” related patents and found a stabilization system for guiding a camera and a tilt compensation for tremor cancellation device [22][23].We could learn from their approaches to detect and counteract unwanted motions which would be useful to implement in our design.

4. USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Given the stakeholder map and the design context, user requirements are concluded in plain descriptions in the perspective of the stakeholders [24][25]. They represent the core interests of the stakeholders. Engineering specifications are concluded in correspondence with the user requirements but in numerical, verifiable engineering terms by Quality Function Deployment [26][27]. The terms are decided based on literature reviews and benchmarking. They serve as a guide as well as a standard to the design process.

User requirements and their corresponding engineering specifications are prioritized and classified into two groups by Kano's model [28]: mandatory requirements and desirable requirements. Mandatory requirements are the core requirements to be fulfilled by the end of the project. Failure in fulfilling these requirements leads to the failure of the project. Desirable requirements are optional requirements by which any accomplishment adds value to the design. The principle of the classification is based on the requirements' relevance to the main objectives of the design.

Mandatory Requirements

Mandatory requirements should be closely relevant to resolving the specific problem that this project is addressing while desirable requirements focus on the added value. Mandatory requirements and their engineering specifications are tabulated in Table 4.1.

Table 4.1. Six mandatory requirements and their corresponding engineering specifications.

Requirement	Specification	Verification Results
Lightweight	The weight of this device should not exceed 8 kg [29]	Passed (3 kg)
Capacity	The device should be able to support a load within 1 kg. [30]	Passed (> 1 kg)
Scalability	The device should be able to hold cylindrical-shaped objects with a diameter varying from 8 cm to 15 cm. [31]	Passed (7.5 - 17 cm)
Stability	The stabilizer should be able to stabilize the water cup with an input of an acceleration of 1 m/s^2 under the condition that the input has a frequency no larger than 1 Hz. [32][33]	Simulation passed Hardware pending
Robustness	The device should be able to stabilize the vibration amplitude to 0.01 m/s^2 if the input frequency is within the range of 1Hz and 10Hz. If the input frequency is beyond 10Hz, the device should ignore the input signal. [34][35]	Simulation passed Hardware pending

Controllability	The actuator(s) should be able to generate an input to move the internal state of a system from any initial state to any other final state in a finite time interval. [36]	Simulation passed Hardware pending

Being lightweight enhances portability and convenience in handling. For most tall robots with multiple trays, the carrying capacity of each single tray is approximately 10 kg [29]. Since we want to support a load within 1 kg as stated for the capacity requirement, the stabilizer could have a mass ranging from 0 to 9 kg. The chosen upper limit 8 kg leaves enough space for design generation and material selection while also leaving about 1 kg capacity for the robot side to accommodate any additional components needed.

The capacity of the product determines the usage. The more the product can accommodate, the more widely the product can be applied in the field and as a result, the more difficult it is to design the controller. An educated guess of the load limit was made in the specification. A weight of 1 kg is equivalent to one liter of water, a 2.2 lbs steak, or about four Big Macs [30]. It is assumed that a weight of 1 kg is a fair amount of food to be delivered each time and it is thus taken into account in the specification.

Scalability differs from capacity by volumes. In the design context, food is prepared in food containers and the shape factors of these containers is the main consideration in scalability. Market research is conducted and common dimensions of food containers are considered [31]. The minimum and maximum diameter of the food containers are listed in the specification.

Referring to the core problem of stabilizing fluid objects under disturbances, the disturbances should be further specified. Different frequencies lead to different means of controller design. We adopted and proposed two frequency thresholds, 1 Hz and 10 Hz, to categorize disturbances. For the sake of physical intuitions, the frequency of finger tapping is approximately 1 Hz [32] and the seismic wave frequency is normally up to 10 Hz [33]. Therefore, disturbances with frequencies less than or equal to 1 Hz are regarded as low-frequency vibrations. Disturbances with frequencies greater than 1 Hz but less than 10 Hz are regarded as high-frequency vibrations. And disturbances with frequencies greater than or equal to 10 Hz are ignored for the sake of simplicity (Many of them have a comparably small magnitude and will be damped out due to the mechanical connections). Special cases would be a non-reciprocal continuous timewise force or impulse with infinite frequency. Fourier transform will be applied to analyze these special input signals by the three categories described above.

In addition to the specification of frequencies, the acceleration of the motion is also specified. When a disturbance with a frequency less than or equal to 1 Hz is applied, its magnitude of acceleration should be less than or equal to 1 m/s^2. An acceleration of 1 m/s^2 is equivalent to the acceleration of an elevator [34], in which elevators and walkways are a common source of disturbances in the application environment. When a disturbance with a frequency greater than 1 Hz but less than 10 Hz is applied, its magnitude of acceleration should be less than or equal to 0.01 m/s^2. An acceleration of 0.01 m/s^2 is the minimum accurately detectable acceleration of an accelerometer [35]. Frequencies smaller than this value are not detectable and thus, cannot be algorithmically stabilized.

In summary, stability is specified such that the product is able to stabilize the object under disturbances with a frequency less than or equal to 1 Hz and an acceleration not greater than 1 m/s^2. Similarly, robustness is specified such that the product is able to stabilize the object under disturbances with a frequency greater than 1 Hz but less than 10 Hz and an acceleration not greater than 0.01 m/s^2.

Controllability is defined such that the actuators should be able to generate an input to move the internal state of a system from any initial state to any other final state in a finite time interval. [36] When the state space model is derived from the system, the controllability is able to be determined by the rank of the controllability matrix. If the controllability matrix is fully ranked, the state space model is said to be controllable. There is no quantity related to this specification**.** Although this theoretical proof provides a solid foundation of verification, we may encounter ambiguities in evaluating the controllability matrix. In case when the closed-form controllability matrix is unobtainable, the definition of controllability is adapted in the sense of kinematics map. In brief, controllability refers to the full mapping from motor motions to desired platform configuration space. This concept is further developed in the Verification section.

Desirable Requirements

Desirable requirements and their engineering specifications are tabulated in Table 4.2.

Table 4.2. Six user requirements are listed as desirable requirements and their engineering specifications are attached.

Requirement	Specification	Verification Results
Low-Cost	The total cost of the entire device should be under $1000. [Mentor]	Passed ($435.75)
Durability	The device should be able to function normally for 2,400 hours without maintenance. [Mentor]	Passed
Easy to Set Up	The complete setup procedure should be less than 5 minutes. [37][38][39]	Failed (expected to be reduced after mass production)
Universal Compatibility	The device should be able to be mounted to a	Passed (4 screws)

	pre-designed rigid structure with no more than 4 components. [40]	
Low Maintenance	The device should have at least three replaceable components and the process of replacing any of the three parts should be less than 5 steps. [37][38]	Passed (4 replaceable parts, max 4 steps)
Easy to use	Users should take no more than 5 seconds to finish loading and unloading. [Mentor]	Passed (loading 3.45 s, unloading < 1s)

Product being low-cost leaves more financial availability to the project. The Mechanical Engineering Department at the University of Michigan and Prof. Kira Barton generously sponsored $1000 for this project. Therefore, the entire project including designing, prototyping and manufacturing is recommended not to exceed the $1000 budget. Also, being low-cost enhances the product's competency in the market.

Durability measures the lifespan of nominal performance of the product. It affects the working efficiency, maintenance cost and customer satisfaction. We formulate the engineering specification as follows. We assume that the device will be in active duty 4 hours a day, 300 days a year, and two years before potential defects. The durability is therefore 2,400 hours which is the total hours before defects.

The requirements of universal compatibility,easy-to-setup, and low maintenance are manufacturer- and user-oriented. They all help improve the overall operation efficiency and maximize profit for the company. Higher conceptual compatibility, an important design concept in Ergonomics, would reduce reaction time of users when operating the system [37][38]. Both easy-to-setup and low maintenance features would reduce non-value-added work and therefore increase the overall equipment effectiveness. If we consider food delivery as a process with food as the flow unit, when the fluid stabilizer is in the setup or maintenance phase, no flow unit can pass through this resource, making all following resources idle and decreasing the flow rate of the entire process. With less time spent on setup and maintenance, we could improve the system flow rate and consequently increase profit for the company according to Eq 4.1.

$$Profit = Flow\ Rate \times (Average\ Price - Average\ Cost) \quad (4.1)$$

Currently, we make a justification that a good standard of easiness in setup would take less than 5 minutes to complete when the user is proficient in doing so. The limit was decided based on setup time needed for similar products (gimbal) [39]. Low maintenance should ensure at least 3 replaceable parts while keeping the steps taken for replacing each part within an upper limit of five. Universal compatibility specifies four-component mountings and ensures the multi-functions of the product by referring to similar designs [40]. Also, ASME Y14.5 standard [11] is strictly followed throughout the design process.

Ease of use refers to the extent to which a product, service, or system is designed to be intuitive, user-friendly, and efficient to use. It is a measure of how quickly and easily a user can accomplish their goals or complete a task using the product or system. The mentor included the ease of use in the design that is not only functional and effective but also accessible and easy to use for a wide range of users. In his specification, users' operation time should not be longer than 5 seconds under normal circumstances.

5. CONCEPT GENERATION AND DEVELOPMENT

Concept generation is assigned to individual team members. Every team member is responsible for generating a multitude of ideas. In general, four methods have been adopted during the process. First, divergent thinking generates ideas that diverge from conventional approaches. Second, brainstorming exploits members' creativity and their unique identity backgrounds. Third, mind mapping is also used to proliferate ideate concepts by connecting design ideas between existent products. Fourth, Yanyu targeted the attributes of the design objective, asking the definition of the attributes and answering it herself. By asking and answering recursively, she was able to reach out to a group of concepts starting from the design objective. Finally, team members also chose to use combinations of existing ideas to create new ones. Team members applied sketching and writing to visualize and develop ideas in a concrete way.

After individual concept generation, the team met during class time and conducted concept development to integrate and expand the reservoir of concepts. First, the team performed function decomposition based on our vision of the possible device. As shown in Figure 4, the functions are decomposed into four categories: Mount (A), Linkage (B), Actuator (C), and Platform (D). The mount (A) is supposed to be the interface between our product and the carrier. The interface should provide rigid attachment. The linkage (B) supports the main weight of the product. The actuator (C) is the core part in this project that controls the dynamics and kinematics of the platform to ensure the fluid stability. The platform (D) supports and secures fluid containers.

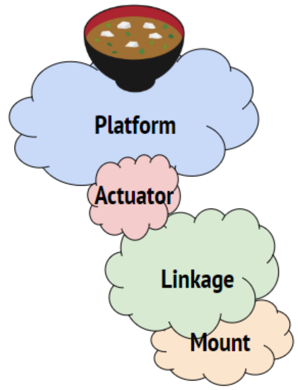
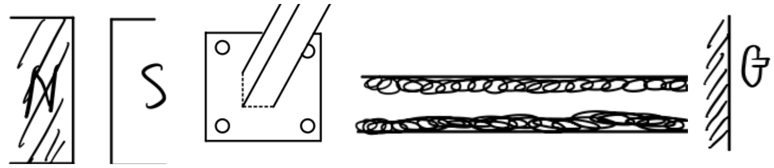
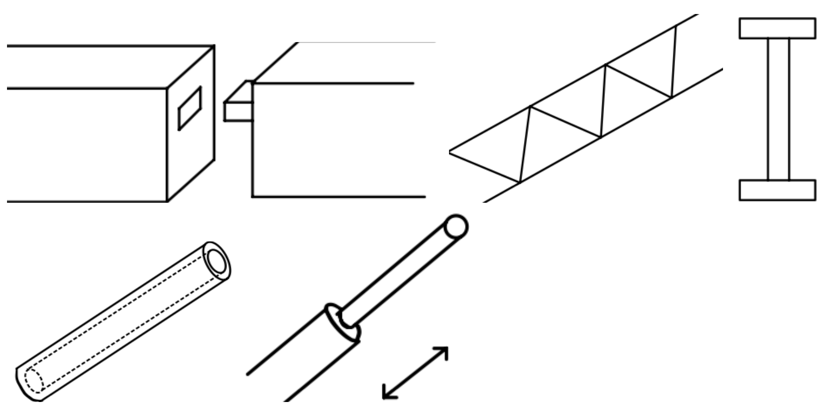
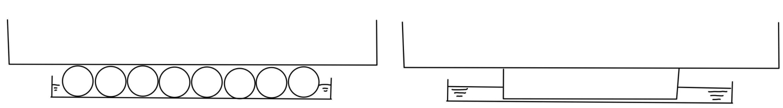
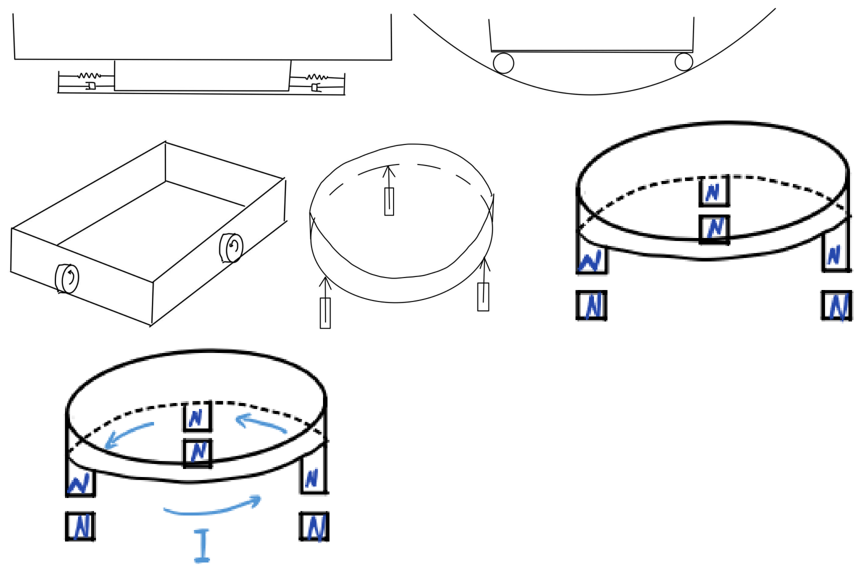
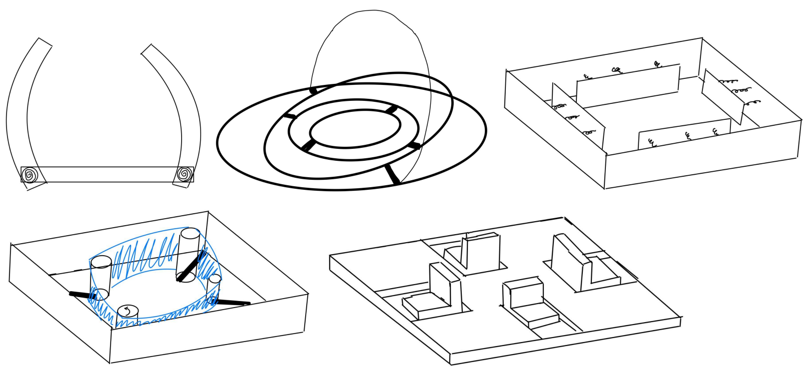


Figure 5.1. The abstract drawing to demonstrate our product.

After function decomposition, the team understood the duty of each component and formulated the objective of each component. The team therefore classified concepts according to functions and mechanisms, and identified available parameters under each classification. Duplicate concepts were crossed out but the concepts with any variety were saved with one single representation. Then, all concepts were sorted in a morphological chart as shown in Table 5.1 and helped us identify the promising combinations of sub-function solutions.

Table 5.1. Morphological chart of solutions to fluid stabilizer.

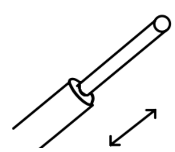
Sub functions	Solutions
A. Mounts	
B. Linkage	
C. Actuator	

	
D. Platform	

Some concepts in Table 5.1 are unique. For example, using velcro tapes is one option to build a mount. In this concept, a piece of velcro tape is fastened onto the linkage and the surface of a carrier by adhesive. When using our product, the user can attach our product onto the velcro tape on the carrier and after finishing, our product can be easily removed from the carrier.

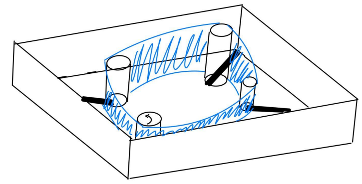
Velcro tape

Another example is to use a telescoping pole as a linkage. The telescoping pole consists of many tubes of slightly different sizes stacking one another. There are quick flip locks on the end of each section to secure the position. The length of the telescoping pole is adjustable by protracting and retracting poles.



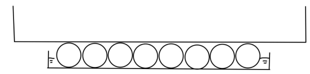
Telescoping pole

The third example is to use a contracting belt to secure the fluid containers on the platform. Three cylindrical pulleys are inserted into four diagonal slots on the platform. There is one motorized pulley that coils up the rubber belt. With the rubber belt being coiled up, the elastic force will push the other three movable cylindrical pulleys towards the center of the platform and items are secured in place. Reversing the motorized pulley releases the rubber belt.



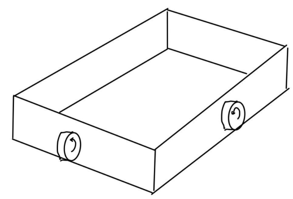
Contracting belt

The fourth example is to use roller ball bearings with shock absorption fluids as a passive actuator. Roller balls in the bearings enable planar movements while being sufficient to support vertical loads. The shock absorption fluid serves as a lubricant between the roller balls and the bearing and as a mechanical damper which slows down the roller balls' speed.



Roller ball bearing in fluid

The fifth example is to use two electric motors as an active actuator. One motor controls roll while the other controls pitch. By the XYX convention in the Euler's angles, the rotation kinematics of the platform is fully spanned by the roll and pitch, although yaw is not considered in this project. The generated rotation is thought of as being able to orient the fluid container so that the poise of the container is maintained.

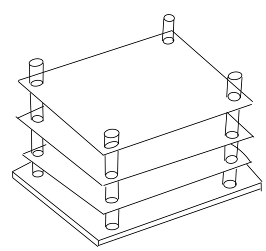


Two electric motors

Other concepts are also elaborated in detail and included in the Appendix A. Beside morphological analysis, design heuristics is also applied to add varieties to our generated designs as well as propose new functionalities. Below are some examples of design heuristics that we have applied.

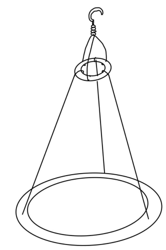
(1) Add levels

"Add levels" suggests higher dimensionalities. We stack multiple platforms in the vertical direction instead of a single platform. These added levels enable more capacities.



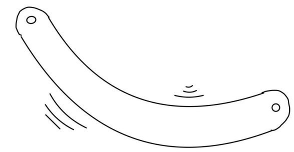
(18) Change direction of access

In current design, the platform is the top mechanism as shown in Figure X. By changing the direction of access, the platform is creatively the bottom mechanism. The diagram shown on the right suggests one possible configuration: the loading platform is at the bottom of the entire device.



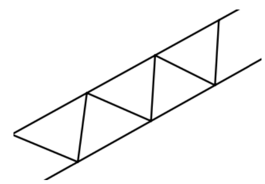
(19) Change flexibility

We interpret flexibility as elasticity. One part that can be elastic in our current design is the linkage. By making it elastic, the linkage is able to reduce small vibrations and deformations caused by the environment.



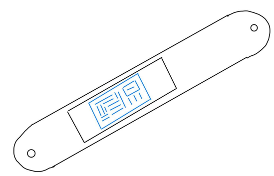
(37) Hollow out

Hollowing out reduces the mass of a component but requires a better design in the structure. To hollow out a linkage, the truss structure would be a good option.



(75) Utilize inner space

Utilizing inner space integrates components of different functions organically. For example, a circuit board can be stored in the linkage where it is hollowed out as shown on the right



6. CONCEPT SELECTION PROCESS

Concept Down Selection for Each Component

The main method we used in the concept selection process was Pugh charts. During down selection, we first created separate Pugh charts for the four components. Each Pugh chart had a different set of criteria, either coming from user requirements or being added additionally as important features or functions to include.

For Mount, we had a total of four concepts (magnet, screw, velcro, and sucker plate) and seven evaluation criteria (secure, universal compatibility, lightweight, easy to set up, low maintenance, durability, and low cost). The first criterion, secure, was not drawn directly from our user requirements. Because the most important feature/functionality of any mounting mechanism is to secure our device on the delivery robot without any vibration, we added it as an additional evaluation criterion for Mount with the highest weight 4. Universal compatibility came from our desired requirement, which was stated specifically for incorporation between the fluid stabilizer and delivery robots, and therefore was assigned with the second highest weight 3. Lightweight is a general property constraining weight of the whole device and thus should apply to all four main components. Since it is a mandatory requirement, but does not target Mount specifically, we assigned it with a weight of 2. All other criteria had a weight of 1, because they are good features to consider in designing Mount, but are all desired requirements and not specifically stated for Mount. During evaluation, we chose magnet as the base design for Mount, and evaluated the other three concepts with respect to it. A score of -1 indicates that the concept being evaluated performs worse than magnet under a specific criterion; a score of 1 indicates that the concept performs better than magnet; a score of 0 indicates that they perform similarly. The final Pugh chart with weights and scoring labeled is shown below in Table 6.1.

Table 6.1. Pugh chart for Mount

	Magnet	**Screw**	**Velcro**	**Sucker Plate**
Secure (4)	0	1	0	0
Universal Compatibility (3)	0	-1	1	1
Lightweight (2)	0	1	1	1
Easy to Set Up (1)	0	0	1	1
Low Maintenance (1)	0	1	-1	-1
Durability (1)	0	1	-1	-1
Low Cost (1)	0	1	1	1
Total	0	6	5	5
Rank	3	1	2	2

According to Table 6.1, screw had the highest score among all four concepts. In particular, screw is the only design that scored 1 under the most weighted criterion Secure because it works best in providing a tight and firm connection between the device and robots. Screw was assigned -1 for universal compatibility because it requires very precise sizing of mounting holes on the robot while the other three concepts generally do not need precise fitting. We could best compensate for this issue through choosing a commonly used size of screw according to ISO 724 Metric Threads standard in order to accommodate more applications [41]. For easy to set up, the screw had a score of 0 because each screw needs to be manually screwed in and we anticipate at least two screws for mounting. The other three concepts generally only need one quick step for setting up. However, since we anticipate that at most four screws will be used to secure our device in place, the screw concept will still meet the easy to set up specification, which is stated as the setup procedure should take less than five steps. For all remaining criteria (lightweight, low maintenance, durability, and low cost), screw was assigned 1. Therefore, screw was our best design concept for Mount.

The same scoring method was applied to both Linkage and Platform with evaluation details explained in Appendix B. Truss was chosen to be the best linkage system, and plate with locks was chosen to be the best platform.

For actuators, we categorized all generated concepts into two groups. The first group, including lubricant, roller and lubricant, spring-damper system, roller and bowl, and 3-DOF magnets, has only passive control to vibrations of the platform, while the second group, including 2-DOF motors, 3-DOF linear servos, and 3-DOF magnets with current, has active control to vibrations of the platform. The same seven criteria (stability, robustness, lightweight, easy to set up, low maintenance, durability, and low cost) were used to evaluate both groups. The first two criteria, stability and robustness, had weights of 6 and 4 respectively because they are the two most important mandatory requirements for our device. Stability was weighted a little higher than robustness since the core design objective was to stabilize liquid during transportation. As explained before, being a mandatory requirement that is applicable to all main components of our device, lightweight was assigned with a weight of 2. All remaining criteria from desired requirements had a weight of 1. Moreover, since actuator is the most important component of the fluid stabilizer, we would like to have more variety in actuator designs in order to ensure that the final selected concept would have both the best individual performance and high compatibility with other components. Therefore, when evaluating actuators with Pugh charts, we chose to keep two high-ranked concepts from each category instead of only selecting the top one design as conducted for all other components. The final completed Pugh charts for actuators with passive and active control are shown below in Table 6.2 and 6.3 respectively.

Table 6.2 Pugh chart for actuators with passive control (Lubricant as base design).

	Lubricant	Roller + Lubricant	Spring-damper	Roller + Bowl	3-DOF Magnet
Stability (6)	0	1	1	1	1
Robustness (4)	0	0	0	0	0
Lightweight (2)	0	-1	0	-1	-1
Easy to Set Up (1)	0	-1	-1	0	-1
Low Maintenance (1)	0	-1	-1	0	0
Durability (1)	0	0	-1	0	0
Low Cost (1)	0	-1	0	-1	-1
Total	0	1	3	3	2
Rank	4	3	1	1	2

Table 6.3 Pugh chart for actuators with active control (2-DOF motors as base design).

	2-DOF motors	3-DOF Linear servos	3-DOF magnets + current
Stability (6)	0	1	0

Robustness (4)	0	0	0
Lightweight (2)	0	-1	1
Easy to Set Up (1)	0	-1	-1
Low Maintenance (1)	0	-1	0
Durability (1)	0	0	1
Low Cost (1)	0	0	1
Total	0	2	3
Rank	3	2	1

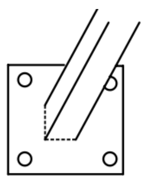
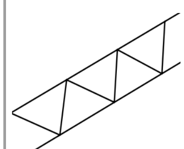
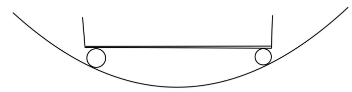
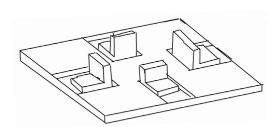
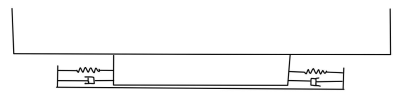
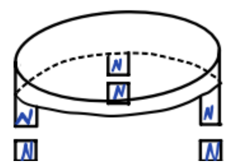
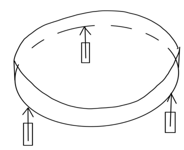
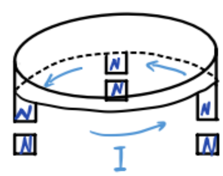
According to Table 6.2, among actuators with passive control only, the spring-damper system and roller and bowl both had the highest score 3, while the 3-DOF magnet had the second highest score 2. In particular, all these three concepts provide better stability as compared to the base design lubricant because we believe that rigid body systems, or at least some integration of rigid bodies, would be more stable than systems relying purely on fluid. The spring-damper system would require more set up and maintenance procedures due to the presence of two separate hardware components, and would have a lower durability because of the change in spring stiffness after long-term operation. The roller and bowl system would weigh more and cost more for production due to the requirement of an additional bowl as a second layer. The 3-DOF magnets would require more set up steps considering the need for setting up 3 separate magnets, and also weigh more and cost more for production.

According to Table 6.3, among actuators with active control, the 3-DOF magnets with current had the highest score 3, while the 3-DOF linear servos had the second highest score 2. Compared to the base design 2-DOF motors, the 3-DOF linear servo system has better stability because of the one more degree of freedom provided. But also due to this additional component, the linear servos would weigh more and require more steps for both setup and maintenance. The 3-DOF magnets with current did not score better than the base design for the stability criterion. Although the magnets provide one more degree of freedom, we considered that motors are generally more stable than electromagnets in response to applied vibrations. But electromagnets would weigh and cost much less than motors. Besides, since electromagnets generally do not have much wear and tear during long-term operations like motors do, the 3-DOF magnets with current system would have a higher durability.

Concept Down Selection for Complete Designs

The concepts selected for each component from the previous section were then combined together into five complete designs, each with the same mount, linkage, and platform but different actuators as shown in Table 6.4 on Pg. 24.

