INTERMEDIATE REPORT 2

ENME 472: *Integrated Product and Process Development*
Section 0104
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Brian Bock, Luxi Huang, Ashley Ollech, Nathan Orwig, Saul Schaffer, Greg Turlik

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Contents

1 Executive Summary

In the field of medical robotics, many promising breakthroughs are happening in sectors from ultrasonography to tele-surgery at research institutions worldwide [1–6]. While these innovations are groundbreaking, many of them are restricted to the lab bench [7] or, for surgical robots, the operating room (OR) [8]. This is problematic because there are many situations where receiving treatment before reaching an OR would be really beneficial, as often the morbidity for such pathologies is very time sensitive, resulting in many deaths *en route* to the hospital [9]. As such, our team decided to tackle the problem of getting medical robots out of the OR so as to be better situated to treat patients.

The specific robot that the team chose is the KUKA LWR MED. The KUKA is often used in hospitals to assist with radiation therapy, and is very popular among medical robotics researchers [10]. The issue that the team saw was that this technology is currently limited to the hospital only. With that in mind, the team began exploring other methods to use the KUKA robot in mobile medical situations, to expand its impact on healthcare. The first solution was to figure out where to affix the KUKA so it can be helpful to a physician or paramedic. Different scenarios were explored and the team eventually decided on the use of the KUKA medical robot inside of an ambulance.

The biggest issue with using the KUKA outside of the hospital is that the robot must be rigidly mounted to prevent any movement so that the robot can execute its path planning algorithms correctly. If the base of the robot is in motion then the KUKA robot will not be able to function properly and execute it's tasks. The issue that putting the KUKA into a ambulance presents is that potholes and other road imperfections will cause the cabin to vibrate and will thus translate the vibration from the mount to the KUKA robot.

The team is seeking to design a mount that can dampen the road vibration caused by road imperfections on the KUKA medical robot. There are a few other products that designed to meet similar goals. One such class of products are the camera mounts used to film car scenes in movies. These mounts are large and rather unwieldy for this application where space is a major issue. During a interview with several EMTs, it was discovered that inside the ambulance, space is cramped, but that enough space is available to fit a KUKA. Now that the team confirmed that there is support and practicality in putting a KUKA into an ambulance a problem scope was formed to show potential modes of failure on the mount such as improper installation.

For the robot to be used inside the ambulance, the team ran a human factors analysis characterize the ways in which the mount would be interesting with people during its life cycle. With that in mind the team explored other constraints that would have to be considered if the mount is to be safe for use with humans such as the noise requirements. The customer requirements define what the user needs the mount to be able to do to complete the task at hand. Once the customer requirements were defined they were weighted so that the team could decide how important each customer requirement is to make sure all the needs of the customer are met. These customer requirements are then turned into engineering characteristics so needs can be numerically defined and met.

The team used a House of Quality to devise decision characteristics for the mount setup. The team then brainstormed on ways to mount the robot inside the ambulance that would dampen vibration and mechanically isolate the robot from the ambulance. Once these were drawn up, a concept selection process was followed through to help come up with a final design. This final design was iterated multiple times, with each successive iteration building off the flaws of its predecessor.

The final design uses three motors rigidly mounted to the ceiling of the ambulance. These three motors rotate three lead screws that attach to the triangular shaped platform through threaded heim joints. These three heim joints are affixed to the platform via a shaft and spring assembly that allow the platform to tilt from side to side. Once the final design was determined, material selection and strength calculations could begin. All the calculations took into account the weight of the robot and the extra forces added by the moving ambulance. All forces were also given a generous safety factor to promote confidence in users that the mount will not fail. Further tests were run such as Finite Element Analysis (FEA) to look at strengths and tolerances of the material used with relation to the shape of our mount. A Failure Modes and Effects Analysis (FMEA) was conducted to see the likeliness and severity of all potential failures.

Now that strengths of the materials were known, the process of finding correct parts to meet these requirements could begin. All of the parts were listed in a complete Bill of Materials. This list includes every nut and bolt as well as the manufacturers of every component. Engineering drawings were organized for each individual part as well to show the specifications and tolerances.

To see the response that a real world vehicle and suspension would have on the inside of an ambulance the team decided to build a prototype and record data of various road imperfections. The team took a series of three accelerometers to test to see which one would provide the most accurate and least noisy data. After selecting the correct accelerometer the team used a plank of wood to create a repeatable baseline for the accelerometer to measure. Once that data was gathered and analyzed the team set out to collect data on "real world" road imperfections such as pot holes and speed bumps.

The team created a comprehensive Product Design Specification to guide the design process and fully define all the needs of the system.

2 Problem Definition

2.1 Initial motivation for product

In the field of medical robotics, many promising breakthroughs are happening in sectors from ultrasonography to tele-surgery at research institutions worldwide [1–6]. While these innovations are groundbreaking, many of them are restricted to the lab bench [7] or, for surgical robots, the operating room (OR) [8]. This is problematic because there are many situations where receiving treatment before reaching an OR would be really beneficial, as often the morbidity for such pathologies is very time sensitive, resulting in many deaths *en* *route* to the hospital [9]. Many medical procedures, such as the Focused Assessment with Sonography for Trauma (FAST) scan, allow physicians to make important triage decisions about the care of a patient before they even arrive, saving time, and by extension, saving lives [11]. Other time-sensitive procedures, such as cardiopulmonary resuscitation (CPR) have recently been robotized and are projected to become mainstays of the emergency medical transportation in the future [12].

After conducting an interview with Dr. Hamed Saeidi, a Post Doctoral Fellow in the Medical Robotics and Equipment (MRE) Lab at the University of Maryland, we gained many insights regarding current state of medical robotics as well as an educated and insightful prediction about its near future. Dr. Saeidi elucidated the fact that from a technical standpoint, most multi-functional medical robots that are being used in research have the ability to self stabilize, but at a large cost. When self stabilizing, the robot is less able to complete another goal, such as a complex medical procedure, because it's joints occupied with the stabilization task. Having the robot stabilized, (*i.e.,* stationary in an inertial reference frame) allows path planning algorithms that dictate the robots motion to proceed uninhibited without potential goal conflicts that would result in undesired behavior [7].

Naturally, the question of why robots haven't already been implemented in ambulances arises. The answer is simple, currently no solutions to mounting a medical robot that mechanically isolates it from the forces in a mobile environment such as an ambulance. And as explained by Dr. Hamed Saeidi, it is not worth it for the medical researchers to attempt to solve this problem. During a interview with several EMTs, it was discovered that inside the ambulance, space is cramped, but that enough space is available to fit a KUKA. However, having these robots in a mobile environment is important, and will need to be implemented in order to allow this technology to reach its full potential.

As such, the overall objective of our project is to develop a system that enables the translation of medical robotics research done on a lab bench to a mobile setting so as to treat time sensitive pathologies such as hemorrhage and cardiac arrest closer to the point of care as well as conduct FAST scans that will allow doctors to make important decisions about a patients condition before they are even arrive at the hospital, saving time overall.

2.2 Bench-marking on competitive products

Though currently no apparatus exists to facilitate the implementation of medical robots into a mobile environment, the underlying challenges of mechanical isolation and vibration control are ubiquitous across all vehicular mounting of precision devices. Thus, in benchmarking on competitive products we looked to existing models for mounting precision devices in settings where random disturbances are prevalent. There are many products geared towards camera stabilization including designs for three-axis gyro-stabilized mounts [13] and inertially stabilized platforms [14]. While these products do achieve a stable platform for a camera that is fixed or rotating about one axis, they cannot compensate for the additional motion introduced by the robotic arm.

2.2.1 Pointer XV

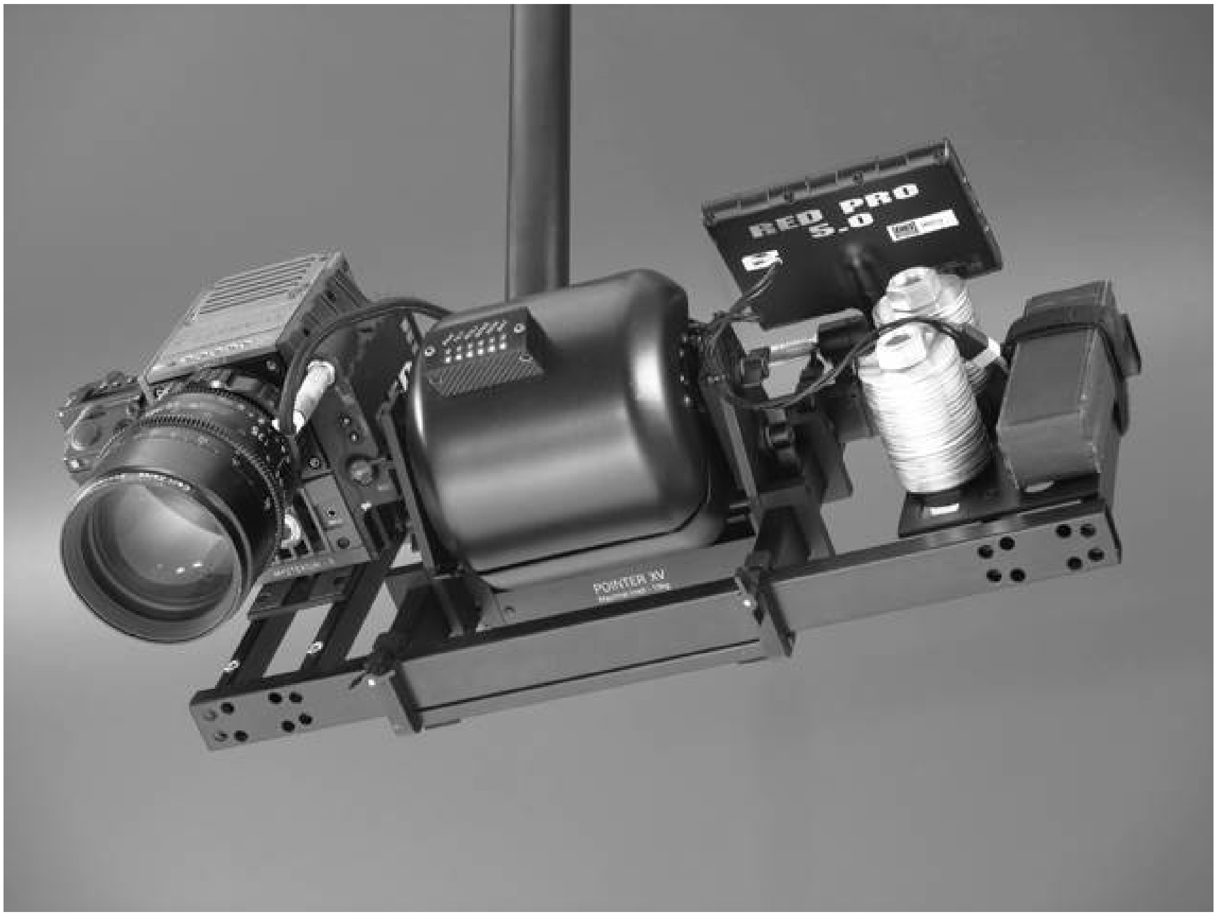


Figure 1: PointerXV Stabilizer for cinematographic equipment [13]

- Max rotation speed to be compensated for be compensated: -1000deg/sec
- Axial tilt limitation: -70 to +120 degrees
- Lateral tilt limitation from -40 to +40 degrees
- Average vibration transfer ratio: -0.002
- Absorbable linear oscillations: up to 0.3 m
- Max noise level: -53 dBA
- Max consumption -80 W

[13]

Advantages

With a unit weight of merely 7.5 kg and mount dimensions of 210cm(width) x 490cm(length) x 620cm(from ceiling) the Pointer XV would satisfy the size constraints of the ambulance. However, as our product will carry a considerably heavier payload, the mount would likely need to be made more robust and therefore these dimensions could potentially need to change to meet these demands. The axial and lateral tilt allowable by the Pointer XV are also acceptable for our design as the robot arm will be able to compensate for needed movement below the platform. At -53dBA the max noise level is well within the -90dBA, 8 hour duration established by the OSHA [15]. Lastly, a key aspect of the Pointer XV design as it relates to our project is the absorbable linear oscillation limit. Based on our preliminary prototype, linear oscillations can be expected up to approximately 0.133 m in our system, which means he linear absorption system in the Pointer XV meets this requirement.

Disadvantages

Although the Pointer XV generally accounts for the same characteristic disturbances we expect our system to be exposed to, some aspects of the Pointer design make it unsuitable for our purposes. A mount capable of securing our robot in an ambulance would need to account for a payload nearly double what the Pointer XV can handle. Another drawback of the Pointer XV design is that the camera is allowed to swing beneath the mount. This motion is acceptable for filming, however, movement of a mount throughout the cabin would introduce a dangerous variable to our system. Though many of our design requirements are satisfied by the Pointer XV, the allowed translation of the mount itself invalidates the Pointer XV as a viable options for mounting a medical robot in an ambulance.

2.2.2 PI Hexapod Platform

Figure 2: PI Hexapod Platform [14]

In addition to products used to stabilize cameras in moving vehicles, we also need to consider other general stabilization devices. The PI Hexapod Platform, is a steward platform that allows "ultra-precision motion control" [14]. These platforms are used to stabilize objects sitting on its top platform when there are outside forces disturbing the bottom of the device. The Hexapods utilize electro-mechanical and piezoelectric platform positioners to account for the outside forces. See Figure 2 for a picture of one of PI's Hexapod platforms. In addition to products used to stabilize cameras in moving vehicles, we also need to consider other general stabilization devices. The PI Hexapod Platform, is a steward platform that allows "ultra-precision motion control" [14]. These platforms are used to stabilize objects sitting on its top platform when there are outside forces disturbing the bottom of the device. The Hexapods utilize electro-mechanical and piezoelectric platform positioners to account for the outside forces. See Figure 2 for a picture of one of PI's Hexapod platforms.

Advantages

PI sells Hexapods in many sizes and have configurations for loads from 2kg to more than 1000kg. They also allow for six degrees of freedom and includes sophisticated controller algorithms. [14]

Disadvantages

These Hexapods do not operate at a speed fast enough to properly compensate for bumps or potholes while driving in an ambulance. They are also not meant to be used upside down, meaning they don't consider effects of gravity with the platform positioners.

2.3 Patent Study

Throughout this search process, the team utilized the Google Patents search tool [16] as the primary means of locating relevant patents. The ability to search through vast patents by keywords made this utility exceptionally useful. As we found semi-relevant results, we gained a better understanding of the pertinent terminology, which we were able to use to further refine our searches. The patents we found were scattered across several different classifications, which limited the practicality of USPTO patent classification system as a means of locating relevant designs. Much more useful to us than the classification system was the Search Similar Patents tool [16] which enabled us to easily locate other relevant patents while we searched. In fact, the versatility and efficiency of the Google Patents search engine rendered most of the traditional, manual search techniques obsolete.

In our search, our team found 6 patents of particular relevance to this project. These are US Patents Nos. US3638502A, US20130085510A1, US20050016515A1, WO2006069288A3, US20160319842A1, US5490655A.

2.3.1 Patent No: US3638502A

Stabilized camera mount [17]
Publication date: 1972-02-01
Inventor: John N Leavitt, Raigo Alas, Edwin C Dafoe

This patent was granted for a system that allows a camera to be mounted on a stabilized platform upon a moving vehicle, subject to both predictable and unpredictable movements. This is accomplished through the use of multiple gyroscopes paired with pendant masses that resist erratic movements as well as the manipulation of compensating weights to resist predictable movements. The patent is relevant because this invention serves the same basic function as our proposed project: to provide a stabilized platform on which a high precision instrument can be mounted to an unpredictably moving vehicle.

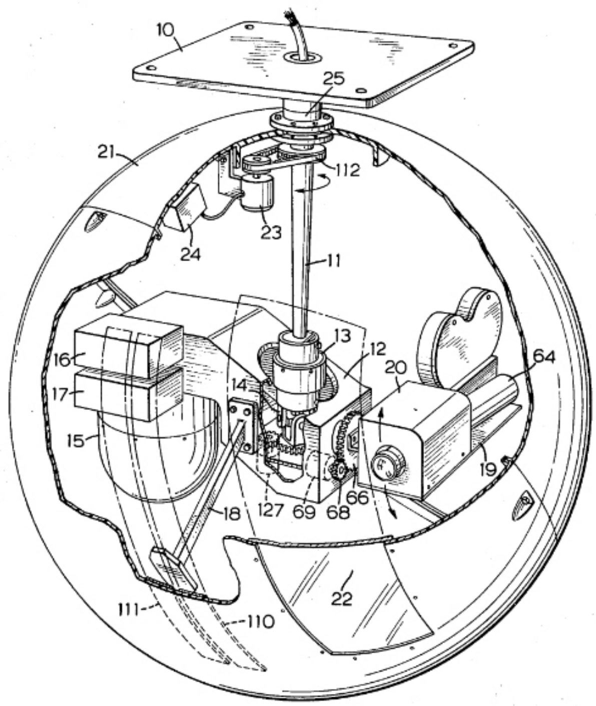


Figure 3: Overview of system including stabilized platform, mounting plate and major components within the fairing [17]

The stabilized camera mount patent consists primarily of a mounting plate (Figure 3.10), a stabilizing platform contained within a fairing (Figure 3.21), and a hollow quill (Figure 3.11) that connects the two. The quill (Figure 3.11) is fitted with a bearing general designation to allow for rotation of the platform. Also attached to the quill (Figure 3.11) are the vibration-isolating assembly (Figure 3.13) and a universal joint (Figure 3.14). Within the platform are a gyro-stabilized assembly (Figure 3.15), electronic components (Figure 3.16) and (Figure 3.17), a location sensing probe (Figure 3.18) and a tiltable bed (Figure 319). This system is ultimately attached to the vehicle via the mounting plate (Figure 3.10). The system allows a stabilized platform to hang below the mount. The components within the failing self-correct for expected weight shifts, such as the movement of film through the camera. Additionally, potentiometers produce signals to indicate rotational disturbances within the gyro-stabilized assembly. Pendulums coupled with driving motors are then utilized to counteract this rotation.

Advantages

By maintaining a constant center of gravity, the platform makes itself less susceptible to the unpredictable disturbances caused by the motion of the vehicle. This is done by constantly ensuring that the displacement of the internal masses (within the fairing) is compensated for with counter weights. The combination of three or more gyroscopes and associated pendant masses allows for responsive torques to be enacted on the platform in any direction. Therefore, any disturbance (with a reasonable magnitude) can be counteracted by the system. The design also conveniently allows for remote operation of the camera from a separate location. Thus, even a device contained within the platform can be accessed by an operator. Because of the alignment of the gyroscopic wheels, the potentiometers only receive a signal when rotation of the platform occurs. Therefore simple translation of a device is allowed and planned rotation can be accounted for. A clever system of half gimbals and rate gyros are utilized in this design. This allows the platform to orient itself in reference to change in angle as opposed to change in position. This is an advantage because rate gyros are significantly cheaper than typical gyroscopes.

Disadvantages

Within the scope of this patent, only a relatively small moment of inertia is being accounted for. The size of the required platform for larger payloads may become a limiting factor in expanding the system to other devices. Since the platform and quill operate using the principles of pendulum physics, the configuration is restricted to the platform hanging beneath the mount.

2.3.2 Patent No. US20130085510A1

Robot-Mounted Surgical Table [18]
Publication date: 2013-04-04
Inventor: David Stefanchik, Omar J. Vakharia

Vakharia and Stefenchiks patent is for surgical table design to accommodate a medical robot and a patient, allowing six degrees of freedom for the patient relative to the mounted robot, and maintain a fixed frame of reference between the patient and the end effectors of the robot, despite patient movement. This is relevant to our project as it outlines the orientation of a surgical robot with respect a patient, geometries that are essential for designing a mount for a surgical robot inside of an ambulance.

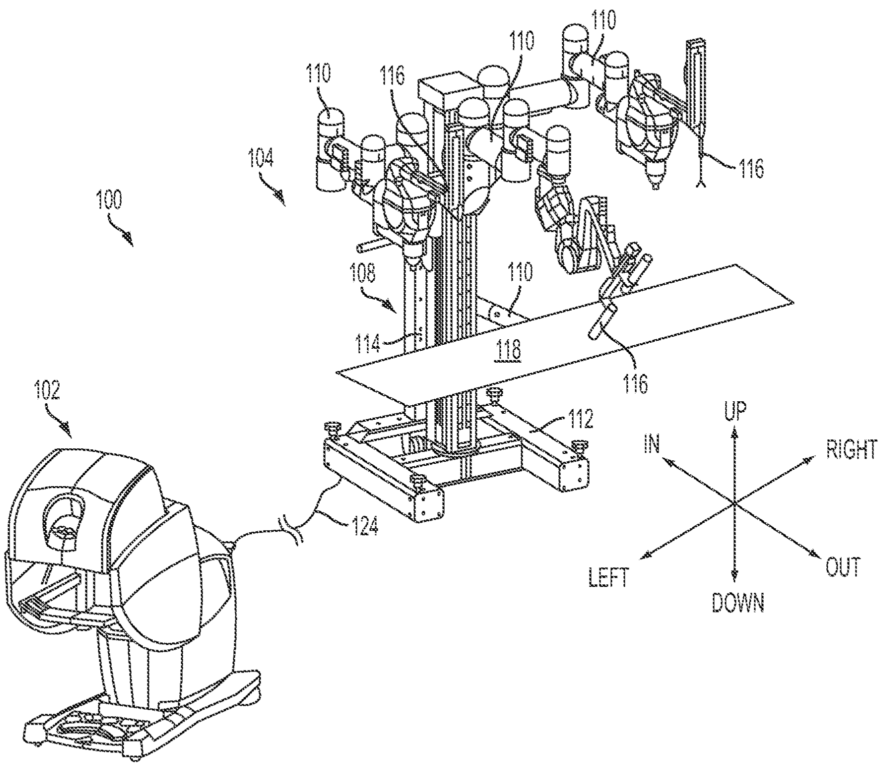


Figure 4: Robot-Mounted Surgical Table [18]

This device is comprised of a table (Figure 4.118) that has 6 degrees of freedom as well as a robot and a controller. It is able to precisely control the location of a patient with respect to a rigidly mounted medical robot that is poised to perform a minimally invasive surgery on the patient. Using embedded sensors that track the positions and orientations of all objects involved, the controller is aware of the relative locations of the patient, the robots body (Figure 4.110) and the robots end effector (Figure 4.116).

Advantages

A strength of this patent for satisfying the functions of our project is that it provides a method for rigidly mounting a robot to a bed with a patient on it so as to perform surgery. By controlling the position and orientation of the bed, the system is able maintain an appropriate spatial relationship between the robot and the patient.

Disadvantages

A weakness of this patent for satisfying the functions of our proposed project is that it is designed to be implemented in an operating room, which is a stationary, spacious and tightly controlled environment. The interior of an ambulance or a medevac helicopter, however, is a much different environment. This system has no means of controlling vibrations or other external mechanical perturbations of the system. In addition, this system lacks a means of interfacing with an independent system, such as the roof of an emergency transport vehicle.

2.3.3 Patent No: US20050016515A1

Paintball Vehicular Mount [19]
Publication date: 2005-01-27
Inventor: Roger Arnaud

This patent is for a mount that attaches a paintball gun to a steering assembly such as a bike, or unicycle, or something similar. This is relevant to our teams project because we are looking to mount a medical robot to some steering assembly that will enable the robot to reach the patient at point of care, where the patient was injured. While our team is looking into mounting in ambulances and helicopters, we are also interested in exploring getting medical robots to point of care in war zones, and therefore mountings to bikes or unicycles are highly relevant to our project. The fact that a gun is what is being mounted is also relevant since paintball guns have a recoil, meaning that it has some movement to consider, similar to a medical robot.

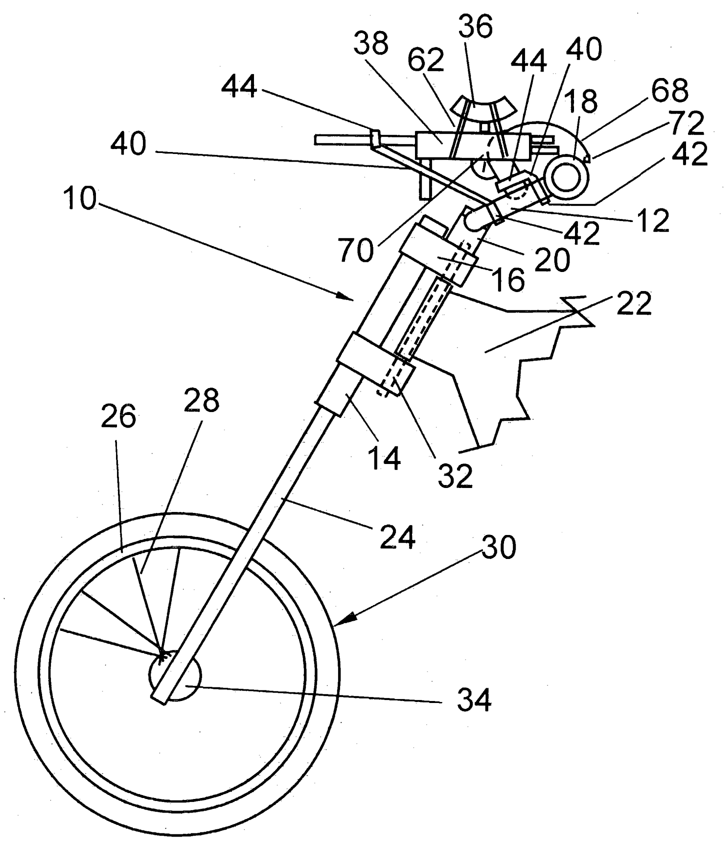


Figure 5: Sketch for a vehicle mounted gun [19]

This device is meant for off road vehicles such as bikes, off-road motorbikes, ATVs etc. The innovation of this invention lies in the fact that paintball is usually played with players holding their guns in their arms, but given the use of this mount, players would be able to mount their guns to a bicycle and use that to hold steer their paintball gun. Figure shows a steer assembly with a paintball gun mounted. The assembly seen is composed of a fork clamp (Figure 5.16) that is attached to the form ram (Figure 5.24) as well as to the vehicle frame (Figure 5.22) at pivot (Figure 5.32). Figure 5.12, which represents the handlebars, attach to the control area (Figure 5.18) and to a handlebar clamp (Figure 5.20). The spokes are shown by (Figure 5.28) and they attach to the hub (Figure 5.34) and to the wheel (Figure 5.26). The hub (Figure 5.34) is also attached to the form ram (Figure 5.24). The bracket (Figure 5.40) coupled with the handlebars (Figure 5.12) and the paintball gun (Figure 5.48), both are coupled through clamp (Figure 5.42). The trigger cable (Figure 5.68) is attached to the trigger control (Figure 5.72) on one end which is mounted to the control area (Figure 5.18). The opposite end of the trigger cable (Figure 5.68) connects to the paintball trigger connect (Figure 5.70), which is attached to the paintball gun. The strap (Figure 5.62) has one end connected to the hopper (Figure 5.36) and the other end mounted to the paintball gun frame (Figure 5.38). The mount itself is made up of the bracket (Figure 5.40), the clamp (Figure 5.42), the trigger cable (Figure 5.68), the trigger control (Figure 5.72), the control area 18 and the handlebar clamp (Figure 5.20). These parts together create a mount that allow the user to mount the paintball gun to a off road vehicle and still control the gun properly.

Advantages

The advantage of this patent is it gives a clear example of a mount for an object that on its own would have to be carried, but here can be mounted to some vehicle and then driven over off road terrain. This is good specifically for the war zone research our team wishes to conduct. The fact that the mount is used for a gun also shows that the mount had to consider dynamic forces since guns have recoil when fired.

Disadvantages

The disadvantage of this patent is that there are no clear diagrams of the mount itself, and so there is no exact understanding of how the mount functions or is built on its own. This makes it harder to apply the same design to a different vehicle or to apply it to a medical robot rather than a paintball gun. The other disadvantage is that this patent is somewhat old. It was submitted twice, the first time in 2003 where it was abandoned and then again in 2005 and its status still remains application. This could be indicative of a bad or outdated design.

2.3.4 Patent No: WO2006069288A3

Overhead mount for a medical robot for use with medical scanning equipment [20]
Publication Date: 2004-12-20
Inventor: Gilbert J. Williams, Robert M. Taylor, Jaydeep Roy

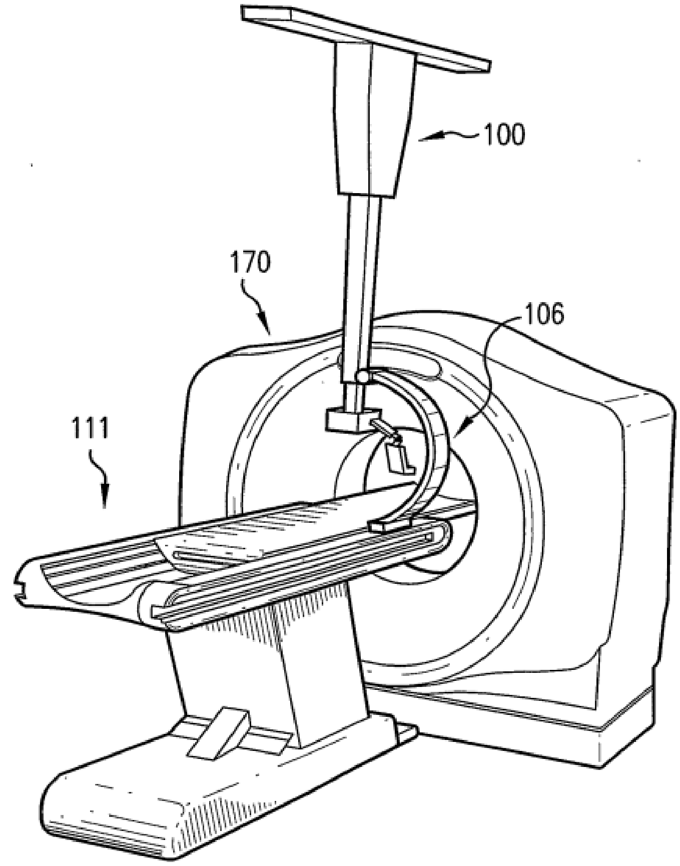


Figure 6: Sketch from patent WO2006069288A3 [20]

The WO2006069288A3 patent is for overhead mount (Figure 6.100) for a medical robot for use with medical scanning equipment (Figure 6.170). The apparatus may include a brace (106) with attaches to the movable table (Figure 6.111). The brace may be rigid and maintain the position of a medical device relative to the movable table while the table is moving. This apparatus could be applied to our proposed project, mounting a medical robot in a medical transport vehicle. The overhead patient mounting method described in this patent could be repurposed to mount our medical robot on the ceiling of an ambulance. In emergency transport vehicles (such as ambulances), the patent is usually on a gurney instead of a fixed table. The gurney is prone to much more vibration than its stationary counterparts. This apparatus could maintain the position of the robot relative to the moving gurney by being affixed to it via (Figure 6.105), enabling the robot to better perform medical procedures while in motion.

Advantages

Overhead mounting of medical robot could open floor space of an ambulance, a space likely to be cramped with additional equipment, a gurney, and the patient. The rigid connection between the table (or gurney) and the mount enables the robot to remain fixed in the same reference frame as the patient, crucial for any robot-patient interaction.

Disadvantages

This patent has several advantages, but also has some shortcomings. The brace (105) can only constrain the table in one direction (horizontally), but cannot constrain in the vertical or forward/backward directions, limiting its ability to fully constrain the motion of the table. Additionally, there may be weight restrictions that this overhead mounting design can support, limiting the range and size of robotics we could mount on it. The ambulance ceiling, ostensibly weaker than a building ceiling, may also provide a similar limitation for weight, although this could probably be overcome with additional bracing if needed. Although the brace can maintain the position of the medical device relative to the movable table, it can not eliminate all vibration in the system, which might be problematic for an ambulance in motion.

2.3.5 Patent No: US20160319842A1

Ceiling fan kit and method of mounting [21]
Publication date: 2015-05-01
Inventor: Charles William Botkin

This patent is for a ceiling fan kit and method of mounting. This patent is relevant because the team is looking for a way to mount a medical robot to the inside of an ambulance for treatment of a patent while they are traveling to the hospital. This patent is useful to the team because this ceiling fan mount could be modified in order to suspend the medical robot from the ceiling of the ambulance.

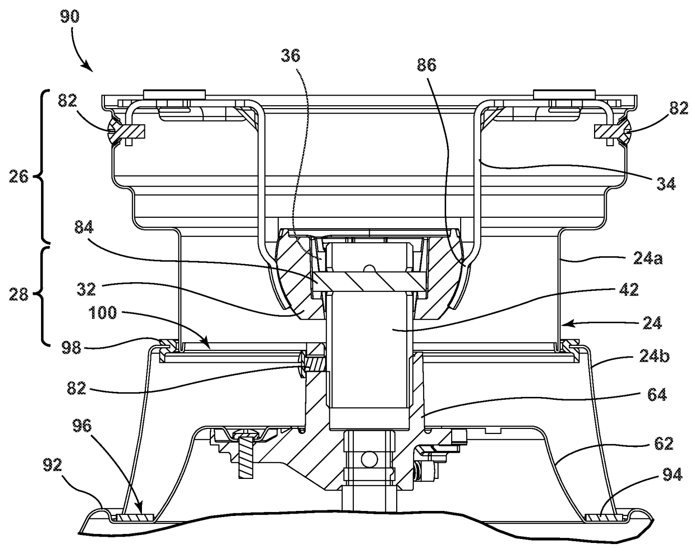


Figure 7: Patent sketch for ceiling fan mount [21]

This ceiling mount is inclusive of a mounting bracket and ceiling plate. The mounting assembly (Figure 7.30) is important to the team because it is what is needed for the mount for the medical robot. The bracket attaches the downrod coupler (Figure 7.36) and the ball (Figure 7.32). These would both be used in order to attach the medical robot to the bracket. This would allow for movement of the robot while also lessening the vibration due to the movement of the ambulance during travel. Most likely the fan motor (Figure 7.70) would need to be removed because it would not be necessary for use on the medical robot. Part of the motor (Figure 7.70) includes power supply wires which will come in useful.

Advantages

The mount is already a part on the setup including all the holes to attach the mount to the ceiling. The power supply for motor of the fan assembly is incorporated. The bracket for the mount has multiple attachment points to the ceiling which will give much more strength to the ceiling-mount interface.

Disadvantages

The mount is made for a much lower weight than what the team will be potentially using this for, as a ceiling fan weighs less than many medical robots. The team would have to modify the structure of the mount to add sufficient strength to hold the medical robot. The fan assembly is not relevant to this project and could be neglected if this patent were repurposed for this class. The mount described is a rigid interface between ceiling and fan; the team may need to incorporate some form of damping or stabilization to make the robot useful inside of a moving vehicle.

2.3.6 Patent No: US5490655A

Video/data projector and monitor ceiling/wall mount [22]
Publication Date: 1993-09-16
Inventor: Nigel P. Bates

This patent describes a ceiling/wall mount for an electronic device such as a projector or monitor. The goal of this project is to design a ceiling/wall mount to retrofit a robotic arm inside of an ambulance and/or a helicopter. The interface between this arm and the vehicle is crucial, and so this patent is a relevant technology.

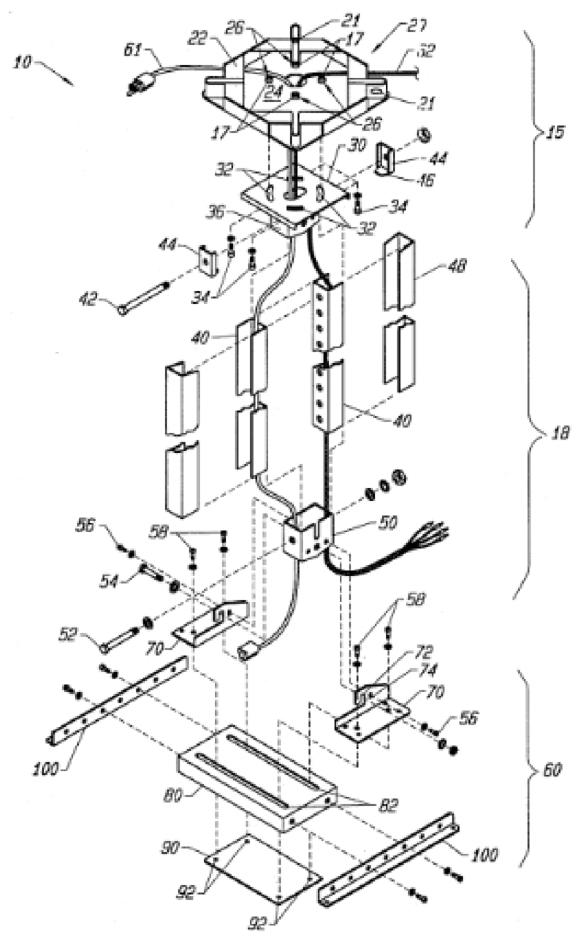


Figure 8: Exploded view of the mount described in patent US5490655A [22]

This patent is designed to replace the traditional pipe style mount with a system intended to be more flexible, and more easily customizable and installable. The designer notes that traditional pipe based mounts are usually custom built on site using costly and potentially wasteful procedures. To alleviate this issue, the system can be assembled and easily customized on site without any special equipment. This design includes several different configurations for alternative connection methods and styles. One design variant includes seismic bracing to secure the system against lateral motion. Another includes a winch and pulley system for adjusting the height of the attached projector.

Advantages

The patent includes channels (Figure 8.40, Figure 8.48, Figure 8.50) to run cables from the ceiling to the device below. The robotic arm will likely need cables for power and data transmission, and having a built-in cable management system might be useful to our design. Without internal cable management, the robot, patient, emergency personnel, or other equipment might get caught on the cables, adversely affecting system performance.

This patent includes modifications for winch driven adjustable height and several pivot points for fine tuning the position of the projector. While adjustable height may not be as useful in the confined space of an ambulance, the adjustable angles of the pivots may be beneficial for accommodating non-orthogonal wall surfaces.

Disadvantages

This device described in this patent appears to lack any damping or stabilizing mechanisms aside from the seismic braces. In order for the robotic arm to perform medical procedures while in motion (such as inside an emergency transport vehicle, like an ambulance or helicopter), it will need a base that remains stationary relative to the patient. In order to accomplish this, the mount will likely need to have some form of damping or stabilization to provide a stable base for the robot, which this patent does not include.

2.4 Opportunities for competitive advantage

As it stands, there exists no product that can accomplish what we have set out to create that is, a method of mechanically isolating a bench-top robot in a mobile setting from the environment. As of now, all robotic mounts for bench-sized robots are rigid, and therefore allow for all forces and torques to be transferred directly to the base of the mounted robot. This is problematic as virtually all kinematic solvers - the algorithms by which the robot is able to perform virtually any motion - assume that the base is stationary. When this assumption isn't valid, the robot will move in unpredictable and potentially hazardous ways. As such, the mechanical isolation of the robot from the ambulance will result in the robot being able to execute its objectives as if it was stationarily mounted. You may think (as we originally did) that a robot of sufficient complexity could just self compensate for base movements, eliminating the need for any stabilized platform. While theoretically true, this creates a pair of semi-exclusive objectives (stabilize the robot; perform it's intended task) that may be very difficult to achieve simultaneously; one objective would likely have to be sacrificed or marginalized to optimize the other.

Optical tables are an semi-related stabilizing solution that are not readily applicable to this project, as they respond to low frequency vibrations and are very heavy. The immense mass and area of these tables makes them ideal for stable optical experiments, but they are far too large to fit in a transport vehicle.

2.5 Problem Scope

The team created a fishbone diagram (Figure 9) to represent the many potential failure modes of the medical robot mount. The causes are split up into categories for "Measurement", "Materials", "Method", "Environment", "Manpower", and "Machine". The causes related to the teams specific problems were in the Environmental section. Specifically the team intends to correct the issue with external forces on the medical robot and its mount. In addition to posing a risk of damage to the robot, external forces and vibrations directly inhibit the robot's ability to safely interact with the patient. Isolating the vibrations from the ambulance is therefore crucial to the operation of the robot and more broadly this entire project.

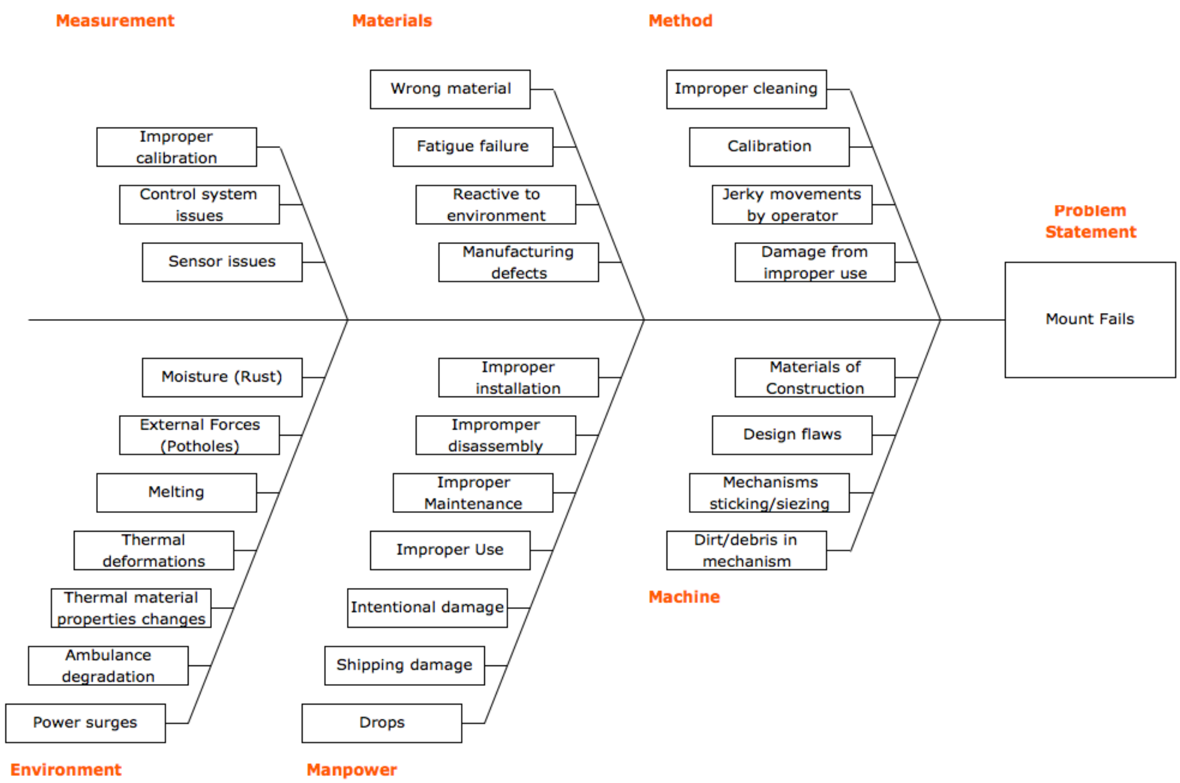


Figure 9: Fishbone diagram of potential failure modes for the system

The failure modes evaluated here cover a wide range of materials and design configurations so as to remain as solution neutral as possible.