Table 6.4. Five complete designs with sketches for each component.

<table>
<tr><th></th><th>A. Mount</th><th>B. Linkage</th><th>C. Actuator</th><th>D. Platform</th></tr>
<tr><td>Design 1</td><td rowspan="5">Screw
</td><td rowspan="5">Truss
</td><td>Roller Bowl
</td><td rowspan="5">Plate with Locks
</td></tr>
<tr><td>Design 2</td><td>Spring-damper
</td></tr>
<tr><td>Design 3</td><td>3-DOF Magnets
</td></tr>
<tr><td>Design 4</td><td>3-DOF Linear Servos
</td></tr>
<tr><td>Design 5</td><td>3-DOF Magnets + Current
</td></tr>
</table>

The five designs were categorized into passive and active controls and evaluated using a Pugh chart. Since this was the last down selection process to our final alpha design, we selected all of the mandatory requirements as evaluation criteria with weights labeled according to their order of importance. The completed Pugh chart is shown in Table 6.5 below with best designs from each group highlighted in yellow.

Table 6.5 Pugh chart for five complete designs

	Passive Control			**Active Control**	
	Design 1	**Design 2**	**Design 3**	**Design 4**	**Design 5**
Stability (3)	0	0	0	1	1
Controllability (3)	0	0	-1	1	-1
Robustness (2)	0	1	0	0	0
Scalability (2)	0	1	1	1	1
Capacity (1)	0	1	1	1	1

Lightweight (1)	0	0	0	-1	0
Total	0	5	0	8	3

According to Table 6.5, Design 1, the roller bowl system, was chosen as the base design. This design has better controllability than the two magnet systems(Design 2 and 5) because it is purely mechanical, and weighs much less than linear servos(Design 4). However, this design has a significant disadvantage in scalability and capacity due to its lack of compatibility with the chosen platform plate with locks. For scalability, the curvature of the bowl will largely restrict the size of the plate which has a flat surface. For capacity, since the weight of both platform and container would be supported by rollers directly and the stabilization would also be achieved purely through the motion of rollers inside the bowl, containers with more weight would cause significantly more wear and tear to rollers and therefore decrease the device's durability.

Design 2, the spring-damper system, scored highest among all designs with passive control. Compared to base design, the spring-damper system provides better robustness because of its ability to filter out very small vibrations, better scalability because it does not require a second layer outside of the platform, and better capacity because the weight of platform and container will not be directly supported by springs.

Design 4, the 3-DOF linear servo system, scored highest among all designs with active control. Compared to the roller bowl system, this design has better stability and controllability due to the more degrees of freedom it provides which would allow more subtle and accurate adjustments. Design 4 also has better scalability and capacity compared to the base design due to the same reasons explained above for Design 2. The only disadvantage of Design 4 is that linear servos, especially three of them, would weigh much more than other systems.

Concept Refinement with Design Heuristics

After obtaining complete designs, we applied the five design heuristics selected during the concept generation process to add more features or side functions to the final design.

The first design heuristic applied was Add Levels. We decided to combine Design 2 and 4 (highest-scoring concepts for passive and active control) together in order to achieve a two-level actuator which would provide both passive and active control. Besides, according to evaluation in Table 9 on Pg. 22, Design 4 will provide better stability and controllability, while Design 2 will provide better robustness, satisfying the three most important criteria from mandatory requirements.

The second design heuristic applied was Change Direction of Access. Previously during concept generation, we had an idea of allowing placement of containers from bottom up into the platform instead of from the traditional up down direction. However, considering the specific application of containers with liquid food in our case, the bottom up direction of access would be actually less convenient and less safe for users when placing containers. Therefore, we abandoned this idea.

The third design heuristic applied was Change Flexibility. During concept generation, we considered making linkages from more flexible materials that would allow deformation during operation. However, this extra flexibility would decrease the linkage strength. Since linkage needs to support the main weight of our device, a weaker linkage system would have lower durability under long-term operations. Therefore, we did not adopt this idea either.

The fourth design heuristic selected was Hollow Out. Through implementing this design heuristic, we expect to reduce the weight of our device and better satisfy the mandatory requirement "Lightweight". This design heuristic was already applied in our linkage system with the final concept chosen to be Truss. We would also consider making hollow platforms if allowed in later stages to further lower the weight.

The last design heuristic selected was Utilize Inner Space. For implementing this design heuristic, we would create pre-reserved slots inside the linkage system or under the platform for storage of our circuit boards.

Comparison with Initial Solution Concept

When we were first assigned with this project, we envisioned a preliminary design similar to the gimbal used for cameras but with the addition of a cup for liquid storage. As explained previously in the Benchmarking section, gimbals are a very successful and widely-used stabilization system due to its ability in counteracting unwanted rotational movements and ensuring pure translational motion of cameras with respect to the ground. Therefore, we decided to learn from the merit of precedents and kept the idea of a gimbal-like actuator from our initial solution concept. In our current design, the active control provided by the 3-DOF linear servo system will adjust the plate to make the bottom of the container remain stationary relative to the liquid surface, which would effectively prevent spills during transportation.

On the other hand, our current design also made many improvements from the initial concept. For the platform, we now use a set of four movable locks for securing containers which would accommodate more different container sizes and shapes, and a big flat plate to increase contact area and provide more reliable support. For the actuator, we added an additional spring-damper system to deal with small amplitude, high frequency vibrations specifically.

7. SELECTED CONCEPT DESCRIPTION (ALPHA DESIGN)

After completing down selection for the completed designs, we determined Design 2 (passive) and Design 4 (active) to be the best two. Based on the results, we decided to take advantage of two designs, where the passive control system provides better robustness, while the active control system provides better stability and controllability, and then combined these two designs together to build a 3-DOF linear-servo-spring-damper system for our alpha design.

Description of Selected Concept

As we mentioned before, we break the whole product design into four components, including mount, linkage, actuator and platform, and the abstract drawing is shown below in Figure to better illustrate our design.

First, let's introduce the mount design: "Screw", whose CAD design is shown below.

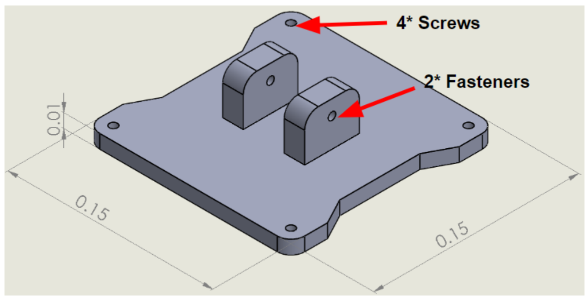


Figure 7.1. Mount component: "Screw". Some significant dimensions are shown in the figure, and the unit is meter (m). "Screw" is a square shape with 0.15 ✕ 0.15 ✕ 0.01 m dimensions.

The base of our alpha design would be mounted onto a delivery robot by 4 screws, and it would be connected to the linkage component (two links) by 2 fasteners. The fasteners should be tight enough to provide friction force to prevent the linkage from easily rotating. The design we choose for linkage to be truss-shape, which is shown below.

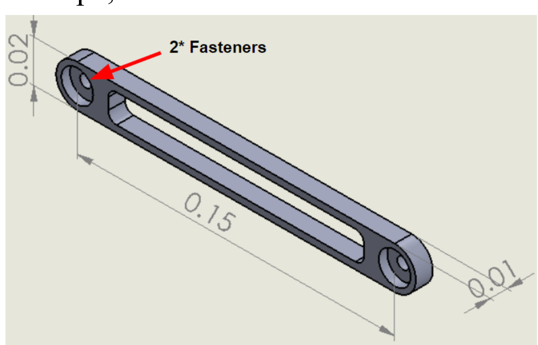


Figure 7.2. Linkage component: "Truss". The "Truss" design is a straight slot shape with a hollow part in the middle. The dimension of "Truss" is 0.15 ✕ 0.02 ✕ 0.01 m.

The linkage component connects the mount component with the actuator component, and the linkage component consists of two parallel "Trusses" to better keep the actuator and platform components balanced. Next, moving to our essential component: actuator. As we mentioned at the beginning of this section, the actuator component would consist of passive control (spring-damper) and active control (linear servo). Since the actuator component involves mechanical both and mechatronic design, and the mechatronic design, particularly, the control algorithm design could be really tough, the design we show here may need to be changed with the project developing. The first draft CAD design of the actuator is shown below.

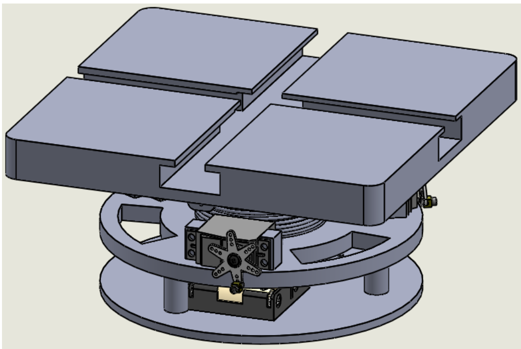


Figure 7.3(a). The trimetric view of the actuator component.

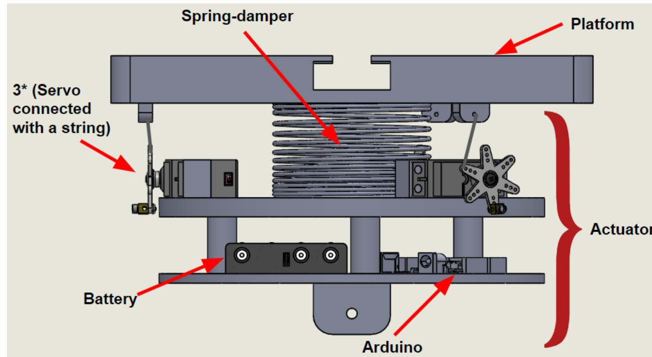


Figure 7.3(b). The front view of the actuator component with a label of each subcomponent.

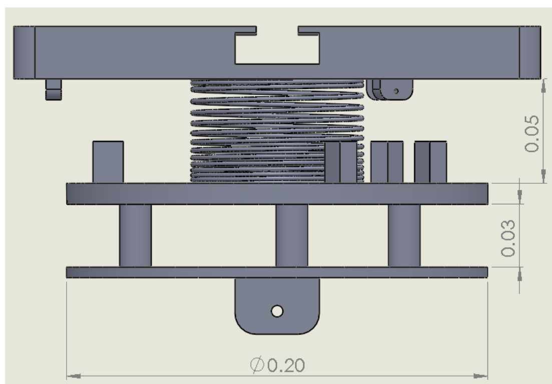


Figure 7.3(c). The main design component of actuator with dimensions indicated on the drawing in unit (m).

The actuator component has two layers, which could be clearly seen from Figure 7.3(b). The distance between the first layer and second layer is 0.03m, and we use this space to put our control system including Arduino, sensors (accelerometer and gyroscope) and power supply. Between the second layer and the platform, we have a 0.08m diameter spring placed in the center to be the main component of our passive control system as well as the support; the space between two layers is 0.05m. Three servos are placed 120 degree apart around the second layer, and each of them is connected with the platform on the top by a string. The concept behind this actuator design is that we want to control the servos to pull the platform through the string so that the platform can form the desired incline angle, which prevents the liquid from spilling out from the container. The three hollow slots on the second layer allow the wires coming out from the servo to pass through and be connected to Arduino. Finally, we want to introduce our last component: platform. After doing the down selection, we decided to use "Plate with Locks" as our final design for the platform, whose CAD drawing is shown below.

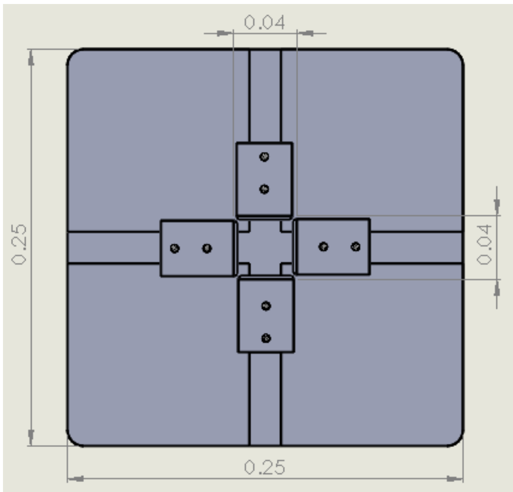


Figure 7.4(a). The top view of the platform when the sliders are in the closest position of each other. Some significant dimensions are shown in the graph.

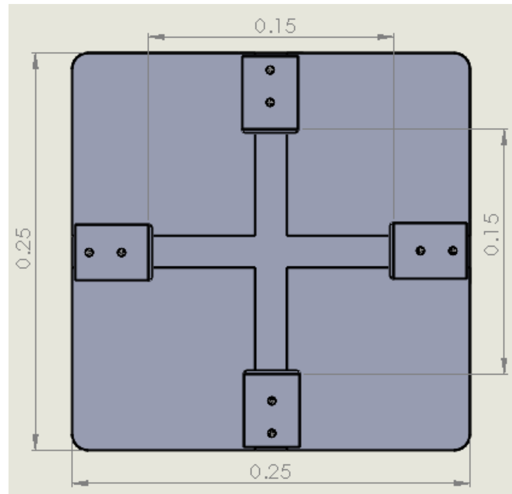


Figure 7.4(b). The top view of the platform when the sliders are in the furthest position of each other. Some significant dimensions are shown in the graph.

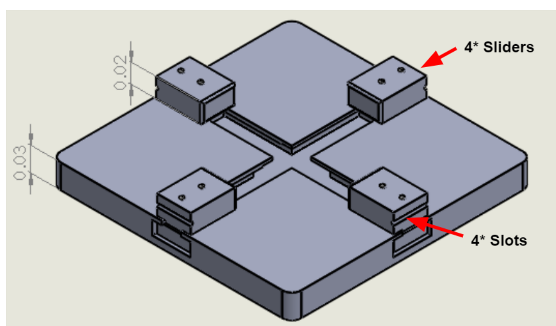


Figure 7.4(c). The isometric view of the platform. The overall dimensions of the platform is 0.25 ✕ 0.25 ✕ 0.03 m.

The design of our platform is square shape with four sliders constraining within cross slots. The slider can be separated into two parts: top and bottom, and we use screws to connect these two pieces. When installing each slider onto the platform, we need to place both pieces of the slider onto the slot and use two screws to tighten them in, but at this point, each slider should be free to move along the slot. After placing a container on the platform, we should move the sliders to the position where the container is constrained in the center of the platform, and then we tighten the screws in until the sliders are locked due to the friction force. Additionally, for our lock design, we have a backup plan to have a secondary constraining mechanism by using a belt or a rubber band. Illustrated by Figure 7.4(c) on Pg. 28, there is a slot on each slider, and by placing a belt or a rubber band, we can also pull four sliders to come together and constrain the container.

Finally, we assemble each component together to form our alpha design, whose CAD model is shown below.

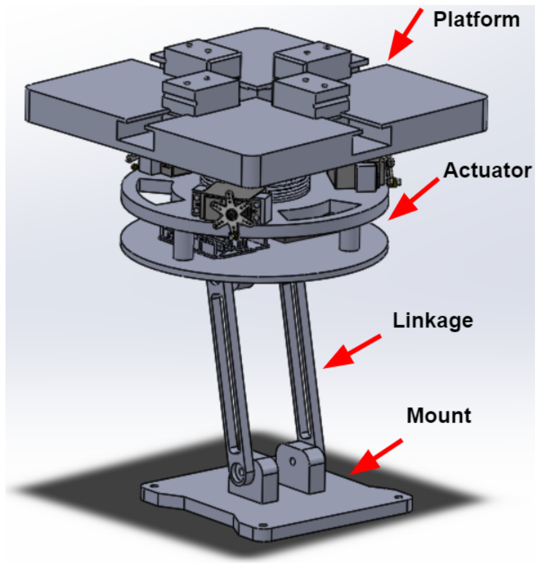


Figure 7.5. The CAD model of Alpha design.

8. ENGINEERING ANALYSIS

Regarding the specifications we added and updated, the engineering fundamentals need to be addressed on another level for the increased complexity. This section will address the engineering analysis and assessment plan for individual specifications we identified in the previous sections.

Stability

One basic requirement is the overall stability of this device. We want the stabilizer to be able to stabilize the water cup with an input of an acceleration of 1 m/s^2 under the condition that the input has a frequency no larger than 1 Hz. This specification is related to the frequency response of the physical system. The most effective way to model this system is to employ ordinary differential equations and design a PID controller to counteract the disturbing dynamics. A schematic of the linear servo motor is shown in Figure 8.1 on Pg. 31 and a first-order linear ODE of the actuator correlating the output angular velocity and input voltage is modeled below in Eq 8.1 on Pg. 31:

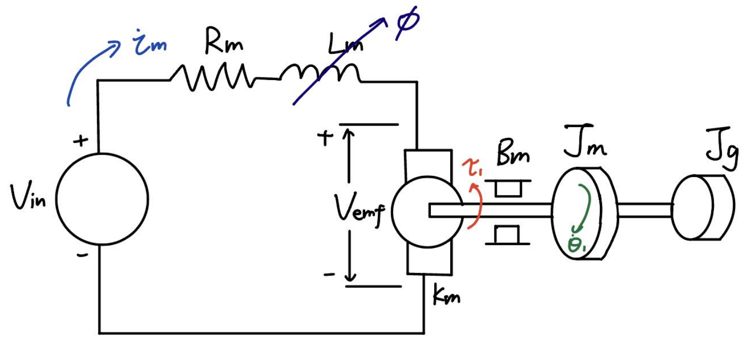


Figure 8.1. A linear servo motor circuit schematic. In this model, the inductance is neglected and all motor-related constants can be found in specification sheets ideally.

$$\frac{\dot{\Theta}_1(s)}{V_{in}(s)} = \frac{K_m}{[R_m(J_m + J_g)]s + (R_m B_m + {K_m}^2)} \tag{8.1}$$

Stability can be assessed using MatLab simulation programs with various input signals. Physical tests will be conducted if time and budget allow.

First and foremost of the system analysis, since we are dealing with liquid phase objects here, one top priority is to analyze fluid motion and surface behaviors. Through hydrostatics and unit tensor analysis, we were able to determine the mathematical expression of the fluid surface and the inclination angle with respect to the horizontal surface. Detailed assumptions and calculations can be found in Appendix C.

In order to counteract the fluid motion, a linkage kinematic motion is required to balance the container. The geometry of the linkages is fairly simple, we define the initial configuration as the lower linkage arm forming an angle of 45 degrees with respect to the lower platform. Because of the geometric constraint of the ball-and-socket joint that attaches the upper platform to the linkage, the maximum angle of rotation is 20 degrees. For conservative consideration, we define the extreme configuration as one linkage is 30 degrees with respect to the lower platform while the other two is 60 degrees with respect to the lower platform, 15 degrees of rotation will not risk reaching the physical limit of the ball-and-socket joint and provide a good enough range of motion. Geometry schematics are shown below in Figure 8.2.

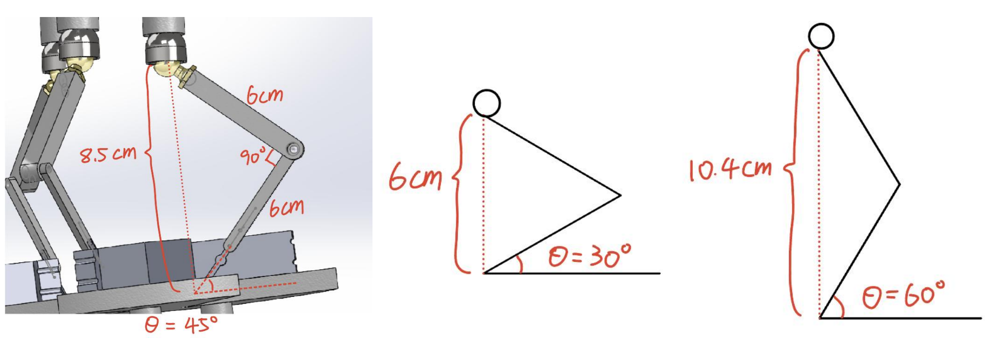


Figure 8.2. Schematic of robotic arm manipulation angles.

To perform such a motion from initial configuration to the extreme configuration, it requires a torque of 0.05 Nm in magnitude. We experimentally acquired the torque-speed curve of the motor we purchased, shown in Figure 8.3 under the assumption of a metal brush motor, 0.05 N-m is close to the stall torque 0.06 Nm and the angular velocity will be around 16 degrees per second at this working condition.

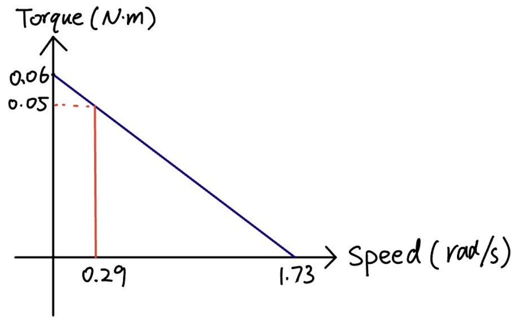


Figure 8.3. Torque-speed curve of FS5106B servo motor.

Considering the range of motion is 15 degrees, this motor provides a fair performance regarding the mechanical requirements of our application. From Figure 11, we can observe that reaching the extreme configuration will give us a maximum achievable vertical displacement of 4.4 cm around the center of the upper platform. From the fluid mechanics model we derived in Appendix C, for our specification of $1m/s^2$ and input frequency of 1Hz, the inclination angle will be around 6 degrees. Considering common fluid containers whose diameters range from 4cm to 20cm, this vertical displacement of 4.4 cm turns out to be more than enough for our specifications.

The primary reason our team chose to analyze the system dynamics in this approach is that breaking down the system into components allows us to tackle each subsystem using specific engineering knowledge and bring down the difficulty. Many assumptions were made in order to simplify the analysis, such as constant acceleration, ideal metal brush motor, negligible inductance, and symmetric linkage motion. These assumptions do somehow impact the prediction accuracy, so we considered an extra safety factor during analysis. The results show the servo motors on our list were all capable of handling such motions.

Robustness

Similar to stability, robustness requirement is also defined using frequency regime terms. We want the device to be able to stabilize the vibration amplitude to $0.01 m/s^2$ if the input frequency is within the range of 1Hz and 10Hz. If the input frequency is beyond 10Hz, the device should ignore the input signal. Basically, we want to design the device in a way that it is sensitive to low frequency inputs and filters out high frequency inputs. This frequency filter design is also related to the frequency response of the physical system. We propose using loop shaping design principles for adjusting controller performance. Robustness specifications can also be assessed using MatLab simulink and simscape.

The engineering analysis of the robustness specification is similar to the one of stability we discussed in the previous subsection. For input of higher frequency and lower magnitude, standard scaling techniques are appropriate to use. All analyses are similar, now if the input frequency is of 10Hz, the maximum achievable vertical displacement is 0.44 cm. The specified amplitude is now 100 times smaller than the value from stability specification, 0.44 cm also meets our need for the given condition described in the robustness statement. All assumptions and risk management strategies were inherited from the stability subsection.

Controllability

One additional requirement we added is the controllability. Controllability issues need to be investigated using the state-space model of linear system theory and analytical solutions are desired for further algorithm development. There is no specific quantity related to this requirement, it is rather a feasibility proof from the fundamental mathematical aspect. Control principles and algorithms need to be implemented properly to achieve the desired specifications. The motion range should be specified using fluid mechanics modeling and sensor data collection. Essentially, the controllability is justified by proving or finding the following statements.

Need to find: Given acceleration, the liquid surface equation is required.

Lemma 1. For any three vertical prismatic motions that have the same distance to the z-axis and are equally spaced, the rigid body can have pure rotation in the space. That is,

$$span(v_1\hat{k}, v_2\hat{k}, v_3\hat{k}) \subset SO(3)$$

Lemma 2: the state space model of the stabilizer's dynamics is time-invariant.

Lemma 3: the controllability matrix of the stabilizer's state space model is of full rank.

While the theoretical model is being set up using robotic kinematics theorems, we need to consider situations where the controllability matrix can not be obtained for our device. We have discussed the range of motion of the linkage arms, because of the physical constraints of the ball-and-socket joints, the maximum rotation range for a single linkage arm is ±15 degrees. That makes the range of motion within [30, 60] degrees. The identified singularity for a two-bar linkage arm is at its vertical configuration which is 90 degrees. It is unlikely that the three linkages will reach singular configuration at the same time if the control law is well implemented. If one linkage reaches singular configuration and its end-effector loses ability to perform instantaneous motion, the entire mechanism will still remain stable and function normally because the other two linkages will be dominating motion control. As for the time for the singular configuration to recover, that will take at most a few seconds if the torque is reversely applied. Hereby, extreme cases have been proved. See Appendix C for the proof of the general case. To sum up, the possibility for the system to be unstable and uncontrollable is extremely low and in case of controllability matrix dropping rank resulting from one linkage reaching singularity, the mobility of the system is not greatly impaired.

Lightweight
Another important requirement is lightweight. According to our expectation, the overall weight of this device should not exceed 1.15kg. This specification is heavily dependent on the material selection and manufacturing processes. Some adjustments can be made to the components in order to further reduce mass such as making some parts hollow inside. Assessment of this specification can be done using mass simulation in SolidWorks with material properties inputted properly.

The overall weight of this device can be investigated and calculated using densities and volumes of individual components. The mathematical expression is described in Eq 8.2 below:

$$M_{total} = \sum_{k=1}^{n} m_k = \sum_{k=1}^{n} p_k \cdot V_k \leq M_{spec} \tag{8.2}$$

The reason we used SolidWorks built-in functions to measure the overall mass of the device is that we can easily identify the material and the software would apply specific material properties in order to get an accurate estimation of the weight. The error percentage is significantly small. This approach did assume even distribution of material, which was also quite close to the real scenario. 3D printing components might be a little off of that assumption but the tolerance was negligible.

Capacity
Capacity is defined as the device should be able to support a load within 1 kg. To actually accomplish desired capacity, we would need to apply Statics and Mechanics of Materials principles to investigate the yield strength and some other material parameters and choose materials properly based off of the calculations. A safety factor needs to be applied for extreme usage considerations. After prototype building is finished, we can also conduct physical experiments to test its capacity.

In an ideal scenario, we would like to conduct a thorough finite element analysis on the build design and investigate the stress concentration from numerical simulated results. However, our team has attempted to employ several softwares such as SolidWorks and Ansys but none of them could yield a satisfying result for our analysis. We later figured out that the reason that the solver could not produce a fine simulation, that is due to the complex structure of our device, actually hiked the difficulty of meshing. A not particularly fine meshing is shown below in Figure 8.4, this meshing is relatively coarse while the solver cannot possibly produce a solution.

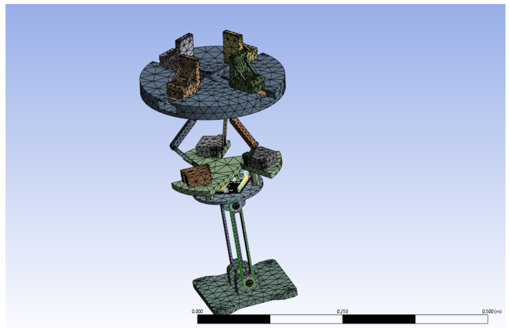


Figure 8.4. Meshing result of the device from Ansys Workbench.

The complexity of the entire system and under-constrained structure sentenced the end of FEA on the entire system. On the other hand, if we break down the system into discrete components and conduct FEA on them, it is possible to obtain some valuable information. However, breaking down into components and hypermesh them individually brings down the complexity of numerical solver while making the initial loading/support conditions unbelievably strenuous to figure out. It is obvious that small deviations on the initial or boundary conditions can greatly compromise the accuracy of FEA and the simulated results may not be precise enough for our engineering analysis. Needless to mention this will be a significantly time consuming task for Ansys beginners, the results without supervision of simulation experts may also be of little value to our analysis. Therefore, our team has decided to investigate the stress concentration on individual components using traditional mechanics of material principles. One particularly fragile component we were paying special attention to was the bolt that connects the motor output shaft and the lower linkage arm; the diameter of this bolt was relatively thin which drew our attention in the first place. We applied standard shear stress analysis on this bolt, the schematic of the structure and the governing equation Eq 8.3 are shown below:

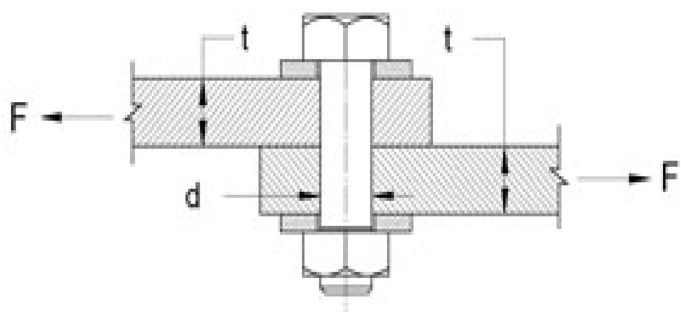


Figure 8.5. Schematic of bolt undergoing shear stress.[42]

$$\tau_{shear} = \frac{4F_{ext}}{\pi D^2} \cdot \frac{1}{SF} \qquad (8.3)[42]$$

After running calculations, we have found that the maximum shear stress on the bolt was 12.73 MPa if we load a 1 kg liquid container on the upper platform per the capacity specification.

Stress of this magnitude is far below the yield strength of common engineering material of any sort. Metals or alloys usually have a yield strength of at least 200 MPa. Therefore, the safety factor in this occasion is on the order of 10^1. Also, to address the potential yield problems within the platform and linkages, we further investigated the material properties of SLA. It is a material specifically designated for 3D printing, therefore its properties are heavily associated with the manufacturing parameters, filament density and other things can greatly affect the final product. After browsing through various sources, the tensile strength of SLA is usually around 55MPa, which we also verified to be sufficient for our device. Therefore, we were able to conclude that this structure can withstand 1 kg of load on the vertical direction without any concern.

One concern of using solid mechanics to estimate the capacity is that the loading situation was oversimplified, we assumed the container can be simulated as a point load on the center of the platform, whereas a distributed load would have been more accurate. Therefore, we added a safety factor for the shear stress in order to compensate for the uncertainty. The safety factor turned out to be larger than 10^1, therefore no potential failure mode was introduced.

Scalability

The last mandatory requirement we requested is scalability. The device is supposed to hold cylindrical-shaped objects with a diameter varying from 8 cm to 20 cm. We have considered this specification during the design ideation phase and settled with the “Plate with Locks” platform in order to meet this specification. Seen by Figure 8(a) and (b) on Pg. 28, the platform can hold containers with diameters ranging from 4 cm to 15 cm. Testing can be done using simple geometric derivations. Physical experiments will be conducted if time permits.

The engineering analysis of scalability is mainly associated with the platform design. We have determined to use the “Plate with locks” design from earlier phases, therefore, we will need to carefully implement the locks in order for it to be adjustable for specified size. Using simple geometry, our team decided to move along with the platform design shown in Figure 15. The platform has four locks that are center symmetric and the stroke is 20cm. Theoretically, this design allows the platform to constrain cylindrical containers whose diameter range from 4cm to 20cm. This range exceeds our initially specified values which means more flexibility for users. To account for non-cylindrical containers such as beer pong cups, some gaskets can be inserted between the surfaces to increase friction. If no gasket was available, the rubber bank was still able to provide enough force to constrain the containers. Slight deformation of the container surface will not impact the scalability and other performance metrics of this device.

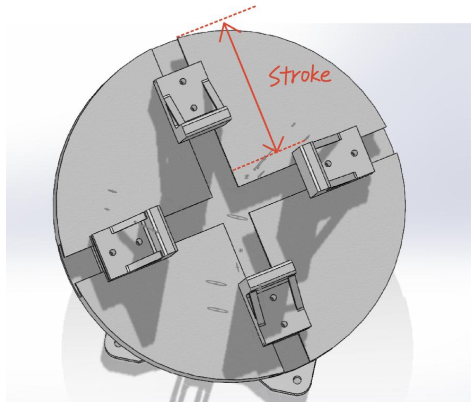


Figure 8.6. Top view of the platform showing the locking mechanism stroke.

Justification for this method is very straightforward, assessing the dimensions physically was the most effective approach. And the dimension of 8 cm to 20 cm was determined after doing rigorous research on beverage containers that are currently on the market.

Low-cost

About the desired requirements, what comes first is the low-cost requirement. The total cost of this device should not exceed $400 in our expectation. The budget control interferes with every design choice and therefore the general performance of the device. We aim to use common products with satisfying performance in the market in order to use as little money as possible.

We have browsed a variety of sources to thoroughly investigate the underlying principles of mass production expenditures and budget control. We first estimated engineering project team manpower cost, assuming the average wage of an mechanical engineer intern is $20 per hour[43]. The overall time the team spent on the project is 8 hours per week for 15 weeks which makes it 120 hours. A team of four means the manpower cost for the project is $9600. Since we employed the 3D printing process in manufacturing, the cost will be $1.24 per hour times 100 hours for our estimated period of occupation. With $400 in material purchase, the total cost of the prototype reaches $10124. It is relatively tricky to find an optimal ratio from prototype to mass production, our team discussed and decided the ratio to be 50 which is the median value of given range[44]. Therefore, the estimated cost of this particular product is about $200, formula is shown in Eq 8.4.

$$Cost = (Engineer\ Wages + Manufacturing + Material) \div Mass\ Production\ Ratio \qquad (8.4)$$

To qualify for our requirement as “low-cost”, we browsed products with similar functions on various e-commerce websites, and found this type of product is usually priced at $280[45]. Thus, with the $100 difference, we conclude that the device meets our specification of being low-cost after mass production.

Easy to use and Easy to set up

The user-related requirements we have are easy to use and easy to set up. It is desired to have both the installation procedure to be under 5 minutes and the unloading/loading process controlled under 5 seconds. Testing of these specifications are relatively straightforward, we can have teammates or other people physically performing the installation and loading process while timing the period of operation. However, ease of verification does not necessarily mean the design itself is easy. To successfully design a system that can be implemented and operated in very few steps requires outstanding mechanical system design assembly knowledge and great precision. Considering the time constraint, the most promising approach is to borrow mechanical system design examples from ME250 and ME350 contexts and make modifications accordingly.

Universal compatibility

We also want the device to have universal compatibility such that it can be easily mounted onto rigid structures with no more than 4 components. During the design down selection process, we have used a Pugh chart to select the most promising mounting mechanism and screws stood out. Among the various choices, screw mount is the one we are most familiar and easiest to conduct analysis to. These specifications can also be verified through the exemplary installation process.

Durability

It is also desirable for this device to have good durability. We specified that this device should be able to function normally for 2,500 hours without maintenance. This specification is associated with many aspects, material properties, electronic component life and assembly reliability are all needed to be factored in the durability analysis. After discussion, we determined that the weakest link in this entire ecosystem is the material. Therefore, we would like to test the durability of the device from the material properties standpoint. Some crucial properties we deemed to be tested are fatigue resistance, support stiffness, stress concentration FEA and anti-corrosion performance.

Of all the material testings, we found that fatigue is of the most importance since the motion of linkage arms is cyclic which induces material fatigue, while other material properties are not as crucial. Similar to the capacity analysis, the bolt that connects the motor output shaft and lower linkage arm is the component we are concerned with. Because compression stress is the dominant type in our application, Goodman's Law approximation is not conservative. Instead, we simply use Eq 8.5[42] and Basquin's Law shown in Eq 8.6[42] on Pg. 38 to compute the lifespan; this assumption was considered to be quite accurate because no tensile stress would be introduced to the components whatsoever.

$$\sigma_a = \sigma_{ar} \tag{8.5}$$

$$\sigma_{ar}(N_f)^b = C_1 \tag{8.6}$$

The calculated stress amplitude, as we discussed earlier in the engineering analysis of capacity requirement, is 12.73MPa which is below the endurance limit of common engineering materials, the lifespan of this component under this cyclic loading condition is on the order of 10^{10} which is far above 2,400 hrs we specified earlier.

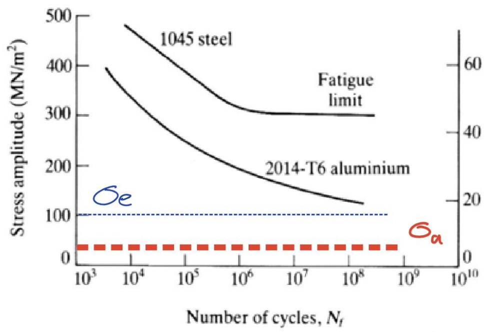


Figure 8.7. S-N curve of the bolt under compressive stress.

Low maintenance
Last but not least, for a relatively small device that is incorporated into another robotic system, low maintenance is a strongly desired requirement. The device should have at least three replaceable components and the process of replacing any of the parts should be less than 5 steps. The values we listed are similar to ones from other desired requirements. The idea behind the specifications is that a person without a significant mechanical engineering background can easily understand the process and maintain the device. For the assessment, we would like to invite someone from a different background to perform the maintenance and evaluate its difficulty.

To sum up, we need to apply knowledge from various fields including solid mechanics, mechanics of materials, fluid mechanics, mechatronic system design, and control system theory to help making specific decisions toward the final design and assessing whether the device meets the listed specifications or not.

9. BUILD DESIGN/ FINAL DESIGN DESCRIPTION

Our build design is similar to our alpha design shown previously, which consistently includes four components: mount, linkage, actuator and platform; however, after carefully discussing as a group, we decided to make our build design (prototype) be a little different from our alpha design indicated. We mainly changed the actuator design from using string to control the incline angle of the platform to using a linkage system to control the platform. The CAD model of the alpha design and the build design is shown below for comparison.

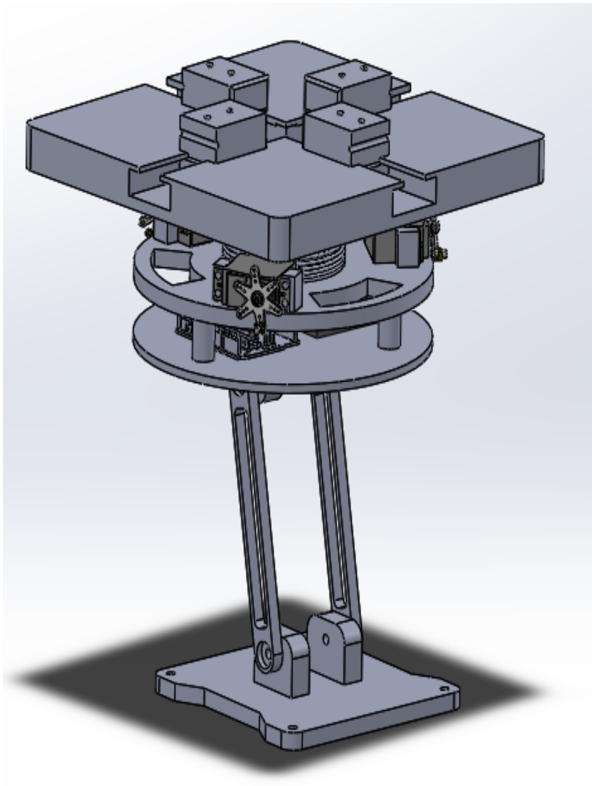


Figure 9.1(a). Alpha design

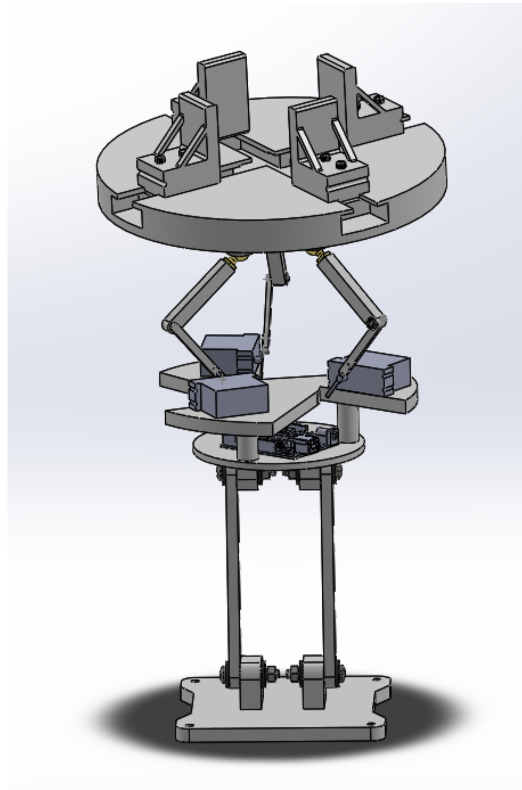


Figure 9.1(b). Build design

One biggest reason why we chose the linkage system to replace the string mechanism is that the linkage system allows us to control the tilting angle of the platform easier and more precisely than the string mechanism. Since we can treat the links as rigid bodies, we can apply rigid body kinematics to predict the state of the platform with respect to the turn angles of the servo motors and build a mathematical model based on it. We will discuss the math model in detail in Appendix C.

Detailed Build Solution

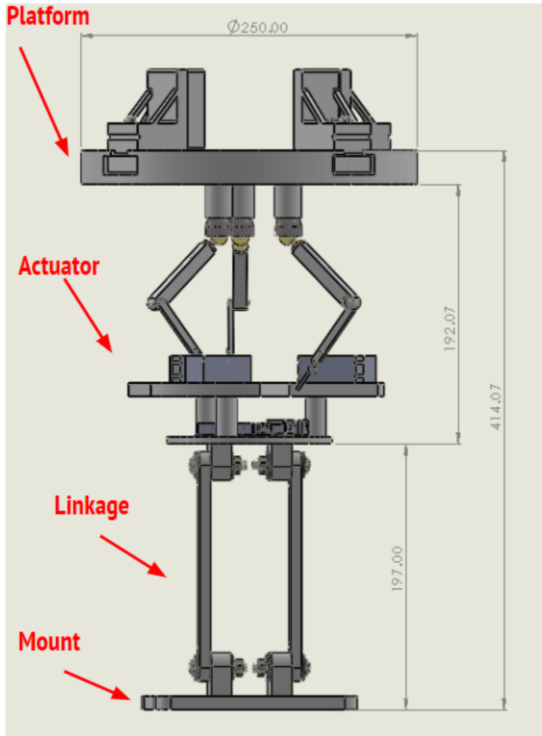


Figure 9.2. The engineering drawing of the build design with dimensions (m).

I. Mount

The mount of the build design would be the same as the alpha design's, and the CAD model borrowed from the previous section will be shown below again.

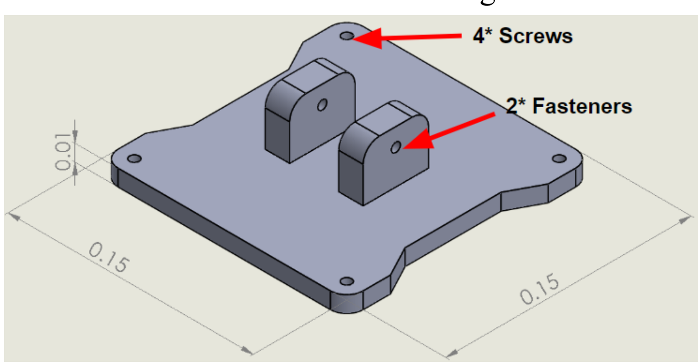


Figure 9.3. Mount component: "Screw". Some significant dimensions are shown in the figure, and the unit is meter (m). "Screw" is a square shape with 0.15 ✕ 0.15 ✕ 0.01 m dimensions.

The reason why we chose these dimensions is because of our requirement for "scalability", which can be seen in the Mandatory Requirements section. In order to mount our prototype onto a testing bench (a programmable toy car with 0.254*0.178 m dimension), a 0.15*0.15 m mount is reasonable.

II. Linkage

The link's build design will be also the same as the alpha design, whose CAD model is shown below.

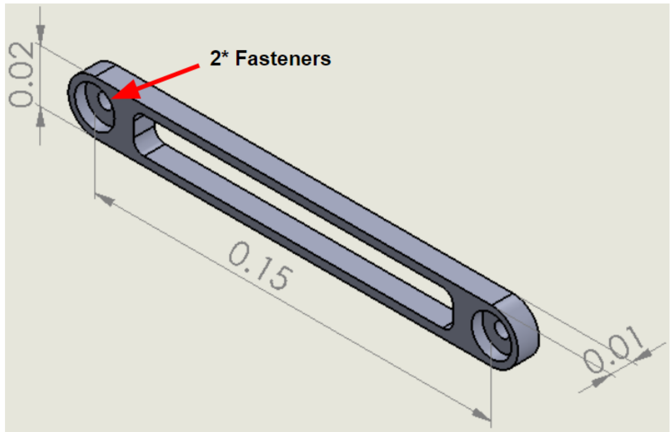


Figure 9.4. Linkage component: "Truss". The "Truss" design is a straight slot shape with a hollow part in the middle. The dimension of "Truss" is 0.15 ✕ 0.02 ✕ 0.01 m.

The dimensions of the link come from the analysis on the dimension of the mount. Since the radius of our mount is 0.075 m, we determine the link's length to be 0.15 m, which is twice longer than 0.075m, so that even in the extreme case: the mount is parallel to the link, our system can still work, which can be shown below.

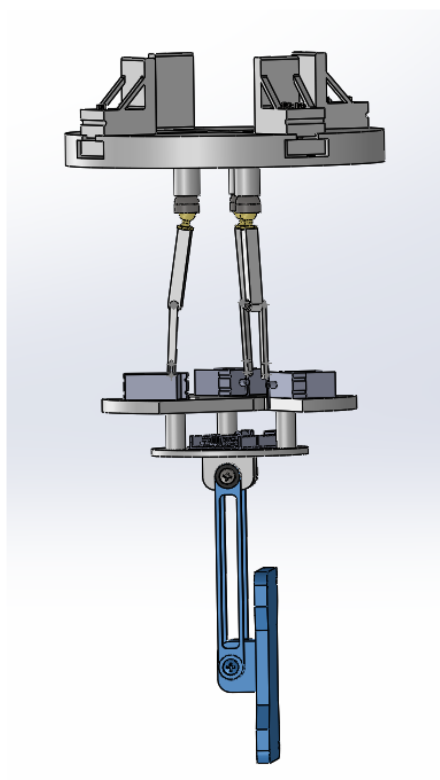


Figure 9.5. The extreme case while the linkage is parallel to the mount.

Two fasteners are used to connect the linkage component to the mount component, whose CAD model is shown below.

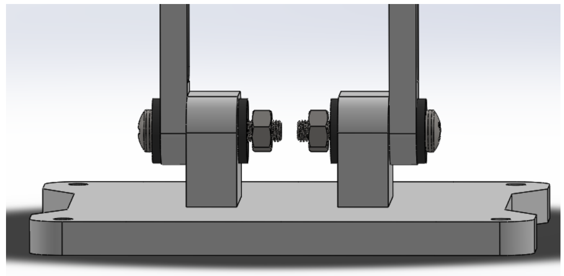


Figure 9.6. The connection mechanism between linkage and mount.

We use two pairs of screws, nuts and rubber washers combination to not only connect two components together but also to constrain the rotation between them by applying enough friction force. The same connection method is used for connecting the actuator and linkage as well, which is shown below.

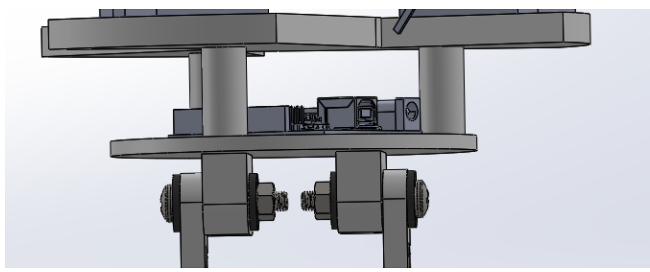


Figure 9.7. The connection mechanism between linkage and actuator.

III. Actuator

The overview CAD model of actuator component is shown below.

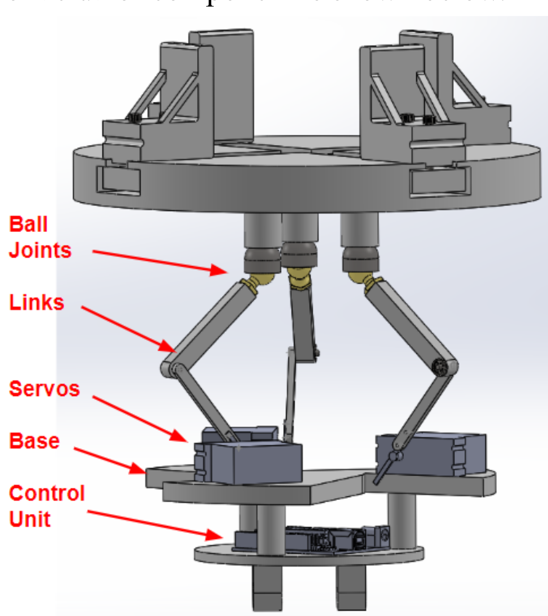


Figure 9.8. The CAD model of the actuator component.

The build design of the actuator component consists of five parts, which are indicated in Figure 24. The base part has two layers, where the bottom layer is used to hold the control unit, and the top layer is used to hold the servo motors. The engineering drawing of the base is shown below.

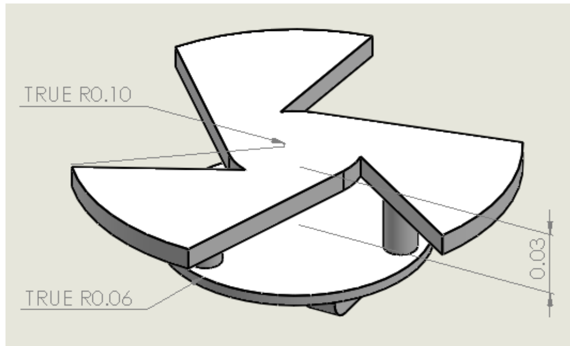


Figure 9.9. The engineering drawing of the base with dimensions (m).

The purpose of making a fan shape top layer is to save some material and allow wires to easily reach the bottom layer and be connected to Arduino; the dimensions are determined based on the functions of the actuator. For example, we designed a 0.03 m spacing between two layers and 0.06 m radius of the bottom layer because we need to place an Arduino Mega in between and also save some space in case we need to use a battery as an extra power supply. The designed 0.1 m radius of the top layer comes from the size of our servos (0.040*0.042*0.02 m).
The next part is the servos. We choose to purchase three identical servos to control the position of the platform, whose CAD model provided by the company is shown below.

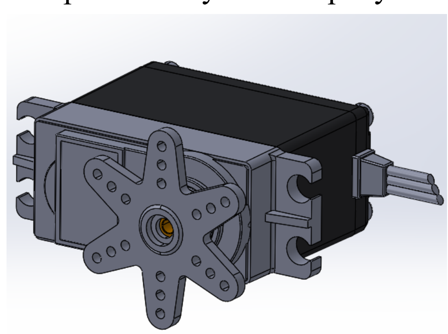


Figure 9.10. The CAD model of the servo.

Each servo is connected to a two-linkage system, and the two links' engineering drawings are shown on Pg. 45.

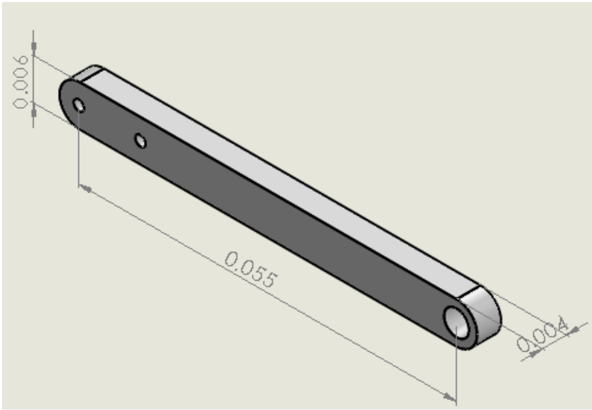


Figure 9.11(a). The drawing of the thinner link with dimensions.

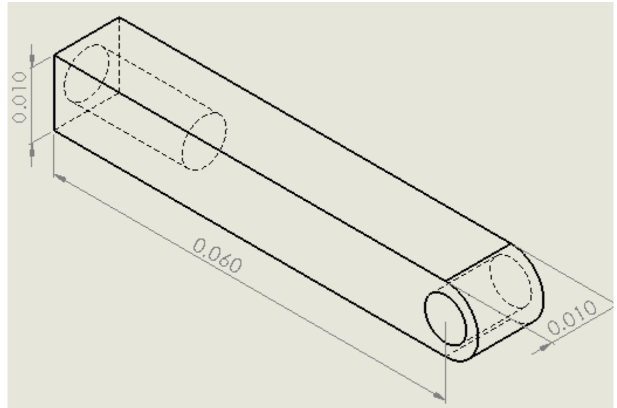


Figure 9.11(b). The transparent drawing of the thicker link with dimensions to better show how the link connects with the ball joint.

For the links' length determination, we basically consider the extreme case of the platform tilting angle. The designed maximum tilting angle of the platform with respect to the horizontal plane is 45 degrees. By doing a linkage geometric analysis, where the detailed derivation will be shown in the Engineering Analysis section, we calculated the maximum tilting angle we can achieve according to the current linkage combination is 55 degrees, which is more than we need. For the links' thickness determination, we make the thinner link be 0.004 m and the thicker link be 0.010 m respectively. There aren't many thickness requirements on the thinner link as long as it satisfies the strength requirement. Since we use SLA as the material to do 3D-print, 0.004 m thickness would provide enough strength to support 2 kg mass (structure mass and liquid food mass). For the thicker link, we make it be 0.010*0.010 m because its end needs to connect with a ball joint whose diameter is 6.8 mm, and one side of the ball joint will be inserted into the link like a screw. The way of connecting two links together is to use a thrust bearing, a dow pin and a retaining ring, which is shown below.

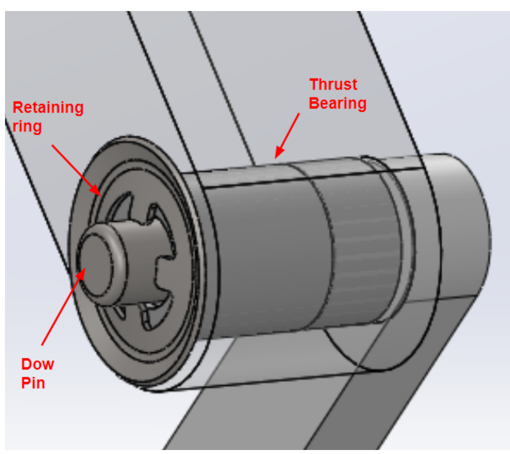


Figure 9.12. The joint design between two links.

The final part in the actuator is the ball joints, which are our purchase materials. The reason we choose to use ball joints is because our linkage design requires the joint to provide angular movement in multiple directions, otherwise the platform is not able to tilt. The CAD model of the ball joint while connecting with the link and platform is shown below.