2.6 Problem Definition

In the ever-evolving healthcare industry, many experts believe a shift towards point of care (POC) technologies is fast approaching and inevitable. While conducting a face to face interview with five EMT's they indicated that space is tight inside of an ambulance so the foot print of the robot has to be small to be feasible. All the EMT's were supportive of the idea to put a medical robot inside of an ambulance cab. According to Milos Todorovic, analyst at Lux Research, Most of the studied indication spaces (cardiology, oncology, neurology, infectious diseases, and ophthalmology) will see POC technologies proliferate outside of the traditional care settings of hospitals and doctors' offices. [23] Additionally, according to the Medical Robots Market by Product, Application, and Region – Global Forecasts to 2023 the current medical robotic market of 6.46 billion USD is projected to reach 16.74 billion USD by 2023. [24] Thus, with the incentivized shift imminent in the healthcare domain, and with funds and interest available in the research domain; we aim, with our product, to solve the complex engineering challenge of bridging the cutting edge medical robotic technologies with current infrastructure. Through the development of a precision stabilized, vibration reducing mount we intend to provide an avenue by which the advances in the medical robotic domain can be adopted by a mobile POC system. Presently, our product would be most useful to those in the medical robotics research domain as they are the ones who are currently developing the kinematic solvers which will allow the robots to function properly [25]. In the development of these methods, our mount would provide a means of securing their robots in order to conduct experimentation in the area of motion control of teleoperative robots. Based on our preliminary research, the market size is 22 medical robotics research companies in the united states.

3 Problem Refinement

3.1 Physics of Task

The main physical phenomena to consider would relate to the weight of the robot as well as the movement of the vehicle. The weight leads to static and material considerations such as buckling, deformation, stress, and other similar material failures. The vehicle movement requires our group to consider dynamics and vibrations, specifically impact, impulse, inertia, oscillations and relative velocity.

Since the mount has to be able to support and hold the robot, weight considerations are important. Depending on how and in what orientation the robot is attached to our device, the force of the robot's weight and center of mass need to be considered to ensure our mount does not fracture, bend, buckle, shear, or fail in any other way. By considering the properties of different materials, as well as the geometry and assembly of our product, our team can avoid these failures.

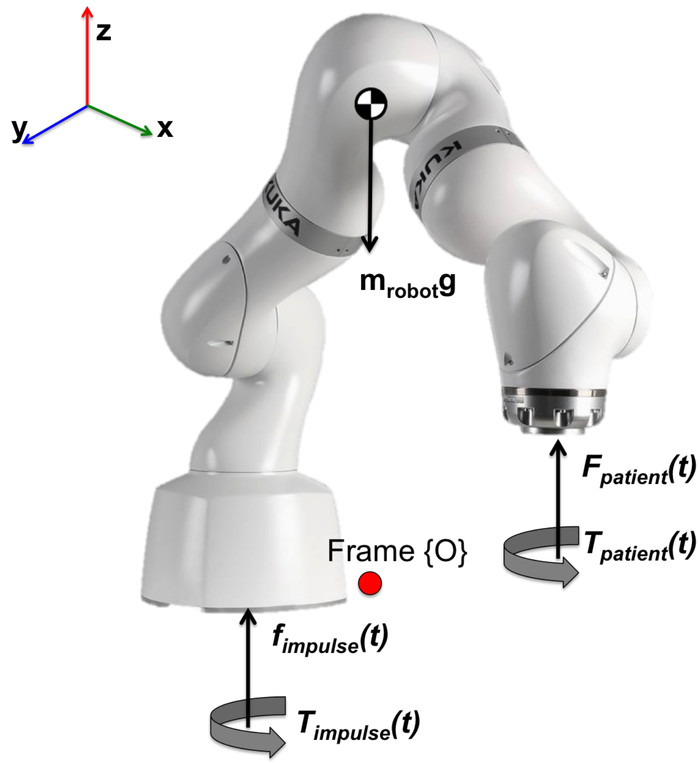


Figure 10: Free Body Diagram of Robot

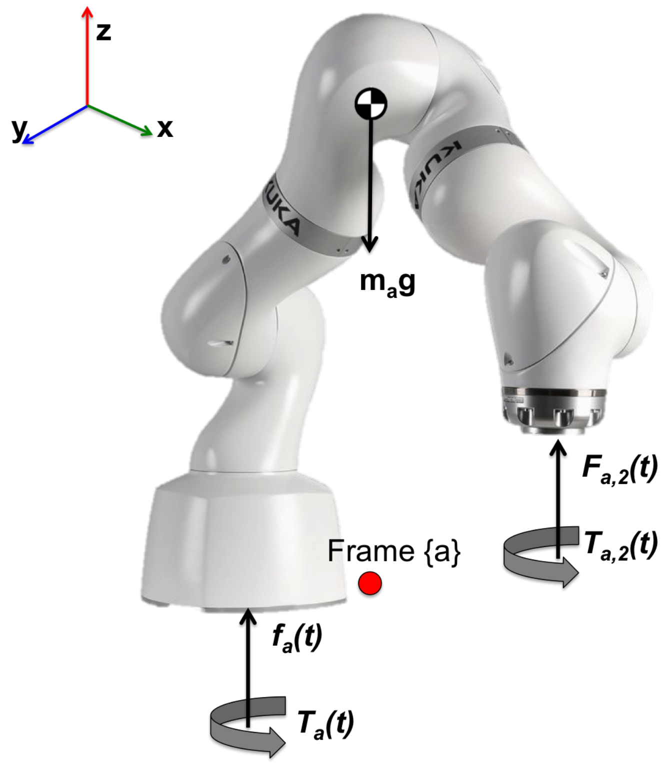


Figure 11: Inertial Diagram of Robot

Our product also has to consider the vehicle movement of the ambulance. This movement requires us to consider impulse, impact, oscillations and relative velocity. The free body diagram (Figure 10) shows the forces that might affect the robot at any time. These forces are functions of time and together include every force the robot is expected to experience over all time, including vibrations, impulses, and steady forces. Note that the center of mass changes as a function of the robot's position, configuration, and current tool. The inertial diagram (Figure 11) shows a similar configuration but evaluates the robot in an accelerating frame, as it might experience in a moving vehicle. With these physics phenomena in mind, our team will be able to select and build a design that will properly account for all potential problem areas.

$$T_x = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & c\theta & -s\theta & 0 \\ 0 & s\theta & c\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$T_y = \begin{bmatrix} c\theta & 0 & s\theta & 0 \\ 0 & 1 & 0 & y \\ -s\theta & 0 & c\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T_z = \begin{bmatrix} c\theta & -s\theta & 0 & 0 \\ s\theta & c\theta & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$^{a}_{o}T = T_x \cdot T_y \cdot T_x \tag{4}$$

$$^{a}P =^{o} P \cdot^{a}_{o} T \tag{5}$$

Where $c\theta$ and $s\theta$ are $\cos\theta$ and $\sin\theta$, respectively.

From equations (1)-(5), we can describe the motion of the robot in terms of an accelerating frame of reference, as one would find in a frame attached to an mobile platform transporting a robot.

3.2 Human Factors Considerations

There are many human factors to consider when designing a mechanically isolating mount for a robot on a mobile platform. The most glaring human factor is how the location of the robot relative to both the patient and any medical professionals are intrinsically coupled. If, for example, the mount was designed in such a way as to take up significant floor space in an ambulance, than it would likely have a sub-optimal affect on the humans in its environment, further restricting their movement in the already cramped space of an emergency medical vehicle. Furthermore, because a key element of our system includes a robot, and the general public harbours a general skepticism concerning the efficacy of robotics in virtually every field, robot-in-the-loop trust dynamics comes into play. The manifestation of this mistrust is sharpened by the fact that human health is task of the robot, as apposed to a lower-stakes, more conventional scenario of a robot assisting in the assembly of a car.

Yet another human factors consideration is the possible collaborative nature of the robot and the medical professional in the vehicle. As the ultimate aim of our mount is to help translate the robotic healthcare breakthroughs of the lab to the field, it is important for the mount to be agnostic to the variety of procedure paradigms a medical robot can undertake. A procedure such as robot-assisted CPR may take the form of a robot conducting chest compressions and an EMT performing mouth-to-mouth. In such a scenario, the robot must be aware of the patient as well as the EMT, and the mount must not inhibit this awareness. Fortunately, robots designed to collaborate with humans, known as co-bots, are characterized by added safety features, such as having torque sensors in every joint that can sense when they have contacted something unexpected in their environment and seize up in response to striking a person, even softly. All commercially available medical robots have this feature, as it is a requirement when a human is expected to be in the work space of the robot, as is the case for when the robot is tasked with interacting directly with a person.

Further still, the installation and maintenance of the proposed mount is a human factors consideration, as the mount should be installable and uninstallable by the research lab that is working on it. It is important that after the initial install, they are able to remove the robot to bring it back inside to their lab for further testing and innovation, returning the robot to the ambulance when it's next ready. This dismount should therefore be of reasonable ease and minimized inconvenience.

3.3 Quantifiable Design Problem Criteria and Constraints

There are many design problem criteria and constraints that exist in creating our mount, specifically in an ambulance setting. The confined space of an ambulance is most obvious constraint we have. A Type I ambulance has 68-72 inches of headroom [26], [27]. Without thinking about equipment inside the ambulance,

> "The width from wall to wall is 48.75 in and the length from the inside of the rear doors to the face of the front wall cabinets is roughly 139.375 in. Cabinet depths are 20.75 in." [28].

When considering equipment that utilizes that space, the main consideration is a gurney. A Stryker Power PROXT stretcher has a length of 2060 mm (81in), a width of 580 mm (23in) and a height, from ground to the top of the patient, of 930 mm (37in) [29]. We're limited to a finite space, already packed with additional tools, equipment, and storage. The design needs to balance the confining space constraints of the ambulance with simultaneously allowing the robot a sufficiently large work space to properly render patient care. The mount must be located such that the robot has full access to the patient and an unrestricted range range of motion allowing it to operate properly.

Weight is another criteria we need to consider. Since this mount needs to be held up and driven by the ambulance it is attached to, the weight distribution has to ensure it does not damage the ambulance when attached and doesn't inhibit the ambulances movement. The Commission on Accreditation of Ambulance Services cites requirements C.5.2-C.5.4, which relate to the weight and weight distribution within an ambulance [30], which must be considered when evaluating our designs.

Another major design constraint is the power supply of the ambulance. Unlike a lab or Operating Room setting, the ambulance has a limited power supply that cannot be supplemented with additional power lines. The Commission on Accreditation of Ambulance Services denotes requirements C.7.4.2-C.7.6.5 (excerpted in part below), which relate to the power outputs of an ambulance.

> C.7.6.2 ELECTRICAL 125-VOLT AC RECEPTACLES: The patient compartment shall be furnished with two (2) 125-volt AC duplex receptacles conforming to NEMA 5-15. [30]

This provides a 125 volt, 15 amp (1875 watt) limit on the power draw our entire system could have. Any system requiring power could simply not be powered by an unmodified ambulance. More power hungry systems might be usable in highly modified ambulances with improved power supplies, but it is likely that such modifications would be extraordinarily costly and limited regardless.

The Occupational Safety and Health Administration (OSHA) places restrictions on the noise levels that workers can be exposed to for extended periods of time. Any exposure that exceeds these levels and durations must be countered by the appropriate Personal Protective Equipment (PPE). The Permissible Noise Exposures table below is from the OSHA noise standard; Table G-16 at 29 CFR 1910.95(b)(2). In general, the louder the noise (sound level), the shorter the period during which employees may be exposed without requiring hearing protection. [15]

Permissible Noise Exposures

Duration per day, in hours	Sound level dBA in slow response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

Figure 12: OSHA Permissible Noise Exposures Table [15]

To design for the most conservative standards, we'll assume that emergency personnel are in an ambulance and exposed to its sounds for an average 8 hours each day. Our system therefore needs to maintain sound levels < 90 dBA in order for ambulance personnel to be present without required hearing protection.

These restrictions limit the size, power draw, and noise level of our apparatus and must be considered throughout our design. These are not, however, the only constraints or standards we must adhere to. The Commission on Accreditation of Ambulance Services denotes requirement C.11.1.1 (Mounting and Location of Medical Equipment and Supplies):

"For any equipment and materials over 3 lbs, not otherwise stowed in a cab-

> inet, equipment mounts or retention devices shall be utilized. The mounts or retention devices shall be installed according to the mount or retention device manufacturers directions. These mounts should be tested in accordance with the requirements of SAE J3043 (Ambulance Equipment Mount Device or Systems). The purchaser shall specify to the manufacturer the desired location and structural requirements for mounting equipment. The manufacturer shall place an appropriate structure in the vehicle to provide support for such an installation." [30]

The standard referenced here, SAE J3043, describes the dynamic and static testing procedures required to evaluate the integrity of an equipment mount device or system when exposed to a frontal or side impact [31]. These will be important standards for us to work towards, as our system will ultimately need to be in compliance. There may be a number of additional standards not mentioned here that our design must comply with; these might include engineering standards on bolt strength, material properties, fatigue failure, electrical draw, sensor calibration, surface properties, reliability, safety, medical standards for medical and/or ambulance equipment...etc. Each will be evaluated as they become relevant to our design process later this semester.

4 House of Quality

To help determine customer characteristics the team developed a compilation of five surveys. These surveys were directed to a few different groups of people that could offer insight to the needs that exist regarding the medical robot mount project. This survey was distributed to physicians, Emergency Medical Technicians (EMTs), hospital administrators, robotics research labs,and fellows peers. Questions such as "What concerns would you have about a robot performing a procedure inside of a ambulance?", "What do you think is the biggest challenge in remote robotic procedures?", and "How much free space is there in the ambulance?" and others were asked to their respective groups. Those answers, coupled with information gathered through research, allowed the team to establish the customer requirements (CRs). Below are the requirements the team was able to obtain.

4.1 Customer Requirements

We created a comprehensive listing of customer needs and wants, which is then ordered by an importance weighting scale from 5 to 1. From this sorted list, we identify the the important CRs (everything with a weight of ≥ 2) and apply those as inputs to our House of Quality (HOQ).

- Can be used in various ambulances and robotics

  - Customer wants the device can be used at various ambulance and robotics.

- Can be easily attached on or removed from robotics

  - Customer desired the mounting system could be attached/removed from robotics easily, so they can quickly exchange various medical robots from mounting system as they need.

- Mechanically isolates robot from ambulance -

- Robot does not fall off mount/ceiling

  - Customer want the mounting system is strong enough, so the robot wouldn't fall off from the ceiling.

- Life cycle

  - Durability/reliability (how long does system last)

- Maintenance frequency and difficulty

  - How often customers need to replace any parts of mounting system or how long does the maintenance take.

- Small footprint

  - Customer desires area the device occupies on the gurney or ambulance floor/ceiling.

- Small size

  - Customer wants small space of device occupies within the ambulance.

- Electrically efficient

  - The device can be powered holistically by an ambulance power supply without impacting existing systems

- Quiet

  - customer wants the product produce low noise.

- System doesn't constrain robots motion

  -the device doesn't effect robot's regular motion, so that the robot can achieve regular speed of motion and full work space.

- Workspace will not interfere with other tasks

  -Customer wants the device doesn't restrict ambulance personnel from performing other tasks

- Aesthetically appealing

  - How stylish is the exterior of the device, Does it fit well into the modern design of ambulance owned? Customers desire a device that looks more appealing to the eye.

- Easy to clean

  - Since the device is used for medical field, customer want the device keep clean, so they desires the device could be easily cleaned.

4.2 Weighting Customer Requirements

We weight the importance of each customer requirement (CR) on a scale from 1-5, with 5 being of the utmost importance.https://www.overleaf.com/1959258513gjqfvkhcxthc

5 weight (Crucial):

- Mechanically isolates robot from ambulance
- Doesn't constrain robots motion
- Workspace will not interfere with other ambulance tasks
- Robot does not fall off mount/ceiling
- Electrically efficient (can be powered holistically by an ambulance power supply without impacting existing systems)

These CRs are the most important, as they define the basic criteria for the robot to operate. The customer needs all of the original functions of the medical robot to be preserved when it is mounted in ambulance. If the system cannot be powered by an ambulance, for example, it obviously cannot be used inside an ambulance, rendering the rest of the project irrelevant. Most of these criteria are so important that they are assumed and not explicitly stated by the customers.

4 weight:

- Small size
- Maintenance frequency and difficulty
- Lifecycle-Durability/reliability (how long does system last)
- Can be easily attached on or removed from robotics

These three CRs are the second most important considerations, as these criteria determine if the product can run smoothly. Those are the most desirable functions for customers.

3 weight:

- Small footprint
- Can be used in various ambulances and robotics

These CRs are less crucial and more flexible than the others above. A customer's tolerance of "3 weight" CRs can stretch if a higher weight performs very well. For example, if the product has a small footprint and is easily maintainable, customers would be willing accept the product even if it is specific to one robot.

2 weight:

- Quiet
- Easy clean

This criteria is less important than 3 weight CRs but still an item of importance to the customer. As long as the noise levels are lower than OSHA limits, the system is technically quiet enough for safe use, although the customer would certainly prefer the system to be as quiet as possible.

1 weight:

- Aesthetically appealing

This criteria is of the least importance, especially for our initial market audience of researchers. While the customer would be happier with a nicer looking device, its appearance has no bearing on its functionality or usefulness. As a medical device, this apparatus will be judged on it's ability to render patient care and not on its aesthetic. Appearance characteristics may contribute marginally to this product's market value, but very little effort should be expended to improve this front.

Base on above weight scale, we define weight from 5 to 4 are important (CTQ) customer requirements, which are defined as the subset of customer needs. These will be used as input for the House of Quality along with some of the lower ranked items. The "aesthetically appealing" CR is least important for customers needs, so we didn't including it on the HOQ.

4.3 Engineering Characteristics

The following is a list of the physical features, variables, or performance metrics that describe the system we are designing. These Engineering Characteristics (ECs) are incorporated into the House of Quality. The following symbols denote how we want to target each

parameter:
(-): minimize
(+): maximize
(*): target

- Base Area (-)

  - As customer wants small foot print, engineer needs to design small base area where device occupies on the gurney or ambulance

- Volume (-)

  - As customer wants small size of device volume the device occupies within the ambulance, engineer should consider to design a device has Small volume

- Power usage (-)

  As customer cares about electrically efficient, so the Engineer need to consider the current and voltage of device doesn't exceed the maximum ambulance system

  How much voltage and current that the device requires

- Weight (-)

  How much weight of the device

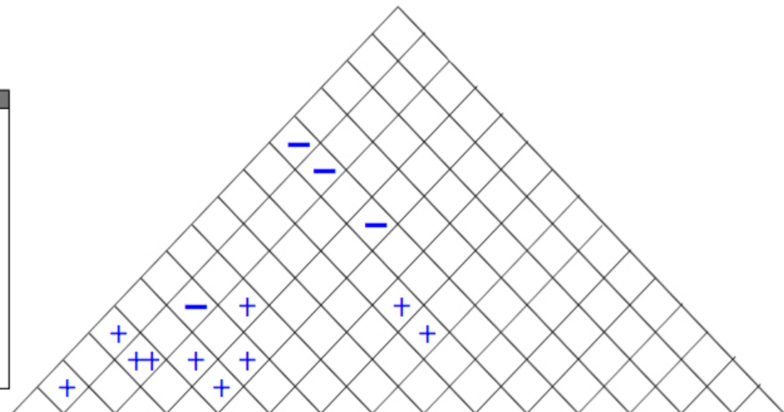
- Noise output (-)
- Thermal conductivity (-)
- Cleanable surfaces (+)
- Mean time of life cycle (+)
- Fitness for various ambulances and medical robots (+)
- Tensile Yield Strength (*)
- Tensile Ultimate Strength (*)
- Torsional strength (*)
- Damping control(+)
- Self-calibration (+)
- Mounting position in ambulance (*)

4.4 Constraints

In addition to the physical constraints present when designing a product, constraints may be imposed by federal regulatory agencies and standards bodies. An important document that must be given consideration when designing our product is the list of standardized equipment for ambulances. Since 2005 the Committee on Trauma, the American College of Surgeons, the American College of Emergency Physicians, and the National Association of EMS Physicians have all agreed to adhere to a standardized list of EMS equipment needs. This agreement sets the requirements for all emergency ambulance services throughout the United States and Canada and in order for a device to be utilized in an ambulance setting, it needs to be approves by this standards conglomerate. The document states that "High-quality consistent emergency care demands continuous quality improvement and is directly dependent on the effective monitoring, integration and evaluation of all components of the patient's care". [32] Given the body's attitude towards improvement of EMS quality, and the present push toward POC technologies, it seems likely that a mounted medical robot arm will eventually make its way onto this list.

4.5 Build and Interpret HOQ

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	▼	▲	▼	x	▲	▲	▲	x	x	x	
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Base Area	Volume	Power Usage	weight	Noise output	Damping Control	Thermal Conductivity	Mounting position in ambulance	Cleanable surface	mean time of life cycle	fitness for vairous ambulances and medical robots	tensile yeiled strength	temstile ultimate strength	torsional strength	
1	9	10.0	5.0	Mechnically isolates robot from ambulance	O	O				▲		Θ			O				
2	9	10.0	5.0	Robot does not fall off mount ceiling	Θ	O		Θ		▲		▲				Θ	Θ	Θ	
3	9	8.0	4.0	Lifecycle-Durability/reliability (how long does system last			▲			▲	▲			Θ		▲	▲	▲	
4	9	8.0	4.0	Maintenance frequency and difficulty	▲	▲		O		O	O	▲		Θ					
5	9	6.0	3.0	Small footprint	Θ	O		▲				O			▲				
6	9	6.0	3.0	Small size	O	Θ		O	▲	▲		O			O				
7	9	10.0	5.0	Electricaly efficient			Θ		▲		O								
8	9	8.0	4.0	Can be easily attached on or removed from robotics	▲	Θ		Θ				▲			O				
9	9	4.0	2.0	Quiet			O	▲	Θ										
10	9	10.0	5.0	Doesn't constrain robot's motion	▲	O						Θ			O				
11	9	6.0	3.0	canbe used in vairous ambulances and robotics		O	▲	▲		▲		Θ			Θ				
12	9	10.0	5.0	workspace will not interfere with other tasks	O	Θ						Θ							
13	9	4.0	2.0	Easy Clean									Θ						
14																			
15																			
				Target or Limit Value															
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)															
				Max Relationship Value in Column	9	9	9	9	9	3	3	9	9	9	9	9	9	9	
				Weight / Importance	248.0	350.0	116.0	220.0	52.0	64.0	62.0	386.0	36.0	144.0	162.0	98.0	98.0	98.0	
				Relative Weight	11.6	16.4	5.4	10.3	2.4	3.0	2.9	18.1	1.7	6.7	7.6	4.6	4.6	4.6	

Figure 13: House of Quality

Chart.PNG Chart.PNG

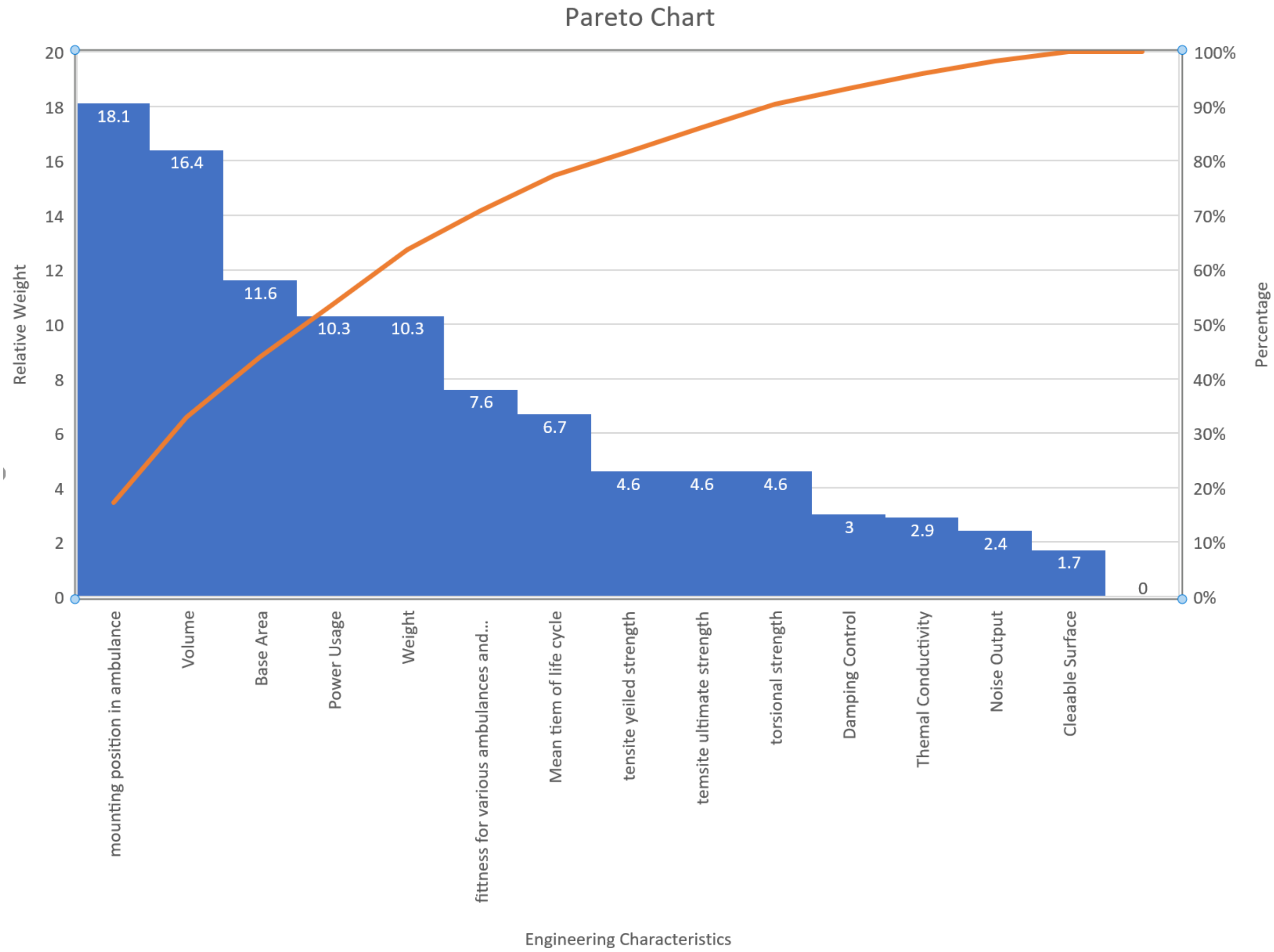


Figure 14: Pareto Chart

Based on the chart (Figure 14), we can find the the mounting position in ambulance is the most important EC, as it is the most critical in responding to the customers CTQ requirements, and 10/13 CR are related to general. Volume is also very important EC since it has secondary relative weight, and 10/13 CRs are related to it. Moreover, the base area and weight are also very important ECs, which are related to a few CRs. Furthermore, from the Pareto chart (Figure 14), noise output and cleanable surface are least critical in responding to the customers CTQ requirement, since only few CRs are related to them.

4.6 Determine your decision characteristics set (DC)

We didn't find any other highly important elements which needed to be removed from HOQ except cost, the only element that significantly impacted every other EC. However, we excluded some unimportant elements from the HOQ such as "Aesthetically appealing" and "color", since neither are directly important to the customer. The engineering characteristic of color only affects the aesthetic, which is often a matter of personal preference anyway and is therefore not easily quantifiable.

5 Concept Design Process

5.1 Present a Set of Five Feasible Concepts

	Possible Solutions						
Isolate Motion	Spring-Damper system	Gyroscopic stabilization	Linear actuators	Hydraulics	Magnetic dampers	Gears	3-axis linkage
Sense Position & Acceleration	Multi-axis accelerometer	Optical sensor	Ultrasonic position measuring	Magnetometer	Lidar		
Power Source	Ambulance (125V, 15A)	Battery	Solar	Diesel generator			
Fastening to Robot & Ambulance	Bolts	Magnets	Weld	Industrial Velcro	Adhesive	Ball & Socket Interface	Heim Joint

Figure 15: Morph Chart

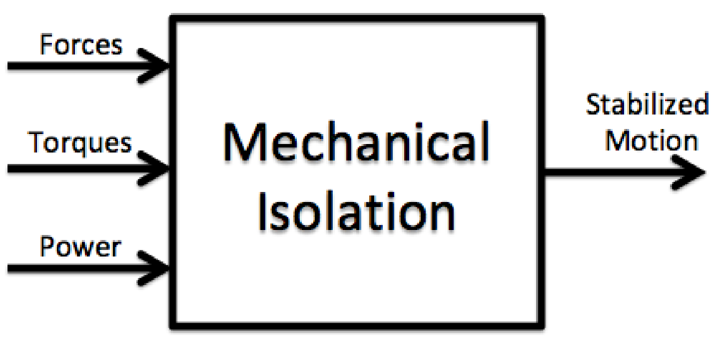


Figure 16: Function structure Chart

This function structure chart displays the broad high level functionality of our design. Quite simply, the system has forces and torques as its inputs, and must output stabilized motion. The additional input of power (likely electrical) enables the system to have active stabilizers instead of just passive. Internal to this system could be sub-functions with sensing and control, but these are not solution neutral so they are omitted from the high level big picture.

5.1.1 Active Impulse Mitigation with Mechanical Actuators

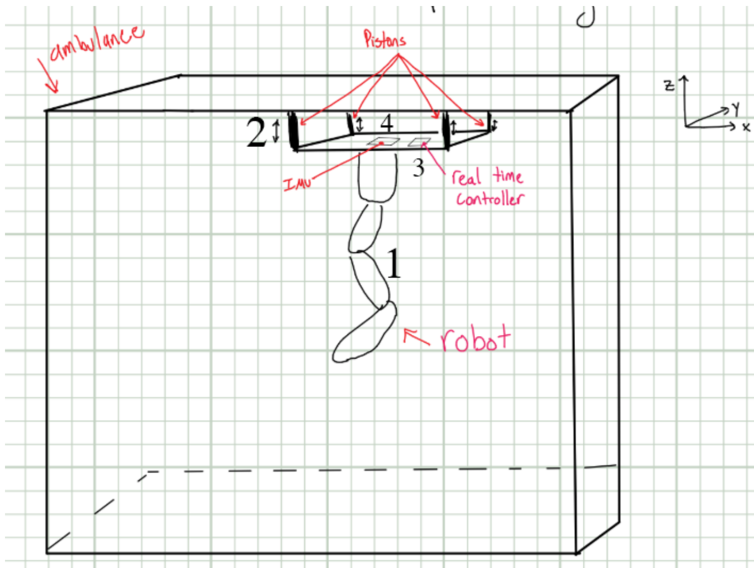


Figure 17: Active Impulse Mitigation

In this concept, the robot (Figure 17.1) is mounted to a platform suspended by a series of linear mechanical actuators, such as pistons or lead screws (Figure 17.2). These actuators actively control the orientation and position of the base of the robot based on sensor data from an inertial measurement unit (IMU) (Figure 17.3) and output of a real time controller (Figure 17.4). The response of the actuators would act to directly counter the vibrations and impulses from the ambulance to the robot. This design could be ceiling mounted, in the orientation shown, or floor mounted (upside down). The mechanical actuators allow high level control over the robot's position within a confined region of the ambulance, but may not be fast enough to actively compensate for unanticipated disturbances, such as potholes. Any active system like this one must consider our limitations on power (elaborated upon in Section 3.3) as well as noise in the sensor data. The sensors must be carefully configured and calibrated to minimize erroneous measurements, which, if acted upon, could detrimentally affect the performance of the robot.

5.1.2 Passively stabilized robot mounted on gurney

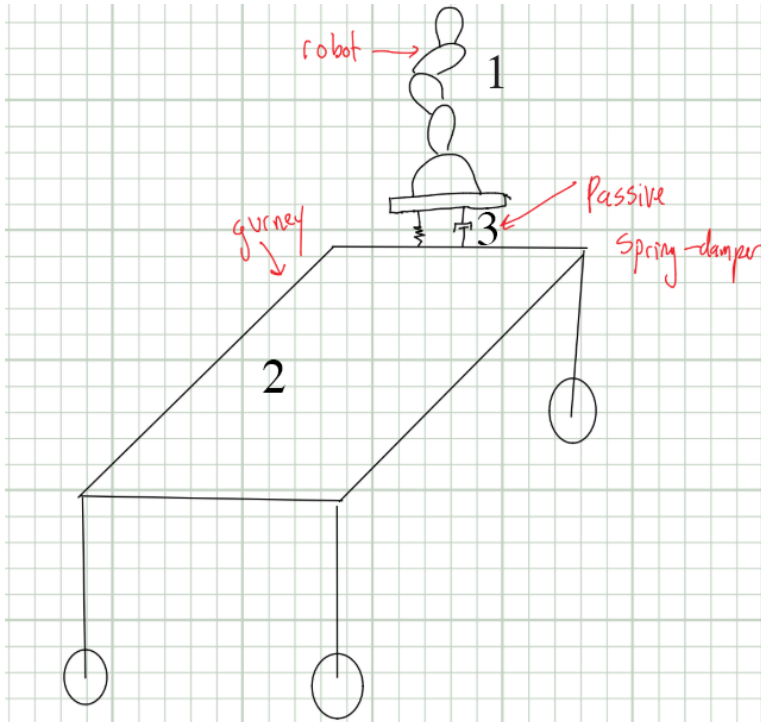


Figure 18: Robot-Damped Gurney (Passive)

This design imagines the robot (Figure 18.1) fixed to a gurney (Figure 18.2) via a passive spring-damper linkage (Figure 18.3). This system would mechanically isolate the robot from the gurney. This design would work in an ambulance, but also theoretically in any scenario involving a gurney, including inside medical helicopters and out in the field where EMTs first respond. Any design that involves a gurney mounted robot also needs to include considerations for robot power. If the gurney contains a battery of sufficient size, the robot can be deployable virtually anywhere, greatly expanding the use and versatility of this platform. However, if the robot is too electrically intensive to make portable power feasible, the robot will need to be plugged in to the ambulance or another power source, restricting it's range of use cases. Gurney mounted system must also consider the added weight and size of it's apparatus, which may change how EMTs interact with and transport the gurney. Stryker's Power-PRO™ XT ambulance cot, for example weighs 125 lbs empty with an adjustable height ranging from 14 in to 41.5in tall. [29] Having a large robot mounted on the gurney may limit where a gurney can be brought, especially areas with narrow corridors, low ceilings, or tight corners. Similarly, the team must consider how the robot fits through the ambulance doorway when mounted on the gurney - it might need to collapse itself to the smallest volume possible to minimize risk for robot or ambulance damage during entry. If not done automatically, this robot re-configuration adds an additional step to the work flow of the EMTs, potentially increasing their cognitive burden.

5.1.3 Passively stabilized gurney with rigidly affixed robot

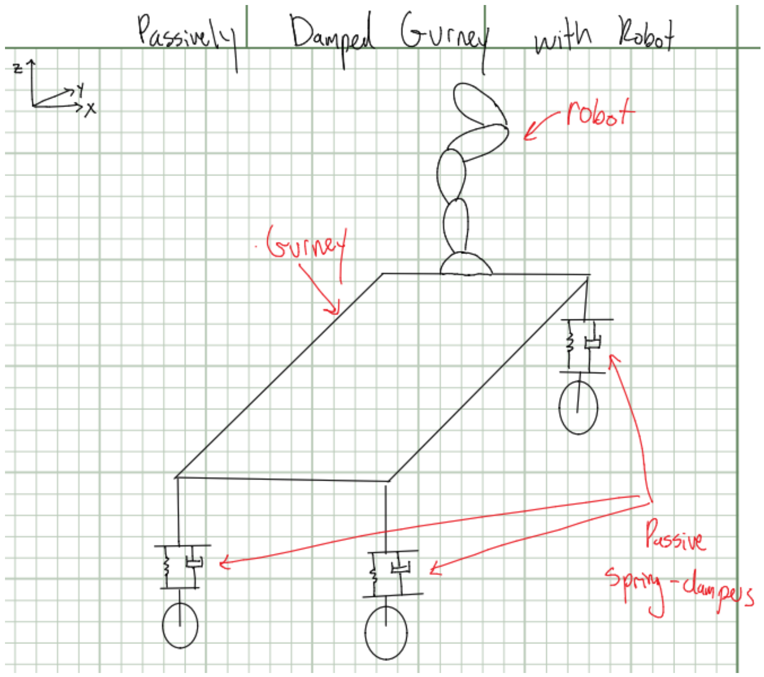


Figure 19: Passive Gurney Stabilization

Instead of damping the interface between the robot and the gurney, this design instead focuses on stabilizing the actual gurney. If robot and patient do not move relative to each other (i.e. are in the same reference frame), the robot can interact with the patient exactly as it would in a fixed environment like a teleoperative surgical suite. A stabilized gurney might also improve the patient experience en route to the hospital and render other care options easier to implement. This gurney mounted design has the same power, size, and weight considerations as the other gurney mounted idea presented above. These spring damper systems must be designed to function well within a large range of patient weights, which may vary by several hundred pounds between patients of different builds. The Center for Disease Control's Anthropometric Reference Data survey from 2011 to 2014 identified the mean weights of US persons as ranging from 141.9 lb to 201.7 lb (varying by age and gender) with standard deviations up to 3.2. The weights recorded varied from 95.3 lb (5th percentile) to 280.8 lb (95th percentile) [33]. Remaining stable over such a wide range of masses increases the challenge of this particular design.

5.1.4 Actively stabilized gurney with rigidly affixed robot

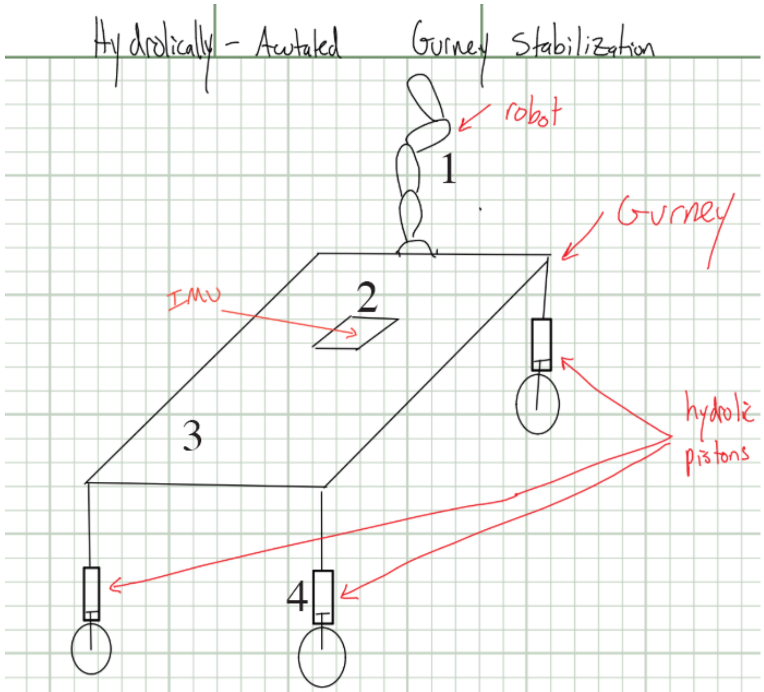


Figure 20: Hydraulically-Actuated Gurney Stabilization

This concept is similar to the previous one in that they both involve a gurney mounted robot and gurney stabilization. This system differs in that it features hydraulic actuators (Figure 20.4) that actively mechanically isolate the patient and the robot together from any external inputs from the ambulance/road. The pistons actuate based on signals from a real time controller processing input from an IMU (Figure 20.2). This design locks the robot and patient into the same reference frame, which simplifies patient/robot interactions. The flexibility of this system allows the robot to perform medical procedures on the patient whenever they're on a gurney, regardless of whether or not they are in an ambulance. Just like the other gurney mounted ideas, this one has limitations related to power and form factor. If the gurney contains a battery of sufficient size, the robot can be deployable virtually anywhere, greatly expanding the use and versatility of this platform. However, if the robot is too electrically intensive to make portable power feasible, the robot will need to be plugged in to the ambulance or another power source, restricting it's range of use cases. Having a large robot mounted on the gurney may limit where a gurney can be brought, especially areas with narrow corridors, low ceilings, or tight corners. Similarly, the team must consider how the robot fits through the ambulance doorway when mounted on the gurney - it might need to collapse itself to the smallest volume possible to minimize risk for robot or ambulance damage during entry. If not done automatically, this robot re-configuration adds an additional step to the work flow of the EMTs, potentially increasing their cognitive burden.