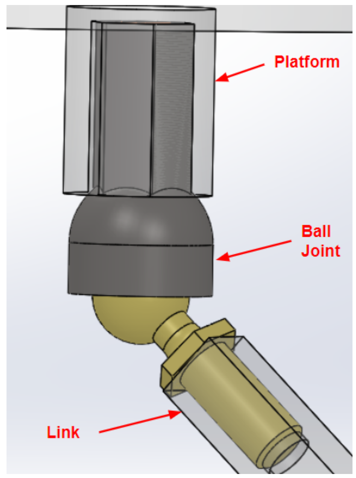


Figure 9.13. Ball joint CAD model in assembly.

IV. Platform

The build design of our platform is a little different from the alpha design. First, we changed the shape of the base from square shape to circular shape in order to reduce the material and weight. In addition to that, we increase the height of the sliders to ensure that the container can be held tighter and more stable. The engineering drawing of the base and the slider is shown below.

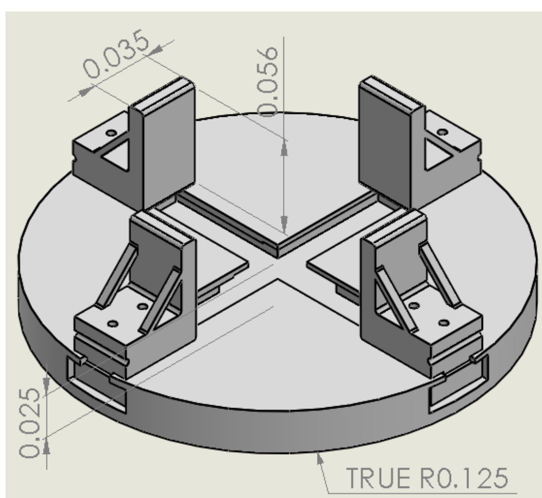


Figure 9.14. The engineering drawing of the platform build design with dimensions (m).

We make the radius be 0.125 m mainly because of our scalability requirement, where we have detailed discussion in the Verification Plan and Results section. In addition, we choose to make the height of the slider be 0.056 m because the general height of a food container is about 0.1 m, and half of that height (0.056 m) should be good enough to hold the container stably. Lastly, we still have the slot for placing a rubber band to provide a secondary safety while carrying food.

V. Electrical Circuit Design and Programming

The electrical circuit prototype is designed as shown in Figure 31. The prototype circuit is powered by a Lithium-ion battery with a voltage source preferably no less than 7.4 volts. The voltage source supplies power to the Arduino board and three servos. These servos are powered under 6 volts regulated from the voltage source through a voltage regulator. And these servos are driven by PWM signals from the Arduino board. A 9-axis accelerometer is powered by the Arduino board and its data flow is transmitted through serial communication. Finally, there is a protection mechanism with an LED light bulb to indicate whether the power supply is sufficient to drive the system or damages could be made to the battery or the system.

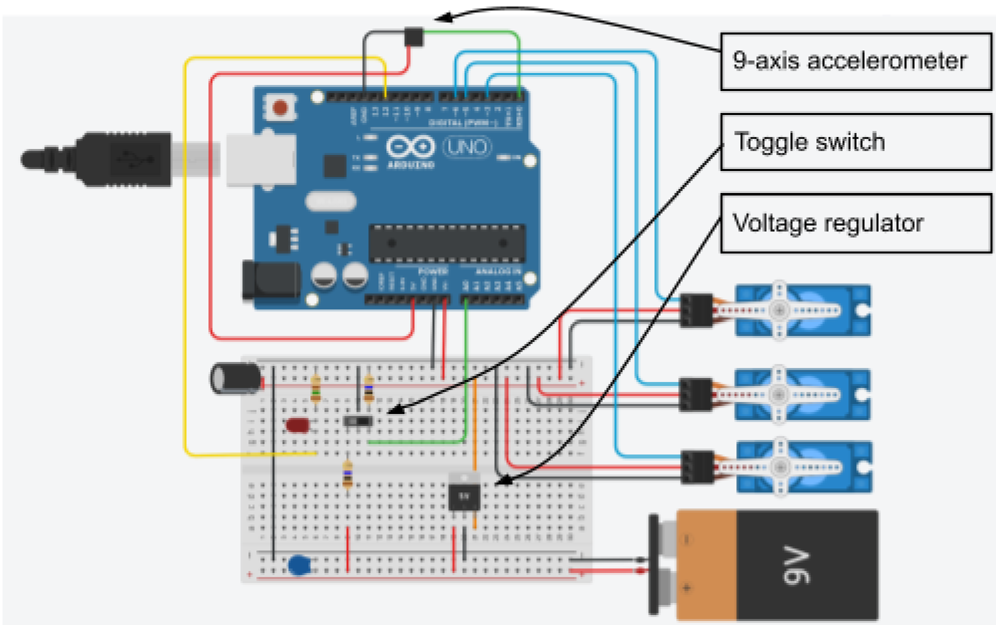


Figure 9.15. An example diagram of the implemented electrical circuit. The actual circuit may be a little different due to component availability.

An Arduino program is coded according to desired functionalities. Figure 9.16 shows an algorithmic diagram of the program and divisions of functions. Data is transmitted from and to memory stacks and processed by functions [46].

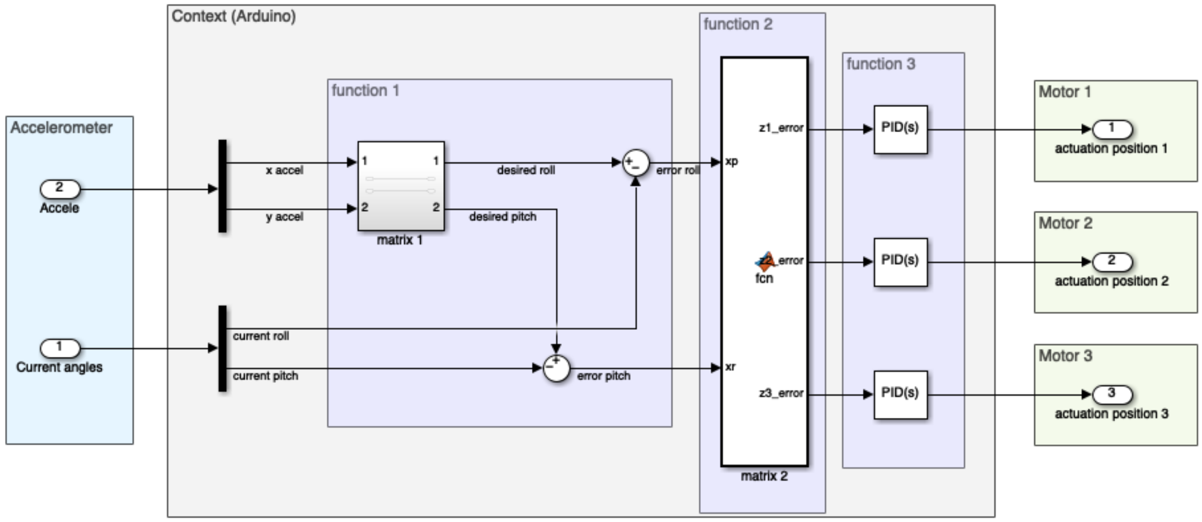


Figure 9.16. An algorithmic diagram of the implemented program. Each colored region represents a functional group.

Implementation details and references are organized and interpreted in Appendix D.

VI. Control System Design

The most important piece of the stabilizer device is the actuation part which can counteract environmental input signals. Ideally, the dynamic behavior of a DC motor can be captured by the most essential motor constants. However, most motor manufacturers on the market do not include any information about the motor parameters on the spec sheet. Therefore, it is important to run a system identification test on a specific motor. The servo motor we purchased has a built-in controller and position feedback wire which can be used for SYS ID. Our team members ran a couple of tests of step input, ramp input, and square wave. With trail data in our pocket, we then utilized the tfest function in MatLab as well as the System Identification Toolbox to investigate the transfer function of the motor.

Unlike a typical DC motor, this servo motor has a built-in controller which also has little information revealed. The algorithm is based on an input PWM signal, suppose the voltage supply is sufficient, the motor will reach the designated angular displacement while the only difference would be the time constant or settling time. Therefore, each operating condition actually corresponds to a different transfer function of the motor, we are merely interested in the transfer function under nominal voltage.

Using the System Identification Toolbox to estimate and validate the model is not simple as expected. Because the feedback data is significantly noisy, the estimated transfer function may not be as accurate while forcing pole/zero placement fitting can produce wide variations. A demonstration of the toolbox estimation is shown below in Figure 9.17.

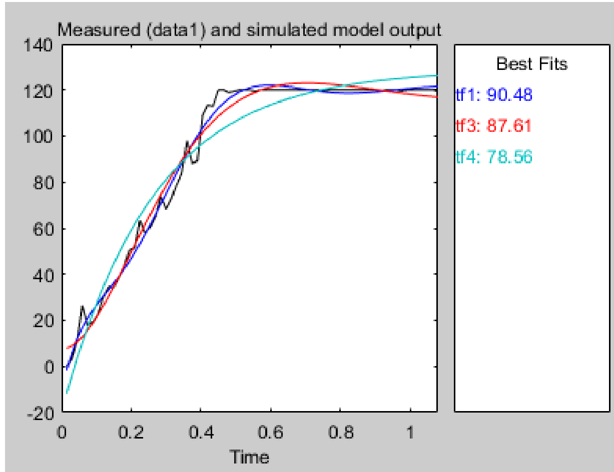


Figure 9.17. System Identification Toolbox Validation

After a few rounds of comparison and changing numbers of poles/zeros, we were able to obtain the most accurate transfer function given as follows.

```
tf1 =
  From input "PWM" to output "Angle":
     4.464 s^2 - 1.361 s + 728.6
  ---------------------------------
  s^3 + 14.04 s^2 + 166.2 s + 719.5
```
(9.1)

This third-order linear ODE with two zeros most precisely captures the dynamic behaviors of the motor(despite oscillation and noise) while having good stability margins and reasonable time constants. Typically, the presence of zeros can introduce undesired behaviors to the system. We would need to tune the PID controller as well as the pre-compensator for more robust stability. Relevant information can be found below.

Table 9.18 System Parameters of transfer function 1

Pole	Damping	Frequency (rad/seconds)	Time Constant (seconds)
-6.11e+00	1.00e+00	6.11e+00	1.64e-01
-3.96e+00 + 1.01e+01i	3.65e-01	1.09e+01	2.52e-01
-3.96e+00 - 1.01e+01i	3.65e-01	1.09e+01	2.52e-01

After deriving the fundamental formula for control algorithm design, we then implemented the system into a Simulink model shown below in Figure 9.18 to simulate the performance of the controller. Two inputs are desired roll angle and desired pitch angle. Their error angles are calculated from current platform orientation and sent to find three stroke lengths. Then, three PID controllers receive the stroke lengths and generate voltage signals to the motors. The motors (subsystem in the figure) output forces and activate the platform dynamics. The platform dynamics (another subsystem in the figure) returns its current orientation by roll angle and pitch angle and feeds it back to the loop. The platform dynamics is derived from force/moment balance and the motor model is concluded by system identification. The motor configuration results in an MIMO control system [47] but because each motor is identical, we can separate the MIMO system into three SISO systems and design one PID controller for all three motors. The PID controllers are tuned automatically by MatLab Simulink according to the system linearization results. One set of optimal parameters is shown below.

Table 9.2. PID Controller Parameters with Smooth Derivative

Proportional Gain (P)	Integral Gain (I*Ts)	Derivative Gain (D)	Filter Coefficient (N)
0.1583	2.6233	-0.0504	3.1393

The input signals vary to test stability or robustness. When the input signals are step functions, the stability can be verified by observing the resultant orientation response. When the input signals are periodic, for example, sine waves, the robustness can be verified in the same manner. One advantage is that simulation gives a good prediction of PID parameters that could control the system well. However, one disadvantage is that it heavily depends on the model of any dynamic component. If any component is updated (ours is the motor), the entire simulation and PID controller need to be redesigned.

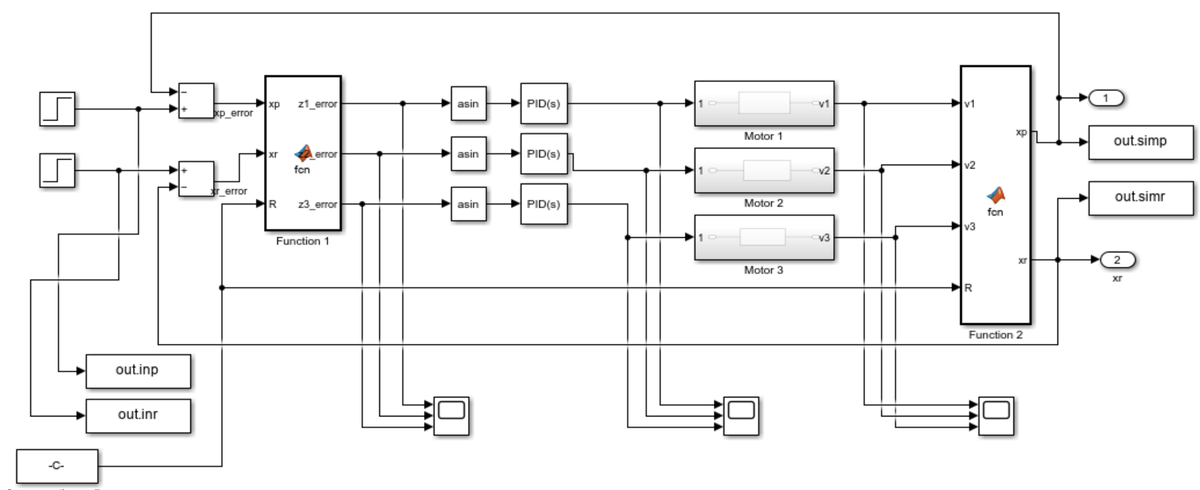


Figure 9.18. The Simulink diagram of the entire system.

We then investigated the stability features of the PID controller K(s) and the motor G(s). The open loop function L(s) = K(s)G(s). The bode plot for the open loop function is shown below.

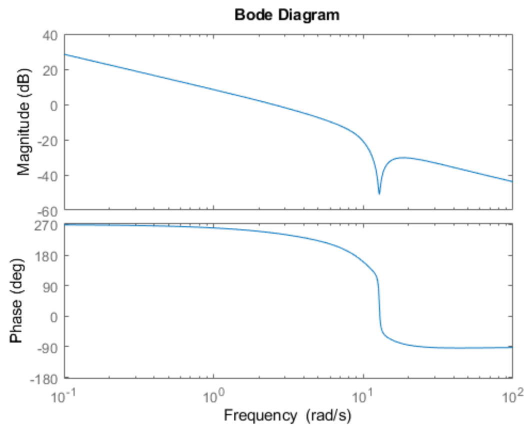


Figure 9.19. Bode plot of the loop function L = K*G

It is always important to check the stability margins of this loop even though stability is enforced when tuning PID gains. This can be done using the allmargin function in MatLab, the stability margin values are shown below.

```
 GainMargin: 6.5667
GMFrequency: 8.6939
PhaseMargin: 65.2296
PMFrequency: 2.4873
DelayMargin: 0.4577
DMFrequency: 2.4873
     Stable: 1
```

Figure 9.20. Stability margins of the loop function L

Another approach to test a function's stability is through its Nyquist plot and the associated disk margin; some details are demonstrated in the figure below.

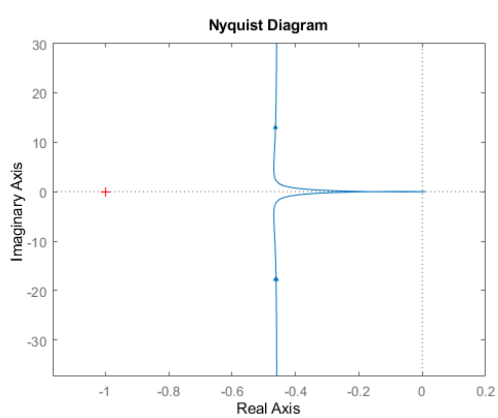


Figure 9.21. Nyquist plot of the loop function L with a disk margin of 0.74 and peak

frequency of 5.3 rad/sec

Materials and Parts

The main body of the prototype consists of several components, some of which are purchased online and others that are designed and manufactured in Solidworks. In addition to these components, there is an electrical circuit that powers and controls the prototype.

The purchased components, listed in Table E.1 in Appendix E, include accelerometers, servos, breadboards, Arduinos, various tools, and hardware such as screws, nuts, washers, and bearings. These components are sourced from various suppliers and have been chosen for their suitability in the prototype's design. The total cost of these components will need to be considered in the budget for the prototype.

The designed manufactured components, listed in Table F.1 Appendix F, are designed using Solidworks and are 3D-printed using Stereolithography (SLA) technology. The components include actuators, platforms, sliders, mounts, trusses, and linkages.

Lastly, the electrical circuit components are also listed in Table E.1 in Appendix E. This includes the Arduino Mega 2560, battery, resistors, LED, voltage regulator, accelerometer, capacitors, slide switch, servos, and breadboard.

Build and Final Design Relationship

The relationship between our build design and final design is quite close, with the primary difference being the manufacturing process. While the build design utilizes 3D printing for producing the custom components, we may choose the final design to use injection molding for manufacturing. This shift in the manufacturing process is intended to increase production efficiency, reduce costs, and improve the overall quality of the components for the final product.

The build design, serving as a prototype, is crucial for processing our verification and validation plan for our final design. By creating a functional prototype, we then can evaluate the feasibility and performance of the final design and ensure that our product is effective in solving the problems posed by the stakeholders and in meeting our requirements and specifications. For example, the build design allows us to test the aspects such as the linkage system, actuator design, and platform stability under realistic conditions. It also enables us to identify any potential issues or areas for improvement before proceeding with the final design.

Although the build design differs from the final design in terms of manufacturing process, the functional performance would be almost the same for both of them. Our build design would work as a solid foundation for the final design, and that the proposed adjustments in manufacturing will result in a more efficient and cost-effective final product.

Lessons Learned From Unsuccessful Outcomes

Throughout the design process, several important lessons were learned. First, adaptability played a crucial role in achieving better results. Instead of using springs as selected in the alpha design, we implemented a three-linkage system connected to actuators, which allowed for more precise control of the platform's tilting angle. Besides, the implementation of a linkage system also allowed the application of rigid body kinematics to predict the state of the platform, enabling creation of a mathematical model that enhanced the overall functionality of our design.

Second, we learned that control algorithms are closely related to hardware. Controller design cannot individually exist without considerations of the hardware. Oftentimes, controller design and hardware implementation are developing and iterating interactively until the best performance is achieved. Therefore, we should be patient and expected to start over the entire algorithm design during iterations.

Additionally, reshaping the platform and actuator components to reduce mass proved to be a beneficial design decision. By altering the platform shape from a square to a circular design and optimizing the shape of the actuator plate, the overall mass of the system was reduced. This not only led to material savings but also improved the efficiency and performance of the prototype.

Lastly, the use of ball joints proved to be a necessary change to the design. These joints allowed for angular movement in multiple directions, ensuring that the platform could tilt effectively as required. By incorporating ball joints, the design offered increased flexibility and adaptability, which contributed to the overall success of the project.

10. DESCRIPTION OF VERIFICATION AND VALIDATION APPROACH

Verification Plan and Results

For each of the engineering specifications, we have developed a corresponding verification plan described in detail below, with the results for completed verification tests included.

Lightweight. We have two verification plans for lightweight. The first plan is to estimate the mass of our CAD model using Solidworks with joints included, add the nominal mass of three servos and one arduino board found from their specification sheets, and then compare to the upper limit, 8 kg, set in the specification. This plan provides us with an assessment of mass in early stages of design before prototyping starts, which allows easier and less costly adjustments if needed. However, Solidworks simulation might not be precise, and the actual mass of servos and arduino board might differ from the nominal values provided as well, which would lead to some small differences between the estimated value and the actual mass of the final product. Based on our current design, the 3D printed parts together weigh about 4.03 lb (≈ 1.83 kg) from Solidworks estimation shown in Figure 10.1 below.

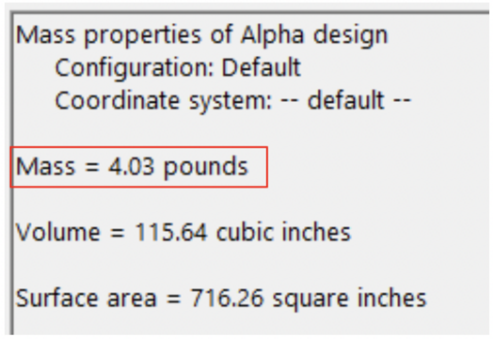


Figure 10.1. Solidworks estimation of mass properties for the prototype CAD model.

According to specification sheets, a servo has a nominal mass of 0.178 kg [48], a lithium-ion battery has a nominal mass of 0.1 kg, and an Arduino board has a nominal mass of 0.037 kg [49]. Therefore, the total mass of the stabilizer is about 2.5 kg (with 3D printed parts, three servos, one lithium-ion battery, and one Arduino board). Since this result is far below 8kg, even with some estimation errors, we are very confident that the mass of our device will be within the set limit, which demonstrates good compliance to the engineering specification.

The second plan is to actually weigh the prototype after it is fully built and wired with a calibrated scale and compare with the set limit of 8 kg. This plan provides an accurate measurement of the device's mass with all mechanical and electrical components including wires integrated. However, it can only be conducted after the prototype is completed, which is near the end of the semester where modifications of design are very effort- and time-consuming and may impact the overall project schedule a lot. As shown in Figure 10.2 below, the mass of the final prototype was measured to be 3.00 kg, well below the upper limit of 8 kg. Therefore, we can conclude that the prototype satisfies the lightweight specification.

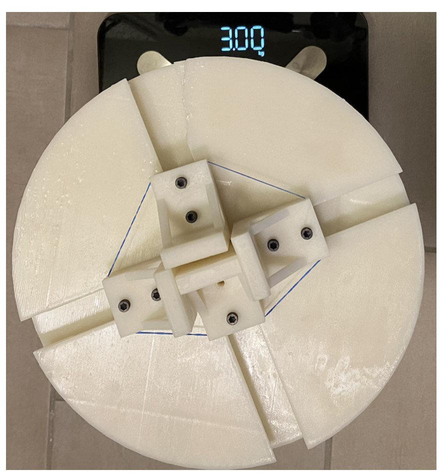


Figure 10.2. Mass of the complete prototype.

Capacity. We will perform physical tests to determine whether our device can support a load within 1 kg. In particular, we would load the device with a mass of approximately 1 kg and observe the response of the systems. If the systems do not exhibit any deflection or crack initiation, then the device is capable of supporting the specified load. This plan provides an accurate and objective measure on the capacity of the device. Compared to material analysis, this physical test provides a more intuitive result that can be easily compared to the specification, but might not be able to take into account potential fatigue in long-term use. The analysis for long-term behavior of materials will be performed later in the verification plan for the durability requirement. As shown in Figure 10.3 below, the prototype was able to hold two bottles of 500-ml water (≈ 1 kg) without any outside support.

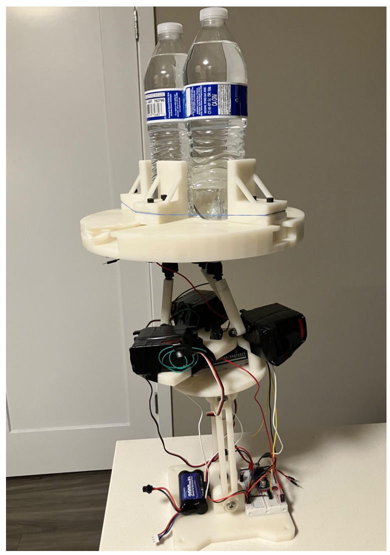


Figure 10.3. Verification test for capacity with the prototype supporting a 1kg load.

In the consideration of saving materials, we did not perform test-to-failure experiments. But we tried to load the prototype with four bottles of 500-ml water, which is approximately twice of the specified capacity, and the device demonstrated good performance in supporting the load without any observable deflection. Therefore, we are confident that our device satisfies the engineering specification for capacity requirement.

Scalability. We have two verification plans for this requirement as well, one as computer simulation and the other as physical testing. Since the CAD model can simulate the mechanism of sliding locks very well, we would first evaluate the minimum and maximum achievable distances between opposite-facing locks using Solidworks. If the minimum distance is less than or equal to 8 cm and the maximum distance is greater than or equal to 15 cm, then our device satisfies the engineering specification for scalability. This simulation test provides an assessment of scalability during early stages of design, which allows easier and less costly modifications as discussed earlier. However, besides letting the locks move freely in their slots, the simulation does not take into account mechanisms for fixing each lock in a desired place during operations. These mechanisms, which are screws and rubber bands in our current design, may pose some additional constraints on the range of lock motion on the actual platform. As shown in Figure 32 below, the minimum distance between opposite locks in the CAD model is measured to be 4 cm, while the maximum distance is 20 cm.

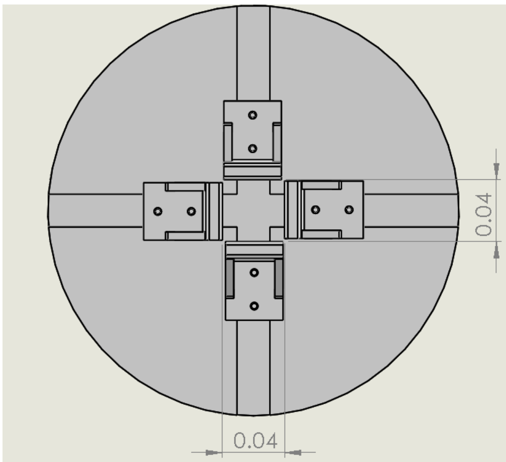


Figure 10.4(a). Minimum distance between locks

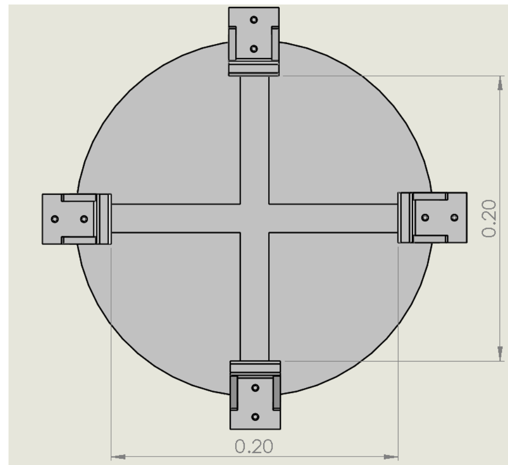


Figure 10.4(b). Maximum distance between locks.

Since the estimated range of lock motion is wider than the specified range, by at least 4 cm on each end, even with some extra constraints from the fixing mechanism, we are confident that the prototype should be able to provide the scalability specified.

The second plan is a physical test where we will actually measure the minimum and maximum distances between opposite-facing locks with a ruler on the printed prototype. This plan provides an accurate measurement of the range of motion for locks, but can only be conducted after the prototype, or at least the whole platform system, is printed and built. As shown in Figure 10.5 below, even with some printing defects on one side of the platform, the locks could still move continuously from a minimum separation distance of 7.5 cm to a maximum separation distance of 17 cm.