5.1.5 Track Mounted Robot

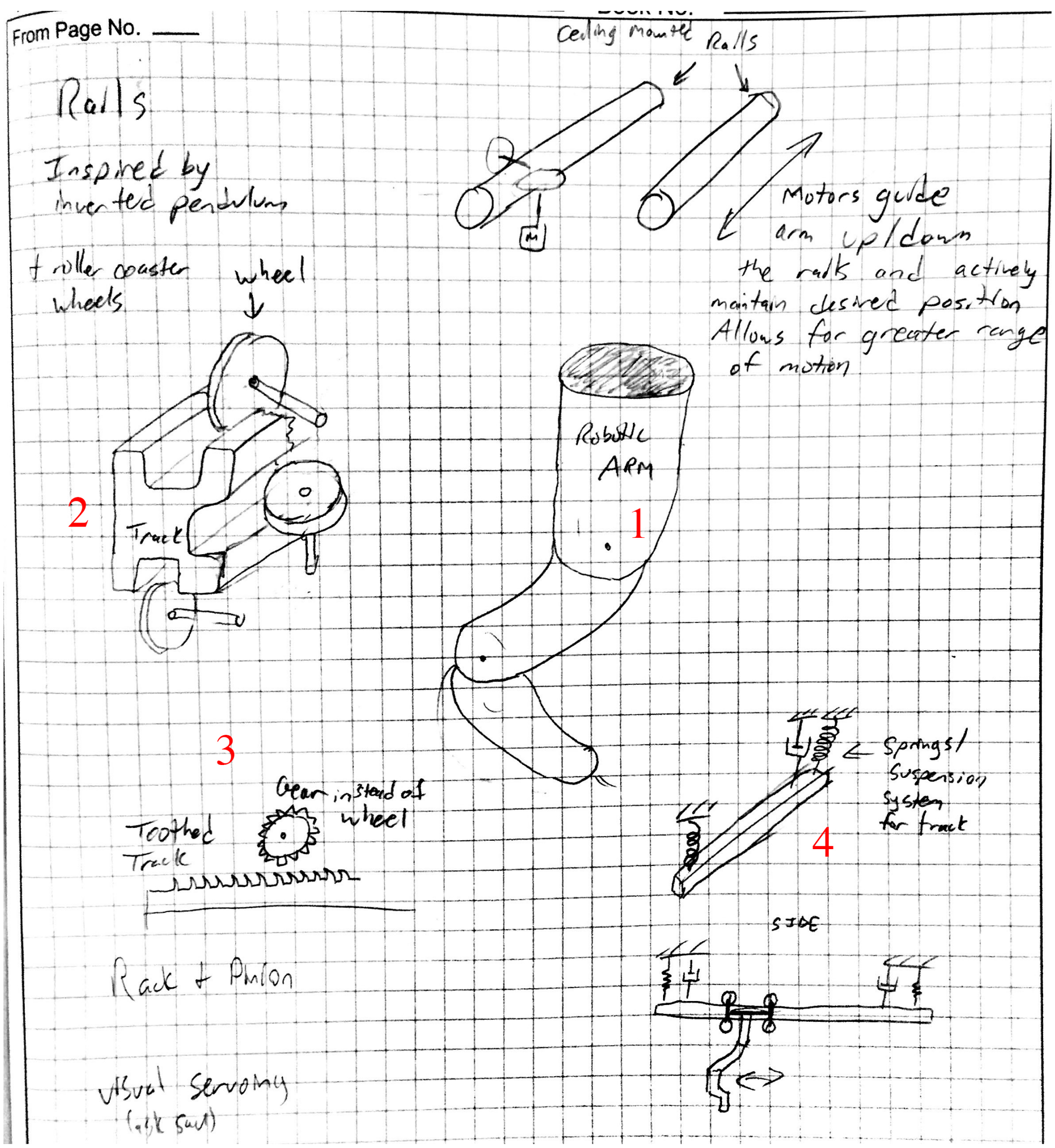


Figure 21: Track Mounted Robot Concept

This design envisions the robot (Figure 21.1) mounted on a ceiling track via rack and pinion(Figure 21.3) or a series of rollers (Figure 21.2). These wheels or pinion gear(s) would be actuated by a stepper motor with a control system that could interface with the attached robot. In addition to providing the robot an additional degree of freedom and greatly extending it's operating range within the vehicle, this system can move the robot laterally to actively compensate for any undesired motion. For additional stabilization, the track could be suspended via a spring/damper system (Figure 21.4) . Another variant of this design envisions a vertical wall mounted track instead of a horizontal ceiling mounted track. While such a system would require motors with significantly higher holding torque, it could in theory actively move the robot to directly counter any vertical disturbances, such as bumps or potholes. This design was inspired, in part, by the classic inverted pendulum experiment, in which a control system maintains an inverted pendulum in the vertical position by adjusting it's base to counter any imbalance. This concept is ceiling mounted with the mass (robot) hanging down instead of pointing up, giving this idea the nickname of the "inverted inverted pendulum".

5.1.6 Circular Ceiling Track Mount

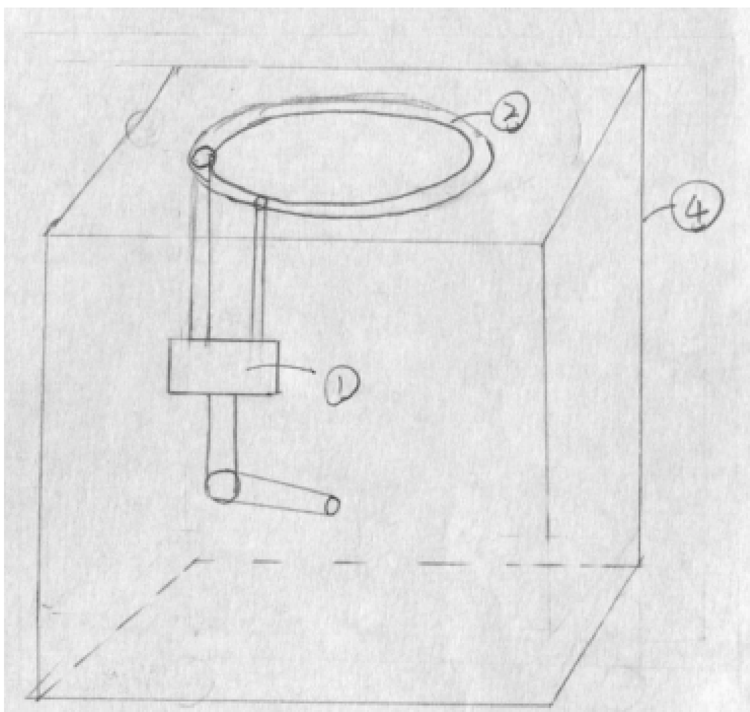


Figure 22: Circular Ceiling Track Concept Design

This concept, similar in nature to the one above, details a circular ceiling track (Figure 22.2) upon which the robot (Figure 22.1) is mounted. This system adds a greater range of motion within the ambulance (Figure 22.4) with a circular (or elliptical) ceiling track (Figure 22.2). This robot, mechanically actuated along this track, can be moved to different sections of the ambulance for increased patient access and also to get out of the way of ambulance personnel or other ambulance procedures. The greater range of motion also enables the robot to store itself in as minimally obtrusive way as possible. Either the track or the robot-track interface would include some form of stabilization system to isolate the robot from the forces from the ambulance. This concept is much more focused on expanding the robot's range of motion than it is focused on mechanically isolating the robot from the ambulance. This design focus doesn't align well with the majors goal of this project.

5.2 Concept Selection Process

Pugh Selection Matrix						
	Alternative Concepts					
Criteria	Solid fixed Robot Mount	Medical Robot Mounted on Track	Active Impulse Mitigation	Robot Damped Gurney (Active)	Passively Damped Gurney with Robot	Inverted Inverted Penulum
Mechanically isolates robot from ambulance	-	+++	+++	+++	+++	+++
Robot does not fall off mount/ceiling	S	+	++	++	++	++
Lifecycle-Durability/reliability	++	-	++	+	++	S
Low maintenance and difficulty	+++	-	+	-	+	-
Small footprint	++	-	++	-	++	-
Small size	++	-	+++	-	-	-
Electrically Efficient	++	+	++	+	++	-
Removable	-	+	+++	++	++	-
Quiet	+++	-	++	++	++	+
Doesnt constrain robot's motion	++	+++	+++	+++	+++	+++
Useable in many ambulances	-	++	++	+++	++	-
Workspace will not interfere with other tasks	++	+	++	++	++	-
Aestheticallly appealing	-	++	++	++	++	++
# of Positives	8	8	13	10	12	5
# of Negatives	4	5	0	3	1	7
# of Sames	1	0	0	0	0	1
Weighted Sum of Positives	18	14	29	21	25	11
Weighted Sum of Negatives	4	5	0	3	1	7
Totals	14	9	29	18	24	4

Figure 23: Pugh chart

When creating the Pugh Chart, the team first came up with the decision characteristics to rate the five concept designs. The decision characteristics were composed of certain customer requirements and engineering characteristics. These were chosen so as to allow for the designs to be rated against as many aspects as possible. The datum design was a solid mount that is currently used in medical robots in hospitals. After rating the solid mount in all of the decision characteristics all five concept designs were comparatively rated against it. The results were calculated so that the sum was taken of all the positives, negatives, and sames. The results of the sums for each were weighted to match and account for the importance of each rating. The best three designs based upon weighted sum of positives were the "Active Impulse Mitigation", followed by "Passively Damped Gurney with Robot" and lastly "Robot Damped Gurney (active)". However the "Solid Fixed Mount" was pretty close to the "Robot Damped Gurney (active)". The best three designs based on the sum of negatives were "Active Impulse Mitigation", followed by "Passively Damped Gurney with

Robot", and lastly "Robot Damped Gurney (active)". Both the weighted sum of positives and the weighted sum of negatives reflect the same three design concept just in a slightly different order. This is good because it yields clear results as to what concepts should be continued to be pursued in this project.

5.2.1 Group Sign Off

Brian Bock

Luxi Huang

Ashley Ollech

Nathan Orwig

Saul Schaffer

Greg Turlik

5.3 Product Design Specification (PDS)

Product Title

- Vibration dampening medical robot mount.

Purpose

- To provide the care of a medical robot in a mobile ambulance.

New or special features

- Allows use of medical robot in an ambulance.
- Small; takes up little space in an ambulance.
- Reduces vibration damage to medical robot.
- Maintains accuracy of medical robot sensors.
- Improves/Maintains patients trust in procedures.

Competition

- Camera stabilization systems for car chase scenes/film making.
- Gun stabilizers on helicopters, tanks
- None of the existing solutions satisfy the needs this product addresses

Intended market

- We will sell direct to medical research labs of which there are just shy of 20 in the DMV area.
- Secondary market will be to ambulance manufacturing companies. 2069 ambulances were manufactured by Ford alone last year. [34]

Need for product

- User survey has shown customer interest in this concept; over 70 percent of people surveyed expressed willingness to receive mobile medical care from a robot.

Relationship to existing product line

- This is a new concept. No other products currently exist.

Market demand

- In 2015 there were 15.7 million ambulance responses with transport to a medical facility. This number is continuously growing. [35]
- There are 22 medical research labs in the united states that would be interested in this product. [10]

Price

- We anticipate selling this medical robot mount at a price no greater than fifteen thousand US dollars. [36]

Functional performance

- Allows medical robot full range of movement.
- Accounts for torques and forces.
- Sturdy enough to withstand vibration and impacts during ambulance commute.
- Secures medical robot firmly in place.
- Dampens vibration transmitted to robot from ambulance.

- Takes up minimal space in ambulance when not in use.

Physical requirements
Some of these physical requirements will be determined later by a closer analysis of ambulance space restrictions and other constraints. Note that the space, weight, and shape of the final design are all inherently bound by the same constraint; the confined space of an ambulance interior. It is difficult to constrain the geometry of our design while remaining solution neutral; this will evolve with our product.

- Volume not to exceed 2 ft^3.
- Weight not to exceed 50 lb.
- Shape triangular but must be within volume constraints.
- Texture smooth and anti-bacterial (or easy to clean).
- Power input must not exceed 125 Volt-AC with maximum of 15A. [30]

Service environment
These characteristics look at the environment the robot will be placed in. Even though many ambulances are insulated and temperature controlled [30], it is important that the mount remain functional and not degrade while the ambulance is parked or otherwise not in use.

- Mount material should be structurally stable from -30°F to 120°F. [37]
- Mount material should be structurally stable in 0% to 100% relative humidity.
- Mount material should be anti-bacterial and easily sterilized.

Life-cycle issues

- Mount mechanism must not exhibit structural failure for minimum 5 years.

Human factors

- No sharp corners or edges that could injure any of the users.
- Installation of mount must be simple and straightforward.
- System should maintain or improve human trust
- System should not interfere with the haptic feedback relied upon by the operator

Corporate constraints

- Must be in the market in five years time because the average ambulance lasts 3-4 years. [32]
- Manufacturing will be contracted to suppliers.
- Will use trademark "Hold My Robot".
- Must conform to ASME code of ethics, specifically *"Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties."*. [12]

Legal requirements

- No toxic materials to be associated with manufacturer. [15]
- Mount cannot exceed 50lbs. [38]
- Materials must be FDA compliant and OSHA compliant for use inside an ambulance. [38]

5.4 Final Concept Sketch and Description

5.4.1 Original "Final" Design and Design Evolution

After deciding on a final concept to pursue, the team began exploring design options. A well developed plan (elaborated upon below) was conceived involving worm drive actuation. As the team began researching worm gear solutions, it soon began apparent that this concept was impractical for a number of reasons. Most commercial screw jack products are prohibitively expensive, often costing several thousand dollars or otherwise having no visible price [39], [40]. Additionally, many of these screw jack systems are large, cumbersome, and many orders of magnitude over-engineered for this project, with some capable of actuating 75+ tons [41]. Some worm drive gear boxes are designed as speed reducers, an unhelpful feature in our environment where high speed adjustments are vital. The complexity of these systems would force the team to source the entire lead screw drive assembly from the same vendor, possibly as a even more costly semi-custom solution. With these issues in mind, the team re-evaluated the design to remove the worm drive system and focus on parts that would be faster, cheaper, and easier to come by. This section (Section 5.4.1) details the full original system as the team had designed, with additional notes about the shortcomings that later became apparent. The next subsection (Section 5.4.2) covers the updated design that the team devised, using heim joints and direct drive transmission to replace the problematic worm drive transmission. As that design progressed, it became clear that intended interfaces would drastically change the weight and cost of the product, prompting the team to redesign again. A third iteration design was created (Section 5.4.3) to address these design issues with custom made swivel flanges. Near the final stages of that design, the team noticed a geometric constraint that limited the effectiveness of solution, prompting one more round of redesign. The final design (section 5.4.4), addresses all of the issues of its predecessors and serves as the ultimate version of this product.

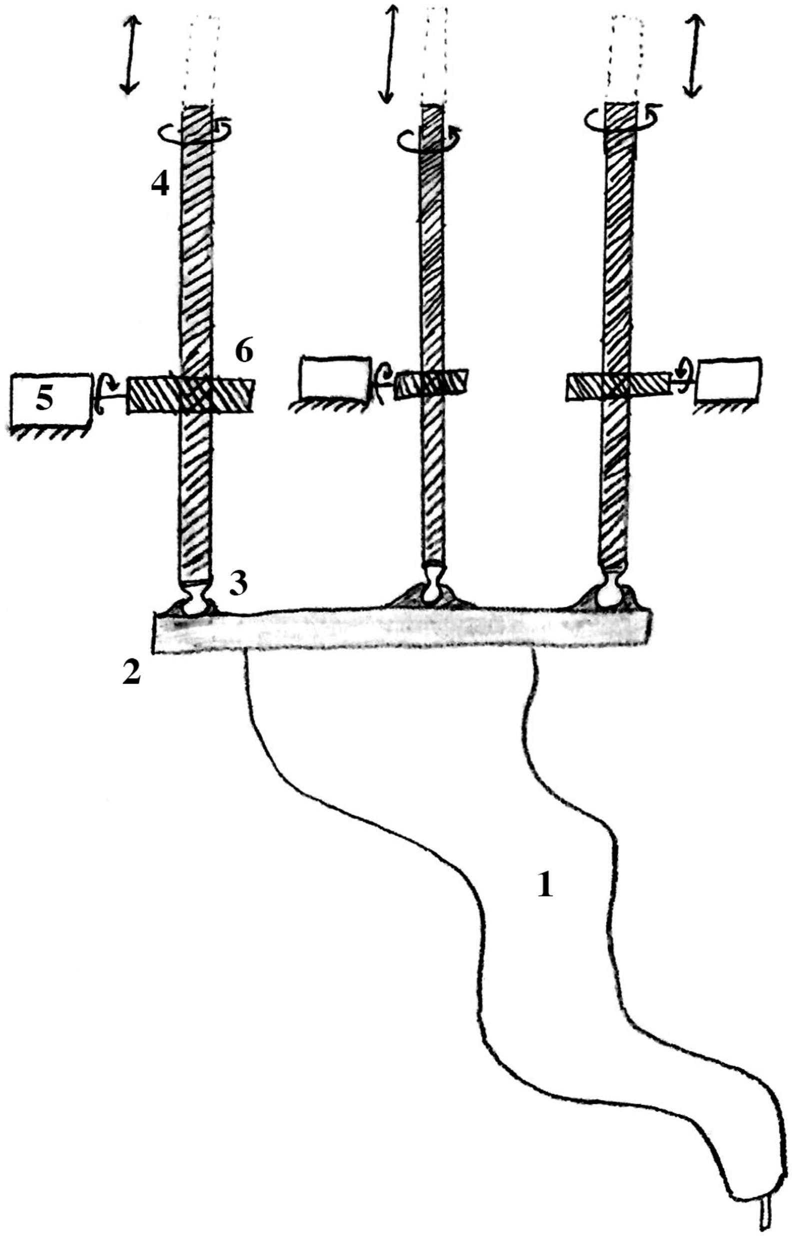


Figure 24: Sketch of Final Design

This concept envisions a medical robot (Figure 24.1) rigidly fastened to a stiff triangular platform (Figure 24.2). At each corner of this platform, there is a ball and socket interface (Figure 24.3), (Figure 25.1), which is then connected to a lead screw (Figure 24.4). A bearing interface between the lead screw and ball ((Figure 25.2) allows the lead screw to spin independently of the ball. This component is one of the problems with this design. We would need a double bearing that allows two components to spin independently of each other while still being fixed to the same joint. It seems that such a component is nonstandard and likely difficult to source.

The three lead screws extend vertically upward from the ball & socket joint, and remain strictly parallel to each other at all times. The lead screws would be perpendicular to the roof of the ambulance. The system requires three lead screws as three points are required to define the plane of the robot platform. Note that the sketches shown are not to scale and have elements enlarged for emphasis and visual clarity. When the design is finalized, the robot will be the most predominate feature of the system. It is likely that the lead screws will only be a few inches long, and the exaggerated screw lengths shown in Figure 24 will not be nearly as dramatic.

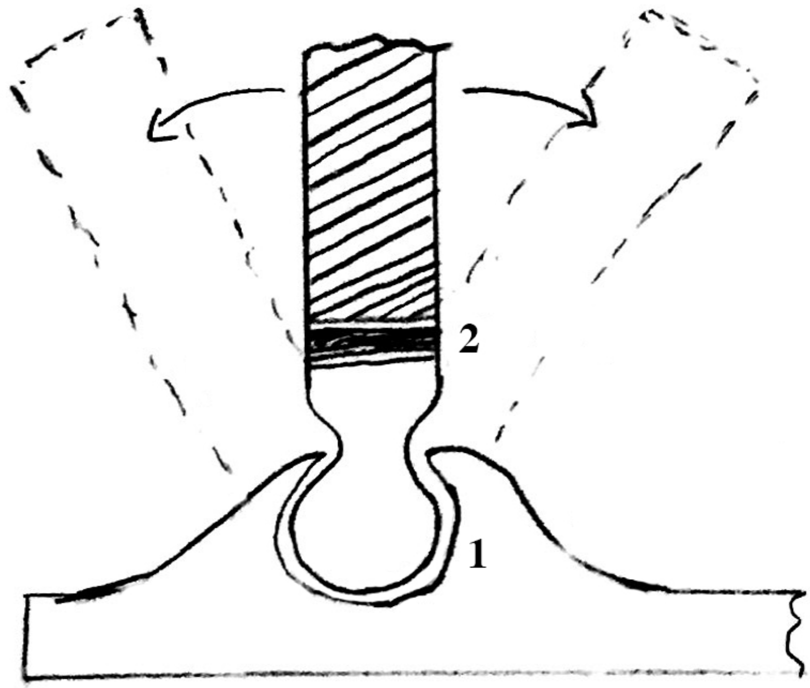


Figure 25: Detail view of the ball & socket interface connecting the lead screws and robot platform.

Each lead screw is actuated by a stepper motor (Figure 24.5) via a worm gear transmission (Figure 24.6). The rotation of each motor directly adjusts the height of it's lead screw, together allowing for excellent control of the pitch, yaw, and height of the platform. The motors would be rigidly affixed within the ambulance, and the lead screws would have sufficient overhead clearance for their full range of motion. How the motor and screw interact, a crucial interface to the success of this design, is another point where this design becomes problematic. If the motor is to connect perpendicularly to the lead screw, it must connect via a worm drive transmission. This system changes the direction of the rotary motion of the motor 90 degrees to drive the screw. This system is commonly used in screw jacks, a mechanism for actuating a screw to lift a large load. Figure 26 shows the internal complexity of a ball screw jack.

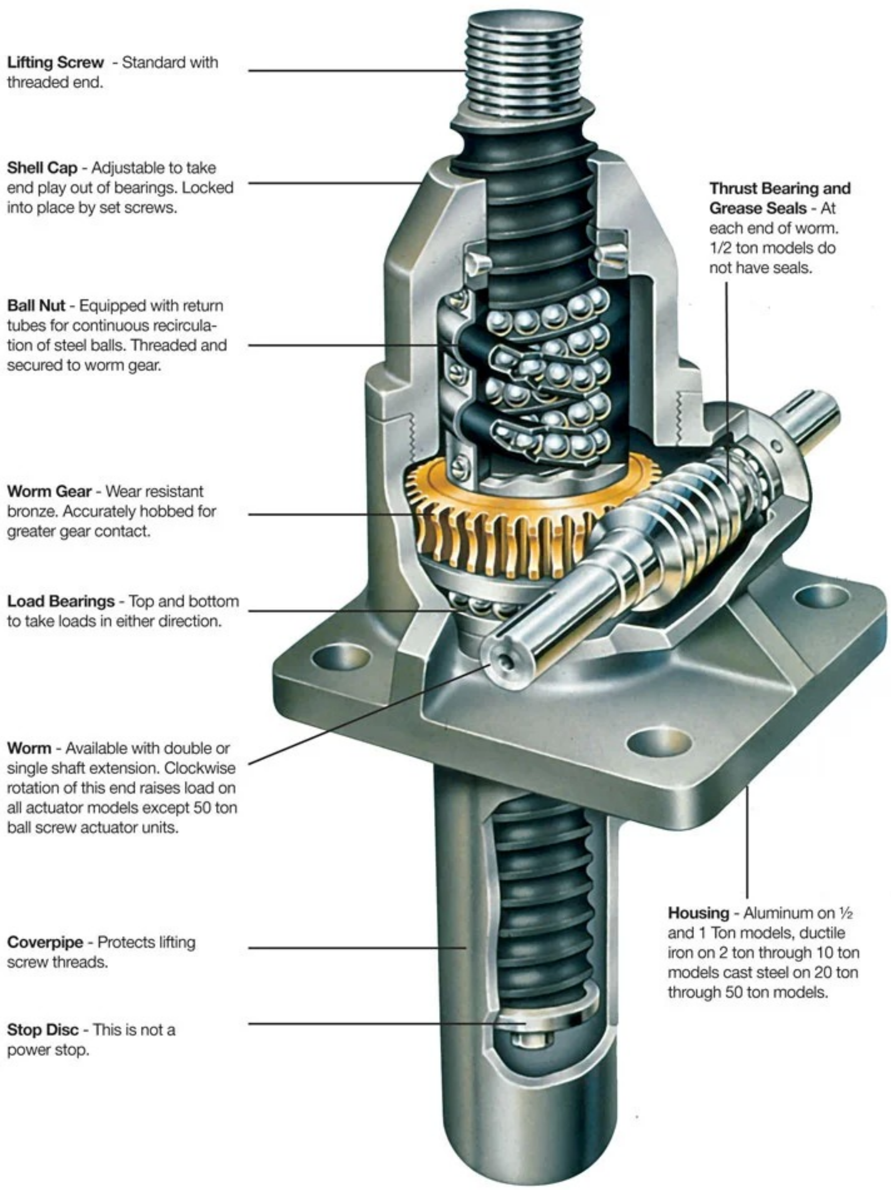


Figure 26: Cutaway of a ball screw jack [42]

Most commercial screw jack products are prohibitively expensive, often costing several thousand dollars or otherwise having no visible price [39], [40]. Additionally, many of these screw jack systems are large, cumbersome, and many orders of magnitude over-engineered for this project, with some capable of actuating 75+ tons [41]. Some worm drive gear boxes are designed as speed reducers, an unhelpful feature in our environment where high speed adjustments are vital [43]. The complexity of these systems would force the team to source the entire lead screw drive assembly from the same vendor, possibly as an even more costly semi-custom solution.

Two multi-axis accelerometers would be employed to gather sensory data for the control system. One, mounted on the ceiling of the ambulance, would provide information about the disturbances that the system needs to counter, while the other, mounted on the robot platform, would serve as feedback to verify the implement corrections. The control system would take these two inputs and use them to actuate the motors (and lead screws) such that the robot platform remains always parallel to and equidistant from a predefined constant "ground" reference plane (Figure 27).

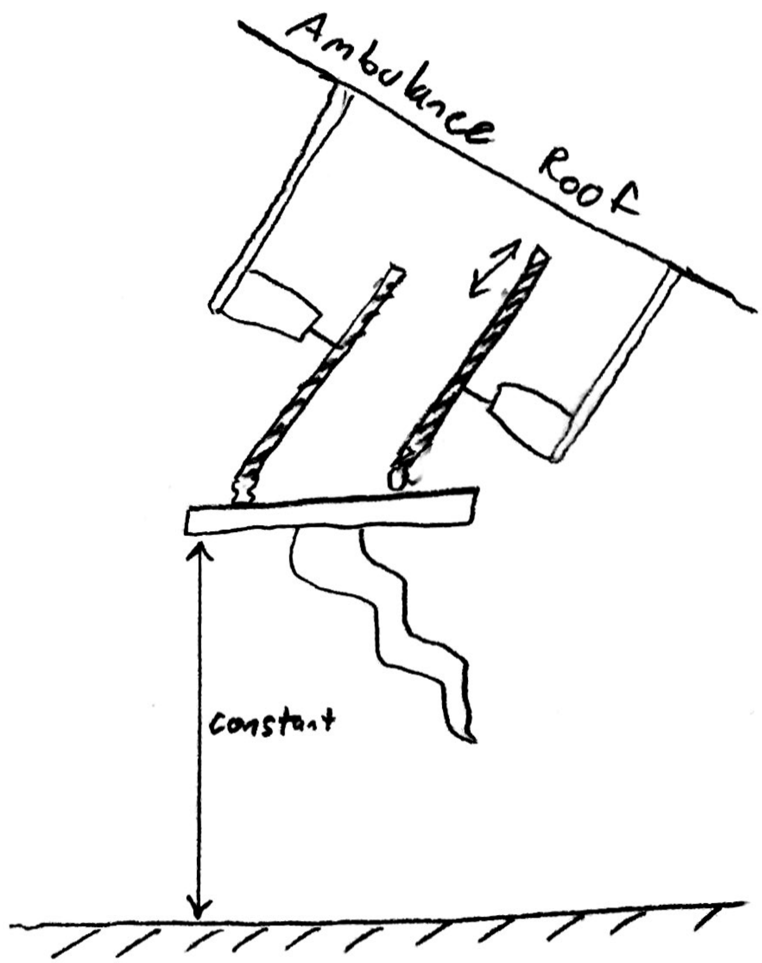


Figure 27: Exaggerated sketch showing the extreme ambulance roof position and the system's response.

It is important to clarify here that this "ground" reference plane cannot actually be the road, as the road imperfections (especially potholes) are exactly what the system is built to compensate against. In theory, the three motors would work collaboratively to directly invert any inputted motion, resulting in a stabilized robot base.

The system, expected to work in an medical environment, must be easily cleanable and resistant to bodily fluids as well as regular dirt and debris. The motors and lead screws, together having extended and complicated surface geometry, would likely be difficult to clean and susceptible to debris. In addition, the mechanical parts of the system pose a risk to the people around it, offering a number of regions that fingers could potentially get caught in and be injured. Both of these issues can be addressed by enclosing the entire system with bellows (Figure 49, Figure 50).

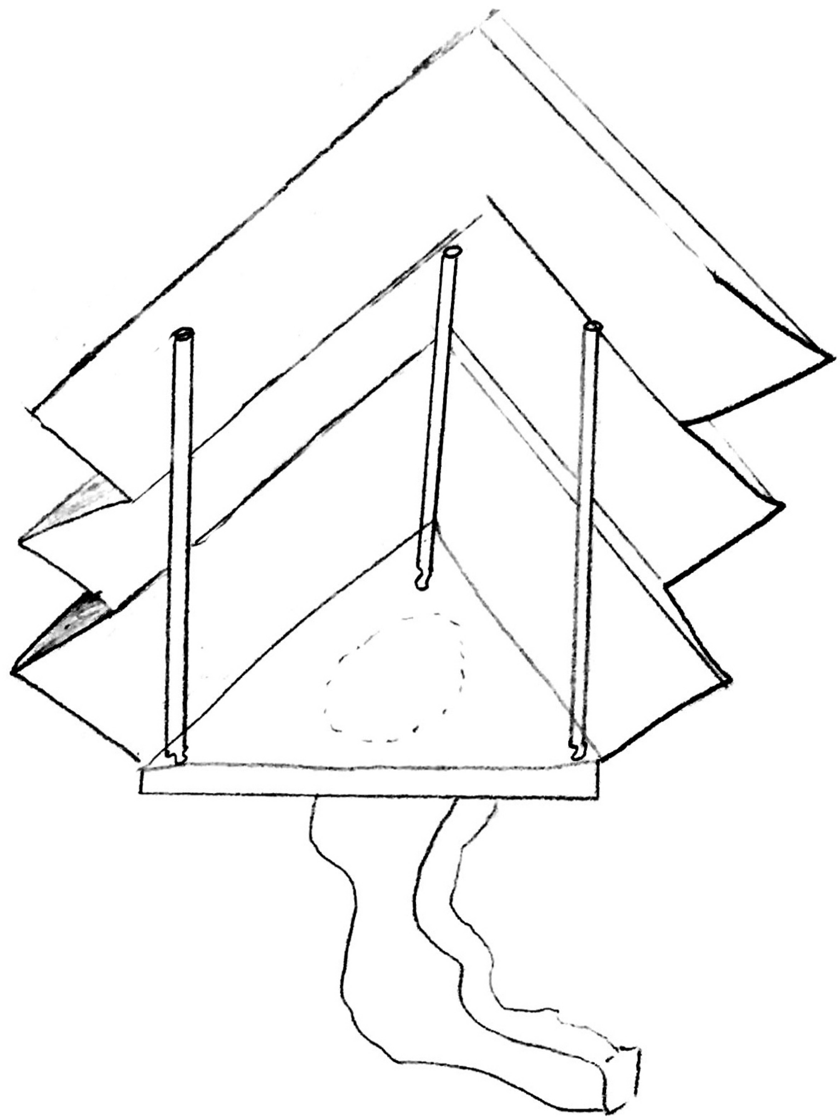


Figure 28: Sketch of the protective bellows. For clarity, the third side of bellows is omitted.

This accordion-like system of folded walls would completely encapsulate the entirety of the mechanical system and be attached to the robot platform and roof of the ambulance. The flexible nature of this design allows the bellows to stretch and move with the robot platform as it is shifted to counter the ambulance's movement.

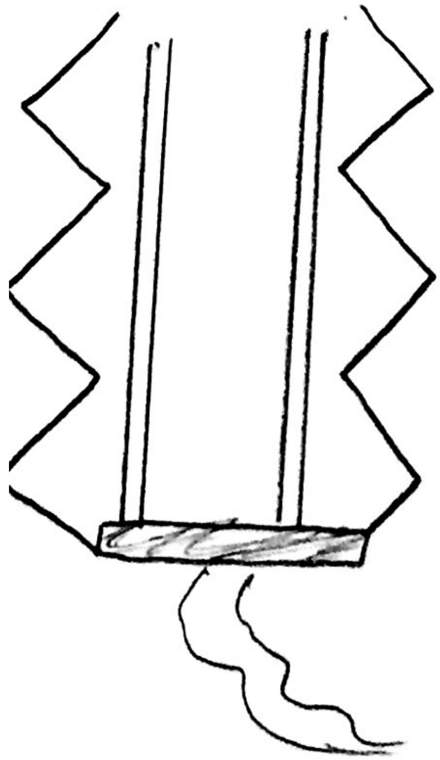


Figure 29: Side view sketch of the protective bellows

The bellows must be made of a flexible, non-absorptive, non-porous material that can be easily disinfected. These material constraints are crucial to the functionality of the bellows.

5.4.2 Second Major Design

This design exists to resolve the issues presented in the worm drive transmission elaborated upon in Section 5.4.1. There are some similarities but also some important differences between this design and its predecessor.

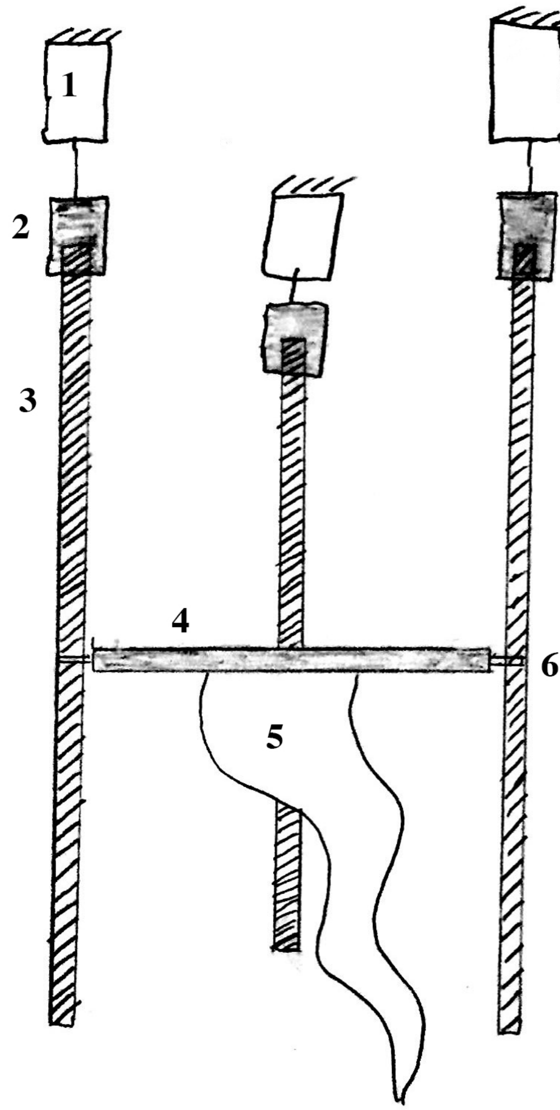


Figure 30: Sketch of 2nd Design. Note that the lead screws are drawn with exaggerated length for emphasis and are not to scale.

The concept envisions a medical robot (Figure 34.5) rigidly fastened to a stiff triangular platform (Figure 34.4).

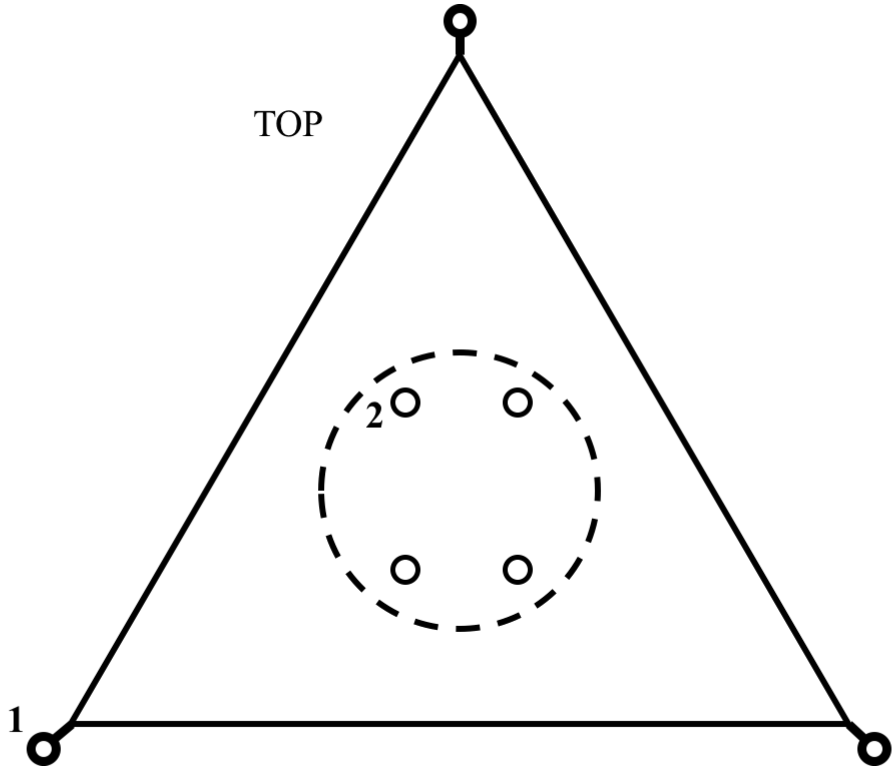


Figure 31: Top view sketch of the robot platform

The robot will be affixed to the underside of the platform via a number of bolts. The position of these bolts will be determined by the geometry of the robot's base and how many points of contact the manufacturer recommends for secure fastening. The platform will include multiple bolt holes (Figure 31.2) to accommodate the robot, and will either be specific to a particular robot or designed with additional holes for increased robot versatility. The strength and material requirements of these bolts will be evaluated in Section **??** Configuration Design.

This is where this design begins to differ from it's predecessor. The troublesome ball socket bearing connections are replaced with heim joints, which protrude from each corner of the triangular robot platform (Figure 34.6), (Figure 31.1). For the practical purposes of screwing in each heim joint, the corners of the triangular platform would be cut flat (not shown) instead of ending at a sharp point. A heim joint is a mechanical articulating joint with a ball swivel [44]. Each heim joint would be coupled with a lead screw nut, through which a lead screw (Figure 34.3) would pass. The heim joint frees the lead screw from the perpendicular constraint it would have within a rigid threaded hole, allowing the platform to tilt as the screws retract or extend. This provides excellent control of the pitch and yaw of the platform. Note that the sketches shown are not to scale and have elements enlarged for emphasis and visual clarity. When the design is finalized, the robot will be the most predominate feature of the system. It is likely that the lead screws will only be a few inches long, and the exaggerated protrusions shown in Figure 34 will not be nearly as dramatic.

Figure 32: Heim Joint [45]

The system requires three lead screws as three points are required to define the plane of the robot platform. The three lead screws extend vertically upward from heim joint, and remain strictly parallel to each other at all times. With the lead screws now able to pass through the platform without constraining its tilt, the motors can be removed from the original horizontal configuration that required complicated worm transmission. The motors are relocated to a much simpler direct drive at the top of each screw. The entire motor lead screw assembly remains fixed perpendicular to the roof of the ambulance at all times. The exclusion of the worm gear transmission frees the design from costly custom solutions, and allows many parts to be purchased much more cheaply Commercial Off the Shelf (COTS). The coupling required to connect the lead screw and motor is a much more common component than the gearbox, making it more accessible and easier to source for cheap.

Each lead screw is actuated by a stepper motor (Figure 34.1) fixed on one end of the lead screw via a coupling (Figure 34.2). The rotation of each motor directly adjusts the height of it's corner of the robot platform, together allowing for excellent control of the pitch, yaw, and height of the platform. The motors would be rigidly affixed to the ceiling of the ambulance. The specifications of these motors will be evaluated in Section **??** Configuration Design. It's important that these motors have sufficient holding torque to prevent the lead screws from turning from the weight of the platform.

Two multi-axis accelerometers would be employed to gather sensory data for the control system. One, mounted on the ceiling of the ambulance, would provide information about the disturbances that the system needs to counter, while the other, mounted on the robot platform, would serve as feedback to verify the implement corrections. The control system would take these two inputs and use them to actuate the motors (and lead screws) such that the robot platform remains always parallel to and equidistant from a predefined constant "ground" reference plane (Figure 56). Note that the sketch shown in Figure 56 is an extreme exaggeration; the actual angles achievable by this system will be considerably smaller ($\approx \pm 5°$).

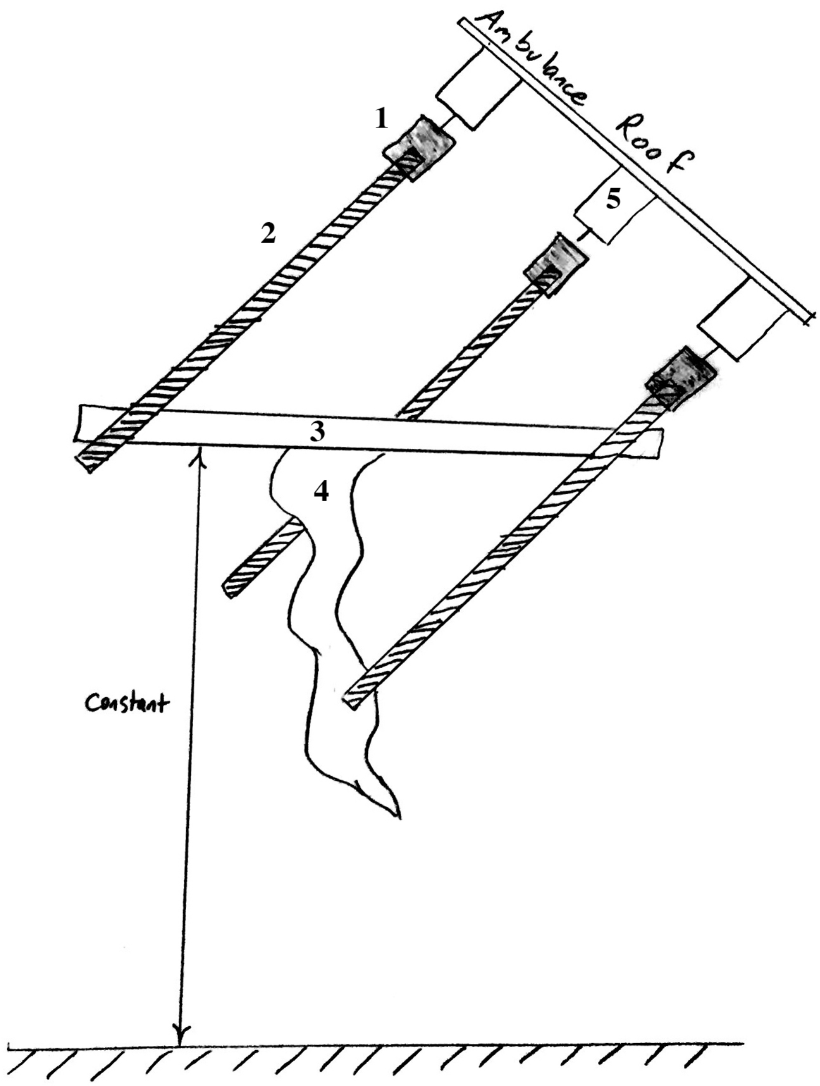


Figure 33: Exaggerated sketch showing the extreme ambulance roof position and the system's response.

It is important to clarify here that this ”ground” reference plane cannot actually be the road, as the road imperfections (especially potholes) are exactly what the system is built to compensate against. In theory, the three motors would work collaboratively to directly invert any inputted motion, resulting in a stabilized robot base. The accelerometers feed real time information into a control system, which analyzes the incoming signals and then actuates the motors to compensate. The sensitivity and repeatability of these sensors is a crucial factor in their ability to measure disturbances in a useful way.

The bellows concept described in the previous concept doesn't work nearly as well with the external screws. Making the bellows work here would require more complicated geometry and be more difficult to implement, so this idea does not include the bellows.

The system contains several components that require electrical power, including the three motors, motor control system, and sensors. The robot also requires power, but does not necessarily have to be connected to the same power supply as the mount. The total external power of both systems is limited to the available power in the ambulance, two 125-volt AC duplex receptacles conforming to NEMA 5-15 [30]. The specifications of the power supply are entirely dependent on the power requirements of the mount's electrical systems, but should have basic surge suppression and conform to all relevant electrical standards.

5.4.3 Third Design

When evaluating the lead screws and corresponding heim joints required for the idea above, a design flaw became apparent. The size of the lead screws determines the size of the inner diameter of the heim joint, which then affects the size of it's attached bolt. For the lead screws we intend to use, we'd need heim joints with an approx 3/4" (or larger) bolt shaft diameter. As the this bolt is screwed into the edge of the robot platform, the platform must be thick enough to accommodate said bolt. This forces our robot platform to be nearly an inch thick, making it a very expensive component to source. With this important shortcoming in mind, the team re-evaluated the design again. The fundamentals of the platform and actuation bear tremendous similarity to those presented in Section 5.4.2 but will nonetheless be recounted here for holistic clarity.

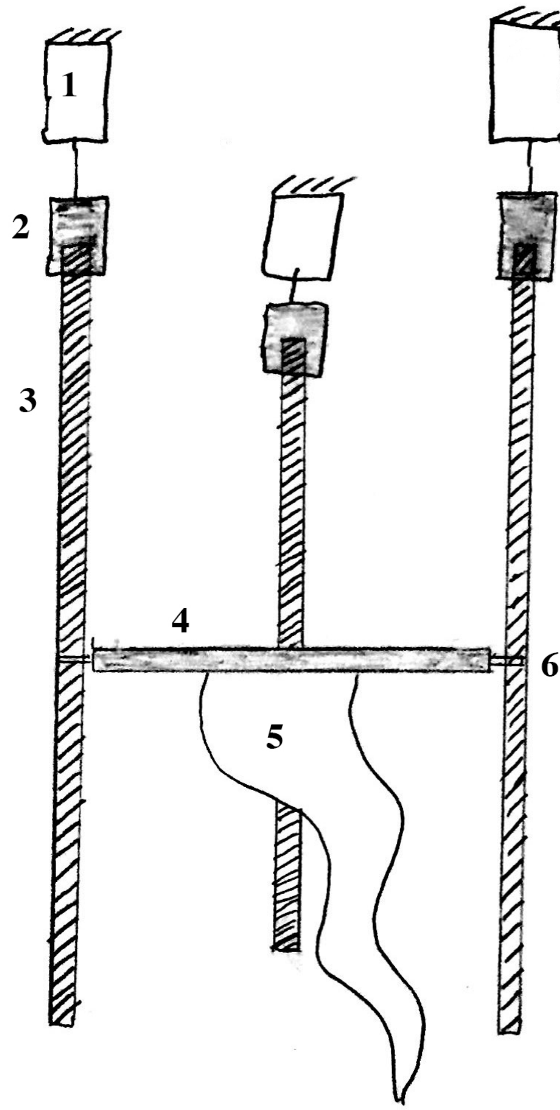


Figure 34: Sketch of Final Design. Note that the lead screws are drawn with exaggerated length for emphasis and are not to scale.

The concept envisions a medical robot (Figure 34.5) rigidly fastened to a stiff triangular platform (Figure 34.4).

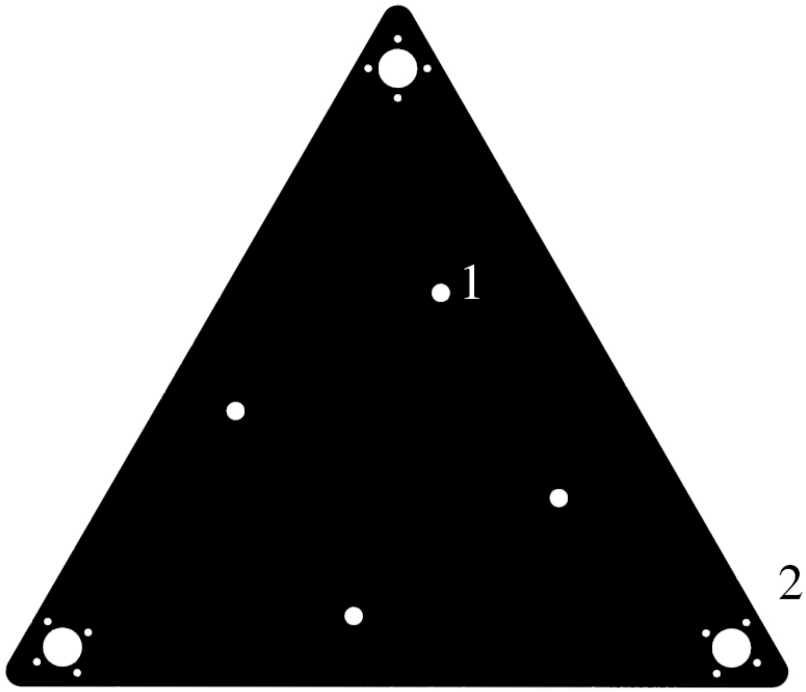


Figure 35: Top view sketch of the robot platform with bolt holes for the robot (1) and the flange assembly (2)

The corners of the triangular platform are now rounded instead of cut flat. The robot will be affixed to the underside of the platform via a number of bolts. The position of these bolts will be determined by the geometry of the robot's base and how many points of contact the manufacturer recommends for secure fastening. The platform will include multiple bolt holes (Figure 35.1) to accommodate the robot, and will either be specific to a particular robot or designed with additional holes for increased robot versatility. The strength and material requirements of these bolts will be evaluated in Section **??** Configuration Design.

This is where this design begins to differ from it's predecessor. The heim joints are replaced with a custom designed ACME threaded ball swivel flange (Figure 36).

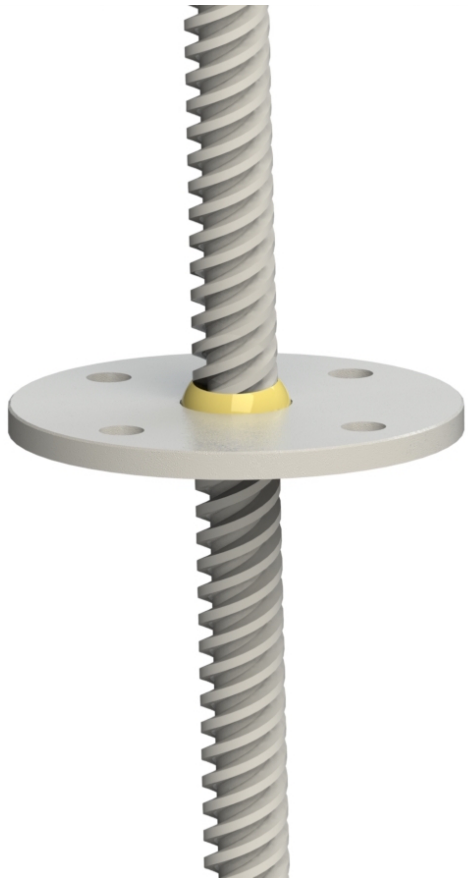


Figure 36: Rendering of the proposed swivel flange

Instead of having socket joints outside of the platform, a flange is implemented to be mounted directly on the top face of the platform. Holes are added to the platform (Figure 38) to allow the lead screws to pass through. The ball component of this new system allows the same swivel flexibility provided by the heim joints (Figure 37).

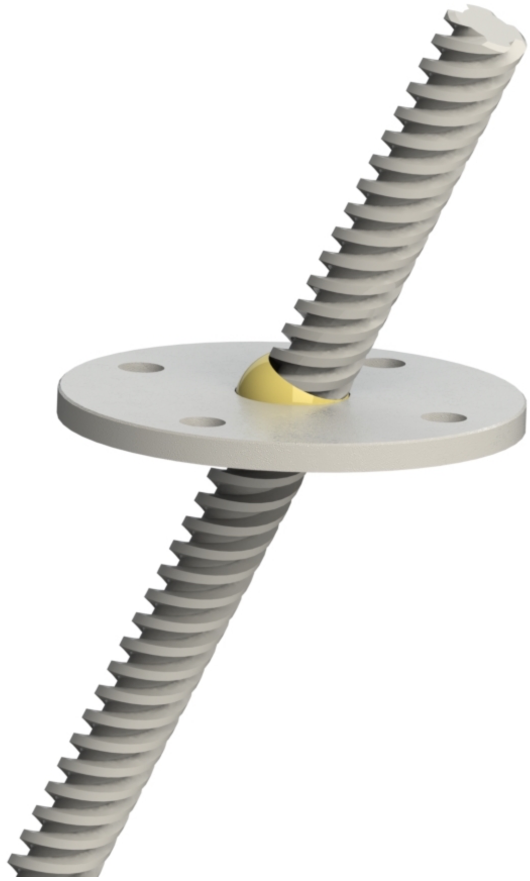


Figure 37: Rendering of the proposed swivel flange showing it's angle flexibility.

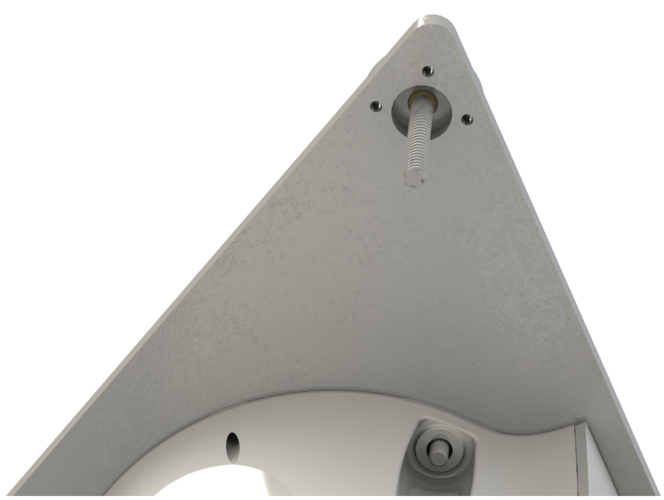


Figure 38: Rendering of the underside of the platform showing the cutout and bolt holes for the swivel flange

If the ball component of the flange cannot be easily tapped with ACME threading (the threading style most common for lead screws), it will need to be redesigned to accommodate an ACME nut (Figures 39, 40, 41).

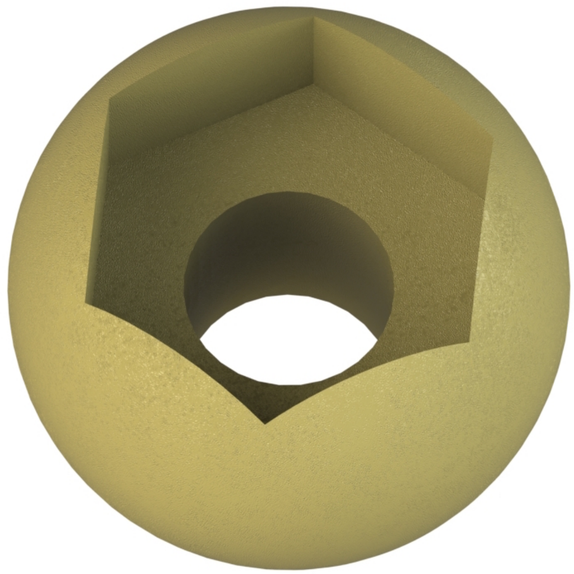


Figure 39: Rendering of the ball with a hexagonal cutout for a nut

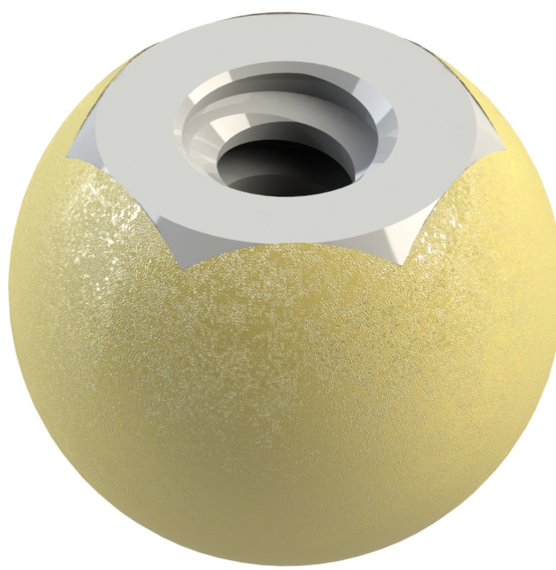


Figure 40: Rendering of the ball with ACME nut shown

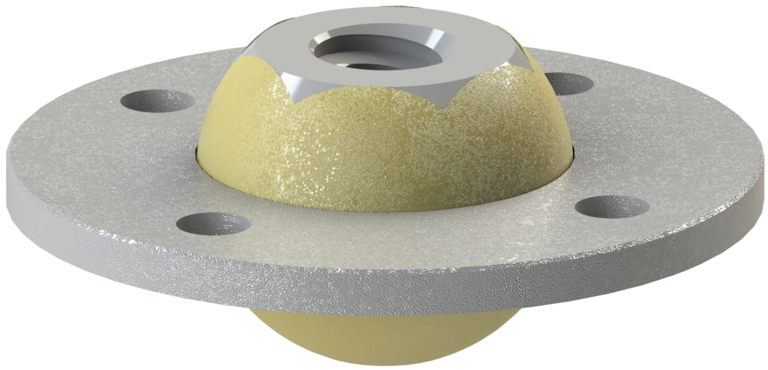


Figure 41: Rendering of the ball and ACME nut inside the flange

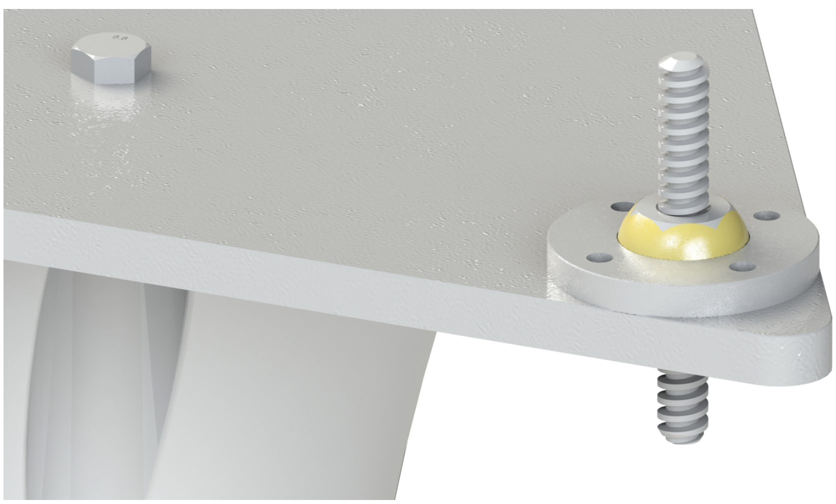


Figure 42: Rendering of the ball, nut, and flange assembly on the platform. Note that the lead screw shown is a placeholder model and not representative of the actual length of the lead screws that will be used

The bolts required to affix the flange assembly to the platform are omitted from Figures 42, 43, and 44.

Figure 43: Additional rendering of the flange assemblies on the platform. The KUKA robot can be seen mounted via four M8 bolts in the center.

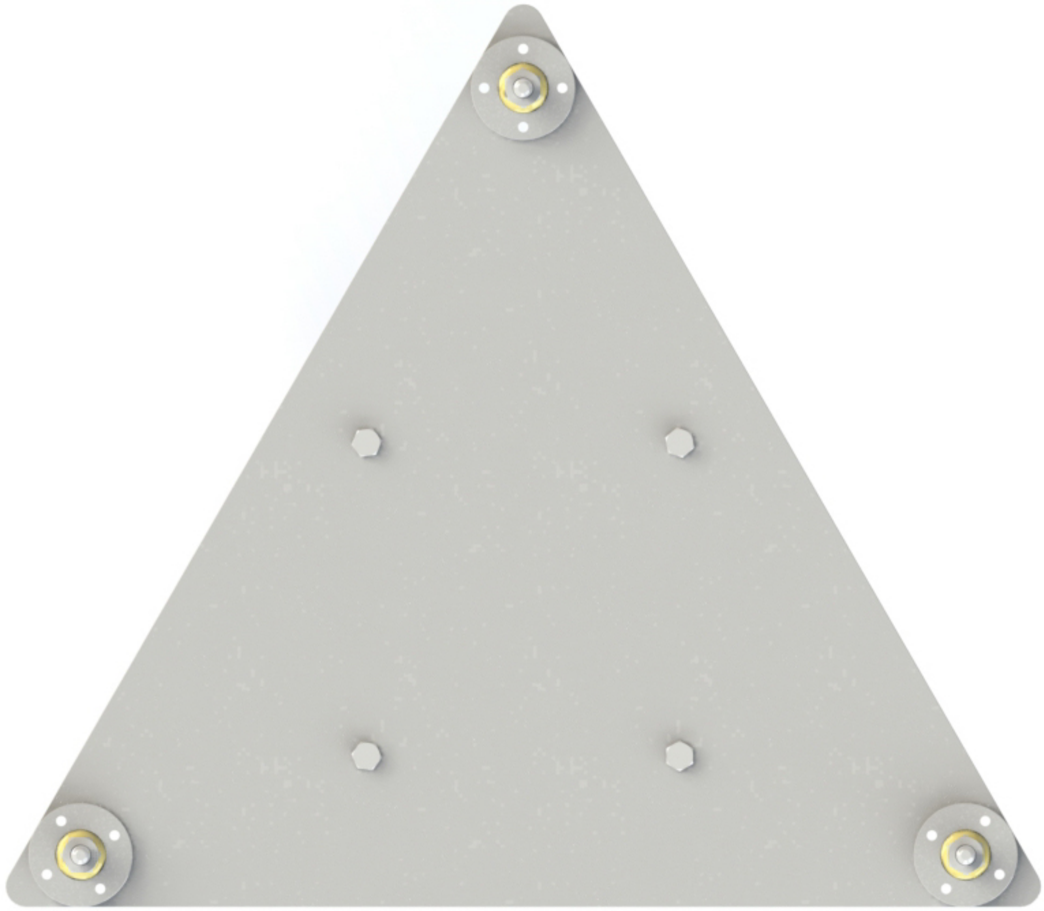


Figure 44: Top view rendering of the flange assemblies on the platform. The KUKA robot is mounted via the four M8 bolts in the center.

The system requires three lead screws as three points are required to define the plane of the robot platform. The three lead screws extend vertically upward through each flange, and remain strictly parallel to each other at all times. The motors remain as direct drive at the top of each screw. The entire motor lead screw assembly remains fixed perpendicular to the roof of the ambulance at all times.

Each lead screw is actuated by a stepper motor (Figure 34.1) fixed on one end of the lead screw via a coupling (Figure 34.2). The rotation of each motor directly adjusts the height of it's corner of the robot platform, together allowing for excellent control of the pitch, yaw, and height of the platform. The motors would be rigidly affixed to the ceiling of the ambulance. The specifications of these motors will be evaluated in Section **??** Configuration Design. It's important that these motors have sufficient holding torque to prevent the lead screws from turning from the weight of the platform.

Two multi-axis accelerometers would be employed to gather sensory data for the control system. One, mounted on the ceiling of the ambulance, would provide information about the disturbances that the system needs to counter, while the other, mounted on the robot platform, would serve as feedback to verify the implemented corrections. The control system would take these two inputs and use them to actuate the motors (and lead screws) such that the robot platform remains always parallel to and equidistant from a predefined constant "ground" reference plane (Figure 45). It is important to clarify here that this "ground" reference plane cannot actually be the road, as the road imperfections (especially potholes) are exactly what the system is built to compensate against.

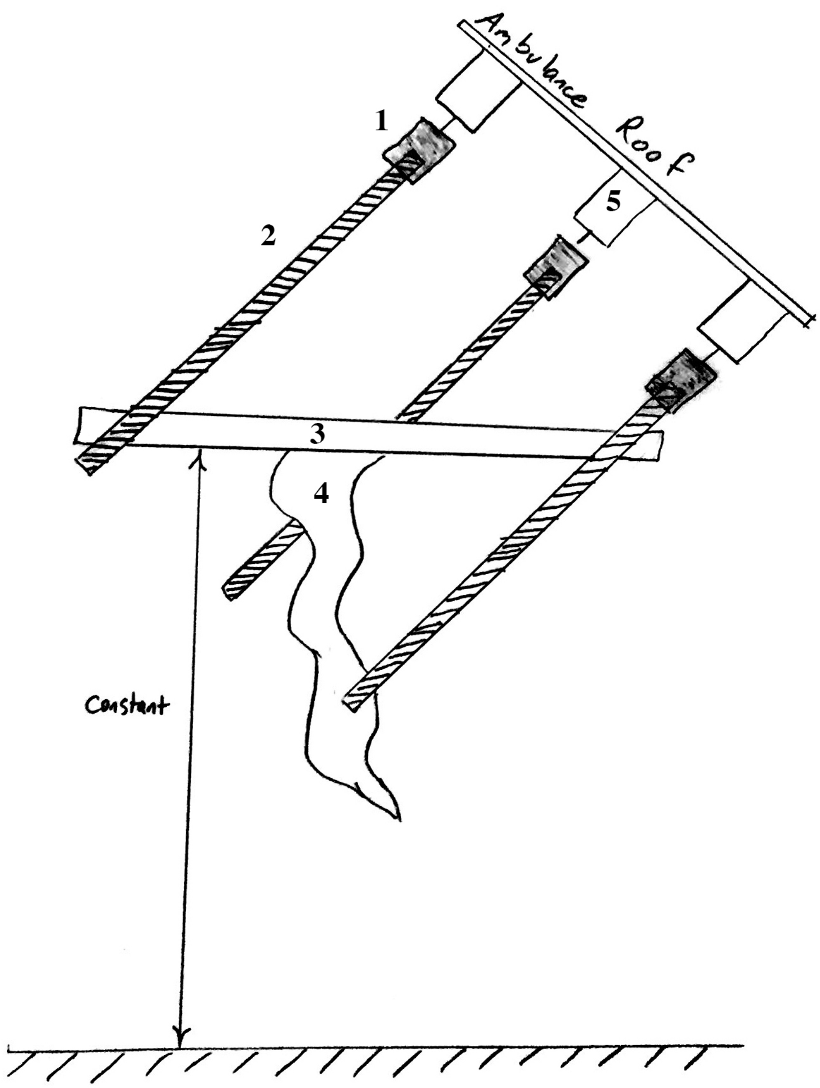


Figure 45: Exaggerated sketch showing the extreme ambulance roof position and the system's response.

Note that the sketch shown in Figure 45 is an extreme exaggeration; the actual angles achievable by this system will be considerably smaller ($\approx \pm 10°$). This angle limitation stems from the geometry of the angled platform.

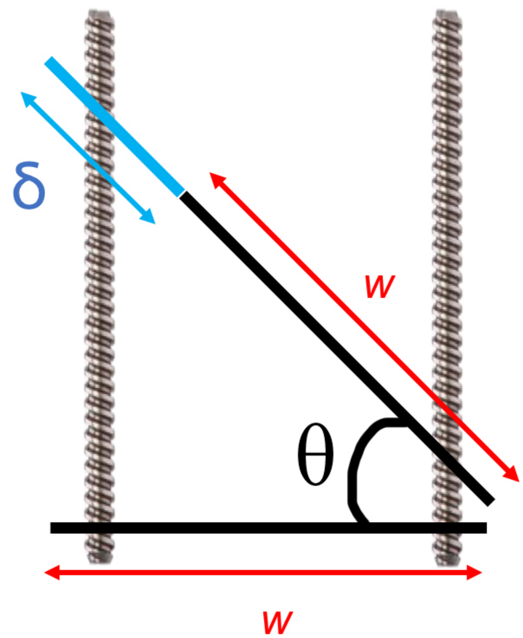


Figure 46: Diagram showing the angle limitation of the system

In Figure 46, the limitation on angles begins to become apparent. The lead screws remain parallel to each other at all times, and the width of the platform (w) is constant. The length of the platform required to remain in contact with the screws, however, increases as a function of θ, specifically $L = w * sec(\theta)$, where $L = w + \delta$. We can re-write this to create a function for δ:

$$\delta = w(sec(\theta) - 1)$$

w, the length of the platform (see Section 7), is approximately 500mm. By plugging in w and plotting this equation in MATLAB, we can see a range of angles (θ) and corresponding deltas (δ).

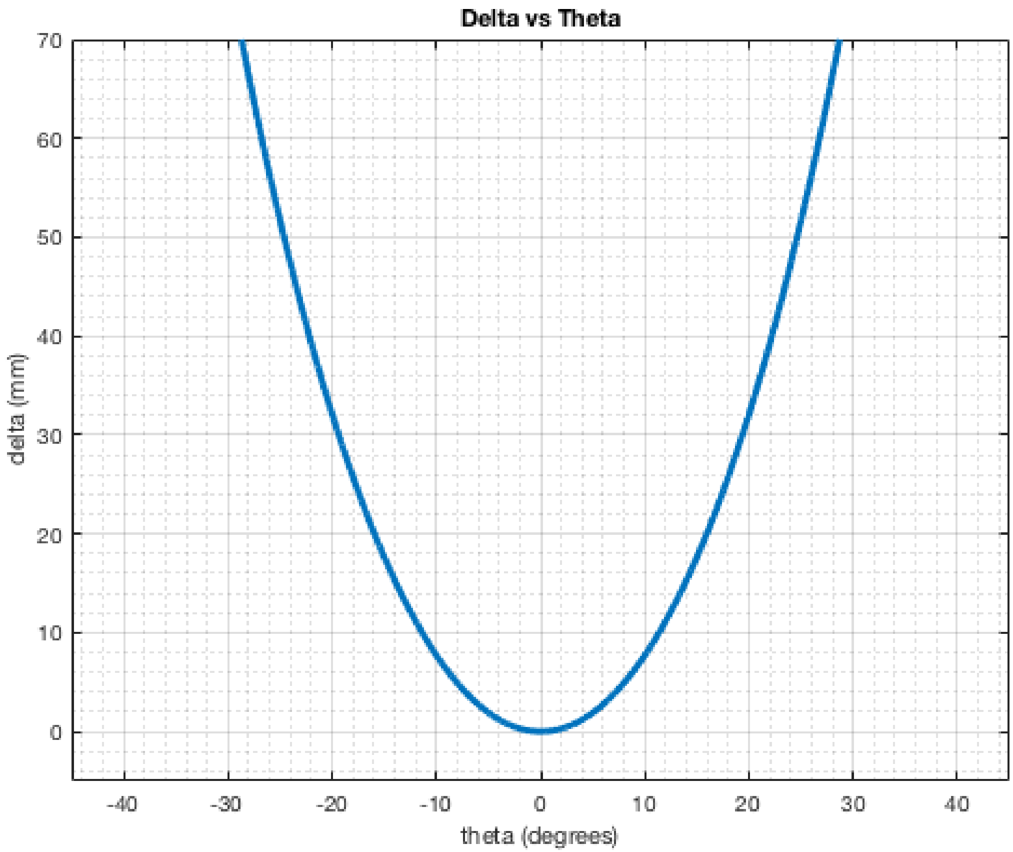


Figure 47: Plot of δ vs θ

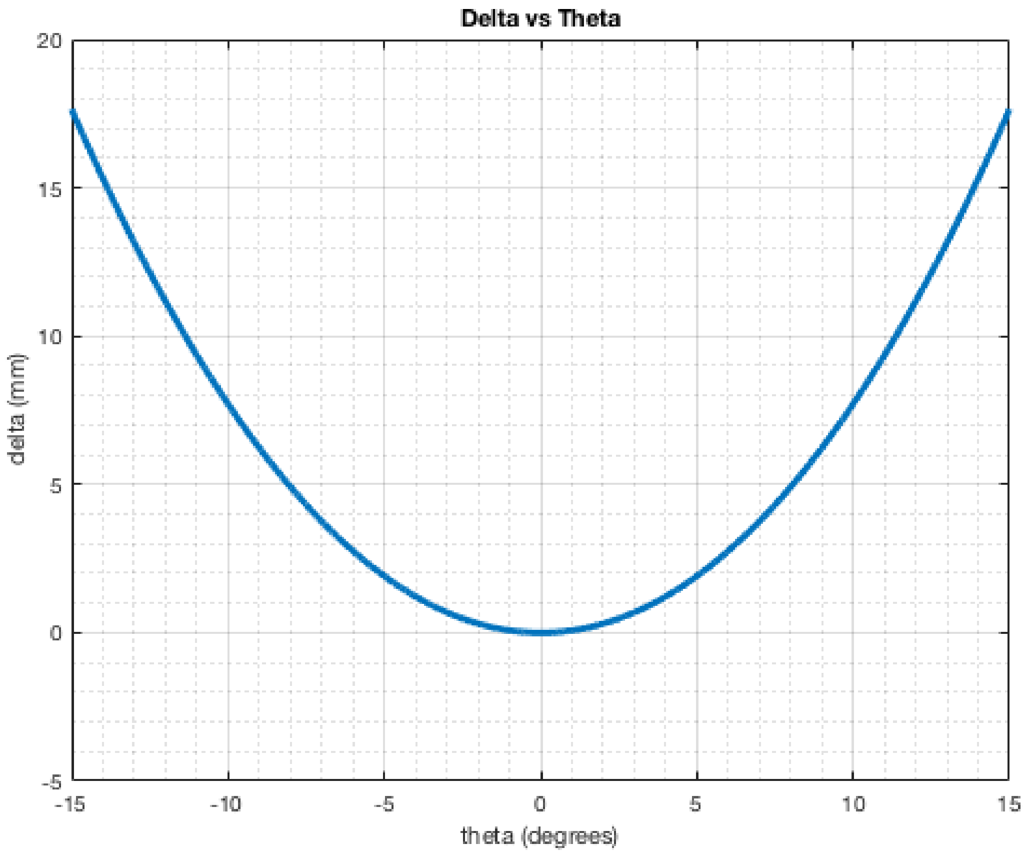


Figure 48: Zoomed plot of δ vs θ

From Figures 47 and 48, we can see a range of angles that are permissible depending on the flexibility and tolerances within the system. For a range of $\approx \pm 10°$ we have a δ of about 1 centimeter. Flexing away this much through a system of rigid components is actually not very easy and strains all the parts of the system. Section 5.4.4 details a revised design to circumvent this flaw.

In theory, the three motors would work collaboratively to directly cancel out any disturbances motion, resulting in a stabilized robot base. The accelerometers feed real time information into a control system, which analyzes the incoming signals and then actuates the motors to compensate. The sensitivity, time response, and repeat ability of these sensors is a crucial factor in their ability to measure disturbances in a useful way.

A robot of sufficient complexity could be used to compensate against base vibrations, but this establishes a dual goal system; stabilize the robot and also perform procedures. The combination of these two simultaneous goals becomes a difficult challenge to achieve [7]. It is much more prudent, therefore, to focus on keeping the base of the robot parallel and equidistant from it's zero reference plane and leaving the robot to focus on the patient. With an "immobile" base, the robot can compensate for the movement of the patient and the gurney through visual servoing. The high level goal of this system is enable robotics researchers to focus on the development of robotic procedures that are environment agnostic, and this is achieved through the described base stabilization.

The system, expected to work in an medical environment, must be easily cleanable and resistant to bodily fluids as well as regular dirt and debris. The motors and lead screws, together having extended and complicated surface geometry, would likely be difficult to clean and susceptible to debris. In addition, the mechanical parts of the system pose a risk to the people around it, offering a number of regions that fingers could potentially get caught in and be injured. Both of these issues can be addressed by enclosing the entire system with bellows (Figure 49, Figure 50).

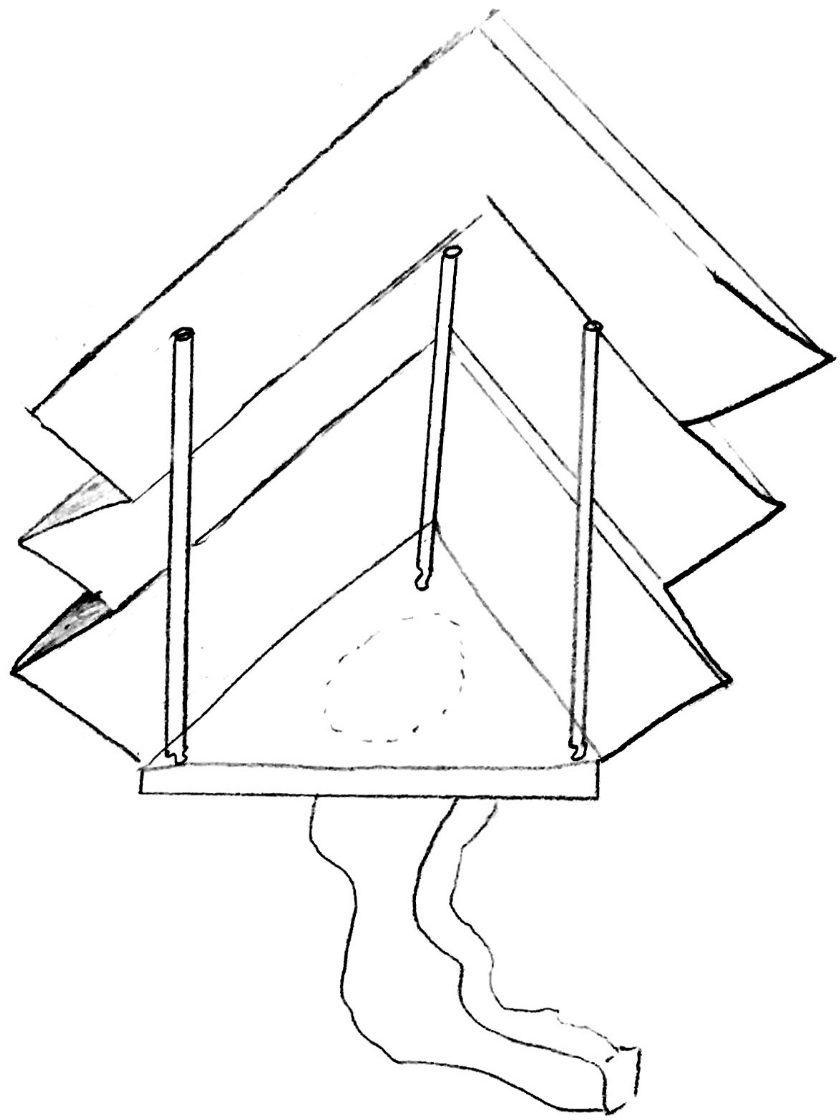


Figure 49: Sketch of the protective bellows. For clarity, the third side of bellows is omitted.

This accordion-like system of folded walls would completely encapsulate the upper the mechanical system and be attached to the robot platform and roof of the ambulance. The flexible nature of this design allows the bellows to stretch and move with the robot platform as it is shifted to counter the ambulance's movement.

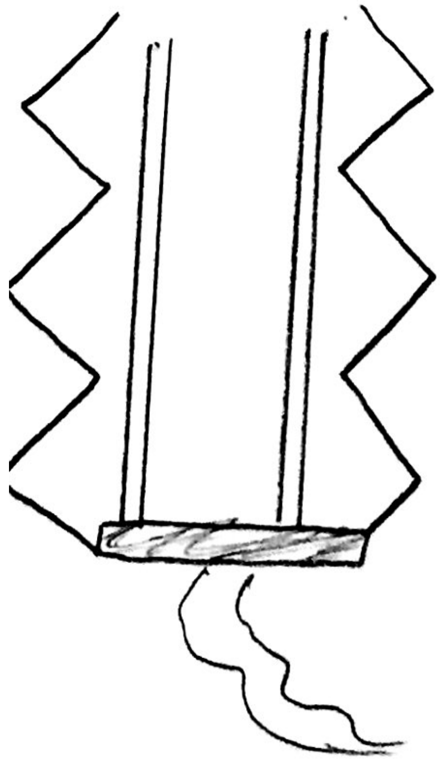


Figure 50: Side view sketch of the protective bellows

The bellows must be made of a flexible, non-absorptive, non-porous material that can be easily disinfected. These material constraints are crucial to the functionality of the bellows. Unlike the design explored in Section 5.4.1, the lead screws pass through the platform in this design. Due to this, the bellows cannot fully encapsulate the entirety of the screws, but rather can only protect the motors and portion of the screws above the platform.

The system contains several components that require electrical power, including the three motors, motor control system, and sensors. The robot also requires power, but does not necessarily have to be connected to the same power supply as the mount. The total external power of both systems is limited to the available power in the ambulance, two 125-volt AC duplex receptacles conforming to NEMA 5-15 [30]. The specifications of the power supply are entirely dependent on the power requirements of the mount's electrical systems, but should have basic surge suppression and conform to all relevant electrical standards.

5.4.4 Final Design

To avoid the length constraint issue introduced in Section 5.4.3 (Figure 51), the team reworked the design again.

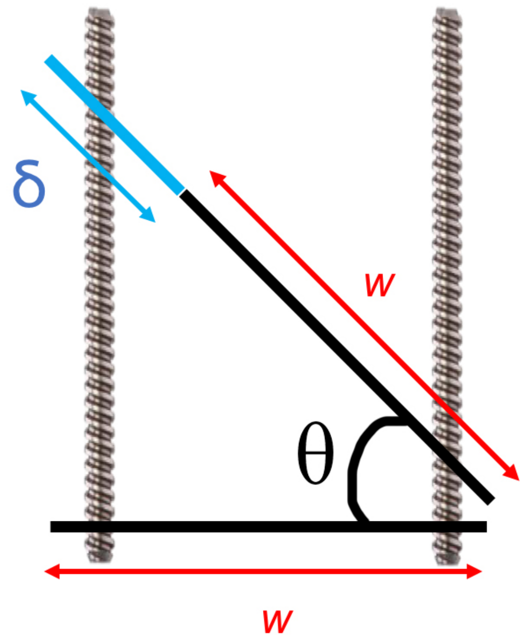


Figure 51: Diagram showing the angle limitation of the system

This design is very similar to the design detailed in Section 5.4.2 but includes important modifications to resolve the aforementioned fixed length issue. Like before, the robot is rigidly fastened to a triangular platform. What's different now is each corner of the platform has spring loaded shaft that allows for linear motion.

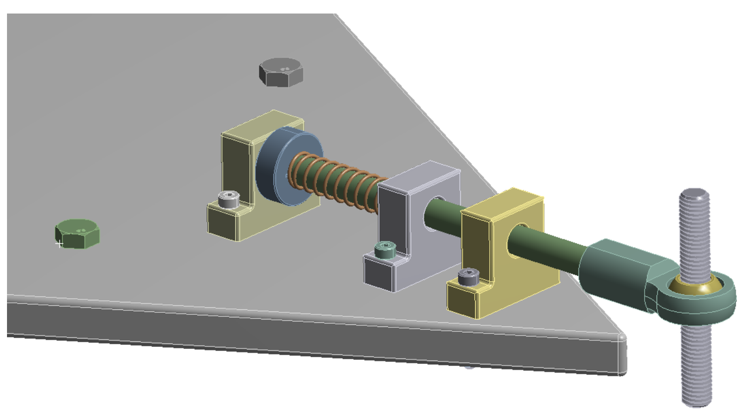


Figure 52: Render of the proposed spring mechanism

Each shaft is male threaded at one end and mated with a female threaded heim joint. Like before, the ball component of the heim joint is ACME threaded, and the lead screw passes through this point.

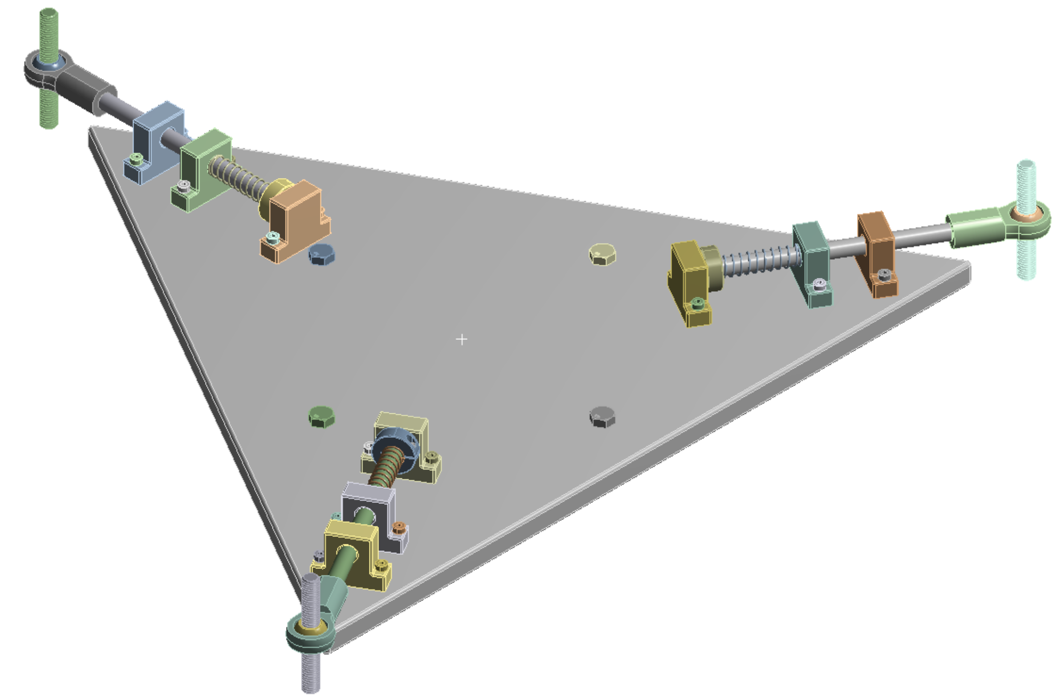


Figure 53: Additional view of the whole platform with all three spring assemblies shown

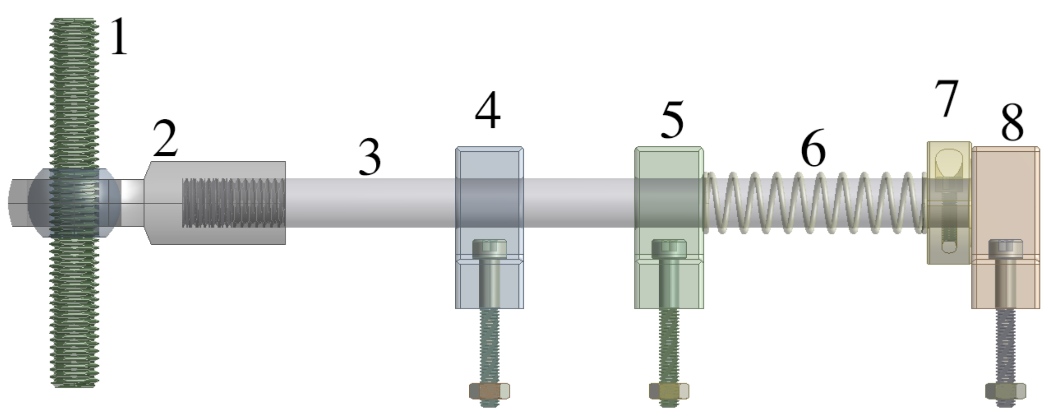


Figure 54: Side view of the spring shaft assembly

The spring assembly is comprised of a shaft (Figure 66.3) connected to a heim joint (Figure 66.2), through which a lead screw (Figure 66.1) is threaded. The shaft is free to slide in only the horizontal direction thanks to three linear bearings (Figure 66.4, 5, 8), which are bolted to the platform. A spring (Figure 66.6) restricts the range of motion of the shaft and ensures that it returns to it's "default" position when the platform is level. A collar (Figure 66.7) secures the spring to the shaft. In Section 5.4.2, the bolt diameter of the heim joints became problematic as they were to be fasted directly into the platform. This constraint is alleviated by coupling the joint with a shaft and mounted bearings.