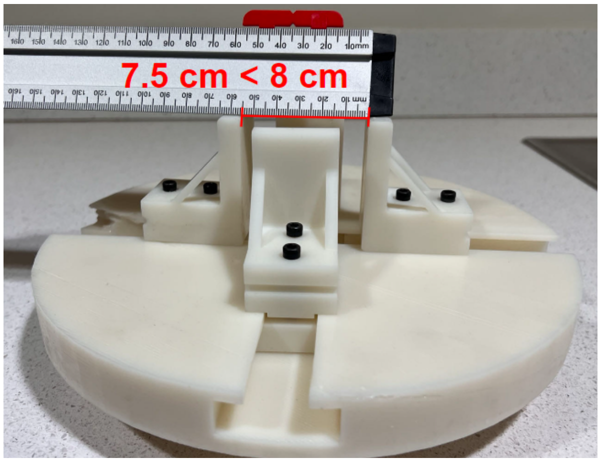


Figure 10.5(a). Minimum distance between locks.

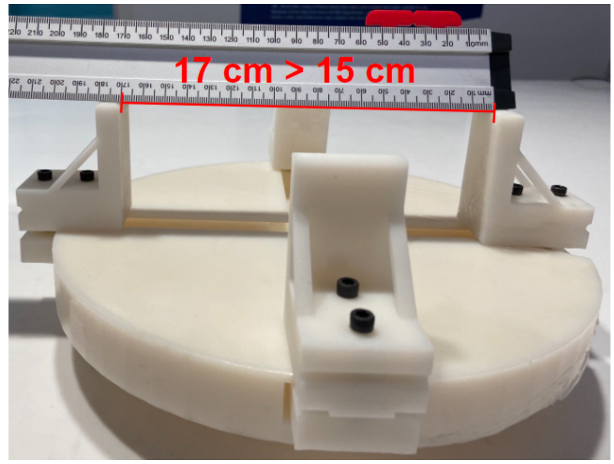


Figure 10.5(b). Maximum distance between locks.

Since the measured range of motion (7.5 - 17 cm) is wider than the range stated in the engineering specification (8 - 15 cm), we can conclude that our design demonstrates good compliance to the scalability requirement.

Stability and Robustness. The verification of stability and robustness are the same and it takes two steps. First, stability and robustness are tested in simulation.

Essentially, the sign for a successful verification would be fast signal tracking and output convergence with minimal steady-state error. Our team conducted several simulations using various formats of inputs, some of the simulation scope evidence is shown below.

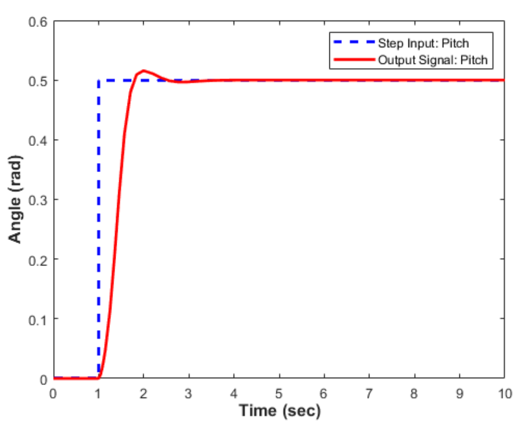


Figure 10.6(a). Step Response: Pitch

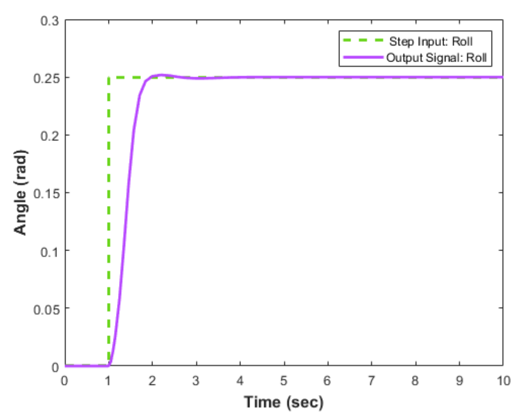


Figure 10.6(b). Step Response: Roll

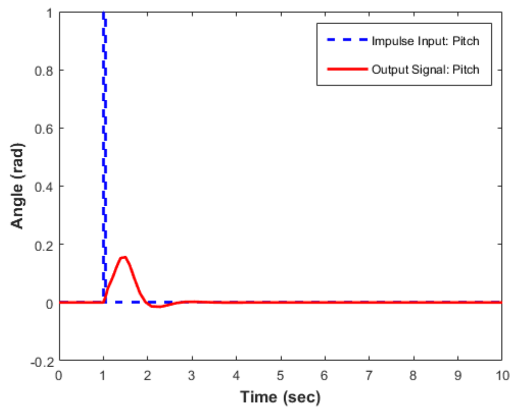


Figure 10.6(c). Impulse Response: Pitch

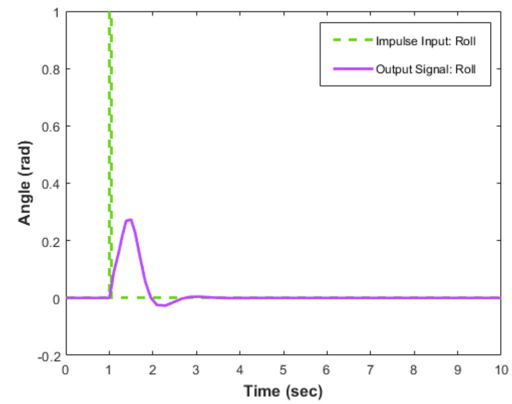


Figure 10.6(d). Impulse Response: Roll

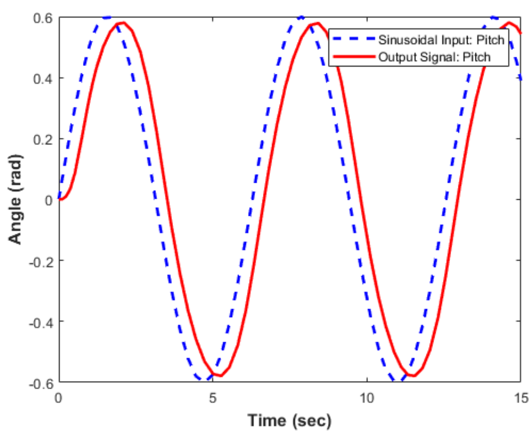


Figure 10.6(e). Sinusoidal Response: Pitch

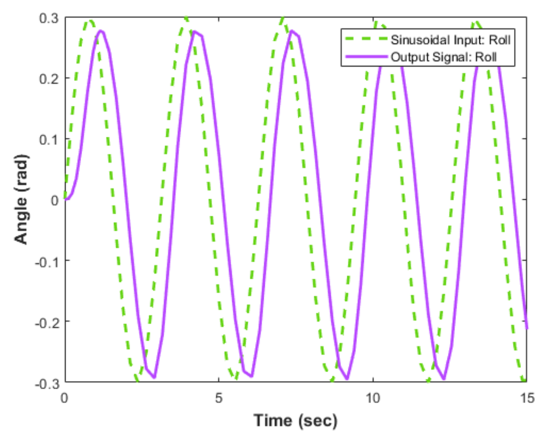


Figure 10.6(f). Sinusoidal Response: Roll

From the step response plots, it is easy to observe that the overshoot is constrained very well. The settling time of the system is around 1 second which satisfies our engineering specifications. From the sinusoidal response plots, we can see that for a relatively large frequency, the system still exhibits a 5% steady-state error. The local peaks shown in Figure 10.6(f) indicate that this higher-order system has some nonlinear behaviors and these dynamics are neglected in our modeling. But generally speaking, despite the existence of minor steady-state errors and nonlinear oscillations, the model we set up is able to track the input signal quite accurately and quickly for designated input frequency and magnitude. So far, stability, robustness, and controllability specifications have all been verified from the software simulation perspective.

Second, besides verification from the simulation side, stability and robustness are tested after a prototype is built and mounted on some test rig. Examples include mounting our device on a programmable conveyor belt or on a simple wheeled robot. The idea behind hardware testing is to iterate PID parameters so that the controller can achieve optimal performance and verify our device works under normal application conditions. As a consequence, we can safely say that our product will work. But it requires extra design and manufacturing for the test rig and it would be a scheduling issue during the current development stage.

Controllability. Controllability ensures that the platform's desired configuration can be achieved by three motors motion. An individual motor has its range of rotation. Linkages project this range of rotation into a range of linear motions. Connected to the platform, three linkage-and-motor systems project their individual motions into the configuration of the platform, assuming the platform is a rigid body. Therefore, the relationship between motor motion and platform configuration is required. At least, the desired platform configuration is within the range of motor motions. The verification of controllability consists of two phases: (1) controllability can be theoretically proved based on the geometry, and (2) hardware testing will be conducted. The theoretical proof in Appendix C has shown that three linear motions at different exertion points on the platform are able to induce desired platform configurations. Theoretical proof provides rigorous support to the realization of the mechanism and prevents wasting time and efforts on trial and error on hardware.

However, several assumptions are made in the proof and fail to consider a real situation. Hardware testing is thus required to add another level of certainty of controllability. A couple of sets of random configurations and edge configurations will be generated and sent to the motor. Then, we observe if all resultant platform configurations belong to the desired range of configurations. If so, controllability is verified. One advantage of hardware testing is that it takes real cases into account and proves feasibility by realization. However, one disadvantage is that it is not sufficient as we cannot generate infinite sets of configurations to test the platform configuration range. Therefore, hardware testing should be performed after theoretical verification.

Low-cost. Since all manufacturing costs are covered by the Mechanical Engineering Department at University of Michigan, to verify if the cost of production for our prototype is within our budget constraint, we would simply compare the material cost with the upper limit $1000 set in the specification. This verification plan is very easy to conduct throughout the whole design process and can provide an accurate evaluation of whether the device meets the corresponding engineering specification. According to the Bill of Materials shown in Appendix E, the cost of purchasing all mechanical and electrical components is $435.75 with taxes and delivery fee included. Therefore, we can conclude that the current prototype shows good compliance to the low-cost requirement.

Durability. For this requirement, we would verify the durability of electrical and mechanical components separately and compare each to the value 2400 hours set in the specification. In particular, for electrical components, we would search on the longevity of an Arduino Mega

2560 board, while for mechanical components, we would conduct fatigue testing for the most stress-concentrated area in our design and compare the result to the material's endurance limit. This plan is more comprehensive since it verifies that neither electrical or mechanical failure would occur during the expected lifetime of our device. However, it does not take into account some specific aspects of the potential operation environment, such as temperature and humidity, which may have influence on the performance of both electrical and mechanical components. Based on our research, the lifespan of Arduino Mega 2560 is quoted as 6000 hours at 105 °C, which is the maximum temperature that Arduino can run at [50]. Therefore, even in the worst case scenario, the Arduino board we use can still provide a lifespan much longer than the durability limit set in our engineering specification. For mechanical components, as discussed earlier in engineering analysis for durability, the part most susceptible to failure is the bolt connecting the motor output shaft and lower linkage arm. According to Figure 9.7 on Pg. 60, the calculated stress amplitude σ_a is much less than the material's endurance limit σ_e, which indicates that the bolt would not fail through fatigue. Besides, as mentioned earlier in engineering analysis for capacity, metals or alloys usually have a yield strength of at least 200 MPa, which is much larger than the maximum compressive stress that the bolt needs to withstand (1.5 MPa). Therefore, the mechanical components of our device would also be able to provide a lifespan that satisfies the engineering specification.

Easy to Set Up. Since the easy-to-set-up requirement is user oriented, we would conduct a user testing in order to verify the corresponding engineering specification. In particular, we would ask 10 people to set up the device, record the average time taken, and compare it to the set limit. We think the background of each testee, especially their experience with hardware building, is an important factor that would influence the setup time. Therefore, ideally, we would find 10 testees with different backgrounds, i.e. students with different majors, to perform this verification test. This plan provides a direct measurement of the setup time which can be easily compared to the specification. But the result is subjective to the sample chosen and therefore might not be accurate or non-biased for the larger population. Based on our test, the total setup procedure took an average time of 6 min, which is longer than the 5 min stated in the engineering specification. However, we expect the setup time to be largely reduced after mass production. For mass production, we expect some of the parts we have right now to be manufactured as one single piece or pre-connected before shipping to customers, and all wirings would be done on the robot's control unit and power system instead. Therefore, the total setup procedure would only include putting four components (mount, linkage, actuator, and platform) together, attach servos and locks, and finally connect the whole system to the robot. We would also consider modifying our design in order to further reduce the setup time in the future.

Universal Compatibility. This requirement should be considered and addressed during the initial stage of design for the mount, which requires a spec-oriented design. Therefore, the verification for universal compatibility can be achieved through inspection on how the mount system is connected to the delivery robot. This inspection can be conducted very easily during early stages of design, which does not require any additional cost (time, effort, and money). As shown in the final design section, our mount system will be connected to the robot through four screws on each corner, which satisfies the specification that the device should be able to be mounted to a pre-designed rigid structure with no more than four components.

Low Maintenance. An inspection on the system design would be implemented to verify the low maintenance requirement as well. As stated in the earlier section on desirable requirements, the device should have at least three replaceable components and the process of replacing any of the three parts should be less than 5 steps. In order to verify this specification, we would first inspect the CAD model for potentially replaceable components and then analyze and also physically test how many steps it would take to replace each of them. The inspection can be performed as early as the CAD model is finalized, while the physical test needs to wait for the prototype to be printed and built. While performing the test, we also need to consider the accessibility of different tools. Ideally, all tools needed to replace those components should be very common and easily accessible to maintenance groups in business buildings. A potential limitation of this plan is that it cannot take into account all possible failure situations. During actual operations, many accidents may arise especially considering the robot's interactions with humans, which may require more different kinds of maintenance than what this verification plan can possibly cover. Based on our initial inspection on the CAD model, currently we have four categories of replaceable components, rubber band, locks (4), ball joints (3), and servos (3), as shown below in Figure 10.8.

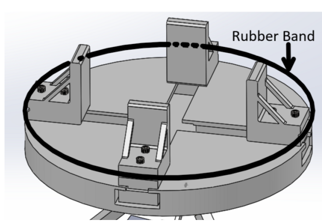


Figure 10.8(a). Rubber band and locks

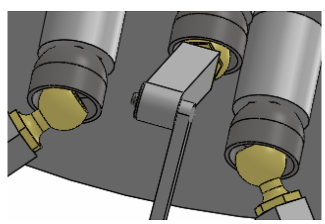


Figure 10.8(b). Ball joints.

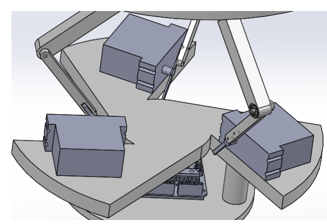


Figure 10.8(c). Servos

Through physical testing on the completed prototype, we determined that it takes two steps to replace a rubber band and four steps to replace each lock, ball joint, or servo. For replacing the rubber band, we only need to take off the old and then put a new one around the locks. Due to the constraint from the rubber band, for replacing each lock, we need to first remove the rubber band, then slide off the lock, slide in a new lock, and put the rubber band back on. For replacing each ball joint, we need to first take the platform off, unscrew the old joint, then screw in a new one and put the platform back on. For replacing each servo, we need to detach the link from the servo, then detach the servo from the actuator plate, attach the link with a new servo and finally attach them together onto the actuator plate. Since all replacement procedures take less than 5 steps, we can conclude that our design shows good compliance to the engineering specification for low-maintenance.

Easy to Use. The verification plan for the easy-to-use requirement is very similar to that for the easy-to-set-up requirement discussed earlier in this section since they are both user-oriented requirements. We would ask 10 people, ideally with different backgrounds, to complete loading and unloading processes with the prototype, record average time taken for each process, and compare it to the limit set in the engineering specification. As explained above, this plan provides a direct measurement of the loading and unloading time which can be easily compared to the specification. But the result is subjective to the sample chosen and therefore might not be accurate or non-biased for the larger population. After the prototype was completed, we asked students in Mechanical Engineering, Electrical Engineering, Industrial and Operations Engineering, Computer Science, and Physics to try to load and unload our device with a bottle of 500-ml water. The average loading time was calculated to be around 3.45 seconds, while all unloading time was less than 1 second due to the automatic retraction of the rubber band and locks after the container was removed. Since both loading and unloading processes were within the limit of 5 seconds, we can conclude that our design satisfies the easy-to-use requirement.

Validation Plan

Validation confirms whether a near final prototype addresses the original problem statement and creates a satisfactory value for users. Since validation needs to focus more on the user's perspective, we propose a market-based testing where we cooperate with a delivery robot company, implement the stabilizer on their robots, and provide a two-week free trial for potential customers in one or two selected buildings. In order to validate whether the stabilizer is capable of solving the critical problem, we would have engineers conducting in-field monitoring of device performance during the entire trial period and analyze the effectiveness of our device in reducing incidents like spills and robot destabilization due to fluid inertia during transportation. In order to validate whether the stabilizer is able to create a satisfactory value for users, we would conduct surveys after trial on customer satisfaction and willingness to buy our product given their trial experience and the cost of purchase.

Due to time constraints, we would not be able to perform the proposed validation plan during this semester. However, since our prototype is very similar to the final product, if the prototype passes all verification tests, then we are confident that the final product would be capable of addressing the original problem statement and providing some positive values for users.

11. DISCUSSION

Problem Definition

Although the project has proceeded greatly, there are ways to improve it. First, the application can be more studied. Food delivery robots vary in size, shape, and holding mechanisms. Not all food delivery robots are suitable for our add-on product. Therefore, a closer examination of the present food delivery robot design is recommended. Also, we need to survey whether food delivery robots are fashionable and preferred in many situations. Our product has the potential to be applied to different application situations other than food delivery systems. If there are a limited number of food delivery robots, we should put less emphasis on stabilization on liquid diet transportation and focus more on ad hoc applications. Pharmaceutical manufacturing, chemical plants, explosive handling, etc. are potential stakeholders to our product yet we know little about their demands. The preferred method to better define the problem is to learn how different corporations conduct manufacturing and communicate with practitioners from different industries to learn if our product would be beneficial to their status quo.

Second, the design ought to be sufficiently iterated. Because of the time constraints, we weren't able to iterate as much as needed. Less iteration inevitably put us in the situation where we had to remediate design imperfections, especially the cooperation between each component. For example, a motorized linkage system was designed to actuate the platform by one member while the platform was separately designed by another member. There was a lack of communication such that linkage-platform pin joints constrained the platform from moving. As soon as we realized, the pin joints were replaced by purchased ball-and-socket joints, which was not a perfect but workable solution. Likewise, more communication between members is highly encouraged as enough communication prevents mismatches between components.

Another method that we should better utilize is to study more similar commercial products. Due to the budget limit, we couldn't afford a thorough study on peer products in the industry so we, to some extent, lacked the knowledge of building a prototype in a schematic and focused way. Such lack of knowledge left us room to apply creativity and develop engineering designs but at the same time posed challenges of completeness and utility. As a result of inexperience, our own design did not have the comparable competence against similar commercial products. If we were able to refer to enough commercial products, we would study the current designs and customize and develop them based on our needs.

Design Critique

Our design has some strengths. (1) SLA 3D printing rendered strong material strength to hold the load and self weight. (2) Our servos could generate enough torque to activate the platform and fulfill our assumption about platform dynamics. (3) The electrical circuit was well designed and wired so the device is protected from electrical accidents and handy to use. (4) Some structures have weight-reduced and artistic designs. (5) Codes were developed in organization and easy to read and maintained.

Our design also has some weaknesses. (1) SLA 3D printing was not a panacea for manufacturing. First, it took a long time to print one part, which delayed our building progress.

Second, the printing quality varied and could barely be controlled, which defected the part. Third, because the printing is solid, it adds a massive amount of weights to the components. For example, the platform that was printed as a single body was too heavy to affect its dynamics and control performance. (2) Joint designs are deficient. First, we did not design fixtures for servos because the choices of servo changed over the process. We taped the servos onto the platform but they were not secured. Second, joints between linkages lacked considerations in force balancing. The heavy load deformed the linkage and caused unexpected stress onto servos. (3) Wirings were exposed and not allocated for the sake of debug convenience. They could be better sorted for aesthetic appearance and avoidance of accidents.

Corresponding improvements are given as follows. (1) The material and manufacturing method should be changed by discernment. For example, the platform could be model injected using PVC to reduce weight and maintain plastic strength. The support bar can be machined from steel stock. (2) Joint designs need iterations with tight tolerances. The material of linkage could be metal to secure joint position. The servo platform can be model injected with designed mounting holes. (3) Wires could be allocated inside the structure. It requires securing the writing in place and redesign the main support structure to store the wires.

Risks

Challenges and risks need to be overcome. (1) Because of the manufacturing method and the goal of minimizing the influence of self weight, mass reduction is required with caution. Mass reduction shouldn't reduce the mass to the extent that the structure loses its material strength while minimal mass reduction has limited effects. It was attempted in CAD by mass evaluation and stress analysis. If the mass-reduced part does not pass the stress analysis, then the mass reduction is not approved and needs redesign. (2) Tolerance control is a pivotal issue, assuring the mechanism to move as designed. Especially controlling the tolerance of the linkage system was the most demanding one with different types of fits existing between bearings, pins, and holes. Failure to maintain a stipulated tolerance design could lead to failure in supporting the movable parts or inability to move. A solution to maintain the tolerance is referring to engineering standards and denoting them in the CAD or design drawing. These denotes should be strictly followed while manufacturing. (3) Since the device utilizes a 7.4 V power source, extra care was taken to handle the wiring of voltage. The polarity of the voltage source, the maximum of voltage capability and choices of resistance were carefully determined. We relied on circuit simulation to test the feasibility and then implemented it so it is error free. (4) The final product was aimed to hold a heavy load and the load is distributed via stress. Therefore, a proper design of structures is required to deal with stress distribution before material failure. As mentioned above, each part went through a stress analysis in CAD to reassure its strength. (5) The programme sends commands to control servos. A simple test is anticipated to learn the polarity of the servos and working range of the servos to prevent the programme from sending destructive commands.

The end-users also face some risks while operating the product. (1) Improper handling of the wiring would result in an electric leak and thus, electrical shock to the user. (2) The strength of the servo is so powerful that improper handling could result in clamping the limps into bruises or fracture. (3) There are some sharp corners which may cause body or eye damage during collision. (4) The entire device along with the load are heavy as it may cause bruises if fell.

12. REFLECTION

Design Impact

Our project is closely related to the public health, safety, and welfare context. As explained in the Project Introduction and Background section, the designed stabilizer aims to ensure a stable transportation of fluid for delivery robots under aggressive dynamics. Through preventing liquid spills and disturbance to robot motion, our device could largely reduce incidents such as people being scalded by hot liquid or hit by malfunctioning robots, and therefore ensure safety for anyone interacting with delivery robots. Besides, with the implementation of the fluid stabilizer, delivery robots would be able to perform a larger variety of tasks and provide better services, bringing more convenience to users.

Through the use of both stakeholder and ecosystem maps shown in Figure 3.1 on Pg. 8, we identified potential social and economic impacts associated with manufacture, use, and disposal of our device. For social impacts, the use of the stabilizer on delivery robots to provide safer transportation of liquid would help increase the public acceptance of robot delivery services. However, the increasing popularity of delivery robots would also cause more jobs to be taken away from delivery people. For economic impacts, the manufacture of the stabilizer brings more business opportunities for resource providers such as powertrain companies and investors. The safer and more convenient robot delivery service would help companies which implement this device attract more customers, but also reduce business opportunities for companies which focus on dealing with issues related to spills and robot malfunctions.

For political impacts, as the use of delivery robots becomes more widespread, governments need to issue new regulations to deal with robots' interactions with pedestrians and influence on public constructions such as sideway walks and street lights. For environmental impacts, the implementation of our device would effectively reduce waste of resources from spills. In addition, the fluid stabilizer does not produce any pollution during operations. Therefore, it should not have any potential negative impact on the environment.

On a global scale, our device would help promote the growth of the delivery robot market through allowing more types of food to be delivered, and increase the public acceptance of robot delivery services through improving the overall safety and user experience. Moreover, our design specifically considered universal compatibility and low maintenance, which further ensures that the device can be used for different types of delivery robots operating in different environments with different levels of access to tools.

Inclusion and Equity

Within the team, all members are very cooperative, supportive, and respectful of each other. Our team consists of four international students from the same country with similar cultural backgrounds. This cultural similarity helped us agree early in the semester that we would take a collaborative approach to the project with all members' ideas being evaluated equally instead of a hierarchical structure. With similar educational backgrounds, we also agreed that we would start all tasks early to allow as much time as possible for any modifications needed, which largely improved the quality of our presentations, reports, and final product. Although we do have team members with different genders and from different years of study, we do not observe any influence in decision-making resulting from these identity differences. All members were treated equally regardless of gender and age. Besides, some members have more experience with hardware design, while others have more experience with system control. Therefore, at later stages of solution development, we were divided into two groups (one focusing on the development of the physical prototype and the other focusing on the development of control algorithms) to let every member play to their strengths. We also ensured effective communication between the two groups at all times not only for better integration between the physical system and control but also for providing members with opportunities to learn what they were not familiar with before. In order to include more diverse viewpoints from team members in our project work, we set regular meetings at least once per week throughout this semester and wrote weekly reports to record any valuable ideas and important updates.

Since we are a student project team with our mentor Xingze being one of the team members as well, we do not have any special interactions with or influence from our mentor other than what was already discussed above. The budget and time constraints from our sponsor, the Mechanical Engineering Department at University of Michigan, do have a huge impact on our design processes. First, we needed to carefully choose materials and components and reduce the possibility of failures in order to control the total expense to be under the budget limit. We also needed to complete specific tasks at specific dates listed in the course syllabus. In particular, since the manufacture of our device relied heavily on 3D printing which was conducted by staffs in the machine shop and required queueing, we had to finalize our CAD model and submitted to the machine shop as early as possible so that we could have time for modifications of design and still be able to complete the prototype before Design Expo.

In the design process, we did not conduct any interviews with end users. However, as college students, our team members are all frequent users of food delivery services. We also conducted in-field observations with the delivery robots operating in Kura Revolving Sushi Bar in both

Novi and Troy. Therefore, during the design process, we also considered our experience as end users of robot delivery services to better understand customer needs.

Ethical Considerations

The invention of our fluid stabilizer would help promote more deployment of delivery robots inside buildings. As more humans and robots operate in the same space, the possibility of hitting accidents would increase. Therefore, it is important for both robot companies and owners of the buildings to issue effective regulations for robots and human operations which would ensure a safer interaction between them.

Besides, as mentioned earlier, the improvement of delivery robots would take away a substantial amount of jobs from delivery people, but at the same time creating more job opportunities for maintenance people. In order to avoid an increase in the overall unemployment rate, we expect that, instead of firing all human workers and replacing them with robots, delivery companies who implement our device would provide additional training for workers and help them stay employed through transitioning from food delivery to robot maintenance.

13. RECOMMENDATIONS

After conducting thorough research and analysis, we highly recommend the following courses of action and possible optimization for individuals or organizations seeking to use the device or further improve it. These recommendations are based on a combination of data-driven insights and best practices in the field, as well as our expertise and experience in tackling similar challenges. We believe that implementing these recommendations will lead to significant progress and positive outcomes, and we urge all stakeholders to carefully consider and act upon them.

First of all, the platform on this device was designed to have a fair amount of scalability for various fluid containers. In fact, this device itself can also be scaled in order to fulfill customer requirements. It would certainly require redesigning specific components and another round of verification, however, the idea behind this is universal. This active motor-controlled stabilizer can be applied to many scenarios beyond beverage cups, with enough power and smart algorithms, this device can even be used to transport hazardous chemical products while minimizing the potential risk.