The robot will be affixed to the underside of the platform via four bolts. The position of these bolts will be determined by the geometry of the robot's base and how many points of contact the manufacturer recommends for secure fastening. The platform will include multiple bolt holes (Figure 65) to accommodate the robot, and will either be specific to a particular robot or designed with additional holes for increased robot versatility. The strength and material requirements of these bolts will be evaluated in Section **??** Configuration Design.

The heim joint frees the lead screw from the perpendicular constraint it would have within a rigid threaded hole, allowing the platform to tilt as the screws retract or extend. In the previous designs, the pitch and yaw of the system were not actually controllable due to the aforementioned length constraint, but, as the lengths of each side can now change, we should have excellent control over the platform's pitch and yaw.

Figure 55: Heim Joint [45]

Identical to the second design, the system requires three lead screws as three points are required to define the plane of the robot platform. The three lead screws extend vertically upward from heim joint, and remain strictly parallel to each other at all times. With the lead screws now able to pass through the platform without constraining its tilt due to the shaft with roller bearings, the motors can be can be raised and lowered in different configurations to change the pitch and yaw of the platform. The entire motor lead screw assembly remains fixed perpendicular to the roof of the ambulance at all times.

Each lead screw will be actuated by a stepper motor fixed on one end of the lead screw via a coupling. The rotation of each motor directly adjusts the height of it's corner of the robot platform, together allowing for excellent control of the pitch, yaw, and height of the platform. The motors would be rigidly affixed to the ceiling of the ambulance. The specifications of these motors will be evaluated in Section **??** Configuration Design. It's important that these motors have sufficient holding torque to prevent the lead screws from turning from the weight of the platform.

Two multi-axis accelerometers would be employed to gather sensory data for the control system. One, mounted on the ceiling of the ambulance, would provide information about the disturbances that the system needs to counter, while the other, mounted on the robot platform, would serve as feedback to verify the implement corrections. The control system would take these two inputs and use them to actuate the motors (and lead screws) such that the robot platform remains always parallel to and equidistant from a predefined constant "ground" reference plane (Figure 56).

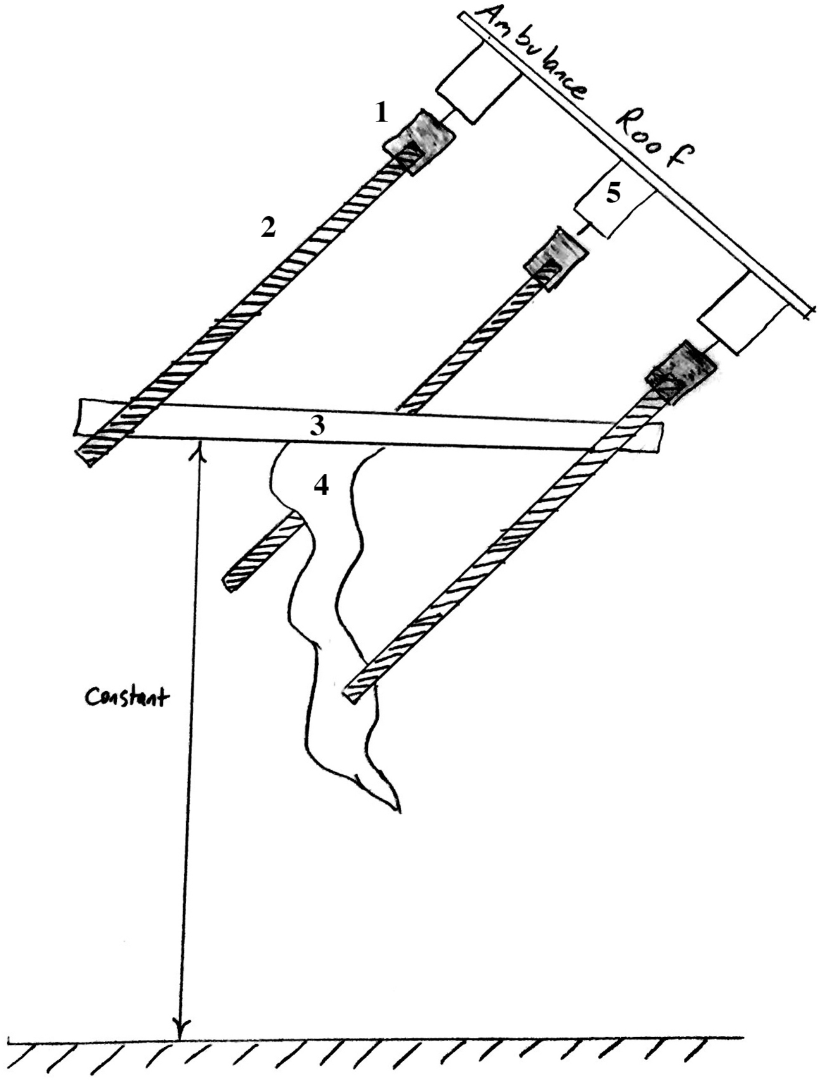


Figure 56: Exaggerated sketch showing the extreme ambulance roof position and the system's response.

It is important to clarify here that this "ground" reference plane cannot actually be the road, as the road imperfections (especially potholes) are exactly what the system is built to compensate against. In theory, the three motors would work collaboratively to directly invert any inputted motion, resulting in a stabilized robot base. The accelerometers feed real time information into a control system, which analyzes the incoming signals and then actuates the motors to compensate. The sensitivity and repeatability of these sensors is a crucial factor in their ability to measure disturbances in a useful way.

The bellows concept described in the previous concept doesn't work nearly as well with the external screws. Making the bellows work here would require more complicated geometry and be more difficult to implement, so this idea does not include the bellows.

The system contains several components that require electrical power, including the three motors, motor control system, and sensors. The robot also requires power, but does not necessarily have to be connected to the same power supply as the mount. The total external power of both systems is limited to the available power in the ambulance, two 125-volt AC duplex receptacles conforming to NEMA 5-15 [30]. The specifications of the power supply are entirely dependent on the power requirements of the mount's electrical systems, but should have basic surge suppression and conform to all relevant electrical standards.

5.4.5 Design Day Proof of Concept

The system explored in Section 5.4.4 details the full system that would be built if this product were to be brought to market. However, based on the time, skill and financial constraints of the team within a semester, it is prudent to instead focus on a simplified proof of concept model of the system.
For design day, we will be focusing our attention on proving the vertical stabilization of our system. Focusing on this subsystem will allow us to ensure our design has a strong basis for its stabilization. While pitch and yaw are important for the overall product, the vertical stabilization needs to be established first. Since we do not have the time to prototype the vertical subsystem before developing our design day product, we will have to leave the pitch and yaw correction factors as theoretical. In addition implementing the sensors and controllers in a pitch and yaw stabilization system is expensive and beyond the scope of our teams existing knowledge and capabilities. Although we have studied linear controls, none of our team members have experience in controlling systems with three degrees of freedom. The amount of time left in the semester does not allow for us to commit to learning these new skills, and our budget does not allow for the proper sensors and controllers. Instead of devoting time and energy to learning new material, the team is better off focusing on a system that can more simply demonstrate the stabilizing concepts. The system is therefore reduced to a one dimensional model that can compensate for motion only in the vertical direction. Control over pitch and yaw are abandoned for this reduced model in favor of simplicity and ease of construction in a short time.

The layout and function of the system are very similar to the designs outlined in Section 5.4.4, but the interface between the platform and lead screws is simplified. The platform could be simply tapped with ACME threads, but threads in an aluminum platform would be worn by the far tougher steel screws. The swivel flange is therefore replaced with a straight rigid T8 nut (Figure 57, 58), allowing the screw to connect with and pass through the platform.

Figure 57: Photo of a T8 nut and lead screw [46]

Figure 58: Photo of a T8 nut and lead screw [46]

With the rise in popularity of commercial 3D printers and CNC machines, T8 nuts and lead screws have become increasingly cheap and easy to source, especially together, making them the idea components for this simplified product. These nuts will be fastened to the platform via four M3 screws each. These nuts lack any swivel capability and will ensure perfect perpendicularity between the lead screws and platform at all times. As a simplified model of the system, this design doesn't need to support the real life KUKA robot, and can instead be designed as a scale model with reduced dimensions. By scaling the components, we can source parts more cheaply and work with a system that is easier to manage. A scaled model of the KUKA robot will be 3D printed and filled with a comparably scaled weight. Instead of sourcing very expensive high end precision motors and complicated control systems, this design will be controllable via COTS motors (Figure 60) and an Arduino (Figure 59).

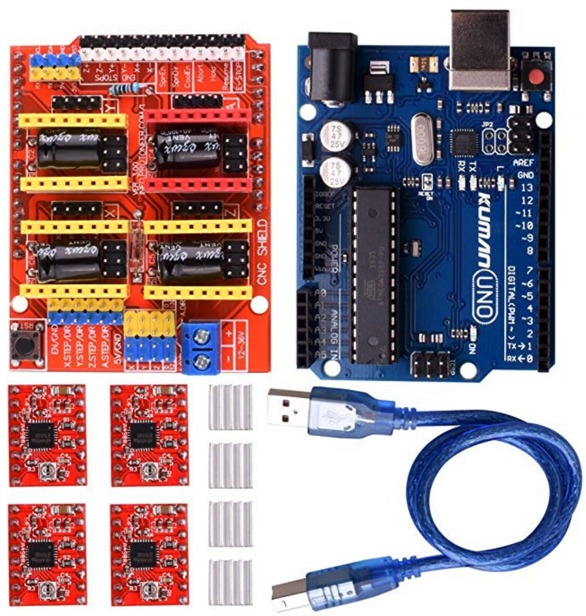


Figure 59: Photo of the Arduino and Motor Control Shield [47]

Figure 60: Photo of the NEMA17 motors [48]

The power supply is similarly simplified as a number of commercial power supplies exist for systems such as these.

6 Embodiment Design Process

6.1 Determine Product Architecture and Configuration Design

The general layout of this system is outlined above, but will be rehashed here for clarity and detail. The intended system is comprised of 11 major subsystems including the lead screws, motors, robot-mount interface, screw-mount interface, sensing, motor control, screw-motor interface, mount-ambulance interface, robot, bellows, power supply. The concept envisions a medical robot (Figure 61.5) rigidly fastened to a stiff triangular platform (Figure 61.4).

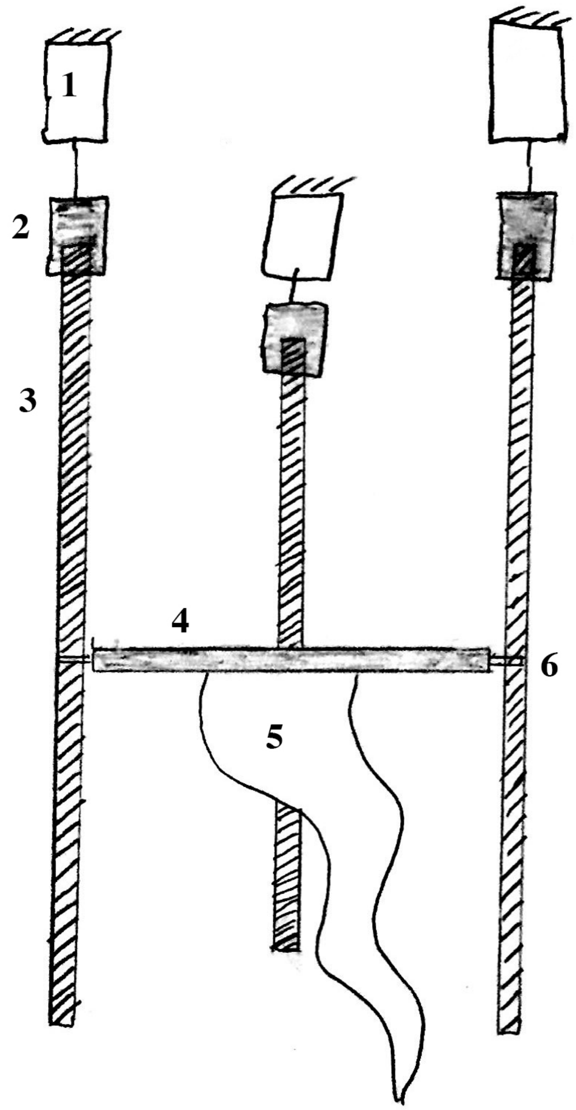


Figure 61: Sketch of Final Design. Note that the lead screws are drawn with exaggerated length for emphasis and are not to scale.

Each lead screw is actuated by a stepper motor (Figure 61.1) fixed on one end of the lead screw via a coupling (Figure 61.2). The rotation of each motor directly adjusts the height of it's corner of the robot platform, together allowing for excellent control of the pitch, yaw, and height of the platform. The specifications of these motors will be evaluated in Section ?? Configuration Design. It's important that these motors have sufficient holding torque to prevent the lead screws from turning from the weight of the platform.

6.1.1 Lead Screws

Three lead screws will be used, with one in each corner of the triangular platform. ACME threading is the most common threading for lead screws [49] (Figure 62).

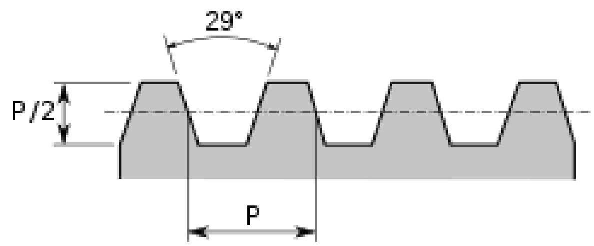


Figure 62: Diagram of ACME threads [49]

These screws need to be thick enough to not fail due to the forces from the robot and other disturbances it may experience. Lead screws are characterized by their diameter, threading, length, material, travel distance per turn, and number of starts. The number of starts (usually 1-4) defines how many independent threads the screw has (Figure 63). Screws with more starts have a greater travel distance per turn and are known as fast-travel lead screws.

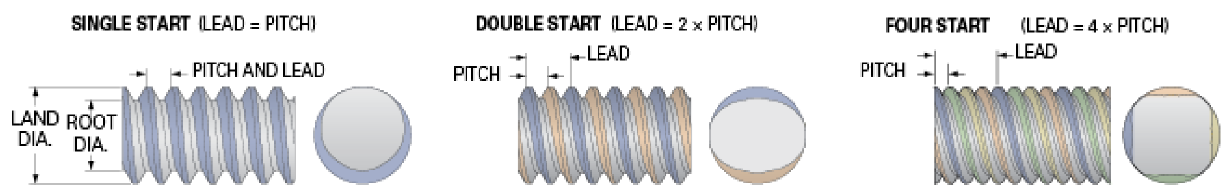


Figure 63: Diagram showing different lead screw starts [50]

This presents a trade-off. Fast travel screws can move further distances more quickly with the same rotation, but lose the fidelity of control that the single start screws (with much smaller travel distances) provide. Single start screws need to be spun much faster to cover the same distance (impacting the requirements of our motors), but can be positioned much more precisely than their multi-start counterparts.

The system requires three lead screws as three points are required to define the plane of the robot platform. The three lead screws extend vertically upward from heim joint, and remain strictly parallel to each other at all times.

We can approximate each lead screw as a cylinder, under a third of the full mass of the robot (22kg/3=7.33). The lead screws are M10 screws (diameter=10mm) with a tensile strength of 55,000 psi = 379.2 MPa. The stress of each lead screw in pure tension can be calculated as follows:

$$A = \pi * r^2$$
$$A = \pi * (5mm)^2 = 0.000079m^2$$
$$F = 7.33kg * 9.8m/s^2 = 71.834N$$

$$\sigma = \frac{F}{A} = \frac{71.834N}{0.000079m^2} = 9.09 * 10^5 Pa$$

We'll add a safety factor of 2, so the stress in the lead screw under tension is $\sigma = 1.82$ MPa. With a tensile strength of 379 MPa, the lead screws will clearly not fail in pure tension. We now evaluate the lead screws as a shaft with the following assumptions:

- Force loading is constant
- Center of mass of the robot is in the center of the platform
- Mass of the robot/platform is equally distributed between the three lead screws
- Lead screw is approximated as a cylinder
- No alternating loads

The moment arm between the lead screw and the center of the platform is approximately 290mm. Following this dimension:

$$M = 7.33[kg] * 9.8[m/s^2] * .290[m] = 20.83[Nm]$$
$$y = \frac{d}{2} = .005[m]$$
$$I = \frac{\pi * d^4}{64} = 4.91 * 10^-10[m^4]$$
$$\sigma_m = \frac{M * y}{I} = 212[MPa]$$

The material selection for the lead screws is listed in section 7 as steel. This selection was made based on the lead screws available from McMaster. The tensile strength of grade 2 steel is 510 MPa, therefore the lead screws are safe and will not fail.

6.1.2 Motors and Motor Control

The motors spin to actuate the screws. As the screws spin at different speeds, the pitch and yaw of the platform is adjusted. In theory, the three motors would work collaboratively to directly cancel out any disturbances motion, resulting in a stabilized robot base. The accelerometers feed real time information into a control system, which analyzes the incoming signals and then actuates the motors to compensate. The sensitivity, time response, and repeatability of these sensors is a crucial factor in their ability to measure disturbances in a useful way.

6.1.3 Screw-Mount Interface

Each corner of the platform has spring loaded shaft that allows for linear motion.

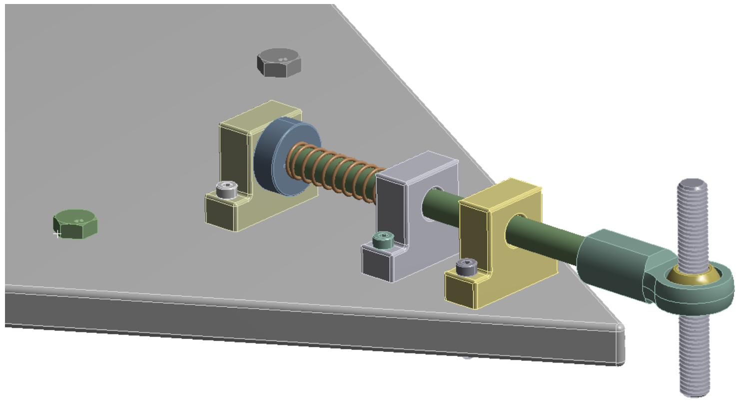


Figure 64: Render of the proposed spring mechanism

Each shaft is male threaded at one end and mated with a female threaded heim joint. Like before, the ball component of the heim joint is ACME threaded, and the lead screw passes through this point.

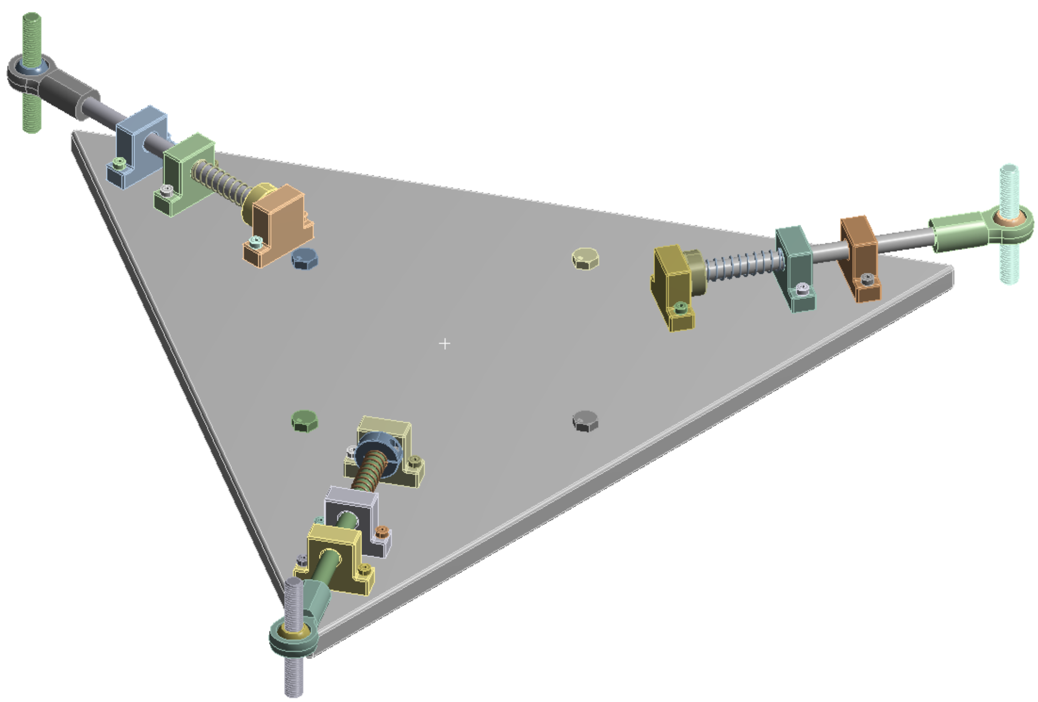


Figure 65: Additional view of the whole platform with all three spring assemblies shown

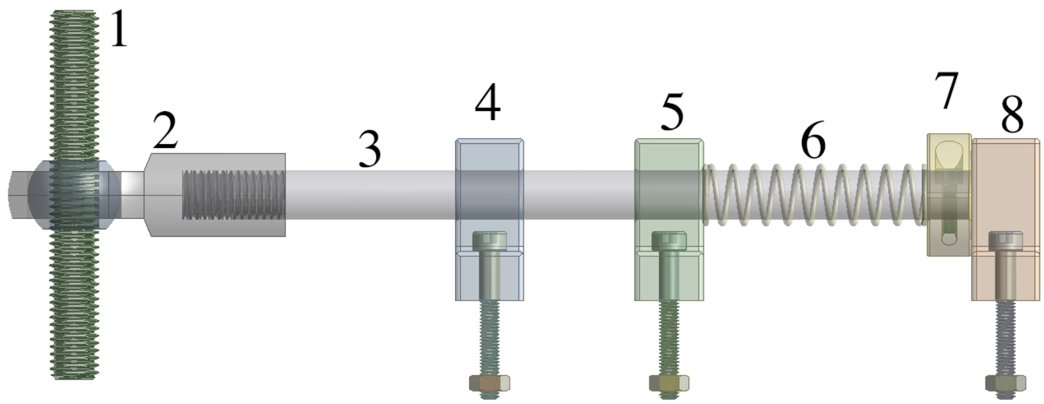


Figure 66: Side view of the spring shaft assembly

The spring assembly is comprised of a shaft (Figure 66.3) connected to a heim joint (Figure 66.2), through which a lead screw (Figure 66.1) is threaded. The shaft is free to slide in only the horizontal direction thanks to three linear bearings (Figure 66.4, 5, 8), which are bolted to the platform. Note that the blue and green components in Figure 66 are actually one linear ball bearing like the one shown in Figure 67. These allow the shaft to slide. The orange component is a shaft stop - a solid piece of metal that constrains the range of motion of the shaft.

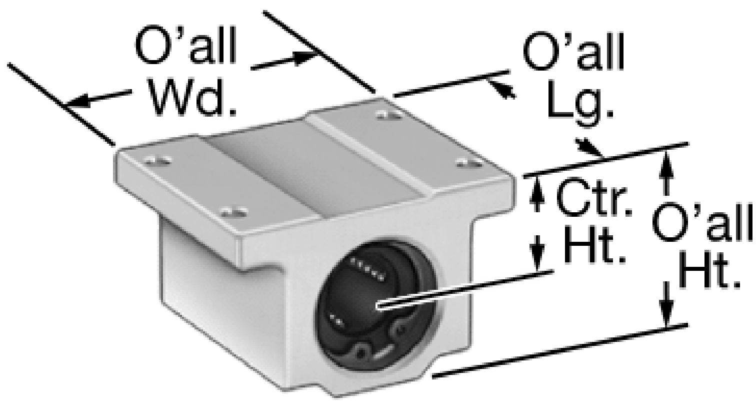


Figure 67: Linear bearing from McMaster

A spring (Figure 66.6) restricts the range of motion of the shaft and ensures that it returns to it's "default" position when the platform is level. A collar (Figure 66.7) secures the spring to the shaft. In Section 5.4.2, the bolt diameter of the heim joints became problematic as they were to be fasted directly into the platform. This constraint is alleviated by coupling the joint with a shaft and mounted bearings.

Figure 68: Heim Joint [45]

The heim joint frees the lead screw from the perpendicular constraint it would have within a rigid threaded hole, allowing the platform to tilt as the screws retract or extend. In the previous designs, the pitch and yaw of the system were not actually controllable due to the aforementioned length constraint, but, as the lengths of each side can now change, we should have excellent control over the platform's pitch and yaw.
The materials used for this subsystem can be found in our bill of materials (Section 7). These materials were determined based on the parts available on McMaster that matched the necessary dimensions.

6.1.4 Screw-Motor Interface

Each motor is connected to its lead screw via a flexible coupling (Figure 69). This component commonly has 2 set screws to tighten it to the lead screw and motor shaft (Figure 69.1). In addition, the center of this coupling has a flexible region (Figure 69.2) that allows for slight misalignment of the lead screw .

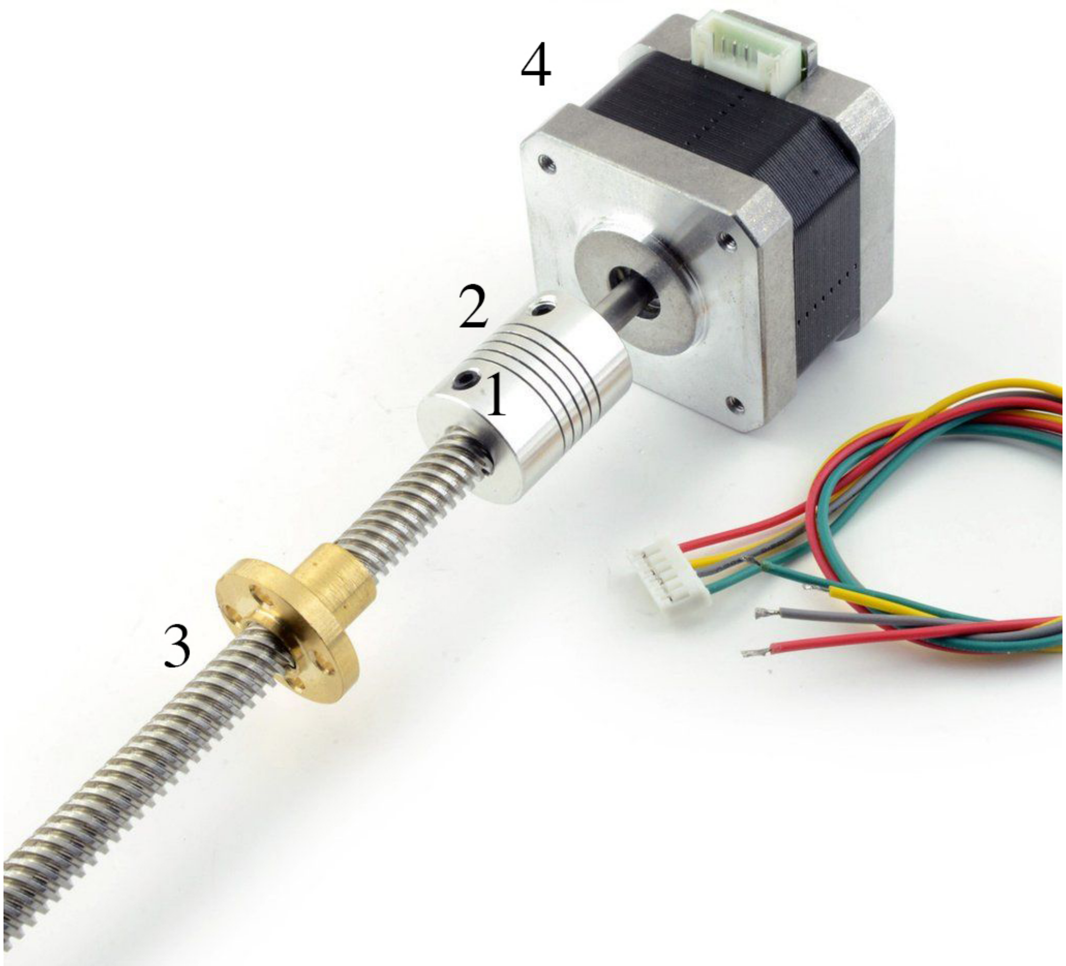


Figure 69: Photo showing a flexible coupling (1,2) connecting a lead screw (3) and motor (4) [51]

6.1.5 Robot-Mount Interface

The corners of the triangular platform are rounded. The robot will be affixed to the underside of the platform via a number of bolts. The position of these bolts will be determined by the geometry of the robot's base and how many points of contact the manufacturer recommends for secure fastening. The platform will include multiple bolt holes (Figure 70) to accommodate the robot, and will either be specific to a particular robot or designed with additional holes for increased robot versatility. The strength and material requirements of these bolts will be determined based on the medical robot we select (Section 6.1.10).

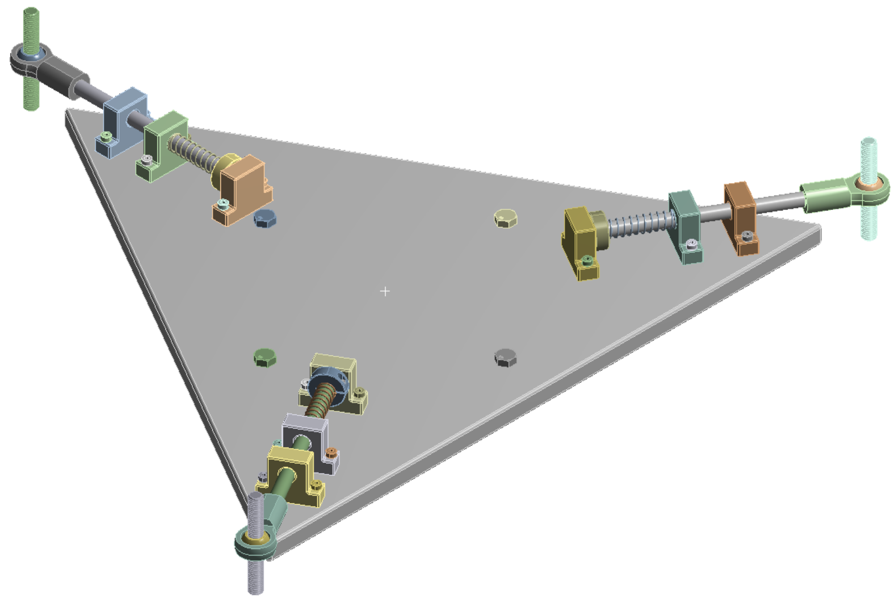


Figure 70: Render of the spring assemblies on the platform

The KUKA robot (as elaborated upon further in Section 6.1.10) requires four M8 bolts to mount it to the platform. The bolt holes shown in (Figure 70) are designed to match the KUKA bolt hole geometry.

6.1.6 Motor Ambulance Interface

The motors must be rigidly affixed to the ceiling of the ambulance. This will be done with brackets and bolts. It is important that the motors remain fixed because they are the base of the entire assembly. A solid and fixed upper assembly allows the team can accurately measure the propagation of the vibration coming from the ceiling of the ambulance. The brackets and bolts will be bought from McMaster and made of steel. This is important since if they were made of aluminum they would deform. More information on these parts can be seen in our bill of materials in Section 7.

6.1.7 Motors

The specifications for our motor are intrinsically linked to the expected response of the cabin of the ambulance under input from the road. The cabin's response is of such importance to our motor choice that characterizing it was the central purpose of our initial prototype. From this testing, we were able to employ numerical integration techniques within MATLAB to translate acceleration-time data into specification requirements for our motor.

The relationship between acceleration, velocity and position is as follows:

$$v(t) = \int_{t_i}^{t_f} a(t)dt$$

$$y(t) = \int_{t_i}^{t_f} v(t)dt$$

where

$a(t)$ = acceleration

$v(t)$ = velocity

$y(t)$ = vertical position

t_i = the time at the beginning of the cabin's response to a bump

t_f = the time at the terminus of that response.

Using numerical integration techniques within MATLAB, we were able to determine that maximum displacement of the cabin over all of our tests was 0.133 meters in 0.127 seconds. Empirical confirmation of these results was achieved through a non-rigorous video analysis of the cabin, using the obstacles as reference length scales. We can use this information, in conjunction with our lead screws, to begin defining characteristics for our motors. To calculate the torque and RPM our motor must produce to achieve stabilization, it is useful to recast the problem. By geometry, an unwrapped lead screw can be thought of as an inclined plane:

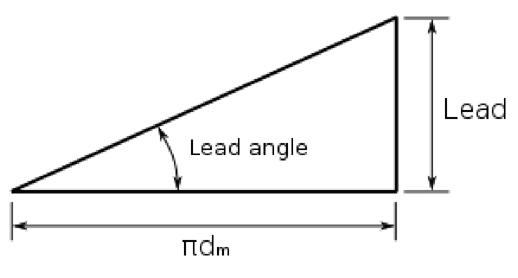


Figure 71: Unwrapped Lead Screw [52]

From this recasting, the torque equations [53] below follow:

$$T_{raise} = \frac{Fd_m}{2}\left(\frac{l + \pi\mu d_m}{\pi d_m - \mu l}\right) = \frac{Fd_m}{2}\tan(\phi + \lambda)$$

$$T_{lower} = \frac{Fd_m}{2}\left(\frac{\pi\mu d_m - l}{\pi d_m + \mu l}\right) = \frac{Fd_m}{2}\tan(\phi - \lambda)$$

where

T = torque

F = the load on the screw

d_m = mean diameter

μ = coefficient of friction

l = the lead

ϕ = the angle of friction

λ = the lead angle

Plugging in all of the appropriate values [52], we find we require 22.0 N-m of torque at 5,770 RPM. Searching a number of different vendors, we found that NEMA 34 84mm stepper motor, which is able to produce 200 N-m of torque at 6,000 RPM [54]. The NEMA 34 motors are often used for Computer Numerical Control (CNC) applications, which much like our task, have high torque, speed and precision requirements.

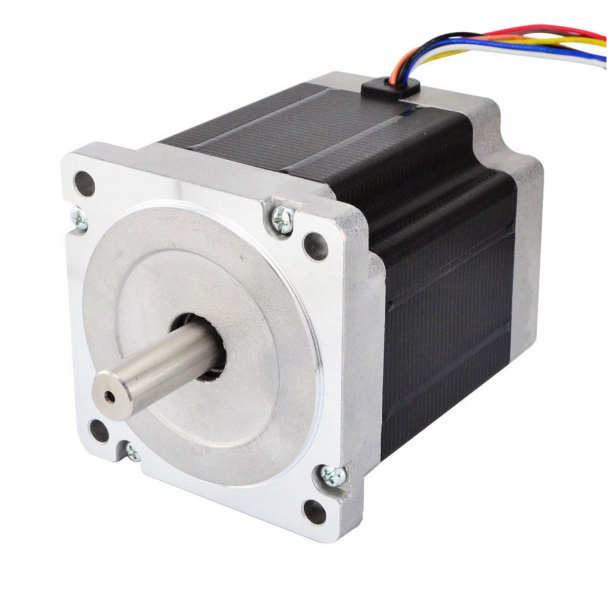


Figure 72: NEMA 34 Stepper Motor

6.1.8 Sensing and Control

For our sensing and control system, two multi-axis accelerometers would be employed to gather sensory data for the control system. One of the accelerometers would be mounted on the ceiling of the ambulance and would provide information about the disturbances that the system needs to counter. The other accelerometer would be mounted on the robot platform and would serve as feedback to verify the implemented corrections. The control system would take these two inputs and use them to actuate the motors (and therefore the lead screws) such that the robot platform remain parallel to and equidistant from a predefined constant "ground" reference plane (Figure 73). Note that the sketch shown in Figure 73 is an extreme exaggeration; the actual angles achievable by this system will be smaller ($\approx \pm 26°$). It is important to clarify here that this "ground" reference plane cannot actually be the road, as the road imperfections (especially potholes) are exactly what the system is built to compensate against.

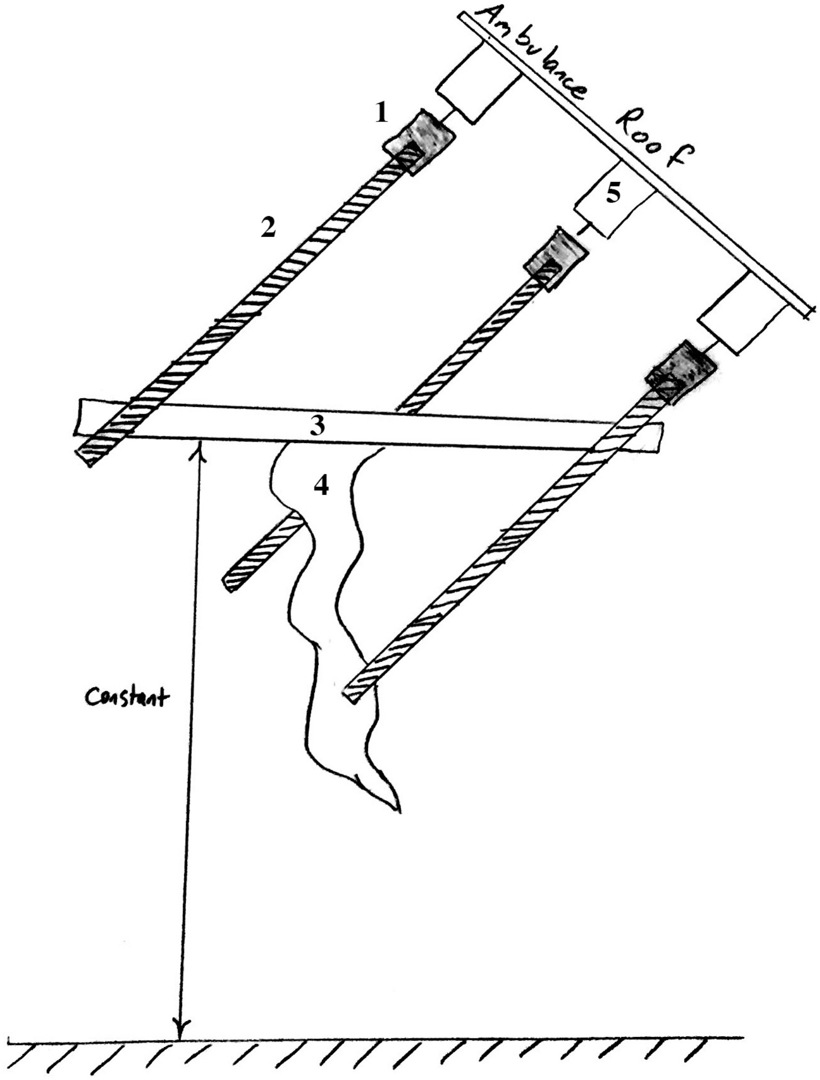


Figure 73: Exaggerated sketch showing the extreme ambulance roof position and the system's response.

6.1.9 Power Supply

The system contains several components that require electrical power, including the three motors, motor control system, and sensors. The robot also requires power, but does not necessarily have to be connected to the same power supply as the mount. The total external power of both systems is limited to the available power in the ambulance, two 125-volt AC duplex receptacles conforming to NEMA 5-15 [30]. The specifications of the power supply are entirely dependent on the power requirements of the mount's electrical systems, but should have basic surge suppression and conform to all relevant electrical standards.

6.1.10 Medical Robot Selection

According to interviews with medical robotics expert Dr. Hamed Saeidi [7], Postdoctoral Fellow at the Medical Robotics and Equipment Lab at The University of Maryland, robots like the KUKA LWR MED and the Universal Robot 5 (UR5) are the standard for medical robotics research, but that the KUKA is more common. As such, we will be focusing on designing a mount for the KUKA. The KUKA is a 22 kg robot with a 100 μm repeatably. From this interview, it was indicated that the future of medical robotics likely lies with a KUKA machine.

The KUKA robot we intend to use has four bolt holes on the underside of its base plate to affix the robot (Figure 74). The documentation provided by KUKA indicates that these should be M8 bolts, so that is what we will use to secure the robot to the platform.

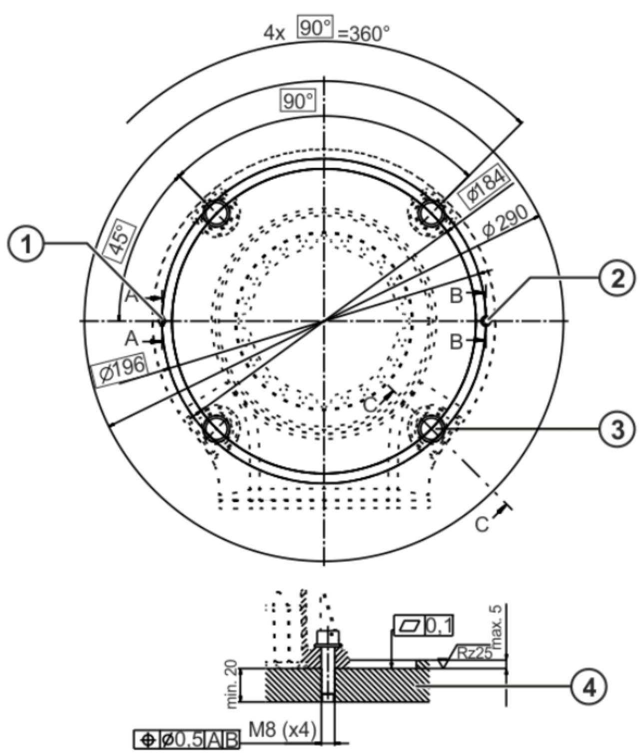


Figure 74: KUKA Base Plate Mount [55]

6.2 Material and Manufacturing Process Selection Analysis

There are a number of material properties that are important to consider for the platform of our product. In this section, we map out the various properties we must consider when choosing a platform material. We then utilize CES, an engineering software, to hone in on which materials fulfill all our requirements.Then we look at the differences between the remaining materials and choose the material we will be using for our platform. This decision will be made using graphs comparing various properties, as well as our own common sense and judgment. The most obvious property we need to consider is yield strength. Since the platform is the main component supporting the weight of the KUKA robot, we need to ensure our chosen material will not fail due to stress. We also need to ensure that the portions where the bolts hold up the platform don't fail due to stress. Using FEA, we evaluated the von mises stresses of the platform given the load of a 22kg KUKA medical robot.