In the meantime, there are also a few design optimizations we realized can further increase the efficiency and performance of the stabilizer device. The transfer function we acquired for the motor is based on a very limited data set and contains noise. Performing grey box system identification using MatLab functions gave us a variety of transfer functions of diverse orders. Despite DC motors usually behaving like a first-order system, this is not quite accurate in our case and may affect later force-dynamic simulations. We made a decision to employ a third-order transfer function but it is also exhibiting other nonlinear dynamics, therefore, a valid approach is to conduct more experiments and collect less noisy data in order to truly capture the dynamic behaviors of the motor. This will improve the accuracy of our model and allows more precise control and actuation when the accelerometer is implemented.

Also, PID controller tuning can be adjusted for desired performance metrics. The current PID gain values were adjusted to minimize oscillations while sacrificing some settling time. The tradeoff between settling time and overshoot can further be optimized for more specific requirements.

To address the potential risks we identified in the discussion section, there are many approaches to mitigate these problems. For mass reduction, it is possible to use different materials for 3D printing in order to reduce density and increase material strength, at the cost of manufacturing complexity and high price. Current setting of tolerance control is fine when the scale of the device is predetermined as such, when the scale is different, the manufacturing process and precision would need to be up another level. Another risk we discussed is the voltage amplitude and programming, since we currently use Arduino for controlling and lithium battery for power, there is a limit of current to which the controller can draw, when this number becomes too large, the device will be at the risk of overheating; one approach is to increase circuit safety features such as voltage regulator to mitigate that issus. Additionally, stress concentration of certain components is worthwhile mentioning, even though we have verified the device will be able to handle the load of 1 kg, there is a risk of clients using this device to support a much heavier load; with that being said, using stiffer material will be a good way to solve this problem, or we can add additional safety factor during engineering analysis if material substitution was too costly.

14. CONCLUSION

The Covid-19 breakout has led to a huge rise in the demand for food delivery robots. However, current food delivery robots are not good at stabilizing liquid, which may lead to spills or disturbance to robot motion from fluid inertia. Through our research, we identified some benchmarkings for stabilization systems, but none of them works for our particular case of liquid food stabilization. Our project aims to solve this problem through designing a fluid stabilizer for food delivery robots that will provide a safe transportation of edible fluids. We have used the ME 450 design framework to guide our process, including defining the problem, exploring concepts, and developing and verifying solutions. In addition, we have identified 14 stakeholders which can be grouped as primary, secondary, and tertiary, where the primary stakeholders are mobile robot companies, workers in the complex, companies in the complex, and cleaning companies. To ensure that we meet our objectives, we have generated 12 requirements and specifications for our fluid stabilizer, including 6 mandatory requirements (lightweight, scalability, capacity, stability, robustness and controllability) and 6 desirable requirements.

During concept exploration, we decomposed our device into four components (mount, linkage, actuator, and platform) and used Pugh Charts to select optimal designs for each component. Engineering analysis was conducted on individual design specifications using prior knowledge such as fluid mechanics and robotic kinematics in order to determine specific concepts and parameters for our design.

The final design uses a four-screw mount, truss for linkage, three servos (each coupled with a two-bar link and placed in a 120° angle with respect to each other) for actuator system, a circular plate with four movable locks and a rubber band for platform. During setup, the device would be connected to a delivery robot through the four-screw mount, and the food container would be secured by the locks and rubber band on the platform. During transportation, the actuator system would first measure acceleration through the accelerometer and convert the 3-axis vector into desired rotational motion in pitch and roll. Then, rotational motion can further be achieved by carefully calculated vertical displacements of the three platform joints. As the servos rotate the links, the platform will be tilted to a position that is parallel to the liquid surface in order to prevent spills.

For each requirement, we have proposed a verification test utilizing methods like computer simulation, inspection, and physical testing in order to evaluate the compliance of our prototype to the engineering specifications. Most of the verification tests have already been performed with results presented in the report. For lightweight, capacity, scalability, controllability, low-cost, low-maintenance, easy-to-use, universal compatibility and durability, the results all show good compliance to the engineering specifications. For stability and robustness, simulation results demonstrate good compliance to the specifications, but further physical testing still needs to be completed. For easy-to-setup,
For validation, we proposed a market-based testing cooperating with a delivery robot company to provide a two-week free trial for potential users in order to validate the functionality of our device and the value it can provide to users. Due to time constraints, we were unable to perform this validation test in the semester.

As for some future improvements, this prototype certainly still has room for optimization and customization. From the system level perspective, it is possible to redesign some components and scale this device in order to stabilize much larger loads. In the meantime, from the detailed level, motor selection and PID controller settings can also be adjusted to fulfill specific customer needs and obtain better performance.

15. ACKNOWLEDGEMENTS

The team would like to express our gratitude to the Mechanical Engineering department for sponsoring our project with a budget of $400. Furthermore, we would like to extend our sincerest gratitude to Professor Barton for her generosity in raising our budget to a total of $1000 and her instrumental mentorship guiding us throughout the project. Finally, we would like to thank Robert, Jonathon, Don, Josh, Kemal, Eliza, and all other staff who have helped us in proceeding the project smoothly.

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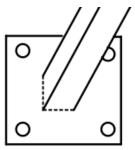
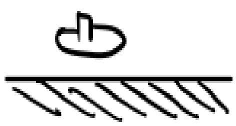
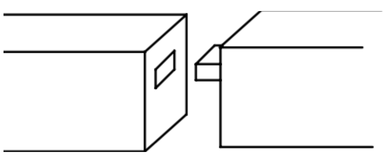
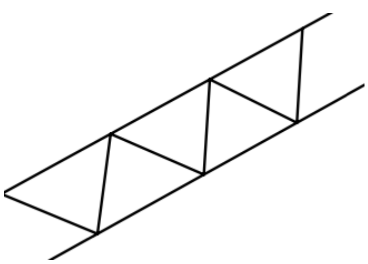
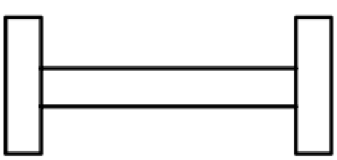
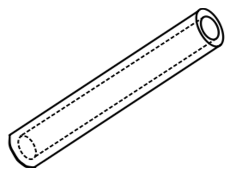
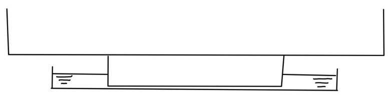
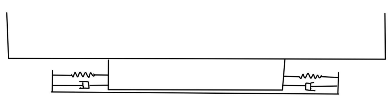
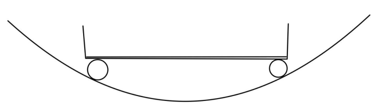
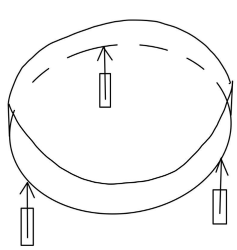
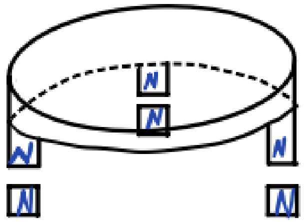
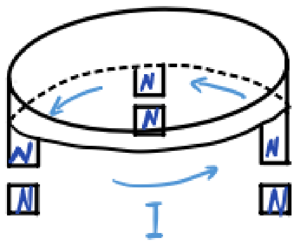
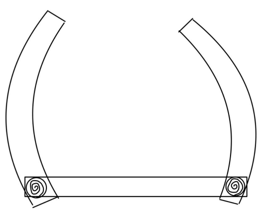
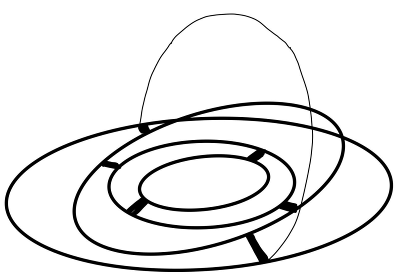
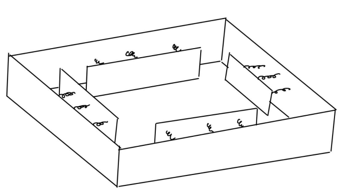
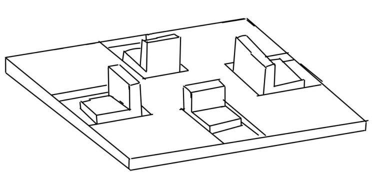
APPENDIX A - Concept Generation

Detailed elaboration of significantly different concepts.

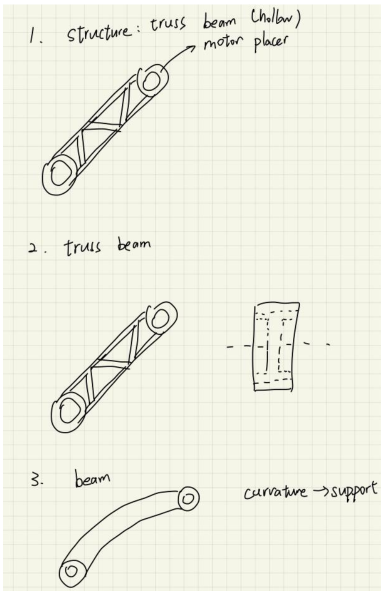
	(A. Mount) Using a magnet as the mount of the device provides great convenience for users. The user can stick the device onto anywhere they put the counterpart magnet. Even if the counterpart does not have a magnet, the device can still attach to the surface if the surface is ferromagnetic.
	(A. Mount) Tightening screws into the predrilled holes is the most common way to secure the base. It is also fast in manufacturing and assembling.
	(A. Mount) A suction plate is used to hold the device in place by creating a vacuum. The suction plate is typically made of a flexible material, such as rubber or silicone, and has a smooth, flat surface with a series of small holes or slits in it. By pressing it down firmly against the flat surface, the vacuum will hold the device in place.
	(B. Linkage) The function of the mortise and tenon joint is to create a strong, stable, and long-lasting connection between two linkages. The mortise provides a secure recess for the tenon to fit into, and the tenon, in turn, provides a large surface area for the glue or other adhesive to bond the two pieces together. The joint is also self-locking, which means it becomes stronger as pressure is applied to it.
	(B. Linkage) A truss is to provide a strong and stable support system that can withstand heavy loads over long spans, without compromising the structural integrity of the surrounding materials. Truss linkages are made up of a series of interconnected triangles, which provide rigidity and stability. The members of a truss can be made of plastic, and are often arranged in a pattern that maximizes their strength and minimizes their weight.
	(B. Linkage) I-beam is to provide a strong and stable support system that can bear weight without bending or sagging, while also minimizing the overall weight of the structure. Its I-shape distributes weight evenly, thereby reducing stress and strain on any one particular point.

	(B. Linkage) A hollow cylinder as a linkage is to provide a structural or functional element that is strong and durable, while also being lightweight. The hollow core of the cylinder can be used to add functionality or reduce weight, while the outer shell provides the necessary stiffness and support.
	(C. Actuator) With a cylinder extended from the platform, a tank of shock absorption fluid is able to affect the dynamics of the platform passively. The extended cylinder submerged in the fluid but the platform remains movable. The tank will be sealed. The shock absorption fluid enables planar movements of the platform (ignoring the vertical movements) and damp out small disturbances. Based on its properties, the fluid can also become rigid to apply some amount of forces under large acceleration. The platform will have some but very little freedom in roll and pitch (free in yaw).
	(C. Actuator) With a cylinder extended from the platform, a system of spring and dampers in the holder is able to affect the dynamics of the platform passively. The extended cylinder is connected to the holder via springs and dampers. The system of springs and dampers enables planar movements of the platform (ignoring the vertical movements) and damp out small disturbances. The platform will have little-to-none freedom in rotations.
	(C. Actuator) The platform with attached roller ball bearings is placed in a bowl. The platform is movable on the curved surface and has the freedom in yaw direction. Given an acceleration, the inertia of the load results in the motion of the platform in the bowl. The motion of the fluid in the load will be converted because of the curvature of the bowl and thus, the fluid will not spill.
	(C. Actuator) Three linear servos that are equally distributed in a circle dominate the dynamics of the platform while supporting the load. It shall be proved that the span of the motions of three equally spaced prismatic joints is a subspace of 3D rotation. If proven, the linear servos can protract or retract the levers so that the platform can tilt in an angle that cancels out the fluid inertia.

	(C. Actuator) Three pairs of opposite magnets that are equally distributed in a circle affects the dynamics of the platform while supporting the load. The repellent magnetic force between magnets serves as the supporting force at a nominal distance. Given some acceleration, the inertia of the objects destabilize the platform by offsetting from the nominal position. The magnetic repellent force is adjusted according to the platform's changed position and trying to restore the balance.
	(C. Actuator) Three pairs of opposite magnets that are equally distributed in a circle and are induced by current dominate the dynamics of the platform while supporting the load. It shall be proved that the span of the motions of three equally spaced prismatic joints is a subspace of 3D rotation. If proven, these magnet pairs can strengthen or weaken the magnetic force between counterparts according to current so that the platform can tilt in an angle that cancels out the fluid inertia.
	(D. Platform) The platform consists of a flat surface where items are placed and two big clamps connected to the flat surface. Torsion springs are embedded on the connecting joints so that the torsion will close the clamp and secure the items in place. It is easy to use as the user pulls the clamps to open and release them to close.
	(D. Platform) The platform consists of several concentric planar rings and these rings are interconnected by two pivots at which the pivots and the center of the ring are collinear. Items (preferably in cup shapes) are placed in the innest rings. The pivots and rings resemble the configuration of Euler's angle. Therefore, the item in the center is free to rotate in space. Also, given an acceleration, the inertia is converted into rotation so the fluid won't spill.
	(D. Platform) Items are secured in the platform by movable walls. These movable walls are connected to platform walls by springs so that the elastic force will close the wall against the item until the item is secured in place. It is easy to use as the user pulls the walls to open and release them to close.
	(D. Platform) Items are secured in the platform by movable walls. These movable walls are inserted into grid slots on the platform and there is a lock in the slot that stops the wall at some distances. When items are placed on the platform, the

	user pulls the wall against the items and then the wall will be locked in place by the slot.

Manuscripts of generated concepts from Xingze. Complete concepts are generated by combinations of components.

<table>
<tr>
<td>
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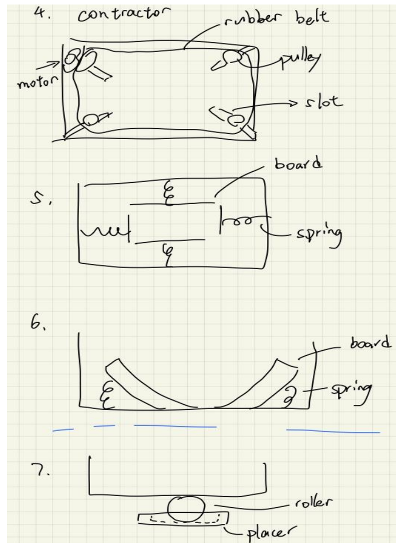
<td>
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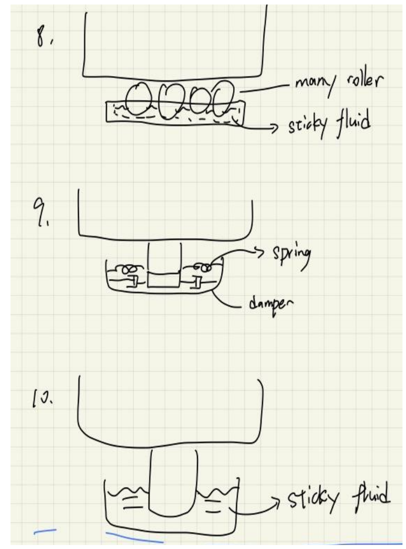
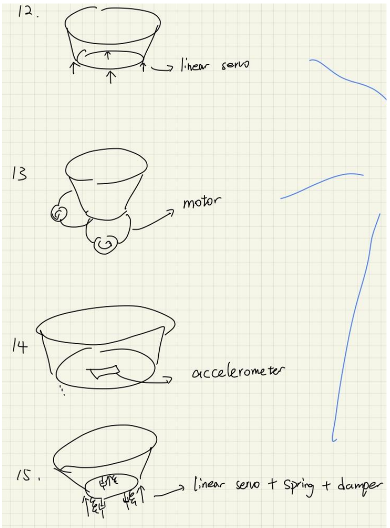
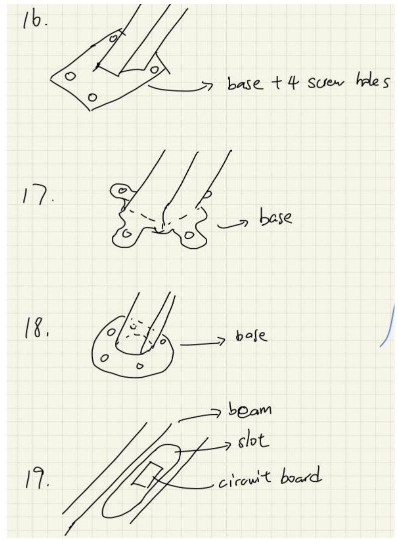
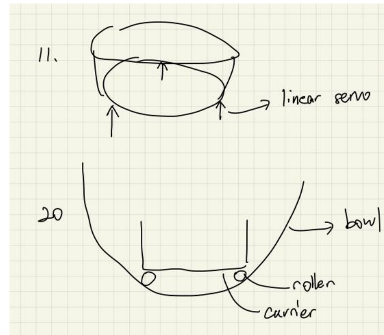
<td>
</td>
</tr>
<tr>
<td>1. The structure of the main support beam is trussed to support load with minimal weight by hollowing out.
2. The cross section is of I-shape.
3. The beam is not straight but with some curvature.</td>
<td>4. Objects are secured by contracting a rubber belt on a pulley system.
5. Objects are secured between contracted walls pushed by springs.
6. Objects are secured between jaws from the bottom contracted by springs.
7. A passive controller. The roller in shock absorption fluid.</td>
<td>8. A passive controller. A ball bearing in shock absorption fluid.
9. A passive controller. The pivot is controlled by springs and dampers.
10. A passive controller. The pivot in only shock absorption fluid.</td>
</tr>
</table>

		
12. Active control. Four linear servos equally distributed. 13. Active control. Two rotary motors. 14. An accelerometer is attached to the bottom of the platform. 15. Active & passive control. Three linear servos with spring-damping systems.	16. Mount. The base of the mount is a square base with four screw holes at all corners. 17. Mount. The base of the mount is after material removal with four holes at flanks. 18. Mount. A round base with equally distributed five screw holes. 19. Carved hole on the supporting structure where the circuit board can be stored.	11. Active control. Three linear servos equally distributed. 20. The platform is a curved bowl where containers with wheels can slide inside the bowl.

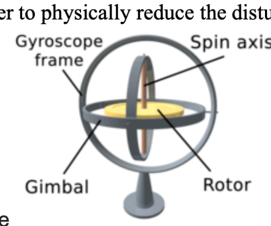
Initial concepts from Jinxin along with iterated concepts in bullet points.

1. Crab shape
2. Crab shape with a spring

3. Gimbal shape
4. Platform shape with four moving supports

5. Magnet mounted component
6. Stablier rings
7. Platform shape with four magnets supports and strings
8. Robotic arm shape
9. Flexible material

10. Drone shape using propeller
11. Use damper to physically reduce the disturbance



12. Gyroscope
13. Super material which can absorb disturbance
14. Using high density liquid to be the holder liquid
15. Use the idea from boat
16. Ball shape with two layers, between them is lubricants
17. A genius computer can solve this problem

18. Circular shape with two layers, and between them are wheels to control the position
19. Idea from 
20. ReuleauxTriangle 

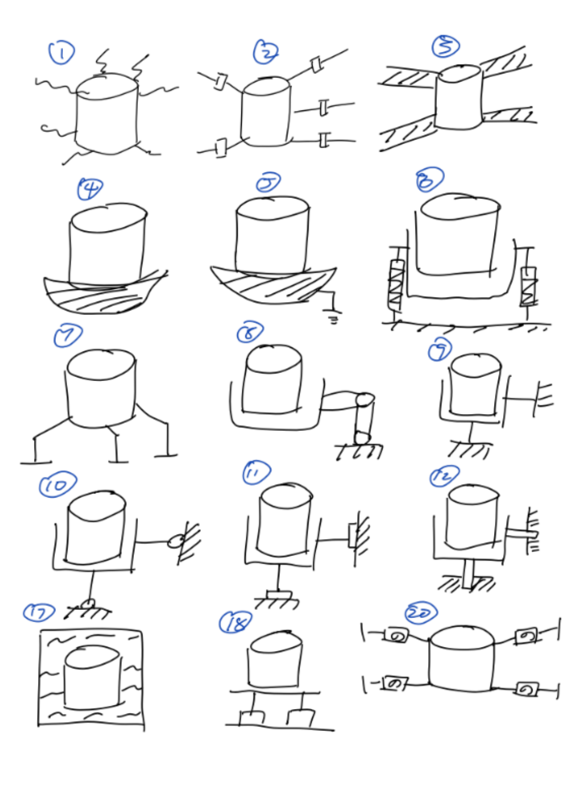
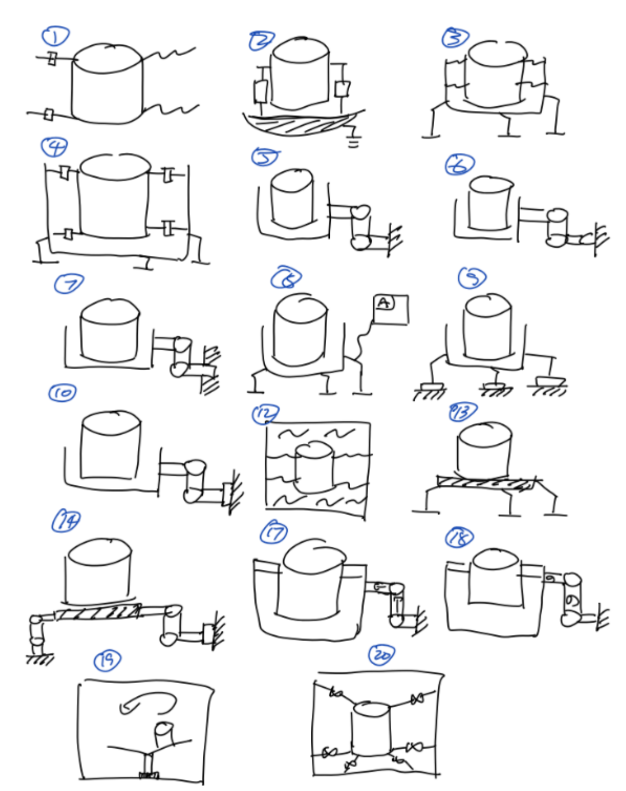
Iterated concepts:

- Crab shape grasper with gimbal shape stabilizer.
- Crab shape grasper with a locker system.
- Use super material which can absorb the disturbance onto the circular platform.
- Design a crab shaped grasper and install it on a drone.

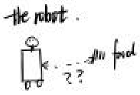
• Circular platform shape with one support in the center. • Gimbal shape support is placed in the center of the platform. • Combine the ring design with the Gyroscope. • Combine Reuleaux Triangle with stabilizer. • Flexible material used on the circular platform. • Use the high density liquid with ball shape design. • Adopt the boad idea into the ball shape design.	• Install a robotic arm on a drone. • Apply a genius computer on the circular platform • Apply a genius computer on the gimbal. • Place some magnets on the ball shape design. • Use flexible material onto the reuleaux triangle. • Inverse motion calculation to cancel the force. • Idea from Maglev. • Combine the drone and gimbal.

Concepts from Zilong with graphs attached.

Initial Concepts:		Iterated Concepts:	
1	Passive spring	1	Spring+damper
2	Passive damper	2	Combination of all sorts of suspension
3	Elastic Fabric	3	Robot arm with passive spring
4	Mechanical suspension	4	Robot arm with passive damper
5	Electromagnetic suspension	5	Gimbal with screw mount
6	Air suspension	6	Gimbal with anchor mount
7	Robot arm	7	Gimbal with mortise and tenon
8	Gimbal	8	Arduino power robot arm
9	Screw mount	9	Robot arm with suction cup mount
10	Anchor mount	10	Gimbal with suction cup mount
11	Suction cup mount	11	DIY controller arm
12	Mortise and tenon	12	Viscous spring cabin with springs
13	Arduino microprocessor	13	Robot arm with internal platform

14	Teensy processor	14	Gimbal with internal platform
15	Launchpad MSP430	15	Robot arm with hydraulics
16	DIY PCB board	16	Gimbal with hydraulics
17	Viscous fluid cabin	17	Multi-DOFs gimbal with mechanical damper
18	Internal platform	18	Multi-DOFs gimbal with eddy current dashpot
19	Hydraulics	19	Rotating inclined platform
20	Eddy current dashpot	20	Robust supporting lock
			

Manuscript of generated concepts from Yanyu (Cassie).

solutions / parameters				
Fluid stay in container	large container	perfectly sealed	Container move w.r.t. fluid surface so that fluid surface will never be higher than container	Apply stress to increase viscosity
Reduce fluid motion	special container design for restricting flow	Control container/platform to stay relatively static to the ground	Increase robot stability with regard to obstacles on the road.	Sensor decting motion of fluid and direct container move to opposite direction
Reduce effect of fluid inertia on the robot	counter-weight that balance out/cancel fluid inertia during transportation.	put food "outside" of the robot. 	Add more weight to robot itself	Uniformly distribute or compartmentalize liquid in different orientations such that their inertia effect will cancel each other
Make transportation smoother.	build {special railways / channels for robots	better vision/perception for avoiding obstacles	Reduce robot acceleration	more straight & level pathways (less turning, elevating or lowering)

Design heuristic:

18. change direction of access:

   instead a cup/bowl-like container where food is put in with support from bottom surface.

   Use a cap like device coupled with a plate 

4. Add to existing product:

   Could use a gimbal platform as base.

8. Allow user to assember:

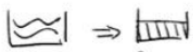
   Mount adaptable to different robot systems

13. Apply Existing Mechanism in a new way

   Utilize existing stabilization (shock absorption) system for robots, use for holders.

Q Stabilize fluid for delievery robot.

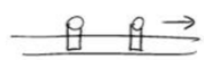
From fuid
① Make the fluid frozen/becom solid



② Restrict flow.
③ sealed container fulfilled 
④ cancel fuid inertice ?
⑤ compress fluid ?
⑥ increase viscosity
⑦ make weightless ?
⑧ make fluid motionless ?

From enviroment.
① channel transportation for robots
② tunnel for liquid to flow

③ railway

From robot.
① large hands to hold/adjust container. 
② teleportation
③ conveyor belt 
④. make the container/platform always stay still.
⑤. bring person/customer down instead of bring fluid up.
⑥. Container always move in opposite direc. of fluid

APPENDIX B - Concept Downselection

For the linkage, we had a total of five concepts (cylinder, truss, I-beam, telescoping arm, mortise and tenon) and six evaluation criteria (strength, lightweight, durability, easy to set up, low cost, low maintenance). The first criterion, strength, was not drawn directly from our user requirements. Because the linkage system needs to be strong enough to support the main weight of our device, we added this additional evaluation criterion and assigned it with the highest weight 4. Lightweight is a general property constraining weight of the whole device and thus should apply to all four main components. And since it is a mandatory requirement, lightweight was assigned with a weight of 3. Remaining criteria all came from desired requirements. Because we want the linkage to provide reliable support in long-term operations, durability was weighted a little higher (2). And all other criteria had a weight of 1. We chose the cylinder as the base design, and evaluated the other four concepts with respect to it. The final Pugh chart with weights and scoring labeled is shown in Table B.1 below.