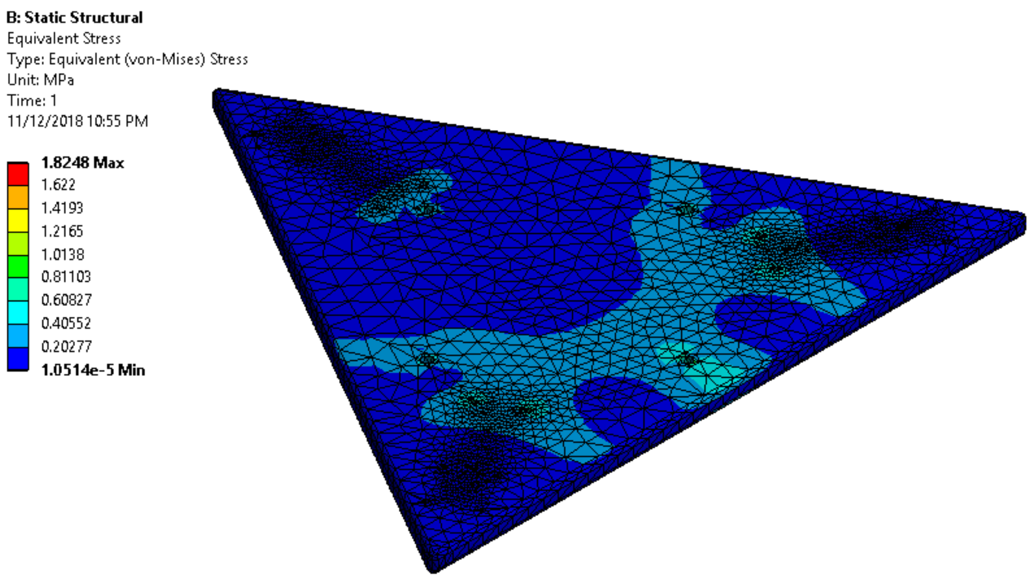


Figure 75: FEA: Equivalent Von Mises Stress on the Platform with a 22kg Load

As you can see in Figure 75, the maximum stress that the platform experiences is about 2 MPa. Using a safety factor of 2, we want to ensure that the material we use has a yield strength greater than 4 MPa. In addition to platform stress concerns, we also need to consider it's weight; the weight of the platform needs to be minimized to reduce stresses on the ceiling of the ambulance, where this system will be mounted. Temperature constraints are also important factor to consider. While the ambulance is in use, with patients and or medical personnel inside it, the internal temperature will be regulated by on-board air conditioning and heating systems, as you'd expect. However, our product will still be in the ambulance while it is parked and not in use. Therefore, we must consider the temperatures the ambulance will undergo when parked in both the winter and the summer. The coldest recorded temperature in Maryland is -40°F [56]. Although the interior of the ambulance will likely be slightly warmer than this, this number serves as a good lower temperature bound approximation and defines the coldest temperatures our system would be expected to survive. In the summer, parked vehicles can get up to 140 degrees Fahrenheit [57], even when the surrounding air temperature is much cooler. It is vital, therefore, that our product be designed to survive in such extreme temperatures without any degradation or increased risk of material failure.

Another material property that's important to consider is brittleness. Brittle failure, which happens abruptly and without warning, would be a total catastrophic failure of the system. If the platform were to shatter, it's shrapnel could further injure anyone in the ambulance, a particularly important consideration in the case of an ambulance crashing. In order to understand the brittle nature of materials we need to look at their compressive and tensile strengths. Brittle materials have high compressive strength while having low tensile strength [58]. The restriction against brittle failure eliminates most (if not all) ceramics and glasses.

Although we do not want brittle materials, we also want to make sure the platform wont deform. In order for the platform to effectively hold the KUKA robot, it needs to be rigid. This means that we need to consider the hardness of various materials. The higher level of hardness a material has the higher its resistance to deformation is [59].

The Machinability of the chosen material is also an important consideration. The platform will have to be manufactured into its triangular shape, most easily via machining. Therefore as we hone in on materials that we want, we need to consider how easy it would be to machine the platform out of that material. This requirement goes hand in hand with cost. We want to make sure that our manufacturing process isn't costly while still being effective. For example, in theory we could use expensive additive manufacturing processes to make this platform, but that would be a waste of money if we can machine it for cheaper. We also need to ensure that the material itself is cost effective. With everything else equal, the cheapest material solution would obviously be the best.

The platform also needs to be long lasting. This product is going to be mounted to an ambulance and should not be changed very often.This means organic materials that can rot easily must be eliminated. Some dense woods might be structurally suitable, but we need a material that does not degrade or decompose over time. Nearly all organic materials are therefore eliminated.

Now that we have mapped out the preliminary requirements of our material we can use CES, a material selection software, to help hone in on the perfect material for our platform. In CES, we started by using the level 2 platform, since it gave us more options to filter by. We started by choosing to filter through all materials and then we began to limit the materials in stages. By using go/no go screenings, we can limit different classes of materials. Temperature and yield strength limits are the first go/no go screening that we used to limit our CES results. We used these values in our stage 1 limits because these two constraints have specific hard numbers to use. In the next stage, we limited three categories, density, price and machinability. According to OSHA standards, [38] a person can't lift more than 22 kilograms (50 pounds) on their own without risk of injury. Since we want the platform to be easily installable, we want a density smaller than this. The footprint of our platform is approximately .003 cubic meters, which gives us a density of approximately 11000 kilogram per cubic meter. Using a safety factor of 3, we get a density of approximately 3600 kilograms per cubic meter, which is the value we used as a maximum density in our CES stage 2 limit. For price we looked at the chart provided by CES, (Figure 76) and saw the range of prices and knew we wanted to stay on the cheaper side of that chart.

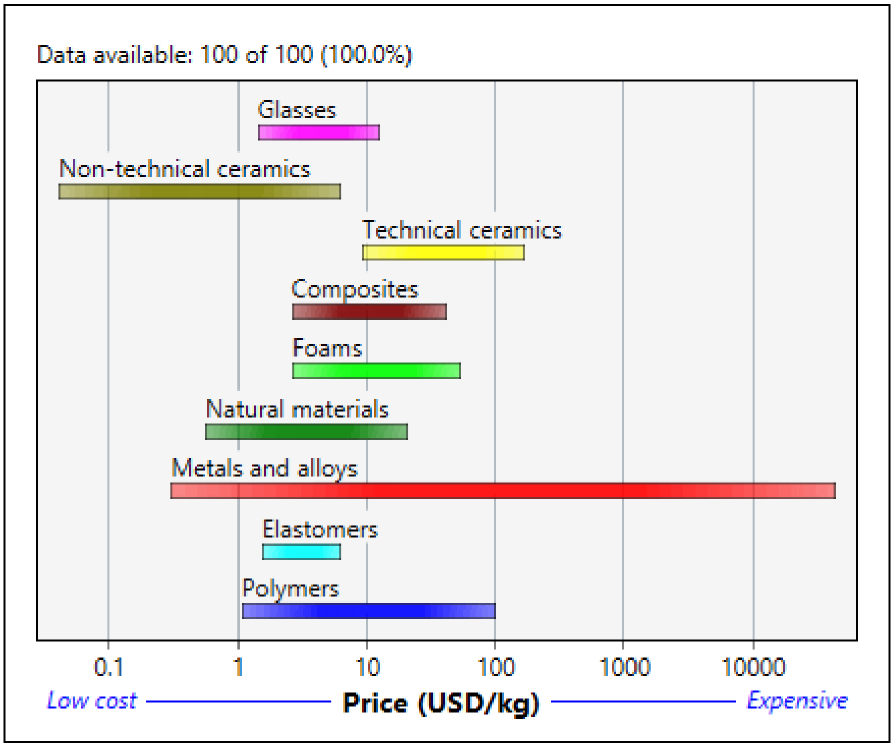


Figure 76: CES Limit Chart: Price

After some iteration, we chose to limit by 10 USD/kg. Finally, we know that the platform is going to be machined, therefore we insisted on a machinability between 3 and 5, based on the CES chart seen in Figure 77.

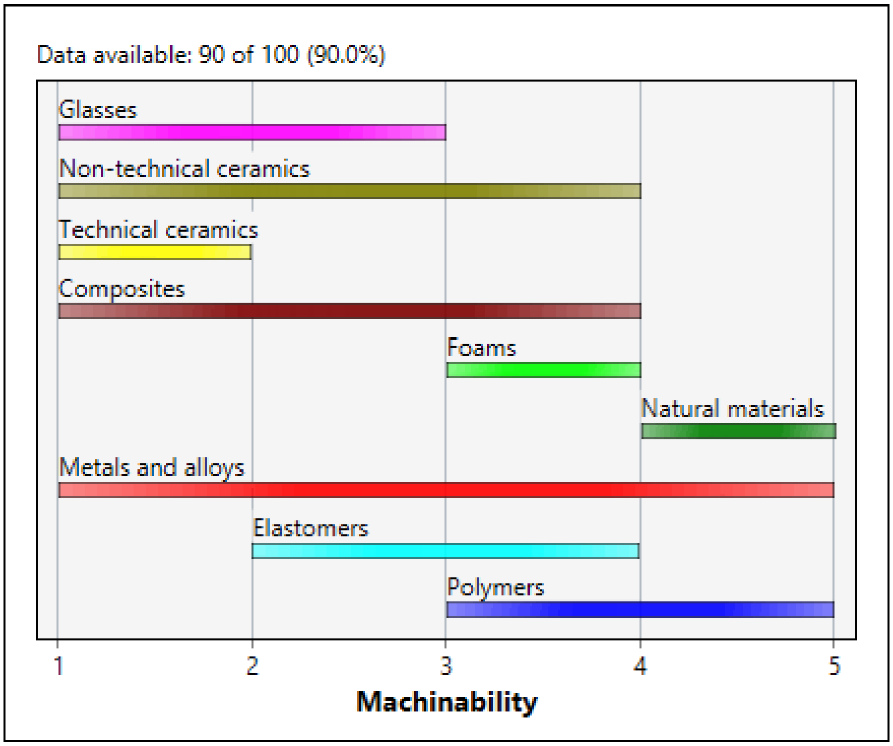


Figure 77: CES Limit Chart: Machinability

After doing the first two stages we plotted compressive strength with tensile strength (Figure 78). This plot displayed the remaining materials and showed us which ones were liable to being brittle. For example, the non-technical ceramics have relatively high compressive strength, while also having low tensile strength. This fact allows us to eliminate these materials from our search.

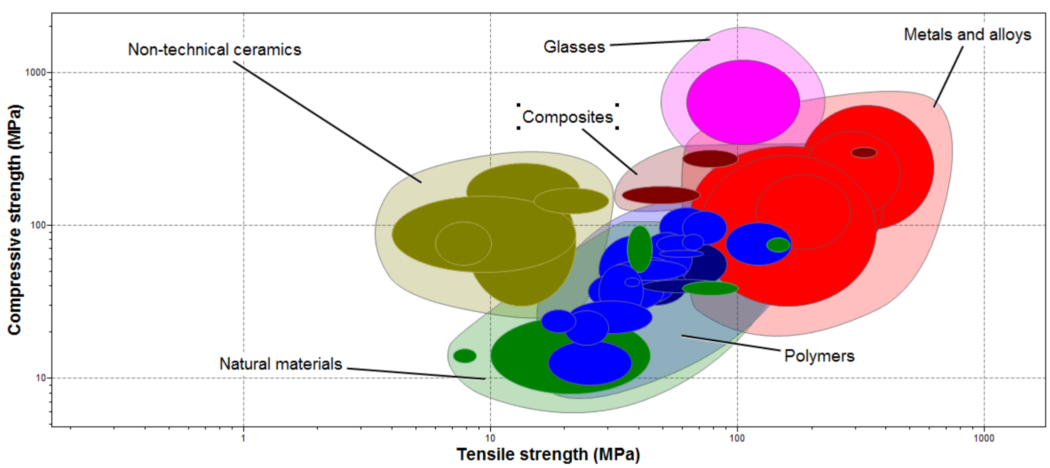


Figure 78: CES Graph: Compressive Strength (MPa) vs Tensile Strength (MPa)

After analyzing the brittleness factors we moved on to consider hardness in stage 4 of the CES limits. Given the hardness chart seen in Figure 79, we decided to set a Hardness minimum of 10, since we needed to ensure our platform would maintain its structure.

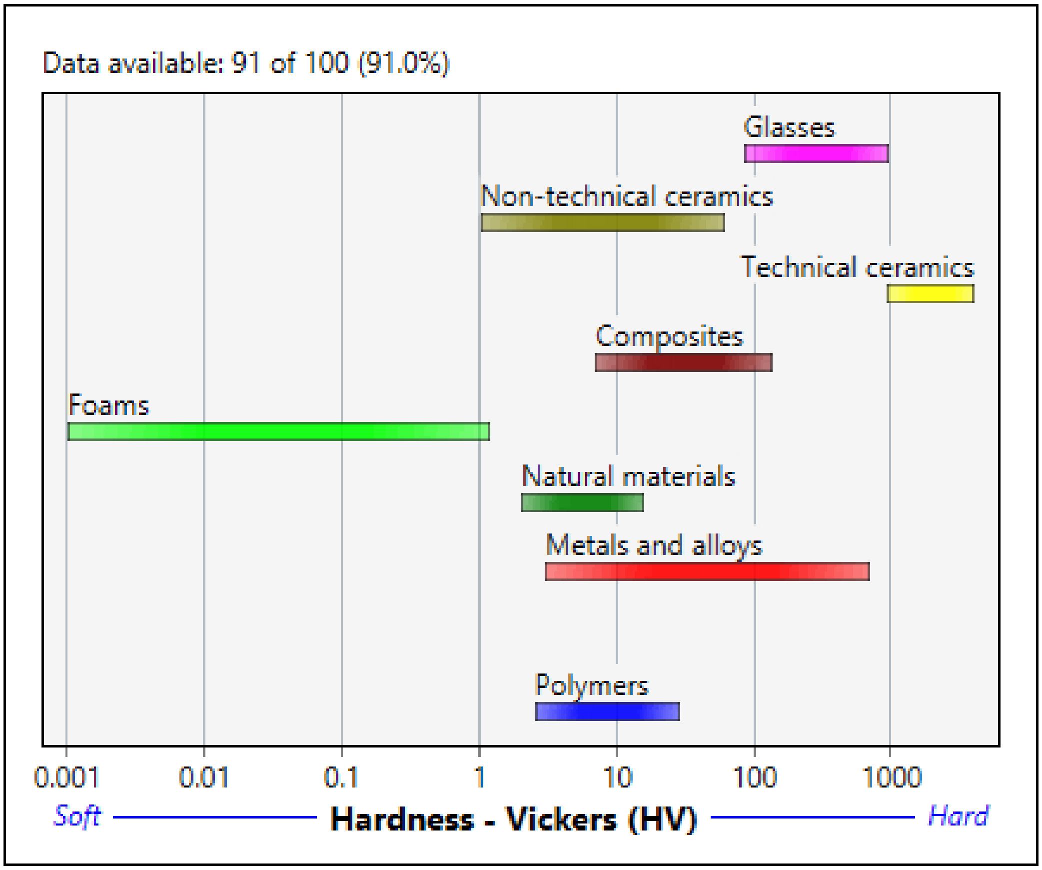


Figure 79: CES Limit: Hardness

Now that we had input our final limiting factor, CES output 6 materials that had passed all of our requirements: Age-hardening wrought Al-alloys, Aluminum/Silicone carbide composite, Cast Al-alloys, Glass ceramic, Non age-hardening wrought Al-alloys, and Wrought magnesium alloys. In order to finalize which exact material to use, we created a graph of fatigue strength versus material, see Figure80. Fatigue strength was not included in our initial constraints since there was no exact go or no go number. However, since the ambulance will be undergoing many bumps throughout the mounts life time, fatigue is important to consider for material selection.

Figure 80: CES Graph: Fatigue (MPa) VS Price (USD/Kg)

Looking at this graph, its clear that our team should either implement Cast Al-alloys or Age-hardening wrought Al-alloys since they are both high in fatigue strength and low in price. Al 6061 is an Age-hardening wrought Al-alloy that is easily accessible. McMaster Carr or any number of hardware sites will sell this type of aluminum sheet. Due to its accessibility, as well as its fulfillment's of all the requirements outlined above, our team chooses to use Al 6061, an Age-hardening wrought Al-alloy, for our platform material.

6.3 Human Factors Analysis

Human factors is an important aspect of design. Since the team wanted to limit as much risk to users as possible, we designed our mount to be out of the way of EMTs, patients or any other personnel residing in the ambulance. To mitigate further risk, the team will be installing the mount to the roof of the ambulance. The robot, which interacts directly with the patient and ambulance personnel, has far greater human factors considerations, but these exist outside of the scope of this project since we are not designing a medical robot, rather the mount that the KUKA will connect to. The only time where the user will interact directly with our product is when connecting the KUKA to the base of the platform. This connection will be done using four M8 bolts.
The KUKA weighs 22kg = 48.5lb. OSHA states that lifting loads heavier than about50 pounds will increase the risk of injury [41]. It is inadvisable, therefore, for an individual to lift the KUKA for mounting on the platform, without external assistance, especially as this will require working in an awkward position over their head. The installation of the KUKA should be done by two persons working together with a jack, lift, or stand for the KUKA. One person should hold the KUKA to stabilize it horizontally and maintain it in the correct position, while the other individual inserts and tightens the bolts. The bulk of the KUKAs

weight should be supported by jack, lift, or stand. For ease of install, a ratcheting socket wrench is recommended to tighten the bolts. If available, a pneumatic socket wrench may further hasten and ease this step of assembly. These assembly instructions will be made clear with labeled pictures and graphics and will be easily accessible both online and on paper. Since the instructions will be pictures, they will be accessible to people of all languages. Assuming individuals installing the KUKA robot follow the assembly instructions provided, the risk to the user is very small.

6.4 Failure Modes and Effects Analysis

To identify potential problems in the design, the team performed a failure modes and effects analysis. The team started with each specific element of the design and came up with various situations that each element would fail to perform its required function. These could be related either to a part physically failing, or any way the user is prevented from completed the goal. The effects of the potential failures were recorded, and given a severity ranking 1 to 10; 1 is represented by the effect not being noticed by the customer, and 10 represents a hazardous and or life threatening effect. The causes of the failure were also recorded, these were also given a scale from 1 to 10. The number one is a extremely remote and 10 is given for a extremely high occurrence. Lastly the detection for the failures were also recorded, the detection factors were also given a scale from 1 to 10. The number 1 is used for almost certain detection and 10 is assigned if there is no chance of detection. After all three were given a number on the scale from one to ten they were multiplied together to find the risk priority number (RPN). Generally, the team should be more concerned about the potential failure modes with the highest risk priority numbers. A ranked list of the top ten potential failure modes and there RPN values are shown below.

1. Dust build up inside stepper motor (144)
2. Threaded rod snaps or breaks (126)
3. Coupling snaps or breaks (63)
4. Bolts self loosen (60)
5. Bolts degrade over time (56)
6. Moisture damages stepper motor (50)
7. Stepper motor overheats (48)
8. Threaded rod degrades over time (48)
9. Accelerometer has electrical short (48)
10. Accelerometer is damaged by water/moisture (48)

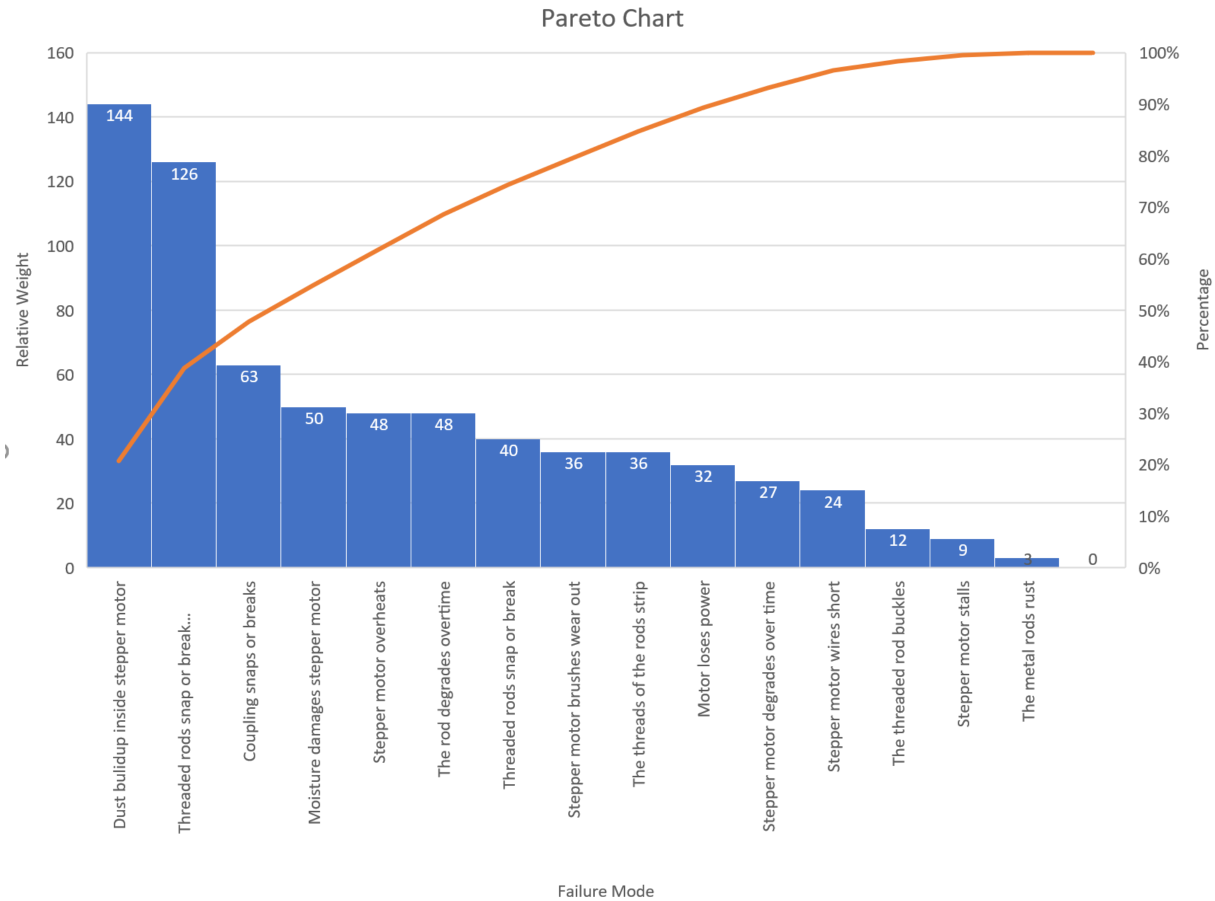


Figure 81: Pareto Chart for FMEA

Based on these results, the top three potential failure modes that the team should consider are dust buildup inside the stepper motor (Figure 82), threaded rod snapping or breaking(Figure 83), and coupling snapping or breaking(Figure 84). The motors are a primary concern for the robotic mount because they are the whole reason that the mount is able to mitigate the vibration to the robot. If just one of the three motors fail then the entire system is unable to function at all. Though this is not a risk to harming the patient it is a total failure to the system. More emphasis should be placed on protecting the motors from dust and other debris that may find its way into the motor and inhibit it from operating properly. The effect that the user has by failing to plug in the power source has a very low RPN of 28 this is due to the fact that no harm will be done to the patient(Figure 86). Also this has immediate and simple detection which results in a very low RPN. This made the team realize that we must choose a motor that has small or no holes for foreign debris to enter through. This would result in a design that is not prone to issues with dust or moisture damaging the stepper motor and preventing it from being used.

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
Stepper Motors	Motor loses power	Motor cannot rotate properly	4	No power to the motor	4	Regularly check power to system	2	32
	Stepper motor overheats	Motor cannot rotate properly	6	Load too heavy, runs for too long	2	Smelling smoke, know weight limits and maximum run time	4	48
	Stepper motor stalls	Motor cannot rotate properly	3	Load too heavy	3	Know weight limits	1	9
	Stepper motor brushes wear out	Motor cannot rotate properly	4	Brushes degrade over time and from use	3	Detection by visual inspection	3	36
	Stepper motor wires short	Motor cannot rotate properly	3	Wire degrades over time	4	Detection by visual inspection	2	24
	Dust bulidup inside stepper motor	Motor cannot rotate properly	8	Dust causes brushes to not conduct electricity	3	Detection by visual inspection	6	144
	Moisture damages stepper motor	Motor cannot rotate properly	5	Water causes short in motor	5	Detection by visual inspection	2	50
	Stepper motor degrades over time	Motor cannot rotate properly	3	Exposure to elements	3	Lower performance from motors	3	27

Figure 82: FMEA Stepper Motor

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
Threaded Rods	Threaded rods snap or break	Cannot move platform up and down	8	Load too heavy	1	Know weight limits	5	40
		Robot falls off mount	9	Threads are damaged	2	Inspect before use	2	36
		Robot falls off mount	9	Manufacturing defect	2	Know weight limits	7	126
	The threads of the rods strip	Platform cannot raise or lower correctly	4	Platform was threaded onto rod incorrectly	3	Detection by visual inspection	3	36
	The threaded rod buckles	Platform cannot raise or lower correctly	3	Bumped by user	4	Detection by visual inspection	1	12
	The rod degrades overtime	Robot falls off mount	6	Repeated use over time	2	Replace rods	4	48
	The metal rods rust	Platform cannot raise or lower correctly	3	Exposure to the elements	1	Detection by visual inspection	1	3

Figure 83: FMEA Threaded Rods

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
Coupling	Coupling snaps or breaks	Robot falls off mount	7	Load too heavy	3	Know weight limits	3	63
	The coupling threads strip	Platform cannot raise or lower correctly	5	Load too heavy	3	Detection by visual inspection	2	30
	Coupling experiences friction failure	Platform cannot raise or lower correctly	3	Not enough lubricant was added to threads and coupling	3	Detection by visual inspection	2	18
	Coupling degrades over time	Platform cannot raise or lower correctly	6	Repeated use over time	2	Regularly inspect	3	36
	Coupling oxidizes over time	Platform cannot raise or lower correctly	2	Exposure to the elements	3	Detection by visual inspection	1	6
Platform	Platform snaps or breaks	Robot falls off mount	9	Pushed or pulled by user	2	Regularly check mounts of system	1	18
		Robot falls off mount	9	Load too heavy	2	Know weight limits	1	18
	Platform deforms	Platform cannot raise or lower correctly	6	Fire in ambulance over heats metal	1	Detection by visual inspection	1	6
	Platform oxidizes over time	Becomes unusable inside the ambulance for health compliance	3	Exposure to outdoor elements	7	Detection by visual inspection	1	21
	Platform degrades over time	Platform cannot raise or lower correctly	3	Exposure to outdoor elements	2	Detection by visual inspection	2	12

Figure 84: FMEA Coupling and Platform

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
Accelerometer	Acceleromter loses power	Motor will not move to counteract impulse	3	No power to accelerometer	3	Regularly check power to the system	5	45
	Accelerometer calibration done incorrectly	Motor will not move to counteract impulse	2	Proper maintenance not done	3	Have system calibrated regularly	7	42
	Accelerometer has electrical short	Sensor will not function properly	6	Vibration causeing wires to fray	4	Connect to oscilliscope to test	2	48
	Acceleromter overheats	Sensor will not function properly	5	Fire inside ambulance	2	Detection by visual inspection	1	10
	Acceleromter fails to emit signal	Sensor will not function properly	3	End of product life cycle	2	Connect to oscilliscope to test	1	6
	Accelerometer emits erratic or incorrect signal	Sensor will not function properly	3	Confusion from other electrical instruments	2	Connect to oscilliscope to test	3	18
	Accelerometer wire degrades over time	Sensor will not function properly	4	Inulation dryness or cracking	3	Detection by visual inspection	2	24
	Acceleromter is damaged by water	Sensor will not function properly	4	Accidentally sprayed with fluid	4	Connect to oscilliscope to test	3	48
	Acceleromter oxidizes over time	Sensor will not function properly	2	Exposure to outdoor elements	5	Detection by visual inspection	2	20
	Accelerometer deforms from flexing or bending	Sensor will not function properly	2	Twisting and or bending caused by rods	2	Detection by visual inspection	5	20

Figure 85: FMEA Accelerometer

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
User	User does not connect power correctly	Motor will not move to counteract impulse	2	Proper maintenance not done	6	Regularly check power to the system	2	24
Bolts	Bolts loosen themselves	Loose joint	6	Under-tightening, vibration	5	Regularly check torque on bolts	2	60
	Bolt threads strip	Reduced thread strength, failure	6	Excessive tensile force	4	Detection by visual inspection	2	48
	Bolt head fractures	Catastrophic failure of bolt	7	Excessive preload	3	Detection by visual inspection	1	21
	Bolt crushes the washer	Loose joint	3	Bolt overtightened	2	Detection by visual inspection	2	12
	Bolt shank snaps	Immediate failure of fastener	7	Over-torque	2	Detection by visual inspection	1	14
	Bolt degrades over time	Loose joint	4	Exposure to elements	2	Replace bolts	7	56
	Bolt degrades over time	Reduced thread strength, failure	6	Exposure to elements	1	Detection by visual inspection	1	6

Figure 86: FMEA User and Bolts

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
Spring	Spring snaps or breaks	Platform will not realign to starting position	2	Spring is pushed too far	2	Detection by visual inspection	1	4
	Spring over extends	Spring will not return to start position	3	Spring is extended beyond range it was intended to	3	Detection by visual inspection	1	9
	Spring experiences friction failure	Platform will not realign to starting position	2	Spring and assembly was not lubricated correctly	2	Detection by visual inspection	1	4
	Spring degrades over time	Platform will not realign to starting position	2	Exposure to elements	4	Replace springs periodically	1	8
	Spring oxidizes over time	Platform will not realign to starting position	2	Exposure to elements	3	Detection by visual inspection	1	6

Figure 87: FMEA Spring

Function/ Element	Failure Mode	Effects of Failure	Sev	Cause of Failure	Occ	Detection	Det	RPN
Bearings	Bearing breaks from abrasive wear	Platform will not be able to pitch, yaw, or return to starting position	1	Dust enters bearings	2	Detection by visual inspection	5	10
	Bearing breaks from subsurface fatigue	Platform will not be able to pitch, yaw, or return to starting position	2	Exposure to elements	4	Detection by visual inspection	4	32
	Bearing breaks from thermal deformation	Platform will not be able to pitch, yaw, or return to starting position	3	Bearing heats up from high usage	2	Replace bearings periodically or after high use	6	36
	Bearing is damaged from moisture corrosion	Platform will not be able to pitch, yaw, or return to starting position	2	Exposure to elements	3	Detection by visual inspection	4	24
	Bearing is damaged from friction corrosion	Platform will not be able to pitch, yaw, or return to starting position	2	Dust enters bearings	2	Detection by visual inspection	5	20

Figure 88: FMEA Bearings

Rating for Detection of Failure

Rating	Description of Detection
1	Almost certain to detect
2	Very high chance of detection
3	High chance of detection
4	Moderately high chance of detection
5	Medium chance of detection
6	Low chance of detection
7	Slight chance of detection
8	Remote chance of detection
9	Very remote chance of detection
10	No chance of detection; no inspection

Figure 89: Table of Detection Values [60]

Rating for Severity of Failure

Rating	Severity Description
1	The effect is not noticed by the customer
2	Very slight effect noticed by customer; does not annoy or inconvenience customer
3	Slight effect that causes customers annoyance, but they do not seek service
4	Slight effect, customer may return product for service
5	Moderate effect, customer requires immediate service
6	Significant effect, causes customer dissatisfaction; may violate a regulation or design code
7	Major effect, system may not be operable; elicits customer complaint; may cause injury
8	Extreme effect, system is inoperable and a safety problem; may cause severe injury
9	Critical effect, complete system shutdown; safety risk
10	Hazardous; failure occurs without warning; life-threatening

Figure 90: Table of Severity Values [60]

Rating for Occurrence of Failure

Rating	Approx. Probability of Failure	Description of Occurrence
1	$\leq 1 \times 10^{-6}$	Extremely remote
2	1×10^{-5}	Remote, very unlikely
3	1×10^{-5}	Very slight chance of occurrence
4	4×10^{-4}	Slight chance of occurrence
5	2×10^{-3}	Occasional occurrence
6	1×10^{-2}	Moderate occurrence
7	4×10^{-2}	Frequent occurrence
8	0.20	High occurrence
9	0.33	Very high occurrence
10	≥ 0.50	Extremely high occurrence

Figure 91: Table of Occurrence Values [60]

6.5 Perform Parametric Design

The base of the KUKA robot (Figure 74) is cylindrical with a 290mm diameter, which serves as the first constraint for the robot platform dimensions. The robot must entirely fit within the platform, so the smallest platform dimension must exceed 290mm. Three points define a plane, so the platform is triangular with the circle of the robot inscribed at it's center.

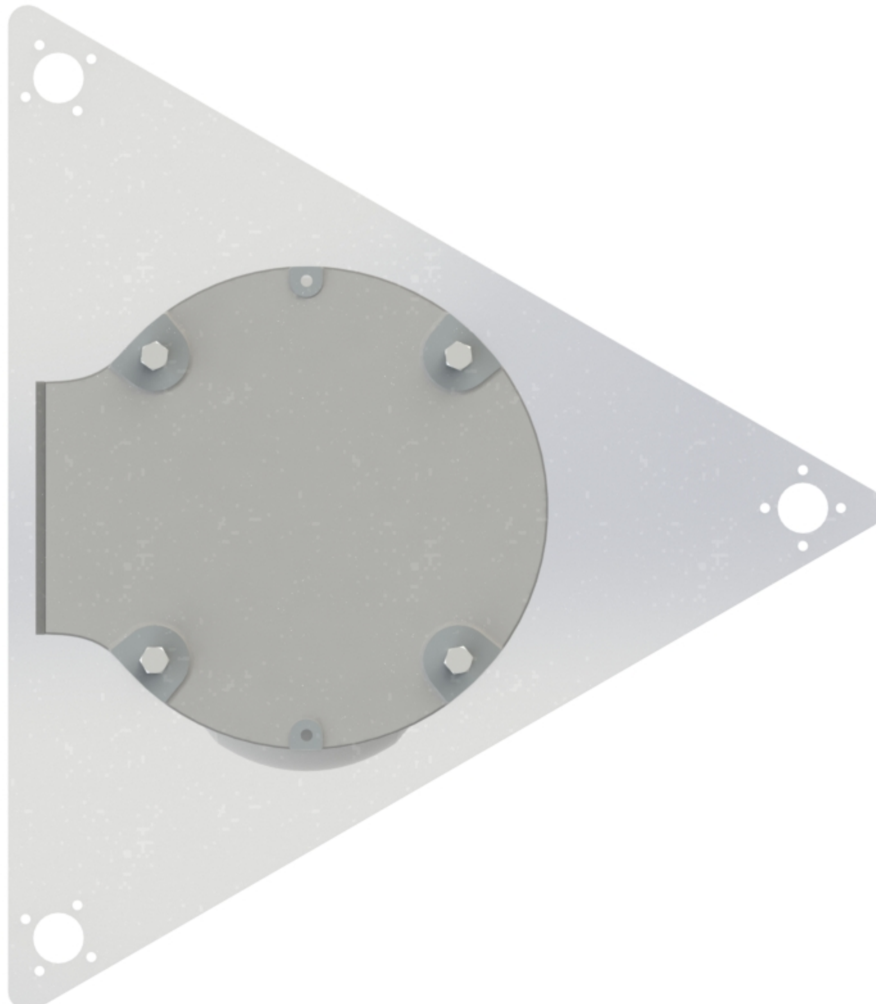


Figure 92: Semi-transparent rendering of the platform with the KUKA shown in the center

The lead screws need to be short enough to not interfere with the movement of the robot, but long enough to provide us the desired range of motion. The length of our lead screws can be parametrized by the geometry of the platform at it's most extreme angle. As you'll recall from Section 5.4.4, the angle of the platform is limited by the angle allowed within the heim joint which was given by 26 degrees 93.

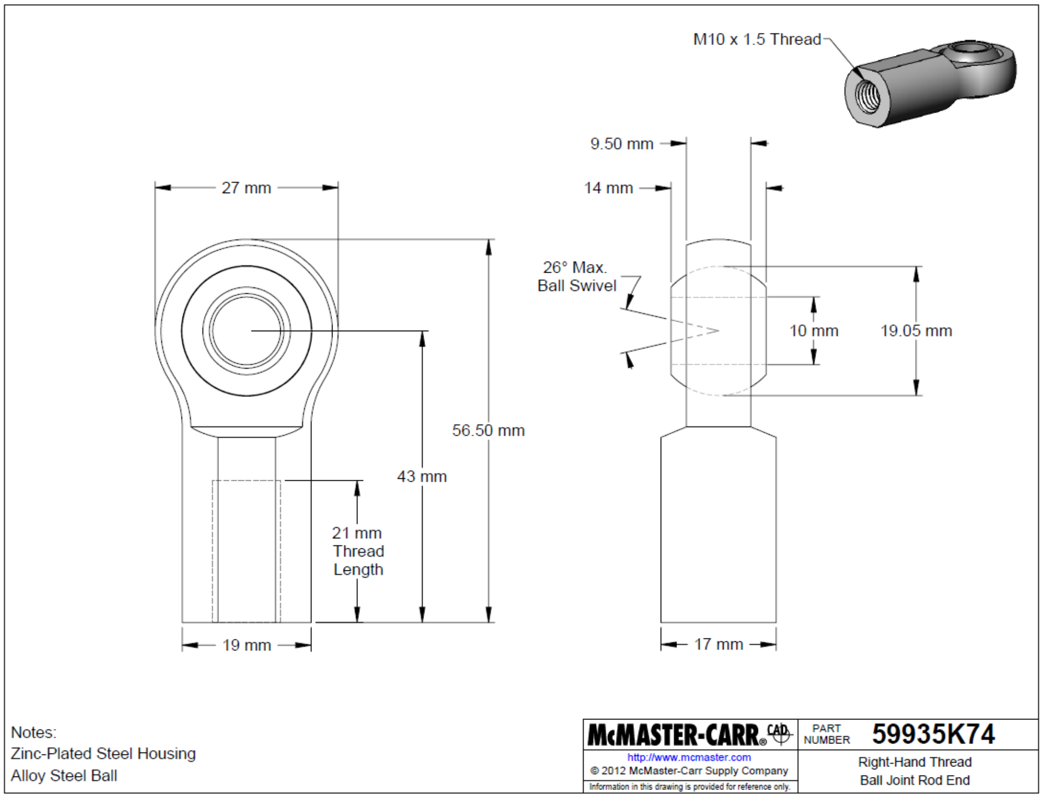


Figure 93: Angle of Heim Joint

With a maximum reasonable angle of 26°, we can define the maximum length our lead screws need to have to accommodate the platform's angles.

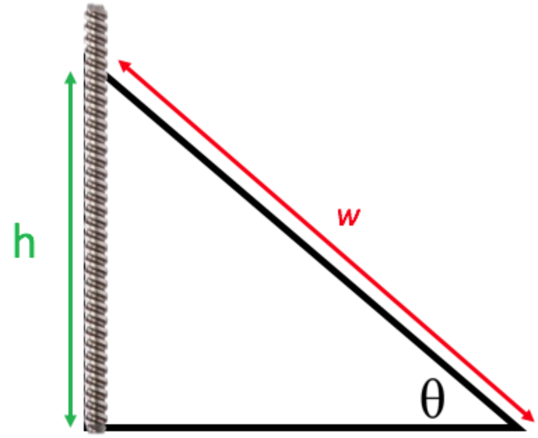


Figure 94: Diagram showing the screw height (h) as a function of θ

$$h = 500sin(26°)$$

$$h \approx 219mm$$

The screws need to be this long with some additional length to accommodate the motor couplings and screw stops. Therefore, we'll use screws of 250mm length.

6.5.1 Design for Manufacturing

Most parts of our design will be purchased and then assembled. The two components that will need manufacturing are the platform and the threads inside the heim joint.
In Figure 95 the full platform assembly can be seen. As seen here, our design includes triangular base, which will be made from aluminum 6061. This shape was decided because three points define a plane, and so the shape will allow for complete control over the platform orientation and position.

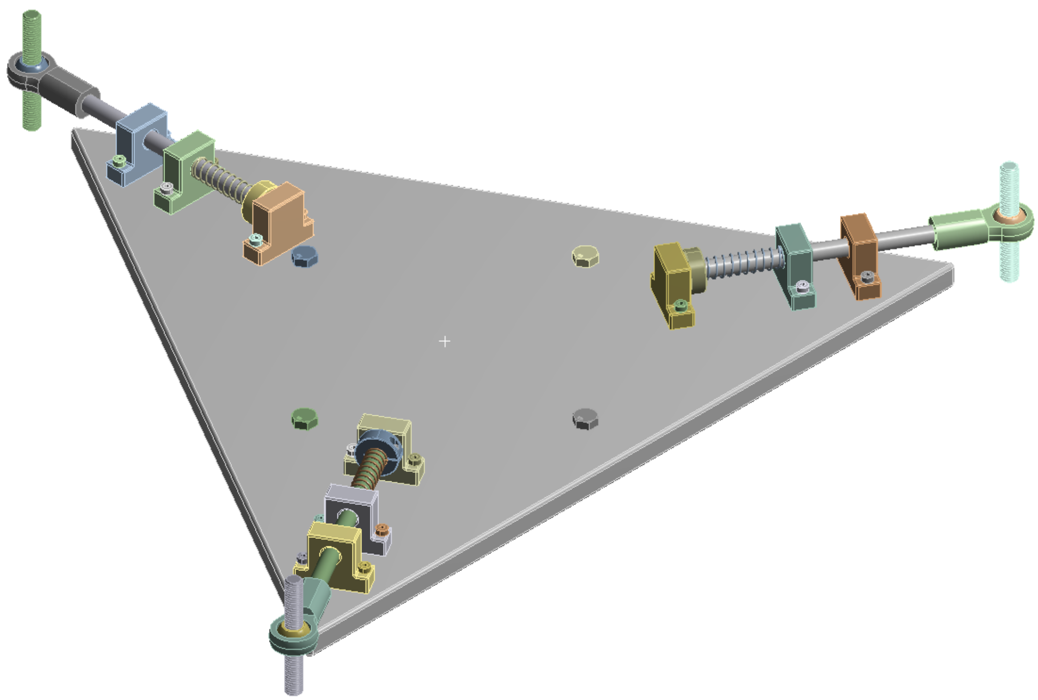


Figure 95: Platform Assembly including spring and heim joint couplings

The geometry of the platform should be relatively simple to machine and has no complicated features that would require more elaborate manufacturing techniques. The platform is simply a flat triangular square with bolt holes to mount the KUKA as well the spring sub assembly.
A vertical mill is the perfect tool to manufacture this platform. The mill would allow the manufacturer to punch holes in precise locations as well as cut out the edges of the triangle

evenly.
The second sub assembly that will need to be manufactured is the thread of the heim joints. The joints themselves would be bought from McMaster, but they then they would need to be tapped using an ACME threads in order for the lead screws to fit properly within the heim joint.

6.5.2 Design for Assembly

The steps for assembling this system are as follows:

1. Connect lead screws and motors
2. Mount the motor screw assembly to the motor plate
3. Mount motor screw plate assembly in ambulance
4. Wire the motors to the controller
5. Mount the ceiling accelerometer and wire it to the controller
6. Assemble spring mechanism assembly
7. Mount spring mechanism assembly on the platform
8. Mount the platform accelerometer to the platform
9. Bring platform into ambulance; thread lead screws through heim joints
10. Wire the platform accelerometer to the controller
11. Mount KUKA to platform

The system is designed to be modular and easy to assemble. The first step of assembly would be to connect the lead screws and motors. This can be done on a tabletop at a comfortable position for the operator, and involves tightening two set screws (per lead screw) with an Allen wrench.