Table B.1. Pugh chart for Linkage

	Cylinder	**Truss**	**I-beam**	**Telescoping arm**	**Mortise and Tenon**
Strength (4)	0	1	1	-1	-1
Lightweight (3)	0	1	0	-1	0
Durability (2)	0	1	1	-1	-1
Easy to Set Up (1)	0	0	0	-1	0
Low Cost (1)	0	-1	1	-1	-1
Low Maintenance (1)	0	0	0	-1	1
Total	0	8	7	-12	-6
Rank	3	1	2	5	4

According to Table B.1, truss had the highest score among all five concepts. In particular, the truss has high strength and weighs less because of its composition of multiple hollow triangular structures. Truss also has a better durability because it does not contain any moving parts like a telescoping arm or require any additional connections like mortise and tenon. The only disadvantage is that truss might cost more in product than cylinder and I-beam due to its more complex structure.

For the platform, we had a total of five concepts (grabber, wobbler, plate with locks, plate with belts, plate with spring clamps) and eight criteria (scalability, capacity, easy to use, lightweight, durability, easy to set up, low maintenance, low cost). Scalability and capacity were both assigned with the highest weight 4, because they are mandatory requirements, and we want our device to have more applications and be able to hold more containers with different sizes and weights. Although easy to use comes from desired requirements, it concerns user experience and targets the platform specifically. Therefore, easy to use was assigned with a weight of 3. As a mandatory requirement applicable to all main components, lightweight had a weight of 2 as always. Remaining criteria from desired requirements all had a weight of 1. The final Pugh chart with grabber selected as the base design is shown in Table B.2 below.

Table B.2. Pugh chart for platform

	Grabber	**Wobbler**	**Plate w/ locks**	**Plate w/ rubber belt**	**Plate w/ spring clamps**
Scalability (4)	0	-1	1	1	1
Capacity (4)	0	-1	1	1	1
Easy to Use (3)	0	1	-1	0	-1
Lightweight (2)	0	1	0	0	0
Durability (1)	0	0	1	-1	0
Easy to Set Up (1)	0	1	-1	-1	-1
Low Maintenance (1)	0	0	0	-1	-1
Low Cost (1)	0	1	0	-1	0
Total	0	-1	5	4	3
Rank	4	5	1	2	3

According to Table B.2, plates with locks had the highest score among all five concepts. In particular, it has good scalability due to locks with continuous motion and good capacity due to the large supporting surface provided by the plate. The design also has good durability because it has higher structural or material strength compared to other concepts. However, since we anticipate the need of four separate locks to fully secure one container in place, this design would require more operating steps for both set up and daily use.

APPENDIX C - Proof for Controllability

Proposition 1. In this application situation, the liquid surface can be analytically represented given a known acceleration.
Proof. It has been proved that in two-dimensional cases, the slope of constant pressure line, *dp=0*, is given by Equation 2.28 [C.1]:

$$\frac{dz}{dy} = -\frac{a_y}{g+a_z}$$

where a_y is the horizontal acceleration and a_z is the vertical acceleration. The constant pressure line is parallel to the liquid surface. This conclusion can be further developed in three-dimensional cases without effort. For any acceleration on the x-y plane, there always exists a plane perpendicular to the x-y plane such that the acceleration lies in that plane. Thus, the planar acceleration is converted to a one-dimensional case as derived above. □

Need to find: the liquid surface equation given accelerations.
Provided the sensor, the accelerations a_x, a_y, a_z, are individually observable. Thus, the liquid surface (constant pressure surface) is expressed in terms of these accelerations. The normal vector of the water surface is given by the vector

$$n = \frac{[-a_x \ -a_y \ (g+a_z)]^T}{||[-a_x \ -a_y \ (g+a_z)]^T||} = \frac{[-a_x \ -a_y \ (g+a_z)]^T}{\sqrt{{a_x}^2 + {a_y}^2 + (g+a_z)^2}}$$

We can set the origin of the coordinator to be always on the water surface. Then, for any point, $P = [x,\ y,\ z]^T$, on the water surface, it can be expressed in terms of the following equation:

$$p \times n = 0 \qquad \text{(X)}$$

Therefore, the liquid surface, *S*, is a subspace of $\mathbb{R}^3$ that consists of all the points, *p*, that satisfies the Eq. X, i.e., $S = \{p \mid p \times n = 0,\ p \in \mathbb{R}^3\}$. For liquid in a container, its surface, $\bar{S}$, is a subspace of *S*, as it is bounded by the container.

Remark. The liquid surface equation leads us to the desired platform configuration. Suppose the platform is at its zero configuration, whose coordinates are parallel to the world coordinates, and consider the liquid container and the platform are rigidly connected. When the platform accelerates, the liquid surface is altered and described by Eq. X. Because of the gradient, there exists a point $p_h \in \bar{S}$ such that $p \cdot [0\ 0\ 1]^T \leq p_h \cdot [0\ 0\ 1]^T,\ \forall p \in \bar{S}$. That is, the point, p_h, is the global highest point on the surface. When the height of this point is greater than the container's brim height, the liquid overflows. A common method to prevent liquid overflow, and this is the method this project mainly adopts, is to tilt the container so that the brim compensates for the lack of height. The ideal condition is when the container's bottom surface is parallel to the liquid surface. It should come naturally to an agreement that in ideal control conditions, the platform's coordinate is parallel to the liquid surface coordinate and different from the world coordinates by orientation. In summary, the orientation composed of one rotation about x-axis and one rotation about y-axis is of our interest.

In this project, we propose that it is sufficient to guarantee any desired platform orientation by assigning the vertical position of three individual points on the platform.

Lemma 1. For any three vertical prismatic joints that have the same distance to the z-axis and are equally spaced, the rigid body can have desired orientation in the space. That is,

$$g(v_1, v_2, v_3) \subset S^1 \times S^1$$

Proof. Assume that the assigned location at $[r, 0, 0]^T$, $[-\frac{1}{2}r, \frac{\sqrt{3}}{2}r, 0]^T$, $[-\frac{1}{2}r, -\frac{\sqrt{3}}{2}r, 0]^T$ where r is the radius from the z-axis. The points on the platform after motions are

$$p_1 = [r, 0, v_1]^T$$

$$p_2 = [-\frac{1}{2}r, \frac{\sqrt{3}}{2}r, v_2]^T$$

$$p_3 = [-\frac{1}{2}r, -\frac{\sqrt{3}}{2}r, v_3]^T$$

Since p_1, p_2, p_3 are noncollinear by construction, they define a bounded plane, $\bar{S}$, which is bounded by the radius. To restrict the motion into two degrees of freedom of rotations, we specify a constraint that $[0,\ 0,\ 0] \in \bar{S}$. As a result, the equation of $\bar{S}$ has the form:

$$\bar{S}:\ ax + by + cz = 0$$

Rewrite it in vector form and we get

$$\begin{bmatrix} | & | & | \\ x & y & z \\ | & | & | \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0$$

Since $p_1,\ p_2,\ p_3 \in \bar{S}$, plugging their position into the parameterized surface equation renders:

$$A \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0$$

$$\text{where } A = \begin{bmatrix} r & 0 & v_1 \\ -\frac{1}{2}r & \frac{\sqrt{3}}{2}r & v_2 \\ -\frac{1}{2}r & -\frac{\sqrt{3}}{2}r & v_3 \end{bmatrix}$$

Thus, $\bar{S}$ is the realization of the nullspace of A.

$$\mathcal{N}(A) = c\begin{bmatrix} -\frac{v_1}{r} \\ -\frac{v_1+2v_2}{\sqrt{3}r} \\ 1 \end{bmatrix}$$

For simplicity, take $c = 1$ and we get

$$\bar{S}: \ -\frac{v_1}{r}x - \frac{v_1+2v_2}{\sqrt{3}r}y + z = 0$$

The normal vector of the surface is $n = \frac{[-\frac{v_1}{r}, -\frac{v_1+2v_2}{\sqrt{3}r}, 1]^T}{||[-\frac{v_1}{r}, -\frac{v_1+2v_2}{\sqrt{3}r}, 1]^T||} = \frac{[-v_1, -\frac{1}{\sqrt{3}}(v_1+2v_2), r]^T}{\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}}$. Let $s = \frac{p_1}{||p_1||} = [\frac{r}{\sqrt{r^2+v_1^2}}, 0, \frac{v_1}{\sqrt{r^2+v_1^2}}]^T$, and $t = n \times s = \frac{[-v_1(v_1+2v_2),\ \sqrt{3}(r^2+v_1^2),\ r(v_1+2v_2)]^T}{\sqrt{r^2+v_1^2}\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}}$.

Suppose there exists a rotation matrix $R_{ab} \in SO(3)$ and a corresponding rotation angle $\theta \in \mathbb{R}$ such that

$$R_{ab}g_{ab}(0) = g_{ab}(\theta)$$

Since $g_{ab}(0) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

$$R_{ab} = g_{ab}(\theta) \text{ where}$$

$$g_{ab}(\theta) = \begin{bmatrix} \frac{r}{\sqrt{r^2+v_1^2}} & \frac{-v_1(v_1+2v_2)}{\sqrt{r^2+v_1^2}\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} & \frac{-\sqrt{3}v_1}{\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} \\ 0 & \frac{\sqrt{3}(r^2+v_1^2)}{\sqrt{r^2+v_1^2}\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} & \frac{-v_1-2v_2}{\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} \\ \frac{v_1}{\sqrt{r^2+v_1^2}} & \frac{r(v_1+2v_2)}{\sqrt{r^2+v_1^2}\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} & \frac{\sqrt{3}r}{\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} \end{bmatrix}$$

According to basic Euler angles, R_x is the rotation around the x-axis with roll angle γ and R_y is the rotation around the y-axis with pitch angle β. They have the form

$$R_x(\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix} \ R_y(\beta) = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix}$$

The general rotation matrix can be obtained by following the XYZ convention.

$$\bar{R} = R_z(\alpha)R_y(\beta)R_x(\gamma)$$

Because the yaw rotation doesn't take place, $R_z(\alpha) = I$.

$$\bar{R} = \begin{bmatrix} \cos\beta & -\sin\beta\sin\gamma & -\sin\beta\cos\gamma \\ 0 & \cos\gamma & -\sin\gamma \\ \sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$$

By observation, we can correspond terms from $\bar{R}$ to R_{ab}.

$$\left.\begin{aligned} \sin\beta &= \frac{-v_1}{\sqrt{r^2+v_1^2}} \\ \cos\beta &= \frac{r}{\sqrt{r^2+v_1^2}} \end{aligned}\right\} \quad \tan\beta = \frac{-v_1}{r} \qquad \Rightarrow \beta = \arctan\frac{-v_1}{r}$$

$$\left.\begin{aligned} \cos\gamma &= \frac{\sqrt{3}\sqrt{r^2+v_1^2}}{\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} \\ \sin\gamma &= \frac{v_1+2v_2}{\sqrt{4v_1^2+4v_1v_2+4v_2^2+3r^2}} \end{aligned}\right\} \quad \tan\gamma = \frac{v_1+2v_2}{\sqrt{3}\sqrt{r^2+v_1^2}} \qquad \Rightarrow \gamma = \arctan\frac{v_1+2v_2}{\sqrt{3}\sqrt{r^2+v_1^2}}$$

Since $v_1, v_2 \in \mathbb{R}$, $v_1 \longmapsto \beta \in (-\frac{\pi}{2}, \frac{\pi}{2})$ is bijective and $(v_1, v_2) \longmapsto \gamma \in (-\frac{\pi}{2}, \frac{\pi}{2})$ are surjective.

Then, we look at p_3. Since $p_3 \in \bar{S}$, plug p_3 into the surface equation and we get

$$-\frac{v_1}{r}(-\frac{1}{2}r) - \frac{v_1+2v_2}{\sqrt{3}r}(-\frac{\sqrt{3}}{2}r) + v_3 = 0$$

We can get v_3 by rearranging the equation,

$$v_3 = -v_1 - v_2$$

For any v_1 and v_2, there always exists a corresponding $v_3 \in \mathbb{R}$. Therefore,

$$g(v_1, v_2, v_3) \rightarrow \bar{R}$$

is surjective. That is, the combination of (v_1, v_2, v_3) spans the desired configuration space. □

To find the relationship between accelerations and three vertical positions, let $s = p_2 - p_1 = [-\frac{3}{2}r,\ \frac{\sqrt{3}}{2}r,\ v_2 - v_1]^T$ and $t = p_3 - p_1 = [-\frac{3}{2}r,\ -\frac{\sqrt{3}}{2}r,\ v_3 - v_1]^T$. The vector *s* and *t* lie on the surface as well and satisfy the surface equation given an acceleration.

$$s \cdot n = [-\frac{3}{2}r,\ \frac{\sqrt{3}}{2}r,\ v_2 - v_1]^T \cdot \frac{[-a_x\ -a_y\ (g+a_z)]^T}{\sqrt{a_x^2+a_y^2+(g+a_z)^2}} = 0$$

$$\begin{cases} t \cdot n = [-\frac{3}{2}r, \ -\frac{\sqrt{3}}{2}r, \ v_3 - v_1]^T \cdot \frac{[-a_x \ -a_y \ (g+a_z)]^T}{\sqrt{a_x^2 + a_y^2 + (g+a_z)^2}} = 0 \\ \end{cases}$$

$$\begin{cases} s \cdot n = \frac{3}{2}ra_x - \frac{\sqrt{3}}{2}ra_y + (v_2 - v_1)(g + a_z) = 0 \\ t \cdot n = \frac{3}{2}ra_x + \frac{\sqrt{3}}{2}ra_y + (v_3 - v_1)(g + a_z) = 0 \end{cases}$$

$$\begin{cases} v_2 = \frac{-\frac{3}{2}a_x + \frac{\sqrt{3}}{2}a_y}{g+a_z}r + v_1 \\ v_3 = \frac{-\frac{3}{2}a_x - \frac{\sqrt{3}}{2}a_y}{g+a_z}r + v_1 \end{cases}$$

In this system of equations, v_1 is a free variable. We need the third constraints to find v_1. The third constraint is that because of pure rotation, the origin should lie on the plane. That is, for any point $q = [q_x, q_y, q_z]^T \in S$, we have

$$q \cdot n = -a_x q_x - a_y q_y + (g + a_z)q_z = 0$$

So does p_1.

$$p_1 \cdot n = -a_x r + (g + a_z)v_1 = 0$$

$$\Rightarrow v_1 = \frac{a_x}{g+a_z}r$$

Therefore, we can uniquely find v_1, v_2, v_3.

$$v_1 = \frac{a_x}{g+a_z}r$$

$$v_2 = \frac{-\frac{1}{2}a_x + \frac{\sqrt{3}}{2}a_y}{g+a_z}r$$

$$v_3 = \frac{-\frac{1}{2}a_x - \frac{\sqrt{3}}{2}a_y}{g+a_z}r$$

APPENDIX D - Arduino Setup

The electrical circuit prototype is designed as shown in Figure 31. Details are explained by functional parts.

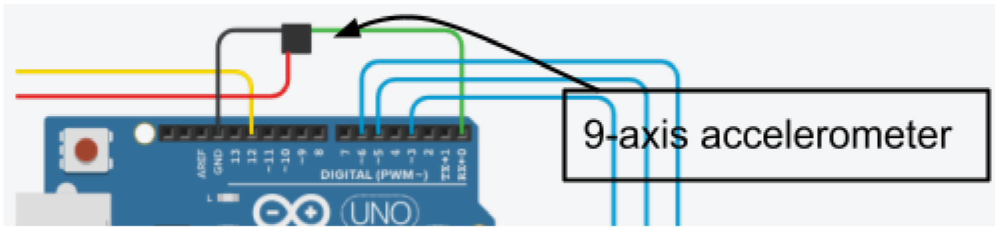


Figure D.1 Connection between Arduino and 9-axis Accelerometer.

The positive lead of the 9-axis accelerometer is connected to Arduino +5V output and its negative lead is connected to the ground. The accelerometer senses data as soon as it is properly powered. The sensor data is sent through the Serial communication portal (RX 0) on the Arduino board [D.1][D.2][D.3][D.4][D.5][D.6][D.7]. The accelerometer hardware has an embedded Kalman filter [D.8] so we do not need to worry about the sensor error. The pseudocode of accessing data are as below [D.9][D.10]:

Algorithm 1: Access Accelerometer data

Initialize static memory *acc* to capacity 3
Initialize static memory *angle* to capacity 2
Initialize sensor object *S*
…
// main loop
…
if Serial.Event( ) **then**
    Update *acc* with *S.acc*
    Update *angle* with *S.angle[0], S.angle[1]*
end if

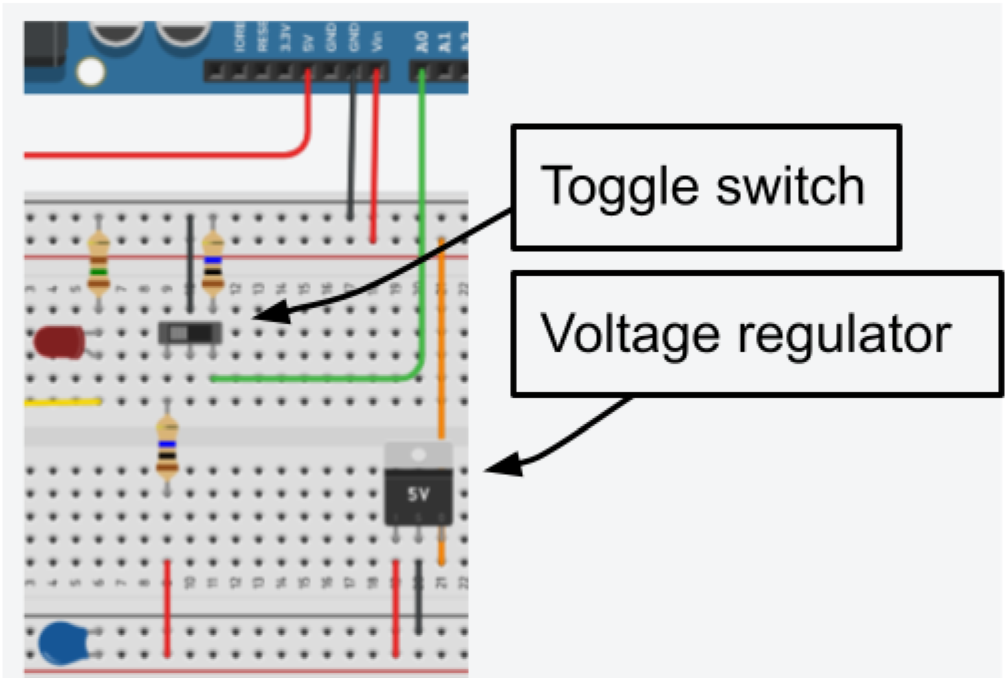


Figure D.2. Voltage protection system.

The 7.4 V source is regulated to 6 V by a voltage regulator and this 6 V powers servos and the Arduino board. A series of 10 Ohms resistors connects between the 7.4 V source and the ground and the midpoint voltage is led to the analog input (A0) on the Arduino board to read the source voltage [D.11]. A digital output (D10) is used to activate the red LED. When the toggle switch is off, the voltage measurement is 0 V and the LED is on. The main program does not run at this stage. When the toggle switch is on, A0 measures the source voltage. If the measured voltage is greater than 6 V, the LED is off and the main program runs. Otherwise the main program deactivates and the LED is on to notify the user. The pseudocode of this is attached below:

Algorithm 2: Voltage protection

```
function protection( )
    volt ← ReadAnalog( )
    if volt < 1.5 then
        WriteDigital(LED, on)
        return status = 0
    else
        WriteDigital(LED, off)
        return status = 1
    end if
end function
…
main(status)
```

…

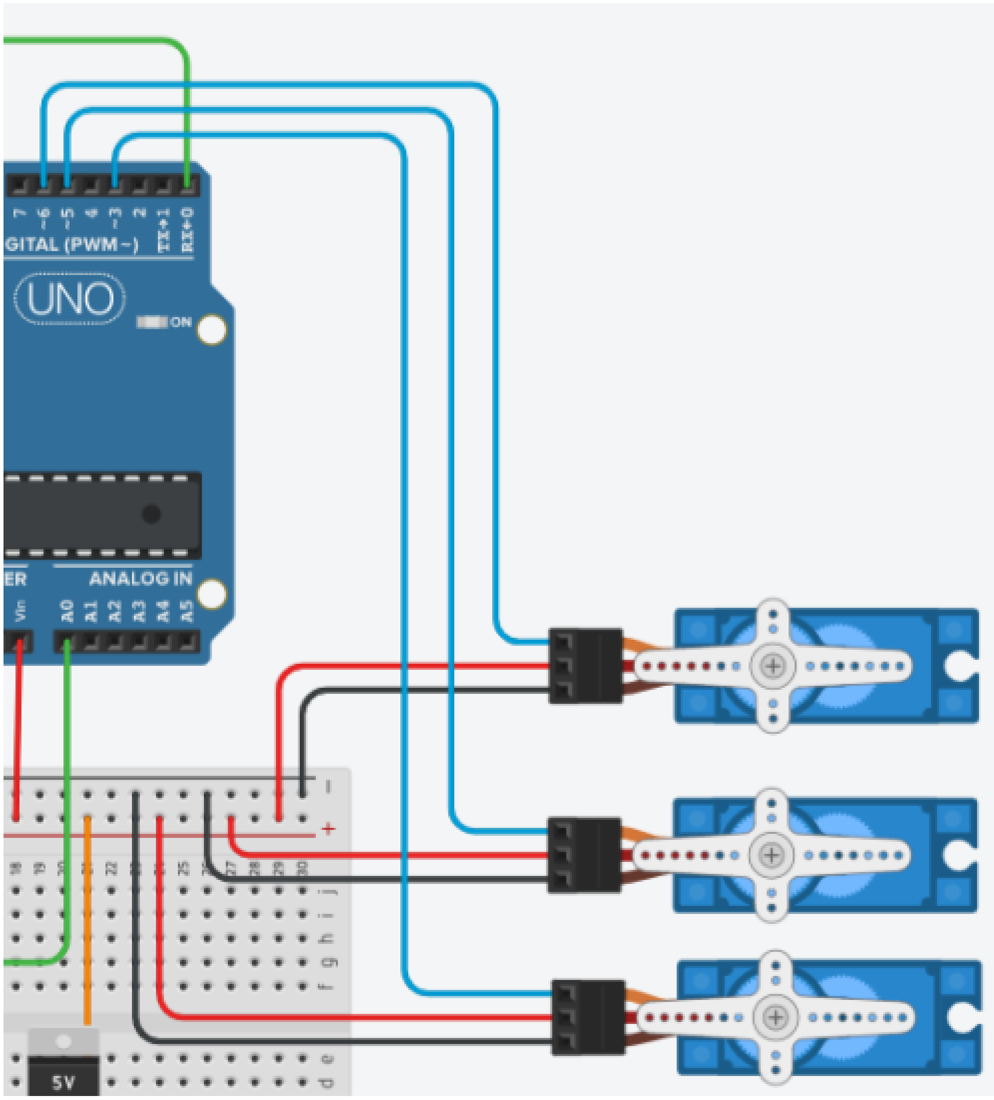


Figure D.3. Regulated voltage source directly supplies three servos. Three PWM signals are separately sent from the Arduino board to each servo.

The 7.4 V voltage source is regulated and stabilized at 6 V which is the optimal working voltage for our servos [D.12]. These servos directly connect to the power supply to gain enough current to drive it (previous servos[D.13] are incapable of generating enough torque). The Arduino board utilizes three PWM signal ports (D3, D5, D6) to control the servos [D.14]. Interrupts are managed to prevent unexpected behavior of asynchronization [D.15][D.16][D.17][D.18][D.19][D.20]. The pseudocode is attached below:

Algorithm 3: Servo Driver

```
Initialize static memory pwm to capacity 3
Initialize the first servo object Servo1
Initialize the second servo object Servo2
Initialize the third servo object Servo3
…
Update pwm
pwm[0] ← saturation(pwm[0], MIN_PWM, MAX_PWM)
pwm[1] ← saturation(pwm[1], MIN_PWM, MAX_PWM)
pwm[2] ← saturation(pwm[2], MIN_PWM, MAX_PWM)
Disable Interrupt
Servo1.drive(pwm[0])
Servo2.drive(pwm[1])
Servo3.drive(pwm[2])
Enable Interrupt

function saturation(value, lower_bound, upper_bound)
        return value within (lower_bound, upper_bound)
end function
```

A discrete PID controller is implemented in the coding base and corresponds to the simulation's optimal result. The controller is identical over three servos as its identicality is proved in previous sections. In this PID control, a discrete time step is chosen [D.21]. A filter coefficient is introduced to implement a derivative gain [D.22][D.23][D.24]. Finally, an anti-windup mechanism is implemented to prevent integration gain from blowing up [D.25][D.26][D.27][D.28][D.29]. The algorithm is attached below:

Algorithm 4: PID controller

```
Define KP, KI, KD     // PID gains
Define N, step        // filter coefficient and discrete time step
Initialize integrate_state to capacity 3
Initialize derivative_state to capacity 3
…
Update angle
pwm[0] ← pid(angle[0], integrate_state, derivative_state)
pwm[1] ← pid(angle[1], integrate_state, derivative_state)
pwm[2] ← pid(angle[2], integrate_state, derivative_state)

function pid(angle, integrate_state, derivative_state)
        filter_coefficient ← (KD * angle - derivative_state) * N
        output ← KP * angle + integrate_state + filter_coefficient
        integrate_state += KI * angle * step + 10 * step * (- output_difference)
        derivative_state += filter_coefficient * step + 2 * step * (-output_difference)
```

```
        return output
end function
```

APPENDIX E - Bill of Materials

Table E.1. The off-the-shelf parts with name, part number, supplier, quantity and price.

Purchased Materials				
Name	**Part Number**	**Supplier**	**Quantity**	**Price**
9-Axis Accelerometer	WT901	WITMOTION	1	$33.90
Digital Giant Servo	FT5335M-FB	Pololu	3	$52.95
Breadboard	US_QSX_1.0.1	SPIRICH	1	$7.93
Arduino	Mega 2560	Arduino	1	$48.20
Solid Wire	B07TX6BX47	TUOFENG	1	$14.99
USB 2.0 Cable Type A/B	M000006	Arduino	1	$6.99
Soldering Iron Kit	B087767KNW	Q-MING	1	$21.99
Lineman's Pliers	HX-1-002	YIYITOOLS	1	$10.80
Mil. Spec. Phillips Rounded Head Screw	91400A862	McMaster-Carr	1	$18.54
Medium Strength Steel Hex Nut	95505A611	McMaster-Carr	1	$6.25
Moisture Resistance cushioning washer	93650A117	McMaster-Carr	1	$5.84
Alloy Steel Socket Head Screws	91864A025	McMaster-Carr	1	$9.21
Metric Thread Machine Taps Set	N/A	Sunxenze	1	$12.70
In-line ball and socket joint	AGRM-08	IGUS	1	$15.44
Dowel Pin	98381A472	McMaster-Carr	1	$9.30
Needle-Roller Bearings	5905K331	McMaster-Carr	3	$35.34
Push-on External Retaining Rings	98430A116	McMaster-Carr	1	$5.65
7.4V Lithium-ion Battery	SM2P RC	URGENEX	1	$12
Adjustable Voltage Regulator	LM2596	Valefod	1	$1.83
10 MΩ Resistor	-	X50 Lab	2	Borrowed
Red LED	-	X50 Lab	1	Borrowed
150 Ω Resistor	-	X50 Lab	1	Borrowed
1 uF, 16 V Polarized Capacitor	-	X50 Lab	1	Borrowed
100 nF Capacitor	-	X50 Lab	1	Borrowed

Purchased Materials				
Name	**Part Number**	**Supplier**	**Quantity**	**Price**
Slide switch	-	X50 Lab	1	Borrowed

APPENDIX F - Manufacturing Plan /Assembly Plan

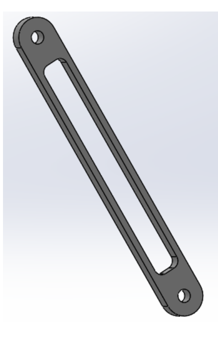
Step 1: 3D-print the parts designed in Solidworks using SLA. The parts are shown in Table F.1.

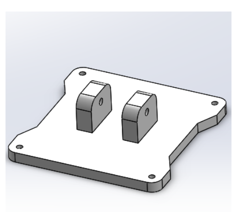
Table F.1. The in-house parts with their name, manufacturing method, material and quantity.

Designed Parts (Name in Solidworks)			
Part's Name	**Manufacturing Process**	**Material**	**Quantity**
Actuator	3D-Print	SLA	1
Platform	3D-Print	SLA	1
Slider up	3D-Print	SLA	4
Slider down	3D-Print	SLA	4
Mount	3D-Print	SLA	1
Truss	3D-Print	SLA	2
6 cm linkage	3D-Print	SLA	3
5.5 cm linkage	3D-Print	SLA	3

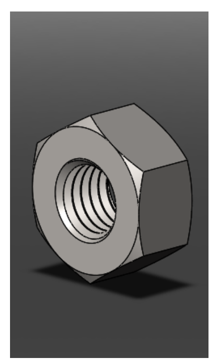
Step 2: Align the hole on one side of the link with the hole on the mount for two identical links. Connect the linkage component to the mount component using two pairs of screws, nuts, and rubber washers by using a No. 3 Phillips screwdriver and a 7/16-inch wrench.

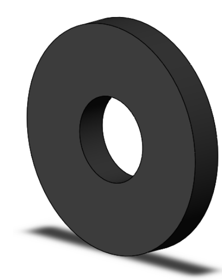
Parts will be used:


2* 3D-printed links

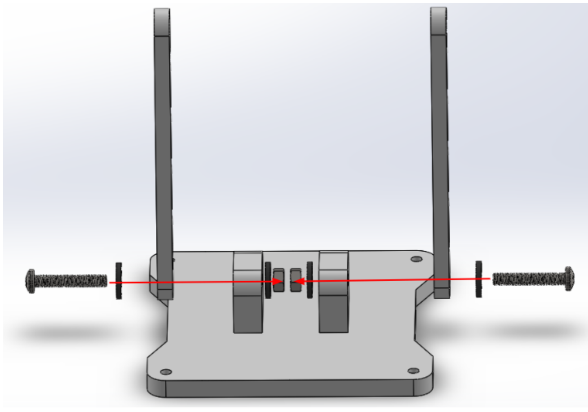

1* 3D-printed mount

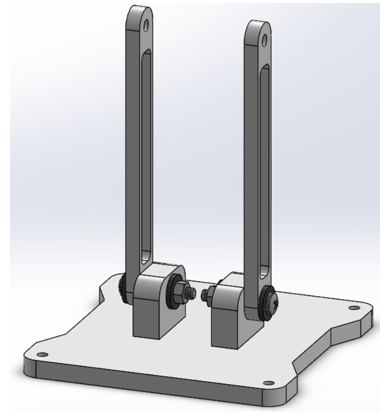

2* Phillips Screws (91400A862 McMaster)


2* Nuts (95505A611 McMaster)


4* Rubber Washers (93650A117 McMaster)

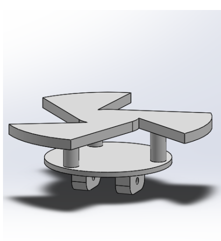
Connection diagram:





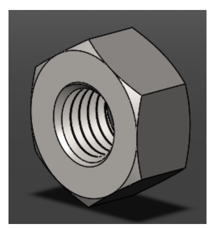
Step 3: This step is similar to step one. Align the hole on the other side of the link with the hole at the bottom of the actuator. Connect the linkage component to the mount component using two pairs of screws, nuts, and rubber washers by using a No. 3 Phillips screwdriver and a 7/16-inch wrench.

Parts will be used:

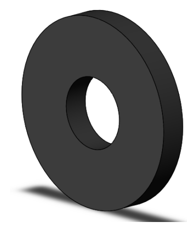


1* 3D-printed Actuator Plate

2* Phillips Screws (91400A862 McMaster)

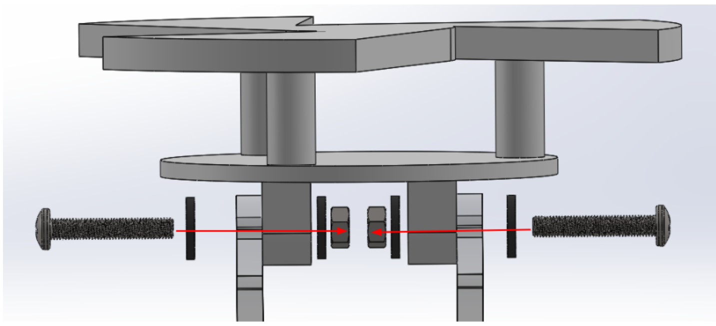


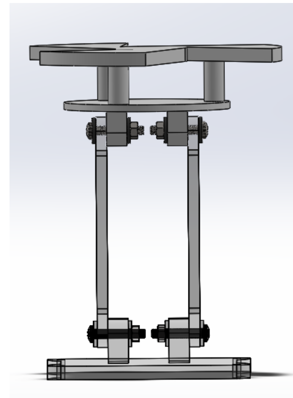
2* Nuts (95505A611 McMaster)



4* Rubber Washers (93650A117 McMaster)

Connection Diagram:



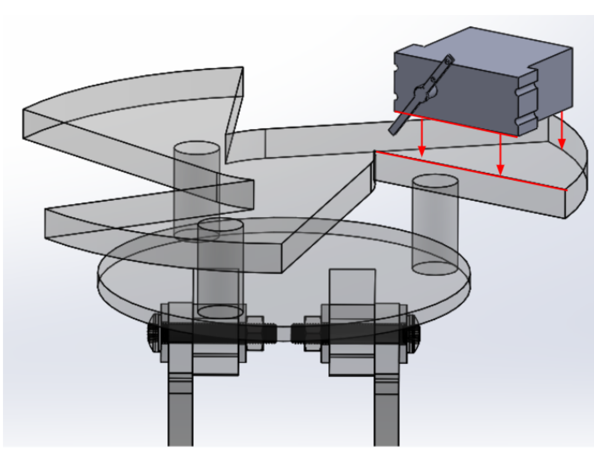


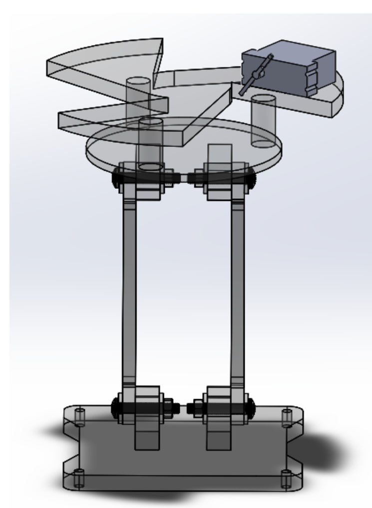
Step 4: Use electrical tape to fix the servo onto the actuator plate. The front end of the servo should be collinear with the edge of one side of the fan shape actuator plate, which is indicated by two red lines in the connection diagram below.

Parts will be used:

1* Digital Giant Servo **(**FT5335M-FB Pololu**)**

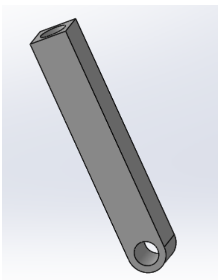
Connection Diagram:



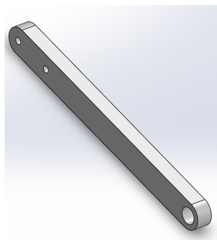


Step 5: First, use an Arbor press to push the dowel pin into the press-fit hole on the 5.5cm linkage, which is shown by the red arrow in the connection diagram. Then, use the Arbor press again to push the Needle-Roller Bearing into the 6cm linkage, which is shown by the blue arrow in the connection diagram. Let the dowel pin go through the bearing, and finally install the retaining ring on the other side of the dowel pin to finish the links connection.

Parts will be used:



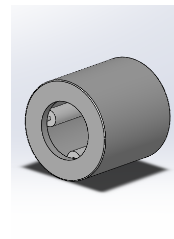
1* 3D-printed 6cm linkage



1* 3D-printed 5.5cm linkage

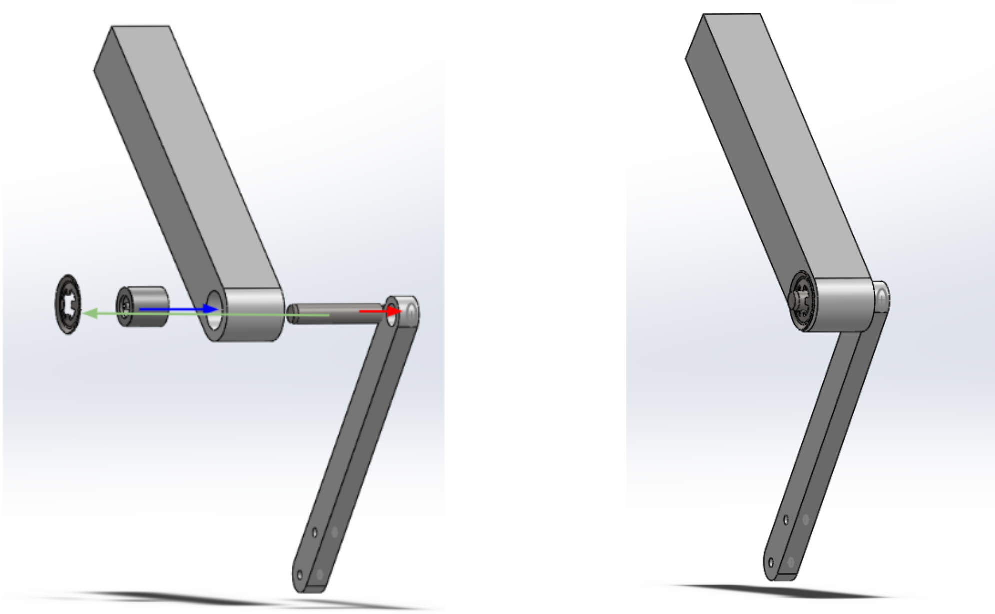
1* Dowel Pin (98381A472 McMaster)

1* Push-on External Retaining Ring (98430A116 McMaster)



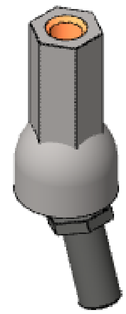
1* Needle-Roller Bearing (5905K331 McMaster)

Connection Diagram:



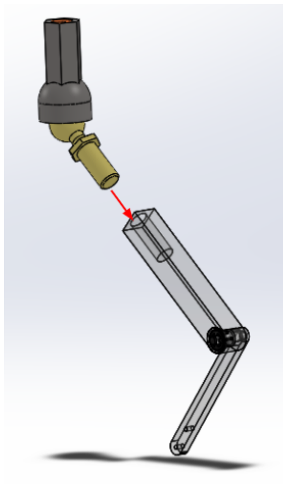
Step 6: First, use M8 hand tap to tap threads in the pre-drilled holes of the 6cm linkage. Then, screw the threaded In-line ball and socket joint into the 6cm linkage link.

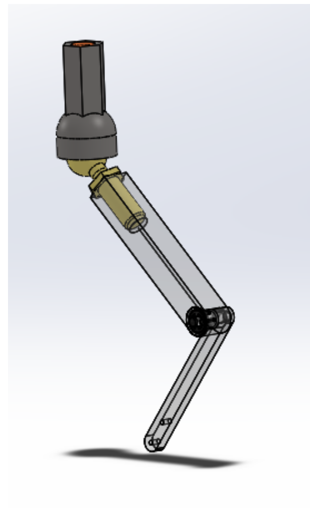
Parts will be used:



1* In-line ball and socket joint (AGRM-08 IGUS)

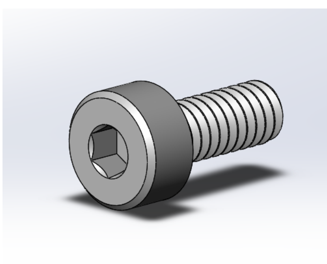
Connection Diagram:

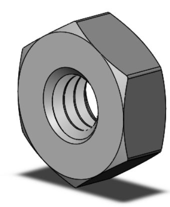




Step 7: Align the two small holes on the 5.5cm linkage with the holes on the servo's link. Connect the 5.5cm linkage to the servo's link using two pairs of screws and nuts by using an M2 size hex screwdriver with a plier to hold the nuts.

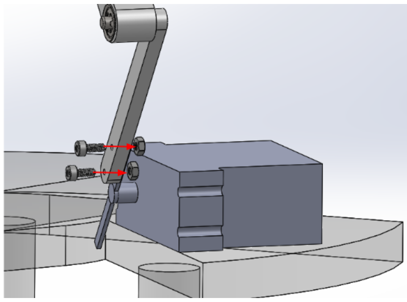
Parts will be used:

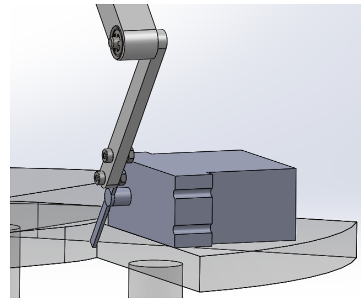




2* M2 5mm Screws (91292A005 McMaster)   2* M2 Hex Nuts (90592A075 McMaster)

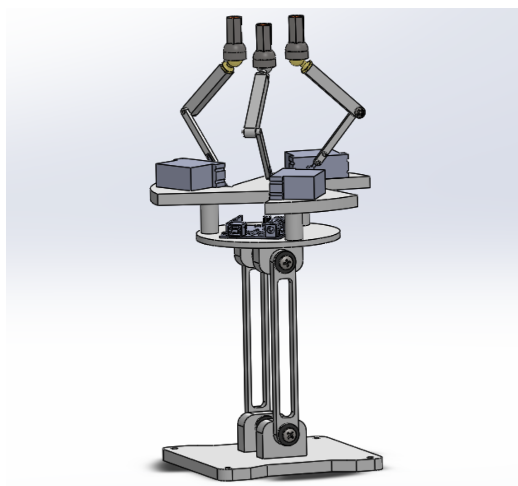
Connection Diagram:





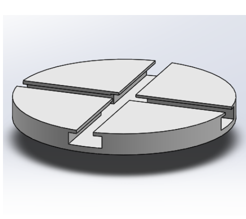
Step 8: Repeat **Step four** to **seven** two more times since we need three servos to form the actuator system.

Connection Diagram: (Mount-linkage-actuator Assembly)

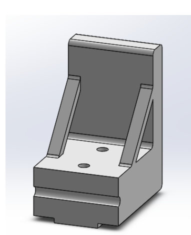


Step 9: First, use #29 hand tap to tap threads in the pre-drilled holes of 3D-printed Slider down. Then, attach the Slider up & down to the platform base slot, and align the holes of them. To tighten the screws, please use a hex key with a size of 5/64". Please take care not to overtighten them as the slider needs to move freely on the platform.

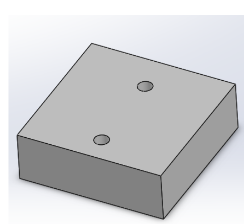
Parts will be used:



1* 3D-printed Platform plate



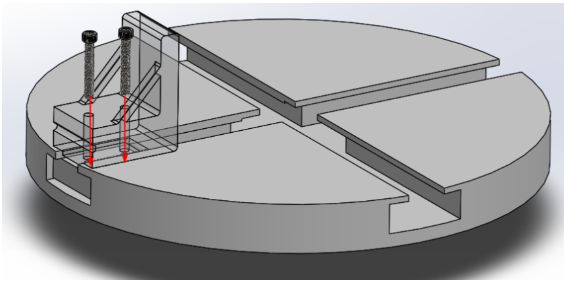
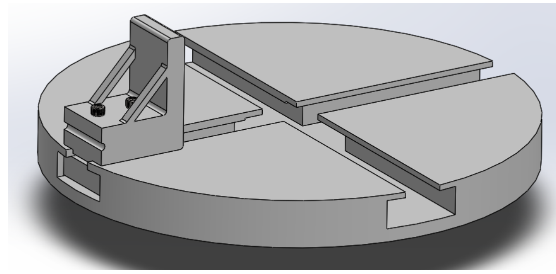
1* 3D-printed Slider up



1* 3D-printed Slider down

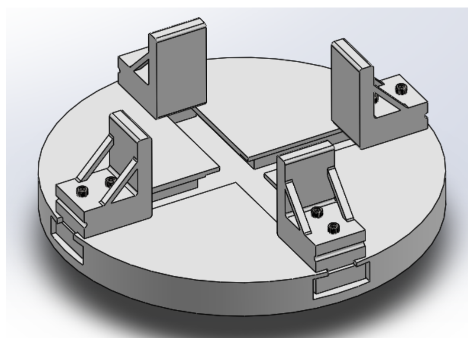
2*Socket Head Screw (91864A025 McMaster)

Connection Diagram:

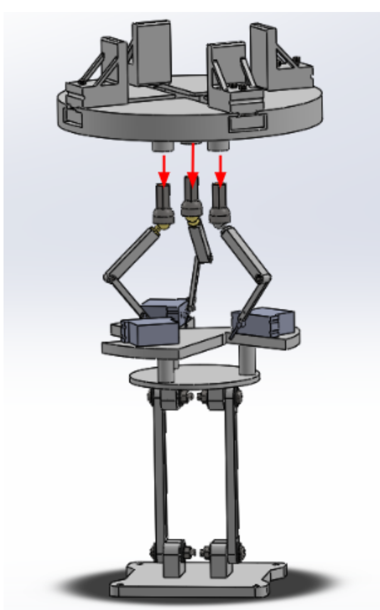
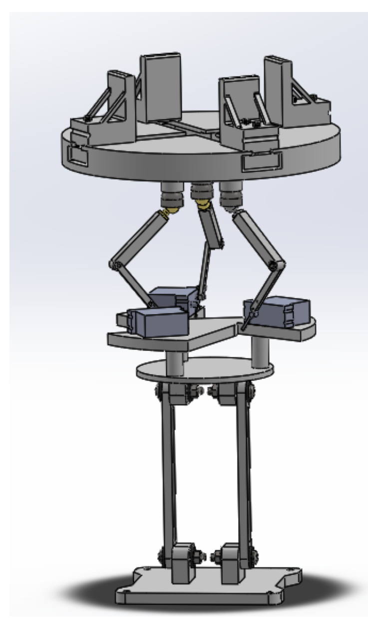
Step 10: Repeat step eight three times more so that there are four sliders moving freely on the platform.

Connection Diagram: (Platform Assembly)

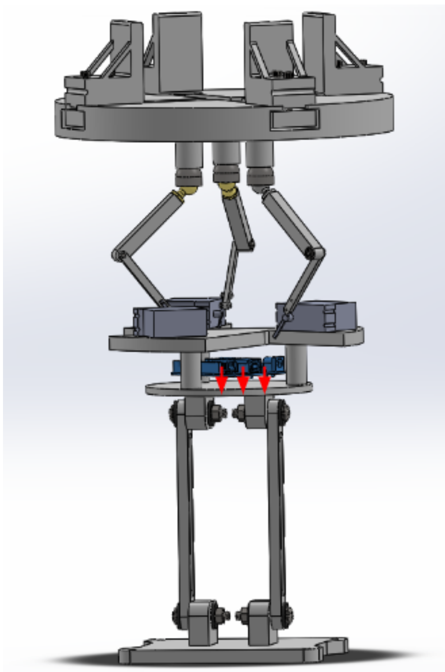


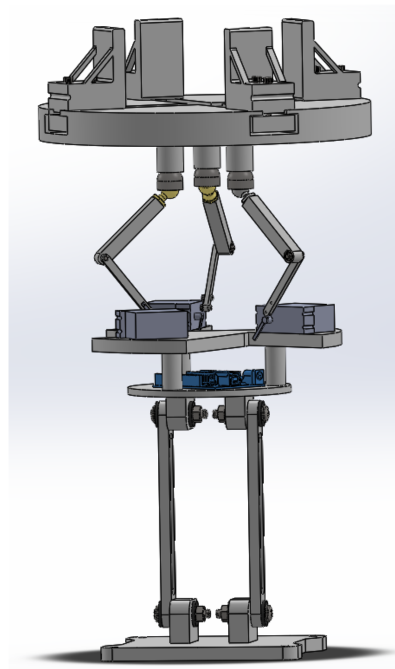
Step 11: Connect the platform assembly to the mount-linkage-actuator assembly.

Connection Diagram:

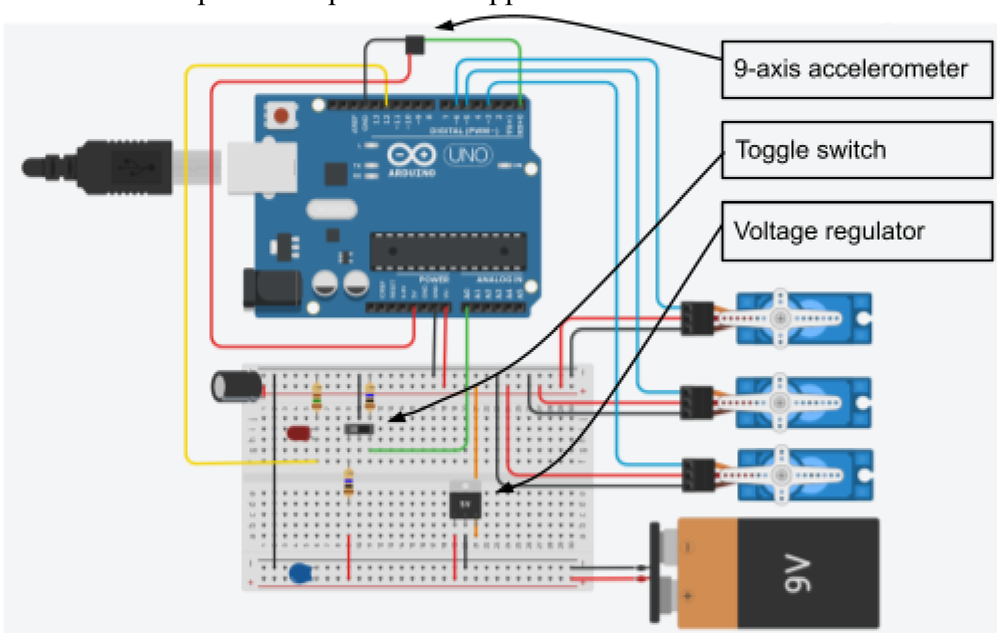



Step 12: Attach the Arduino Mega to the assembly by using hot glue.





Step 13: Connect unit. Specific steps refer to Appendix D.



Xingze Dai

Senior in MechE

Age: 22 years

Pronouns: He/Him/His

Email address: xngzdai@umich.edu

Personal Background

I am an undergraduate student at the University of Michigan studying Mechanical Engineering, concentrating on Robotics. I'm also minoring in Electrical Engineering. I will graduate in April 2023 with a Bachelor of Science in Engineering. I am originally from Shanghai, China, and love to play drums and electric guitar.

Academic Interest & Why ME

I would like to be a control engineer in the fascination of machine automation and that's why I started with Mechanical Engineering first. I have a few experiences developing robotic control algorithms and have played the KINOVA KORTEX arm for a while. I attended the Engineering Honors Program in the realization of contributing to our community using robotics technology.

Fun Facts

I love to fix my old Honda in my spare time.

Zilong He

Senior in MechE

Age: 22 years

Pronouns: He/Him

Email address: hzl@umich.edu

Personal Background

My name is Zilong He. I am currently an undergraduate senior majoring in Mechanical Engineering at the University of Michigan, Ann Arbor. I'm born and raised in northern China. I spent my high years in Lexington, Massachusetts.

I personally love outdoor activities including hiking and mountaineering. I'm also a motorcycle enthusiast and the owner of a Honda CBR650R.

Academic Interest & Why ME

My interest is in mechatronic systems and control systems design and analysis. I hope to continue staying in academia and earn a master's degree in a related field.

I started college as an Applied Mathematics major and switched to Mechanical Engineering soon after because I like to work with something I can physically touch.

Fun Facts

- My favorite book is *Zen and the Art of Motorcycle Maintenance.*
- One of my near future goals is to learn how to fly a propeller plane and get a private pilot license.
- I hiked for three days at an altitude of 18,000 ft in Tibet and plan to challenge higher elevations after graduation.

Yanyu (Cassie) Chen

Junior in MechE

Age: 21 years

Pronouns: She/her/hers

Email Address: yanyuc@umich.edu

Personal Background

My name is Yanyu Chen, feel free to call me Cassie! I am from Jiangsu, the east coast of China, and went to high school in Virginia Beach, the east coast of the United States. I am currently a junior double majoring in Mechanical Engineering and Industrial and Operations Engineering at University of Michigan.

Academic Interest & Plans

Influenced by my family business in the automotive industry and being a member of the Robotics Club at high school for three years, I developed a strong interest in designing and building things and decided to major in Mechanical Engineering in college. After completing my Bachelor's Degree at University of Michigan, I plan to apply to graduate schools for further study in Mechanical Engineering or Robotics.

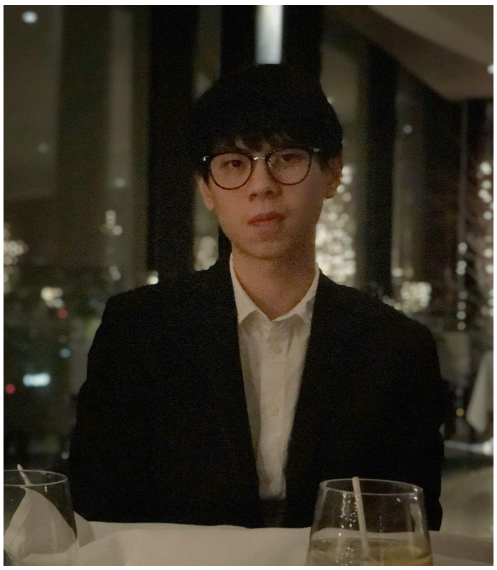
Hobbies & Fun Facts

I enjoy road trips with my family. We have driven to 25 provinces/municipalities in China.

Before high school, my dream was always to be a fashion designer. I really love beautiful clothes and accessories, dressing up myself and my friends in different styles, and designing my own pieces.

Jinxin Li

Senior in MechE



Age: 23 years

Pronouns: He/Him

Email address: lijinxin@umich.edu

Personal Background

My name is Jinxin Li, and I go by Ricardo. I am a senior student majoring in mechanical engineering with a minor in physics. I am from Guangzhou, in the south part of China.

I personally love music and concert bands, and I did get a chance to perform in the Disney World Music Festival.

Academic Interest & Why ME

I am interested in the topic of mechanical design and control systems. My future career plan is to work in a robotics related company such as Amazon Robotics.

Fun Facts

- Some interesting facts about me are when I eventually found out where the Chipotle was, I ignored the gap in front of me and fell off the scooter.