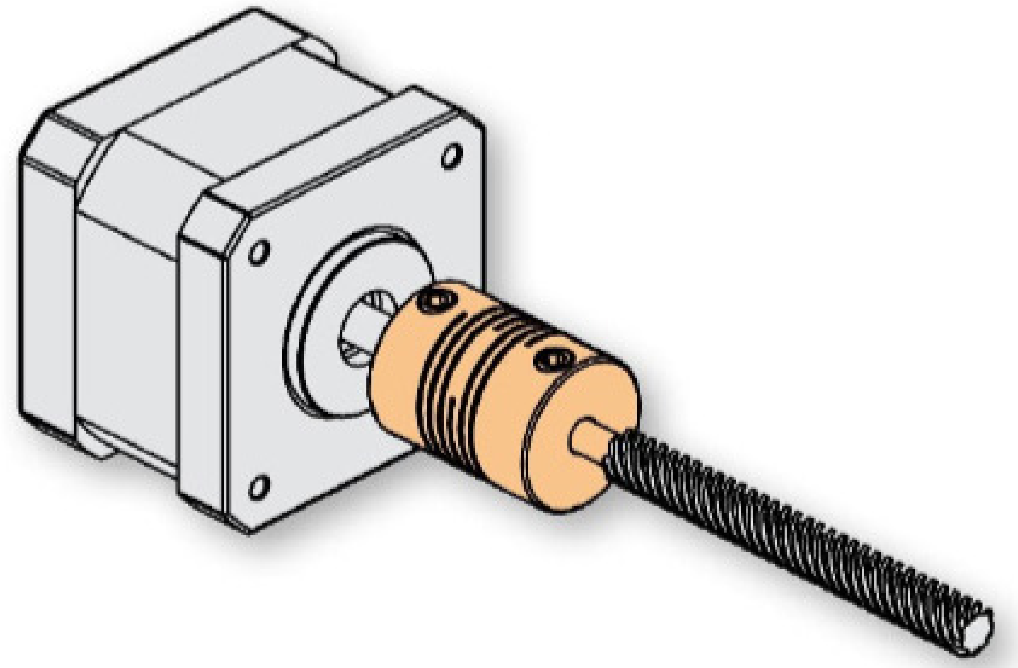


Figure 96: Sketch of the motor, coupling, and lead screw [61]

Use the motor plate as a template to mark the locations in the ambulance ceiling to drill for the plate bolt holes. Each motor-screw assembly should now be mounted onto the motor plate. This plate fully constrains the positions of the motors and ensures they'll be in alignment with the robot platform (to come later). It also facilitates install of this sub-assembly in the ambulance, which is the next step.

Once this is complete, the motors can be mounted in the ambulance.

Assemble the spring mechanism assembly (Figure 97). This can also be done on a tabletop within comfortable reach of the operator. Start by threading the heim joint onto the end of the shaft and hand turn until tight. Next slide the first linear bearing onto the shaft. This one is shown in blue in Figure 97. Similarly, slide on the second bearing and spring onto the shaft. Slide the collar on to the shaft and tighten it into place with the internal set screw. This can be done via an Allen wrench.

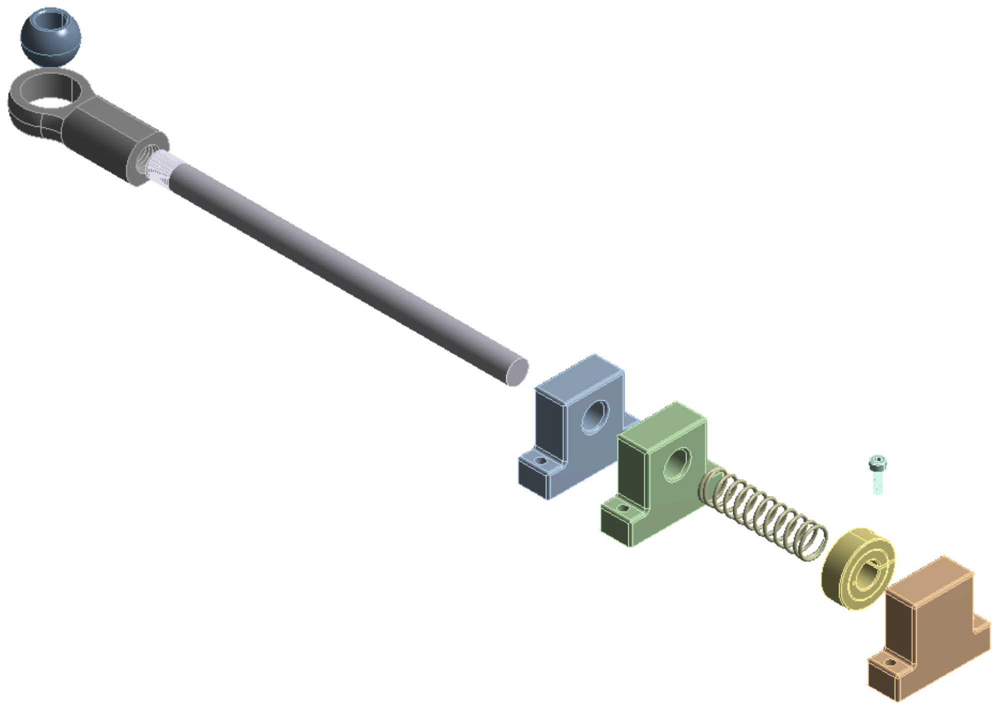


Figure 97: Exploded view of the spring assembly

Note that the blue and green components in Figure 97 are actually one linear ball bearing like the one shown in Figure 98. These allow the shaft to slide. The orange component is a shaft stop - a solid piece of metal that constrains the range of motion of the shaft.

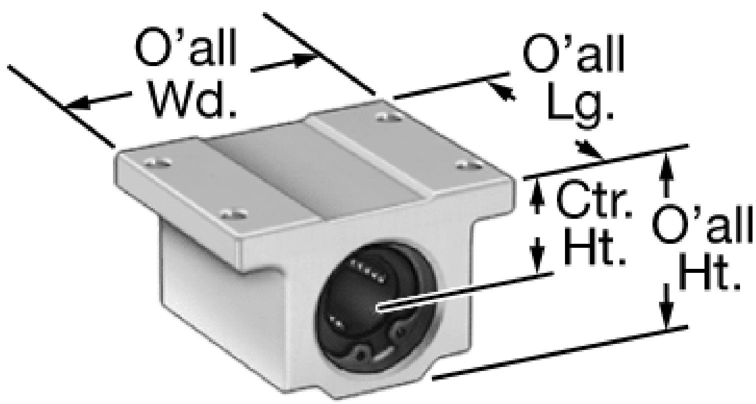


Figure 98: Linear bearing from McMaster

Now it's time to mount each spring assembly on to the platform (Figure 99). Lay the platform on a table with one corner hanging over the edge. Align the orange shaft stop with its bolt holes, and pass the bolts through the platform. Thread a nut onto each bolt and tighten by hand and then tigthen further with an Allen wrench.

Align the spring assembly with the holes in the platform. Thread each bolt through its hole, and partially hand tighten each bolt. When the components are fully aligned, use an Allen wrench and a combination spanner to fully tighten the rest of the bolts. Repeat this for the other two corners.

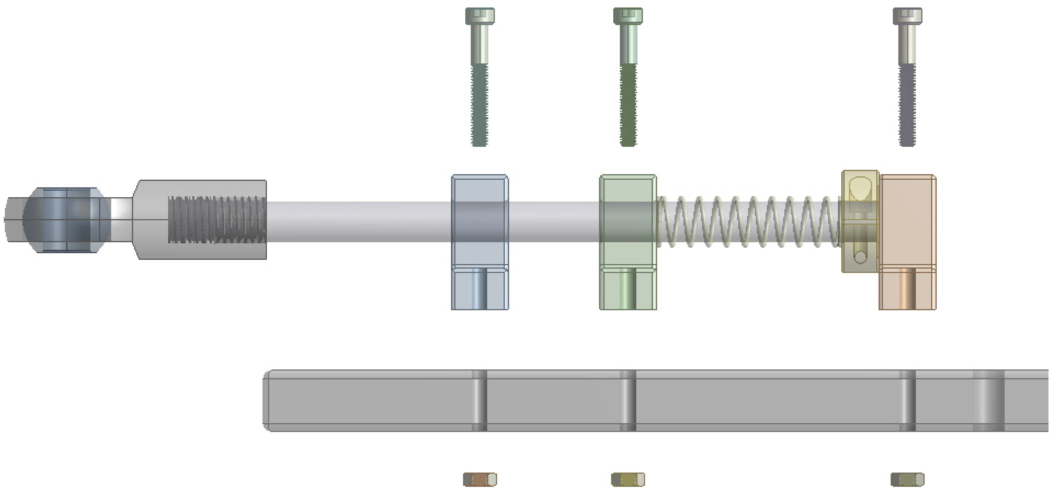


Figure 99: Exploded view of the spring assembly on the platform

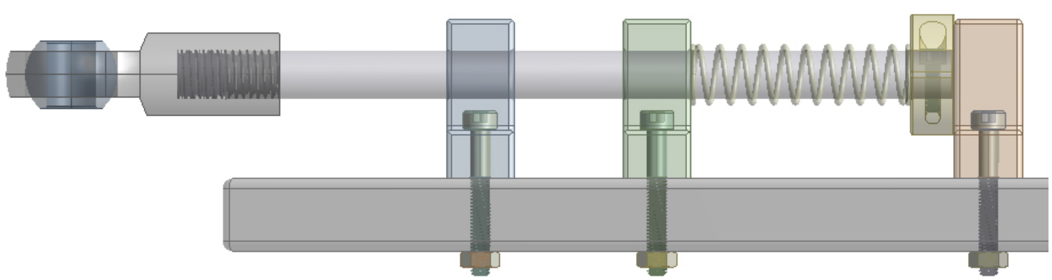


Figure 100: Spring assembly mounted on the platform

Mount the platform accelerometer to the platform following the diagram printed on the platform. Now, bring the platform assembly into the ambulance. Thread each lead screw through it's respective heim joint. This step may be easiest with one person holding the platform in position and another person helping to align everything.

The KUKA is mounted to the platform via four M8 bolts (Figure 101) and corresponding M8 nuts (not shown).

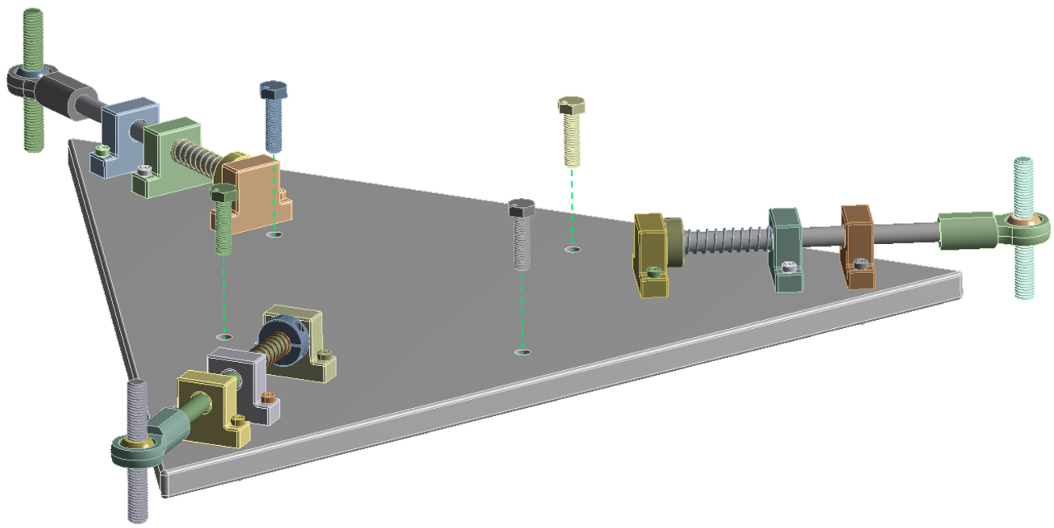


Figure 101: Rendering showing the bolt assembly for the KUKA

The KUKA weighs 22kg = 48.5lb. OSHA states that "lifting loads heavier than about 50 pounds will increase the risk of injury" [38]. It is inadvisable, therefore, for an individual to lift the KUKA for mounting on the platform, without external assistance, especially as this will require working in an awkward position over their head. The installation of the KUKA should be done by two persons working together with a jack, lift, or stand for the KUKA. One person should hold the KUKA to stabilize it horizontally and maintain it in the correct position, while the other individual inserts and tightens the bolts. The bulk of the KUKA's weight should be supported by jack, lift, or stand. For ease of install, a ratcheting socket wrench is recommended to tighten the bolts. If available, a pneumatic socket wrench may further hasten and ease this step of assembly. Once the KUKA is secured, wire the accelerometers and motors to the controller.

7 Engineering Drawing Set

7.1 Parts List and Bill Of Materials

Model Number for purchased parts	Part Name	Qty in Assembly	Purchased or made	Suppliers for purchased parts	Material
89155K761	Platform	1	Purchased and made	McMASTER	1060 Aluminum
97048A751	Lead screw	3	Purchased and made	McMASTER	Black Oxide Carbon Steel
9338T52	Mounted linear ball bearing	3	Purchased	McMASTER	6061 Aluminum
59935K54	Ball Joint Rod End	3	Purchased and made	McMASTER	Zinc-Plated Carbon Steel
NEMA 34	Stepper Motor	3	Purchased	Motor de Passo	-
5395T312	Lead screw motor coupling	3	Purchased	McMASTER	Black-Oxide Steel
90128A219	Zinc-Plated Alloy Steel Socket Head Screw type 1	18	Purchased	McMASTER	Zinc-Plated Alloy Steel
90591A255	Nuts	18	Purchased	McMASTER	Steel
94125K123	Spring	3	Purchased	McMASTER	Music-Wire Steel
6940T18	Shaft	3	Purchased and made	McMASTER	1060 Aluminum
4471T61	Block	3	Purchased and made	McMASTER	A2 Tool Steel
9506T5	Collar	3	Purchased	McMASTER	2024 Aluminum
91292A131	Hex Screw Type 2	4	Purchased	McMASTER	Zinc-Plated Steel

Figure 102: Parts list and BOM

- Platform: The piece of Aluminum is purchased from McMaster and then machined into the appropriate shape, as defined in Section 7.2. This involves cutting the sheet into a triangle and then drilling the holes for all of the bolts.
- Lead screw: Two 500 mm lead screws will be bought from McMaster Carr, and then cut in half to get screw lengths of 250mm.
- Ball Joint Rod End: The Ball Joint Rod End (also known as a heim joint) is sourced from the McMaster, then tapped with ACME threads through the ball hole.

- Rod: a 6' long rod is sourced from the McMaster, and then cut in thirds. Each end of these sorter shafts will be threaded with a lathe, as shown on engineering drawings in Section 7.2.
- Block: A piece of steel block bought from McMaster is then cut into the shaft stop.

7.2 Engineering drawing and Tolerances

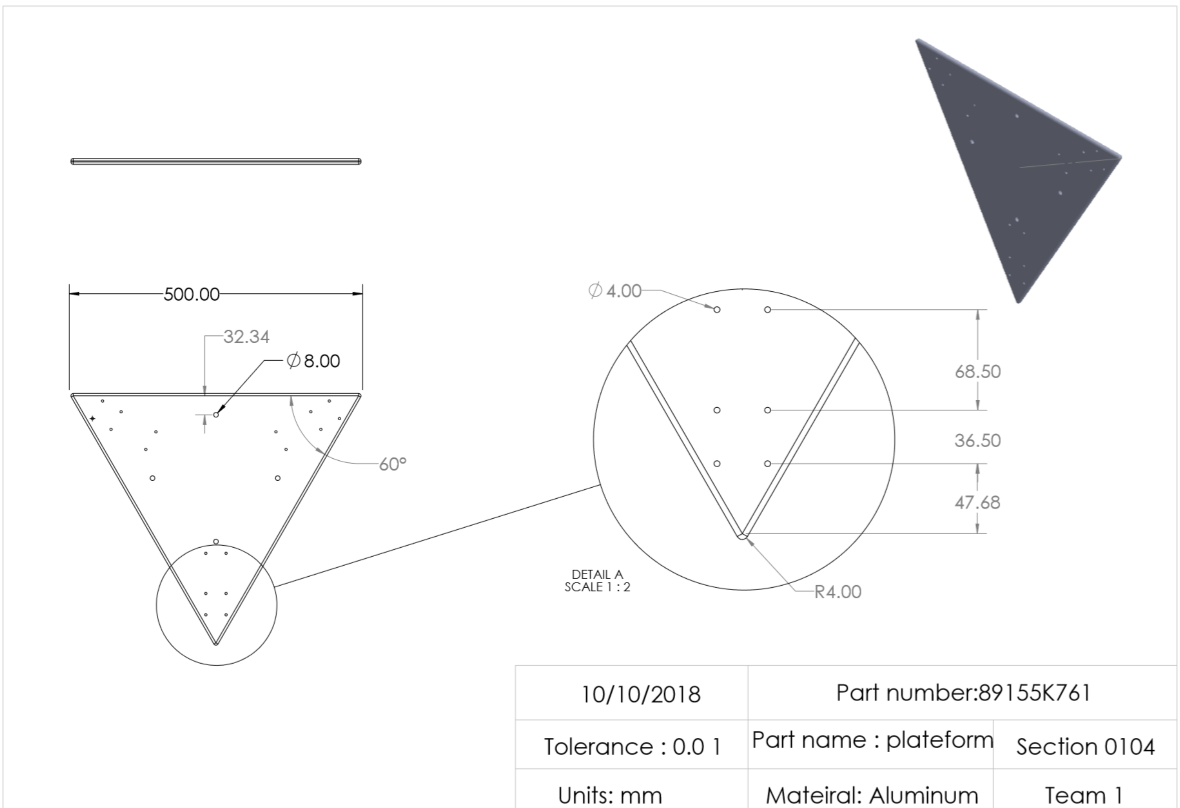


Figure 103: Engineering drawing of the robot platform with bolt holes for the robot

When evaluating the tolerances for the platform, we should think about the tolerances we need and their associated costs. Figure 104 shows how the relative cost of a part increases with the fineness of it's tolerances.

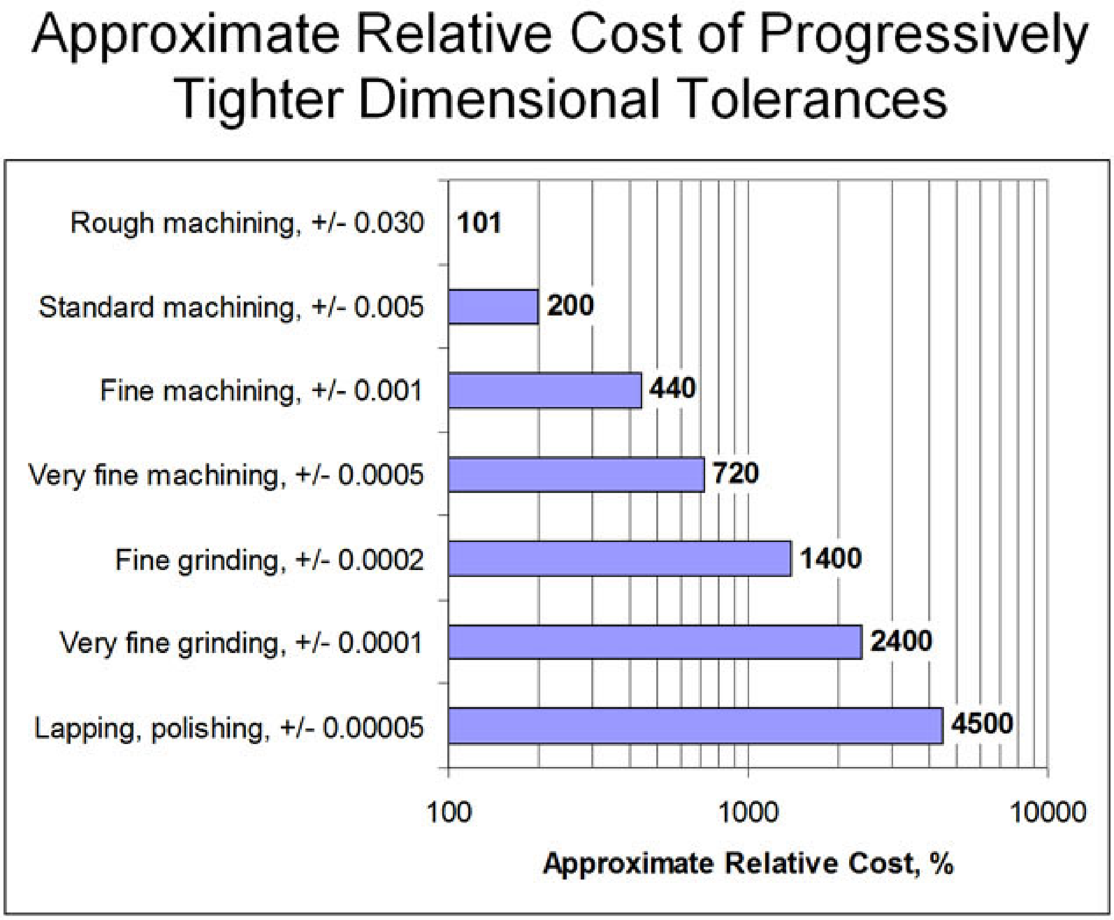


Figure 104: Chart showing the increased costs with increased tolerances [62]

The surface finish of the platform is not relevant to it's function. The most crucial dimensions of the platform are the bolt hole diameters and their positions, but even these do not require stringent tolerances. All of the bolt holes in the platform are just holes - there's no threading to be concerned with. The holes just need to be big enough for the bolts to slide easily through, which is trivial with tolerances of this size. The side length of the platform has the most flexibility with it's tolerances; so long as the bolts are correctly positioned relative to each other, the length of the platform is not very important. Any variance in side length is automatically compensated for by the spring assembly. With this in mind, we'll select Standard Machining from Figure 104 and use that as the tolerance for our manufactured components, allowing us a platform dimension tolerance of ±0.005".

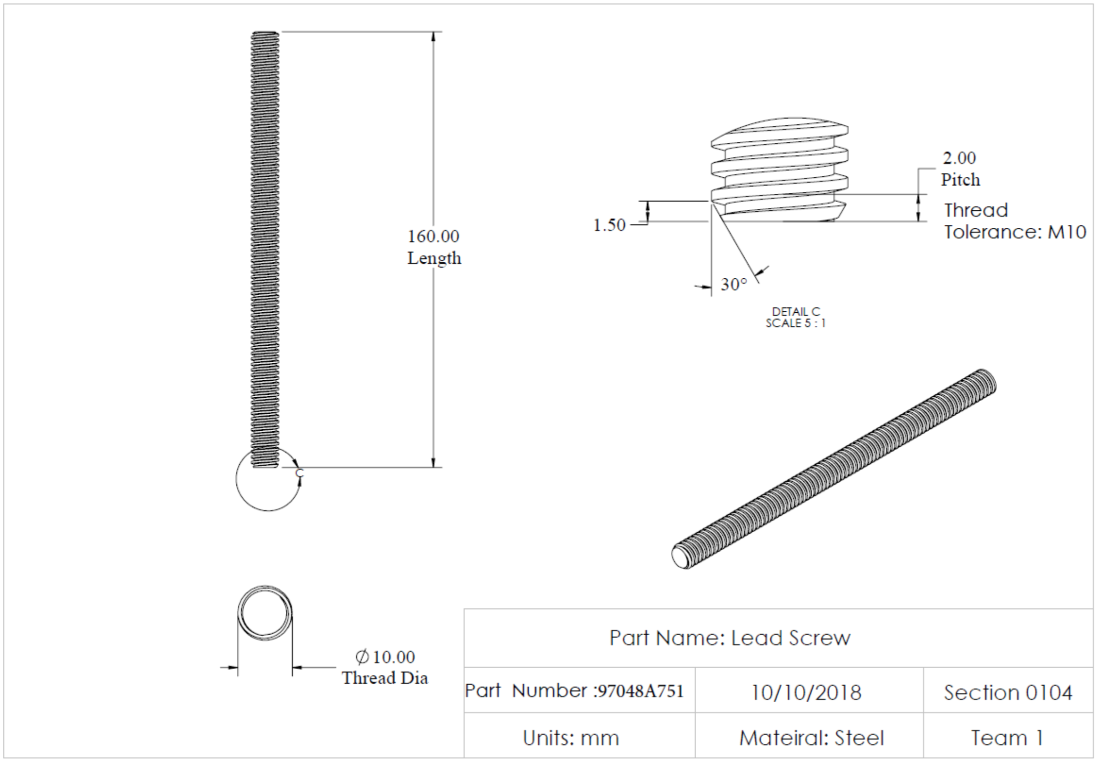


Figure 105: Engineering drawing of lead screw

The lead screws we intend to use are Class 7E M10 ACME screws with a 2mm pitch. Class 7E defines the standard that the screw is compliant with, which then defines its tolerances [63]. ACME is the thread geometry, and M10 defines the screw diameter (10 mm). The tolerances of these parts are only of concern to the team in the sense that the ACME threads we tap in the heim joint must be the same geometry and standard.

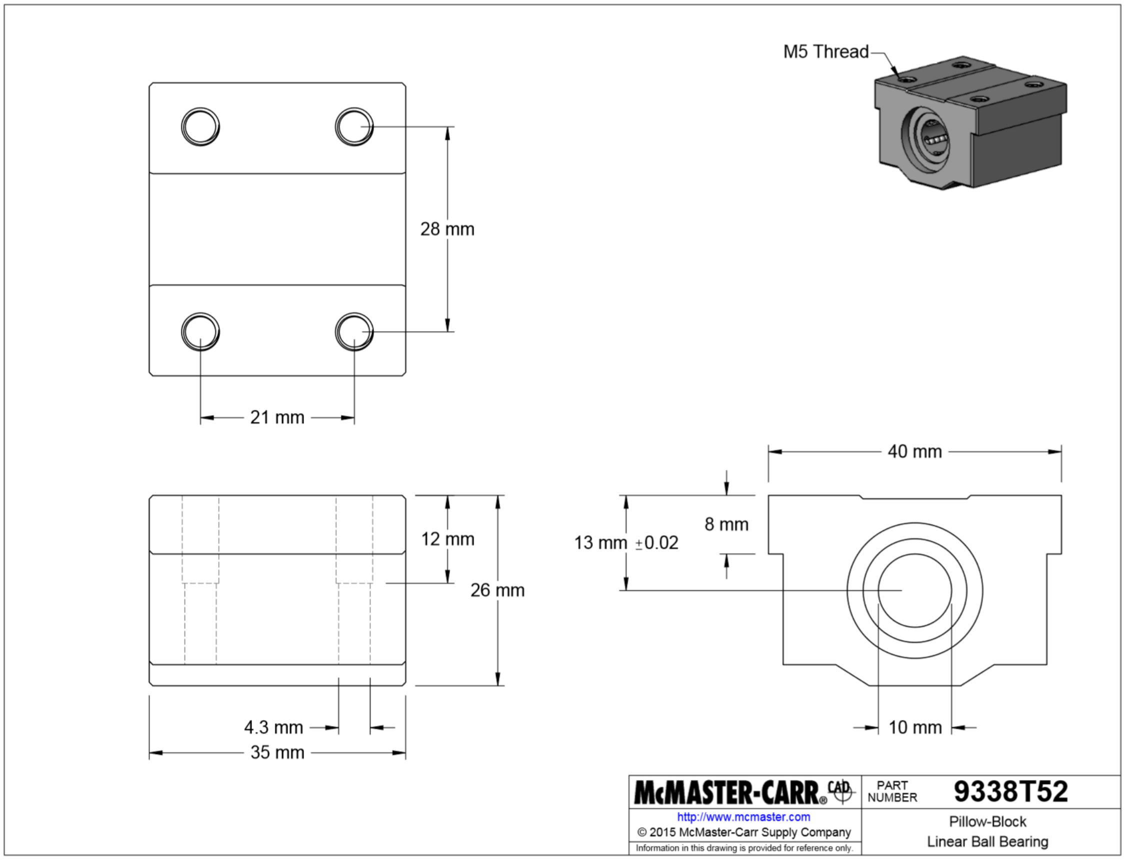


Figure 106: Engineering drawing of linear bearing mount

This component is sourced from McMaster. It's center height tolerance is ±0.02mm. The shaft will pass through this bearing, so the tolerances of the shaft as well as this part are crucial for the functionality of the spring shaft assembly.

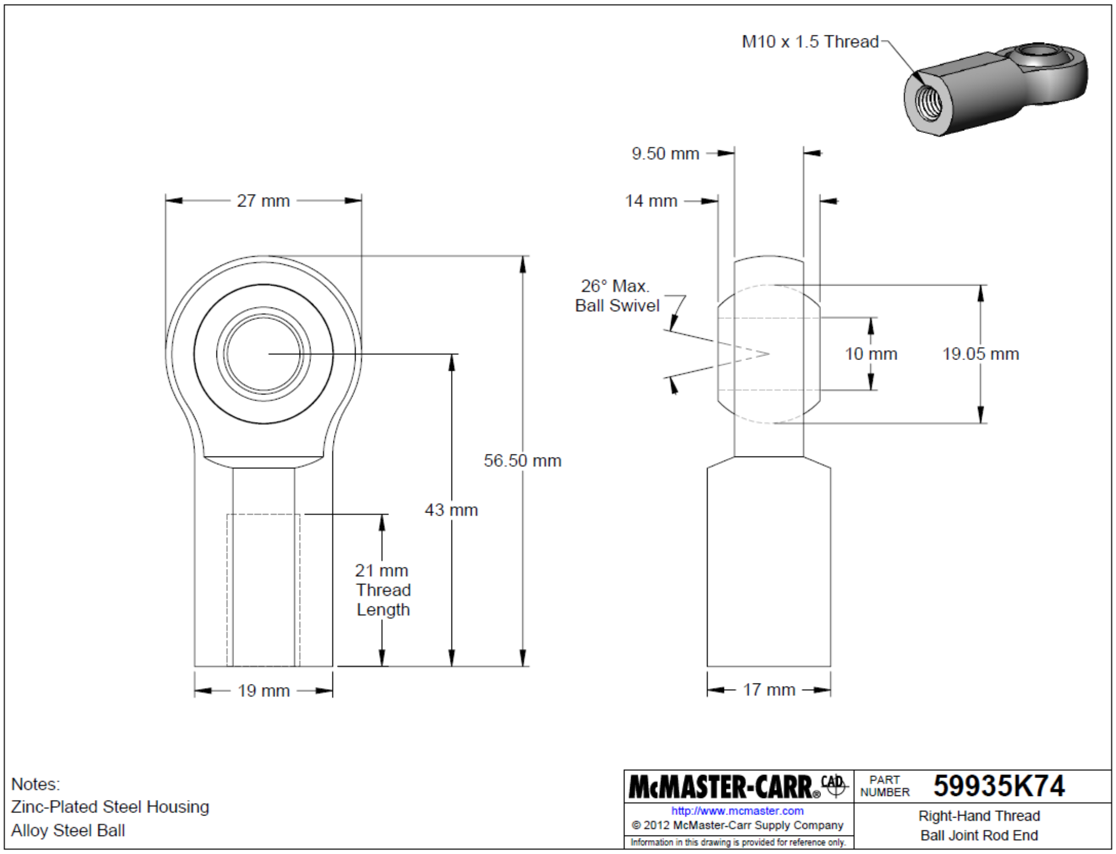


Figure 107: Engineering drawing of the heim joint

The pitch and tolerance of the female M10x1.5 threading of the heim joint is important as it dictates the geometry and tolerances that will need to be matched on the shafts, but this is contained within the M10 standard [64].

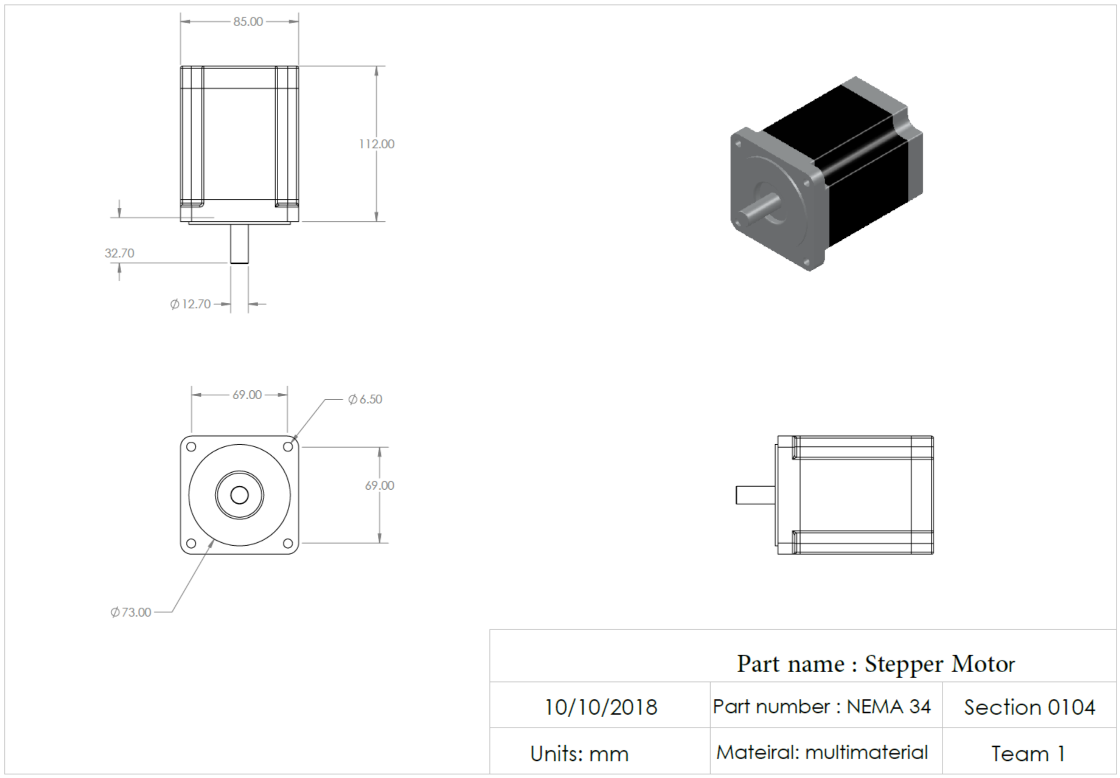


Figure 108: Engineering drawing of NEMA 34 stepper motor

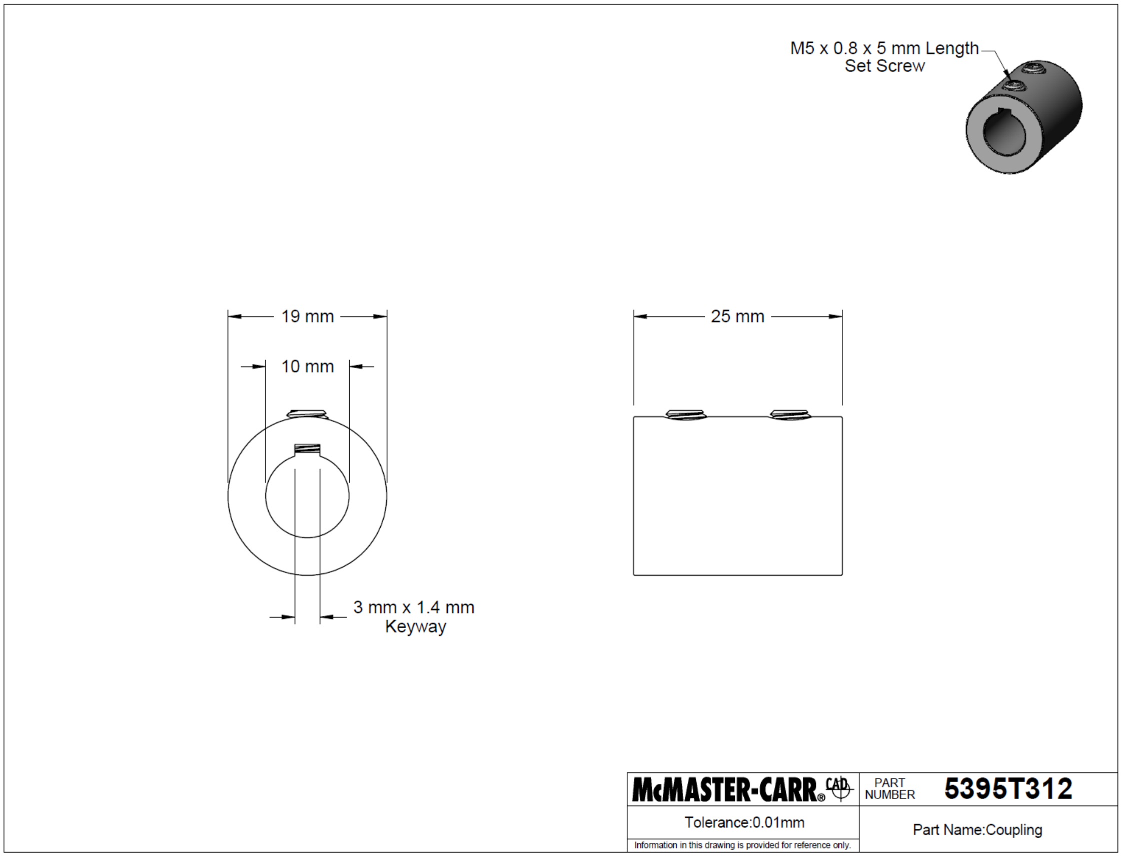


Figure 109: Engineering drawing of lead screw coupling

The lead screw coupling is also sourced from McMaster. There isn't much information about the tolerances of this component, but it comes with the set screws preinstalled, so we don't need to be concerned with their fit. Our only concern with this part is that it fits on the M10 lead screw and any looseness can be compensated for by the set screws.

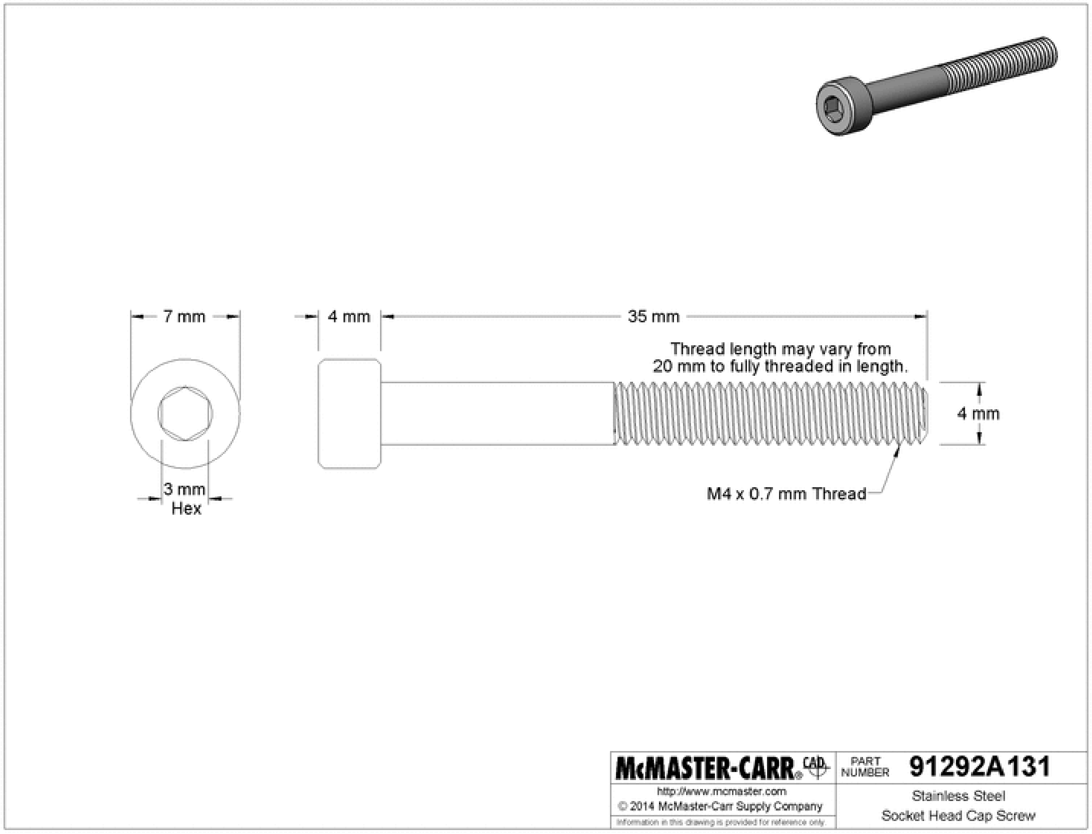


Figure 110: Engineering drawing of the M4 Socket Head Screws for securing the spring assembly to the platform

Like the lead screws mentioned above, this bolt is sourced from McMaster, so we don't need to be too concerned about it's tolerances. It's a class 5g6g screw, which establishes the tolerances of the pitch [65]. It's important that the nut we source matches the same geometry and standard.

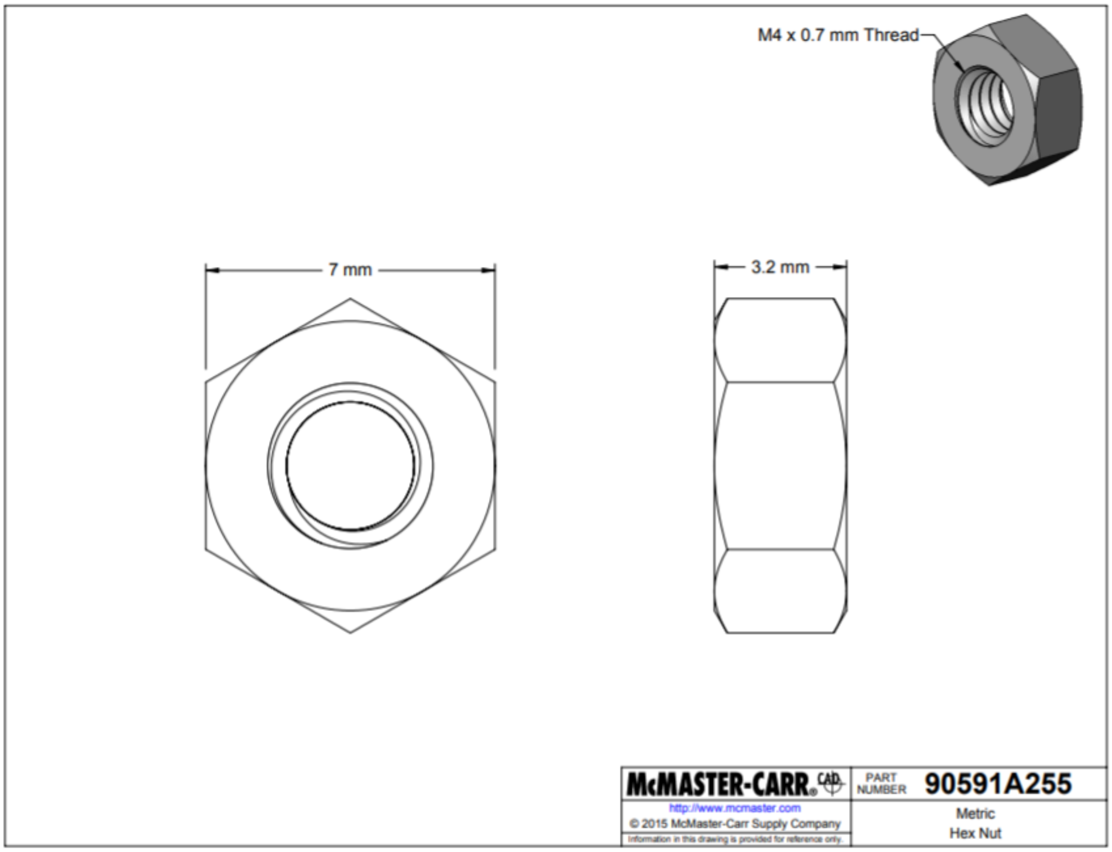


Figure 111: Engineering drawing of nuts

The tolerance of the nuts is only dependent on the standards of the screws shown above. These nuts are class 6H, which defines their pitch tolerance. As the nuts are bought from McMaster, and the team doesn't need to manufacture anything related to this part, the team doesn't need to consider other dimensions of this component.

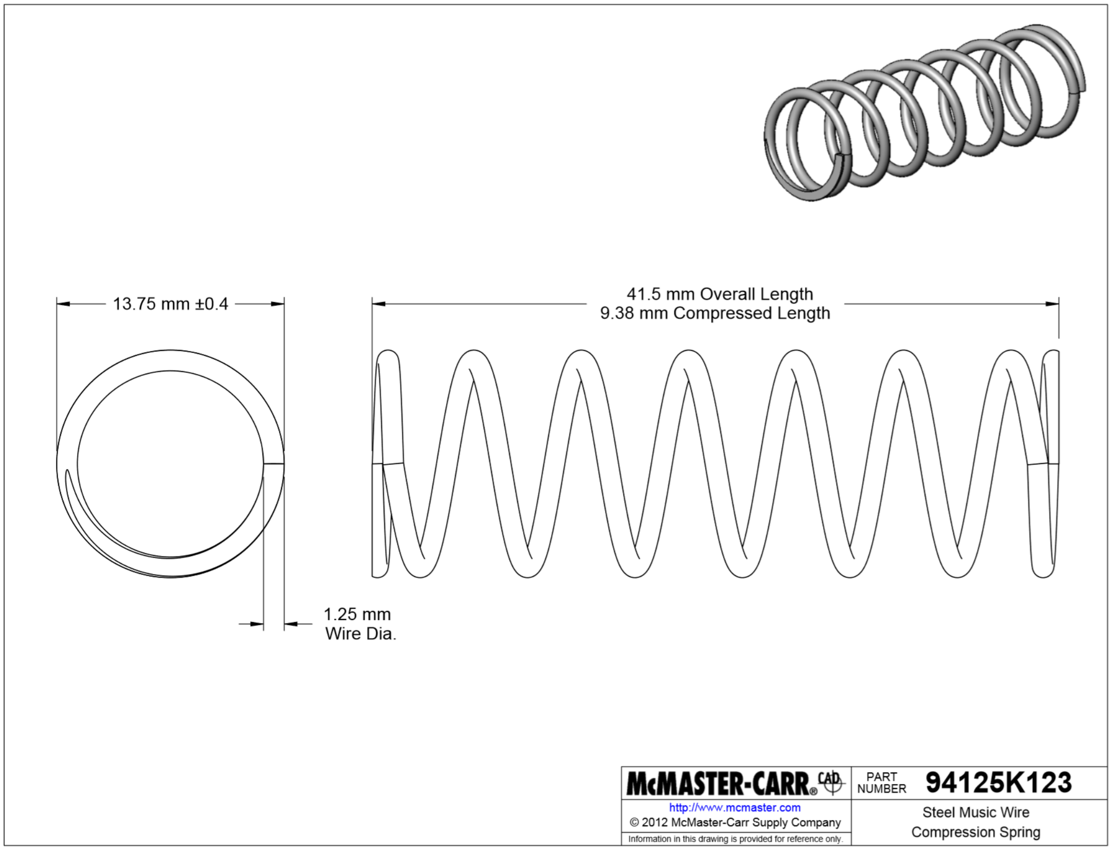


Figure 112: Engineering drawing of spring

The tolerances of the spring are included in the technical drawing from McMaster. The tolerance on the outer diameter of the spring is ±0.4mm. The shaft has a 10.0mm diameter. The smallest inner diameter this spring could have is:

$$13.75 - .4 - 2(1.25) = 10.85mm$$

This fits comfortably around the shaft with a 0.85mm clearance, perfect for this application.

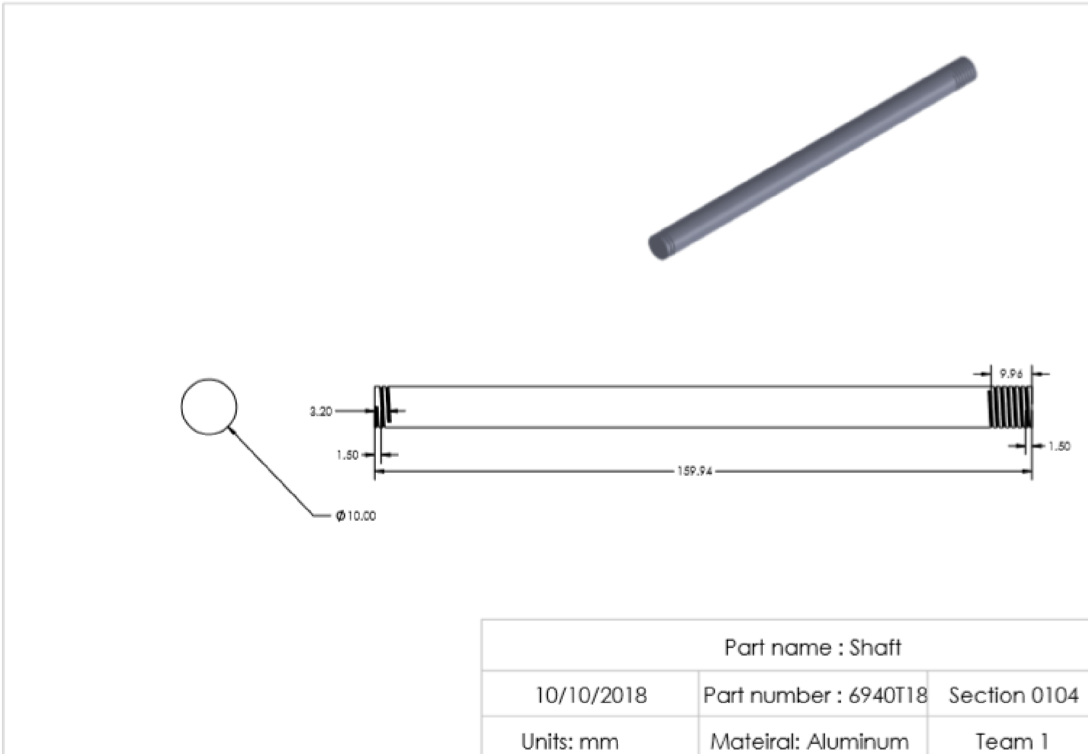


Figure 113: Engineering drawing of shaft

The shaft comes from McMaster's Tight Tolerance rod collection. The diameter has a tolerance of ±0.013mm. It's straightness tolerance is 0.021" per ft, meaning that it won't deviate from true straight more than a quarter inch over a foot of length. It also has a precision ground finish, which together should allow it to fit nicely within the linear bearing. The end of the shaft is threaded with M10x1.5 to interface with the heim joint's female threading. These threads will be cut with a lathe and need to match the same standards as the heim joint's threads.

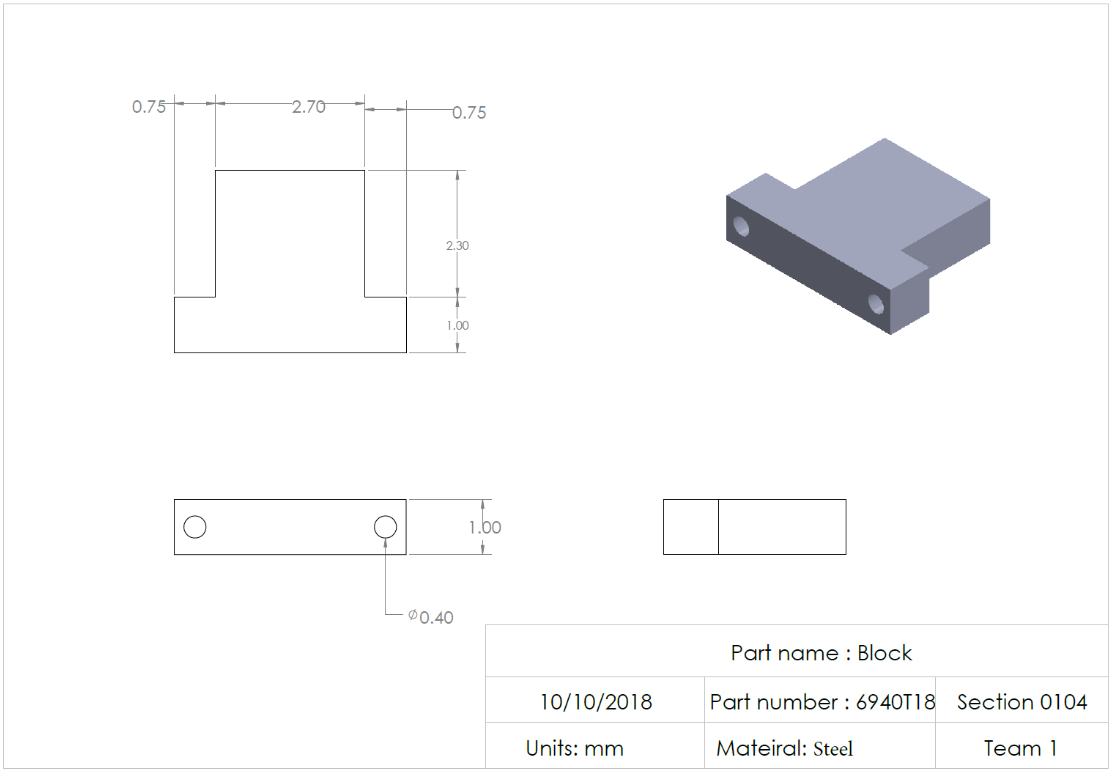


Figure 114: Engineering drawing of shaft stop

This componet constrains the range of motion of the shaft. It will be CNC milled from a block of steel. Without any dimensions of crucial importance, the tolerances on this part can be large, so we'll set them equal to the same standard used for the platform (±0.005in).

7.3 Key-Sub-assembly drawings

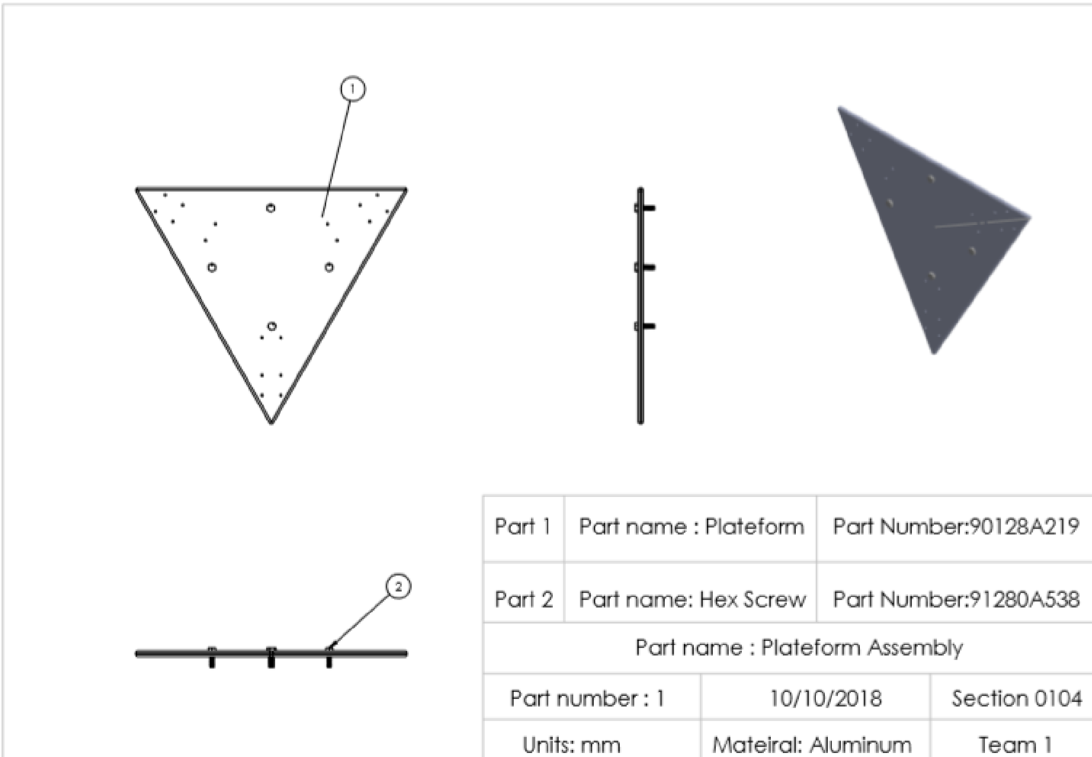


Figure 115: Engineering drawing of the robot platform with bolt holes for the robot

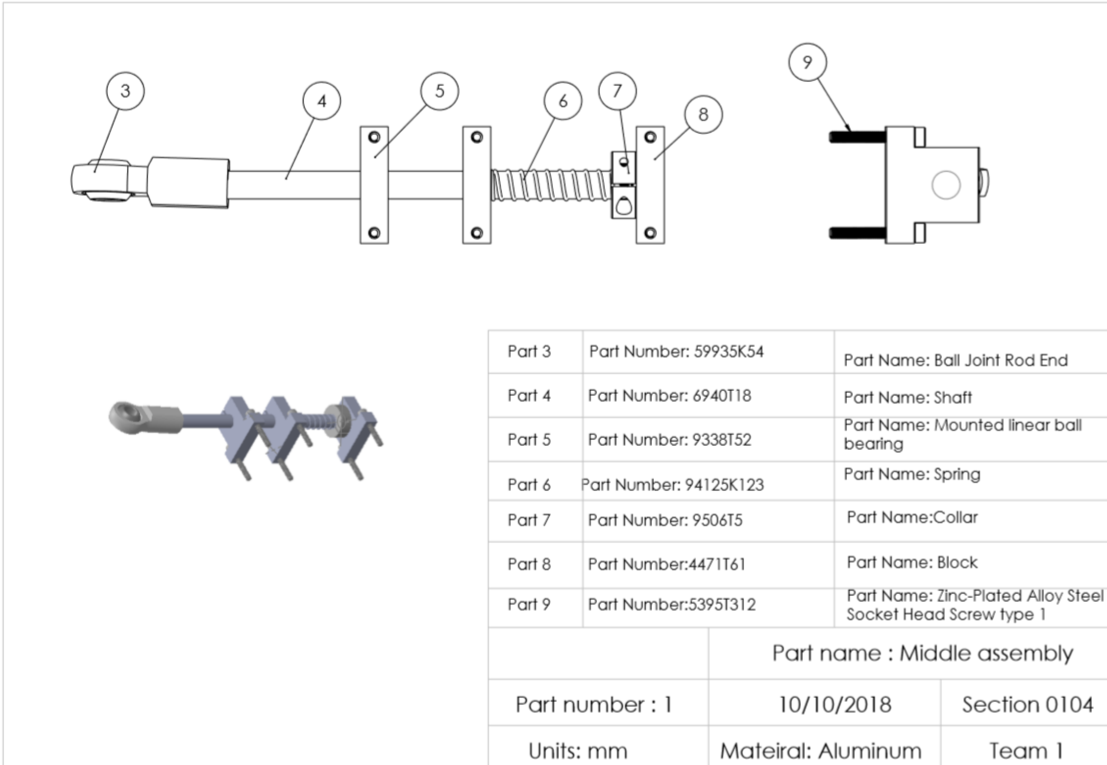
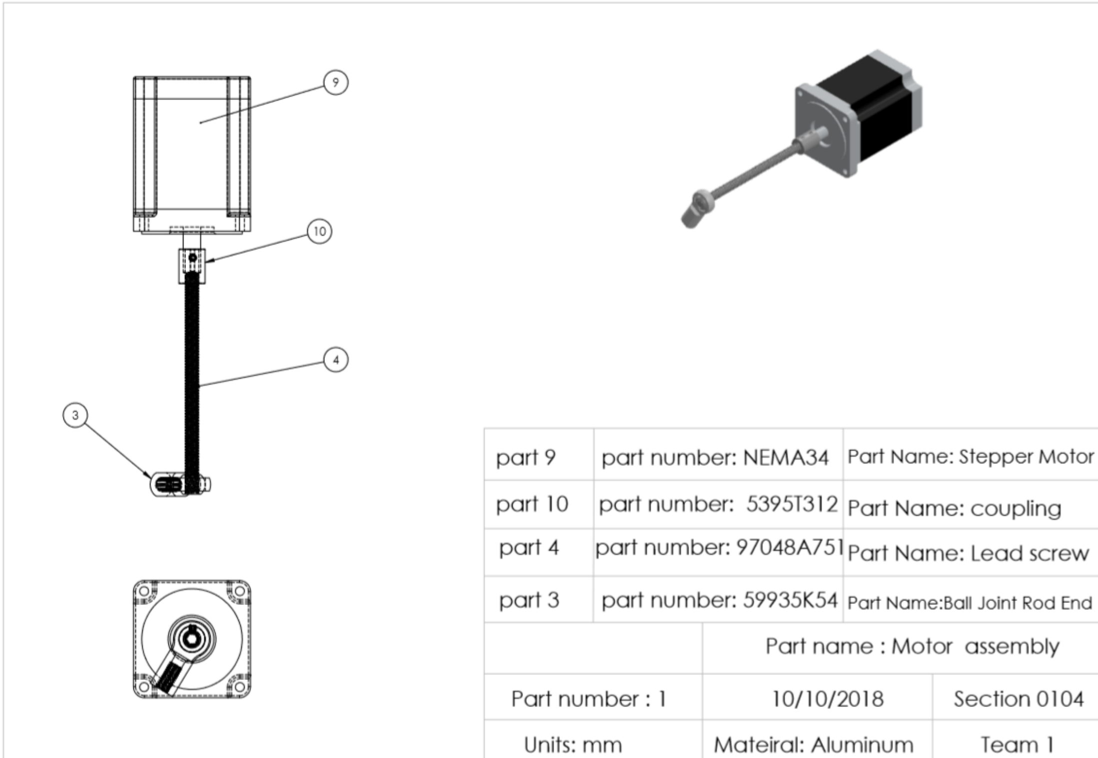


Figure 116: Engineering drawing of the robot platform with bolt holes for the robot



part 9	part number: NEMA34	Part Name: Stepper Motor
part 10	part number: 5395T312	Part Name: coupling
part 4	part number: 97048A751	Part Name: Lead screw
part 3	part number: 59935K54	Part Name:Ball Joint Rod End
	Part name : Motor assembly	
Part number : 1	10/10/2018	Section 0104
Units: mm	Mateiral: Aluminum	Team 1

Figure 117: Engineering drawing of the robot platform with bolt holes for the robot

7.4 Dimension Analysis

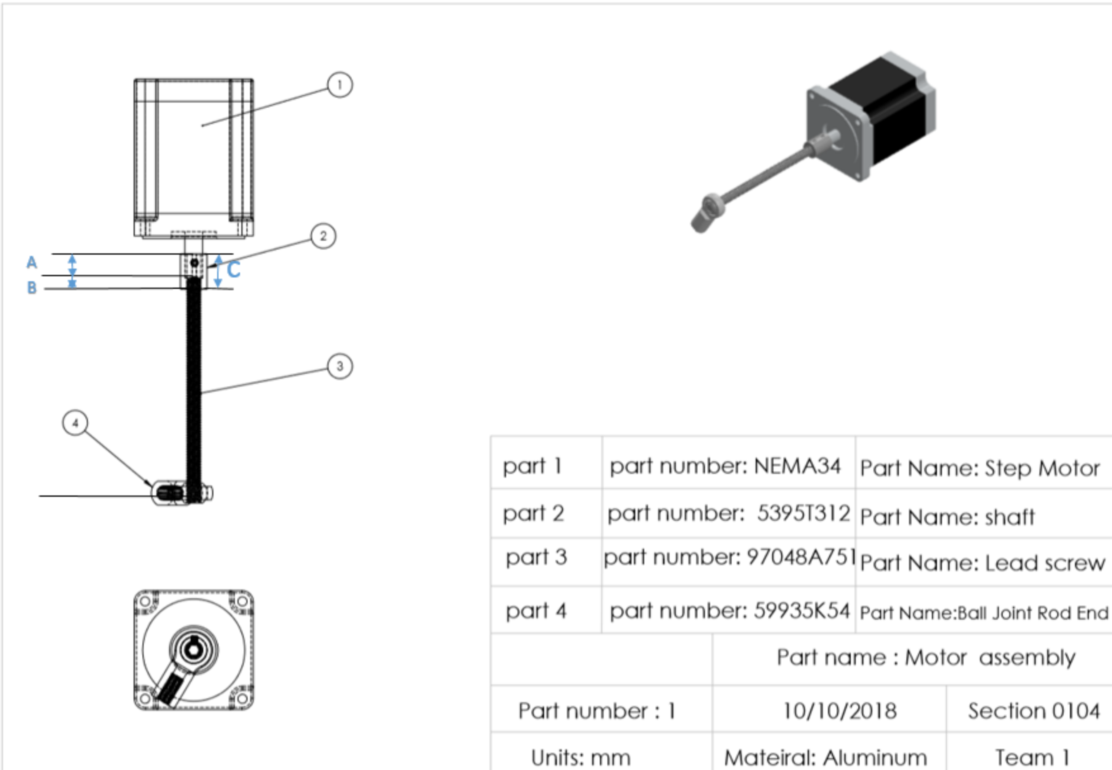
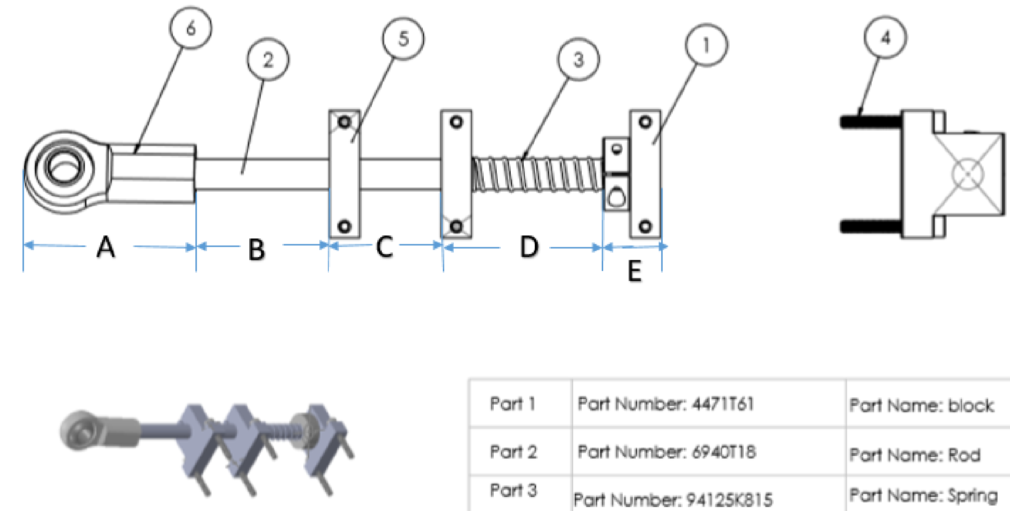


Figure 118: Engineering drawing of the robot platform with bolt holes for the robot

The motor assembly set is shown below in Figure 120. As per the design, the heim joint is fastened to one end of threaded rod. The distance A is the length of heim joint, which is always constant due to the fact that the ball cannot translate from side to side. The distance B from the end of heim joint to the the right edge of Base-Mount Shaft Support is flexible, since the rod is able to move back and forth. The second Base-Mount Shaft Support is also fixed, so both distance B and C on the figure are variable. The team plans to cut the 500mm long stock rod to the length of 160mm by CNC lathe machine using standard machining. The tolerance of the rod is relatively small, at 0.127mm, so it wouldn't effect other parts moving. The spring is could be impressed, which means the second ball Joint Rod could change the position my compression or release the spring. The other side of Spring is connect to the collar, and then connect to the block, since the collar is purchased OEM, the tolerance wouldn't effect the result of two block's motion.



Part 1	Part Number: 4471T61	Part Name: block
Part 2	Part Number: 6940T18	Part Name: Rod
Part 3	Part Number: 94125K815	Part Name: Spring
Part 4	Part Number: 59935K54	Part Name: Hex Crew type 1
Part 5	Part Number:61815K32	Part Name: Base-Mounted Shaft Support
Part 6	Part Number:59935K54	Part Name:Ball Joint Rod End

	Part name : Middle assembly	
Part number : 1	10/10/2018	Section 0104
Units: mm	Mateiral: Aluminum	Team 1

Figure 119: Engineering drawing of the robot platform with bolt holes for the robot

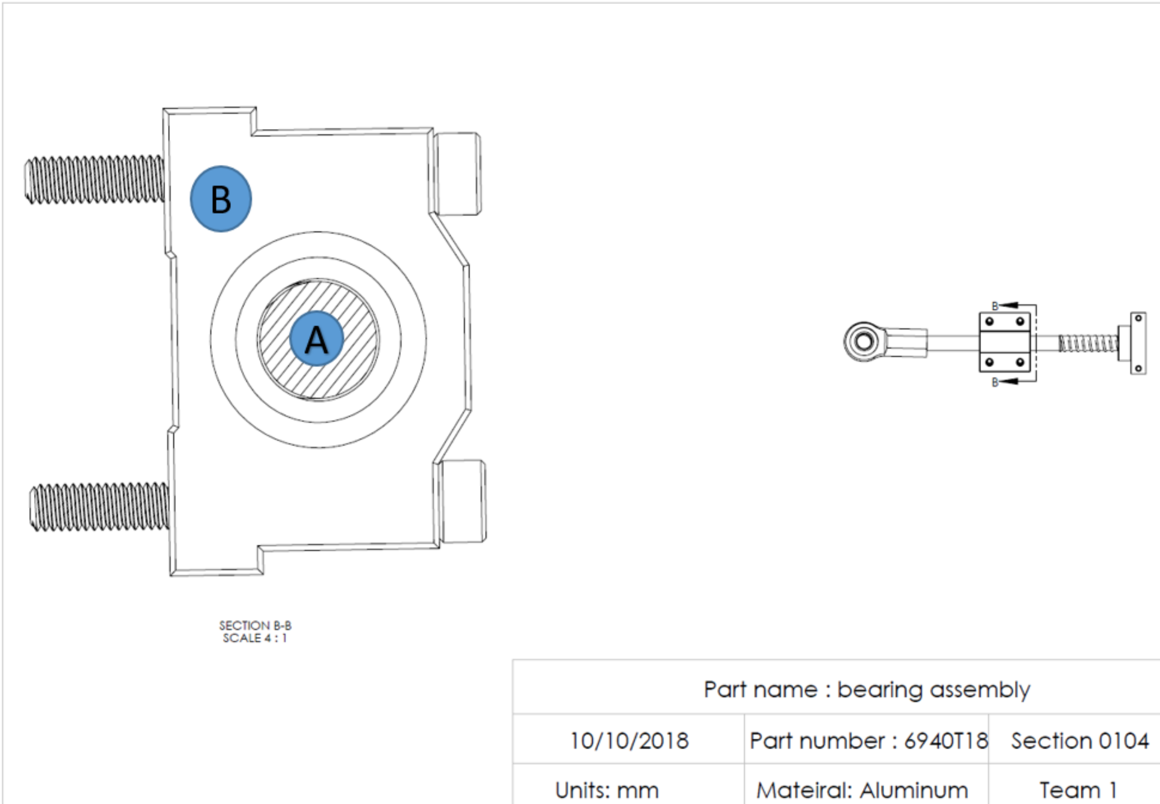


Figure 120: Engineering drawing showing a cross section of the bearing and shaft

STACK-UP 1: Shaft to Bearing Wall						
Label	**Description**	**Nominal (mm)**	**+/- Tol (mm)**	**Cp (mm)**	**STDEV**	**Sensitivity**
A	Shaft diameter	10	0.013	1	0.004333333333	**39.39%**
B	Bearing the inner distance	10	0.02	1	0.006666666667	**60.61%**
					0	**0.00%**
	Xnominal =	**20**				
				CumStdev:	0.007951240295	
				3*CumStdev:	0.02385372088	

	Arithmetic Stack-Up (+) ---> Clearance (-) ---> Interferance	**Statistical Stack-Up**
XNominal (mm)	20.00	0.90
Tolerance (mm)	0.03	0.02385372088
XMax (mm)	20.03	0.9238537209
XMin (mm)	19.97	0.88

Figure 121: Tolerance Stackup on the Shaft-Bearing Interface

8 Planning: Prototype & Testing

Many aspects of a vibration dampening system can be modeled computationally. However, one major component of such a system that we could not model was the vibratory response of the cabin of an ambulance to potholes, speed bumps and other obstacles on the road. As such, characterizing the mechanical response of the cabin of an ambulance to local road conditions was the goal of our prototype and testing.

8.0.1 Preliminary Sensor Testing

The team purchased 3 separate accelerometers to test, with the idea that among 3 sensors, at least one was likely to function in a way suitable for this project. The team was most interested in the response of an accelerometer to the impulse-like input of a car hitting a disturbance in the road, a response difficult to characterize computationally or by only looking at the product specification sheet. The three accelerometers chosen were:

- UCTronics MPU-9255 9-Axis Sensor Module E-compass Accelerometer Gyroscope Magnetic Field (Figure 122)
- Velleman VMA 208 MMA8452Q (Figure 123)
- Industries FLORA Accelerometer/Compass Sensor - LSM303 v1.0 (Figure 125)

All three sensors utilize I^2C and communicate digitally with the Arduino over pins A4 and A5. While all three sensors were wired in similar ways, the code required to interface with each of them varied. The Arduino code used for each sensor can be viewed in the Appendix.

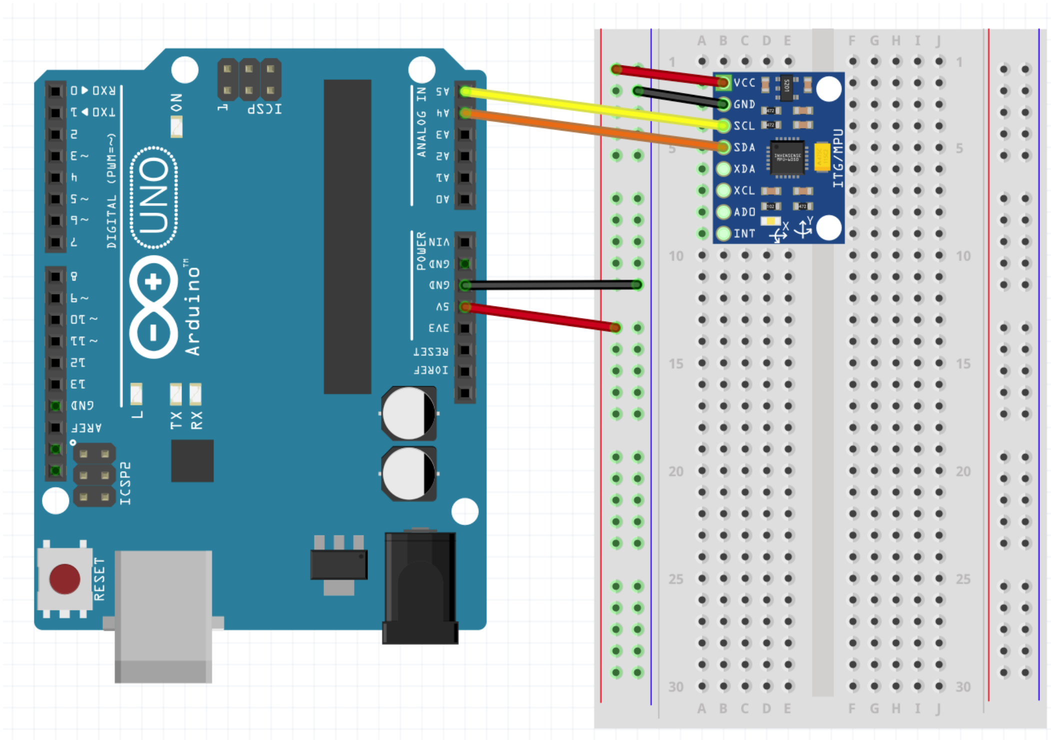


Figure 122: Wiring diagram for the UCTronics Accelerometer

The code required to interface with this sensor can be found in Section 10.1.

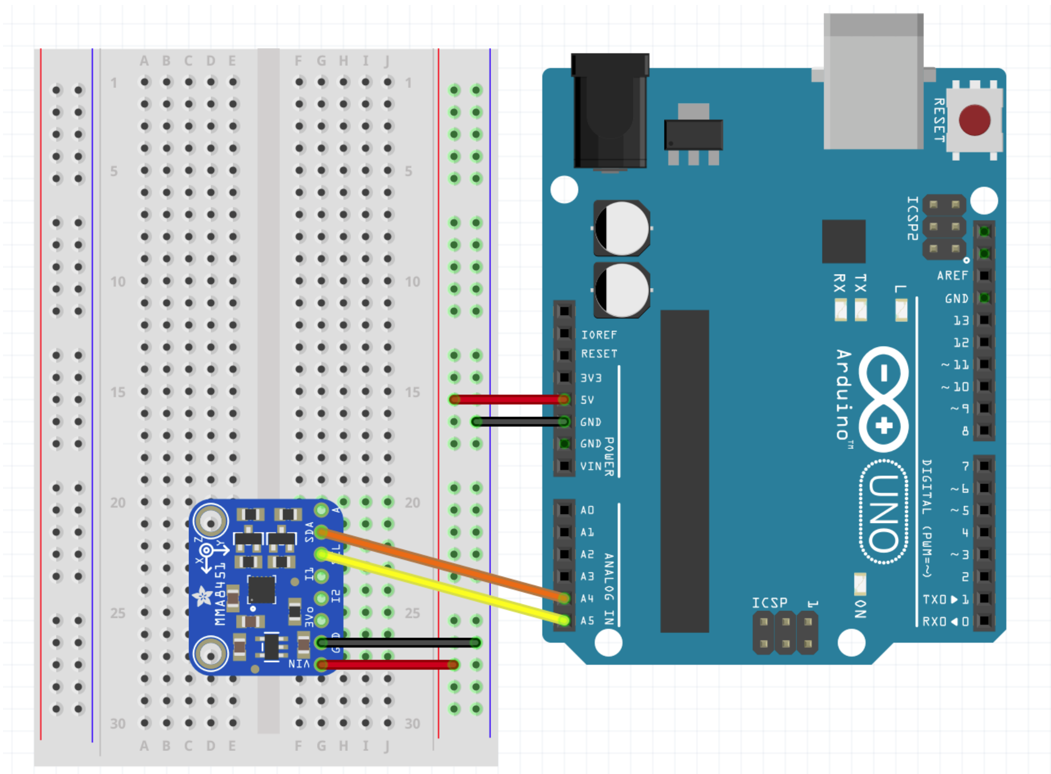


Figure 123: Wiring diagram for the Velleman Accelerometer

The code required to interface with this sensor can be found in Section 10.2. Note that the graphic shown is based on the same accelerometer in a slightly different form factor. Our version had a white board with 90°pins (Figure 124).

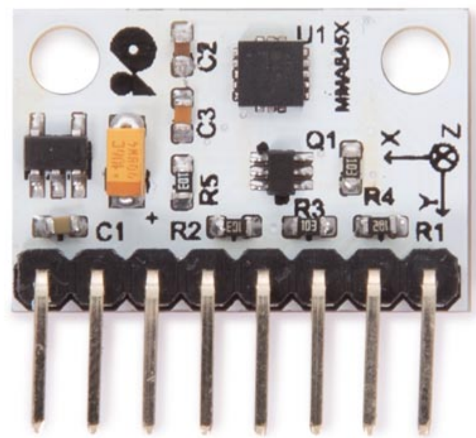


Figure 124: Photo showing the VMA208 Accelerometer

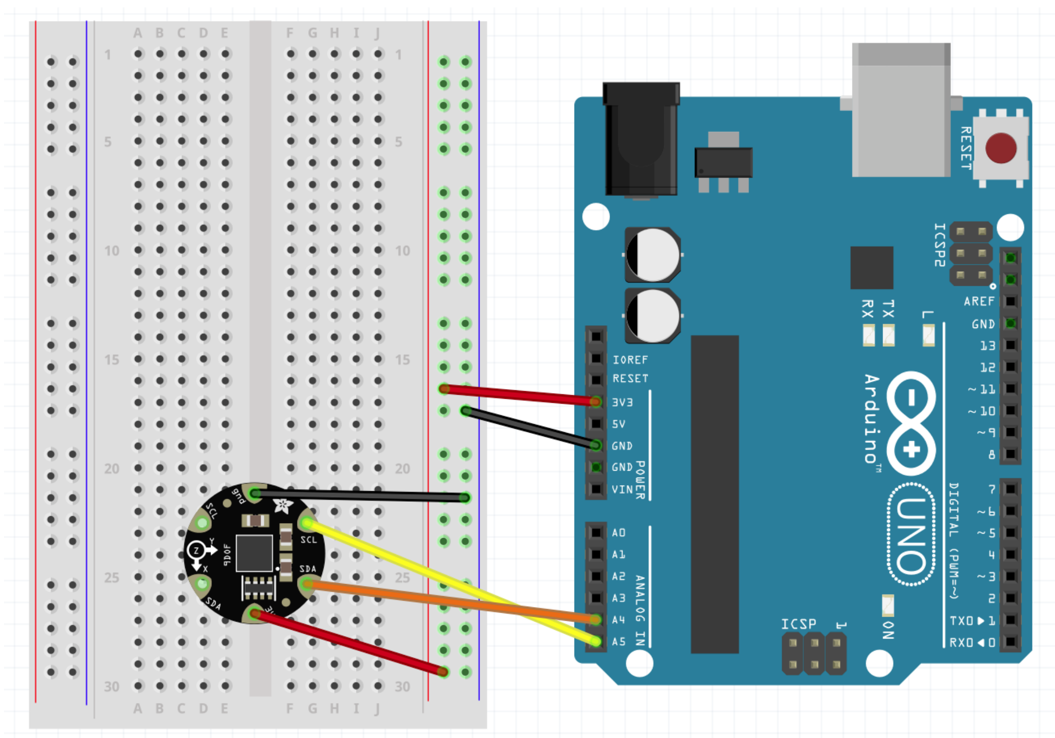


Figure 125: Wiring Diagram for the FLORA Accelerometer

The code required to interface with this sensor can be found in Section 10.3. All three sensors required pin headers to be soldered on. The FLORA accelerometer's pin hole configuration did not allow all 6 pins to fit concurrently in a breadboard. To circumvent this design issue, two of the six pins were replaced with wires (Figure 126).

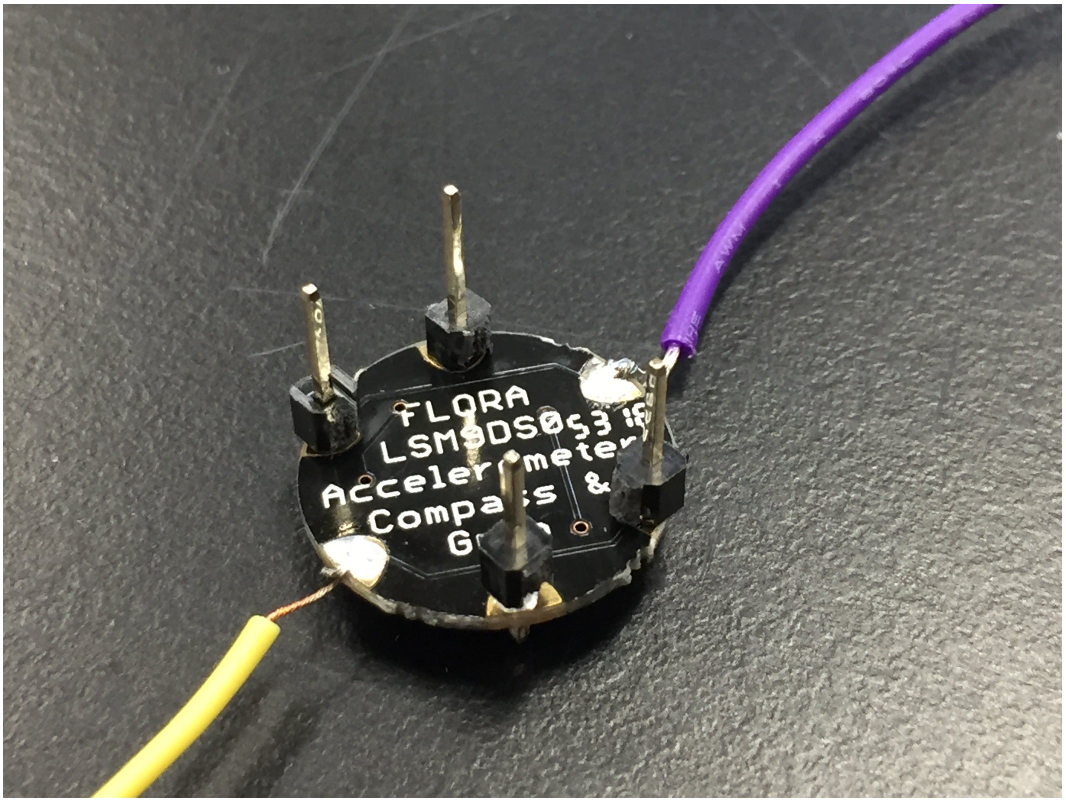


Figure 126: Photo showing the pin wire configuration of the FLORA circular accelerometer

The team tested each sensor individually and observed the sensor's behavior through the Arduino serial plotter. We started by examining the base response of the accelerometer subject to no input other than gravity, and then rotated it to compare the response of each axis under just gravity. We expected to see near zero values for both non-vertical axes, and value near 1g for the vertical axis. Both the UCTronics sensor and the FLORA accelerommeter failed to consistently provide these expected responses. Even at rest, the response of the FLROA sensor (Figure 127) was terribly noisy, immediately and obviously eliminating the value and usefulness of this device.

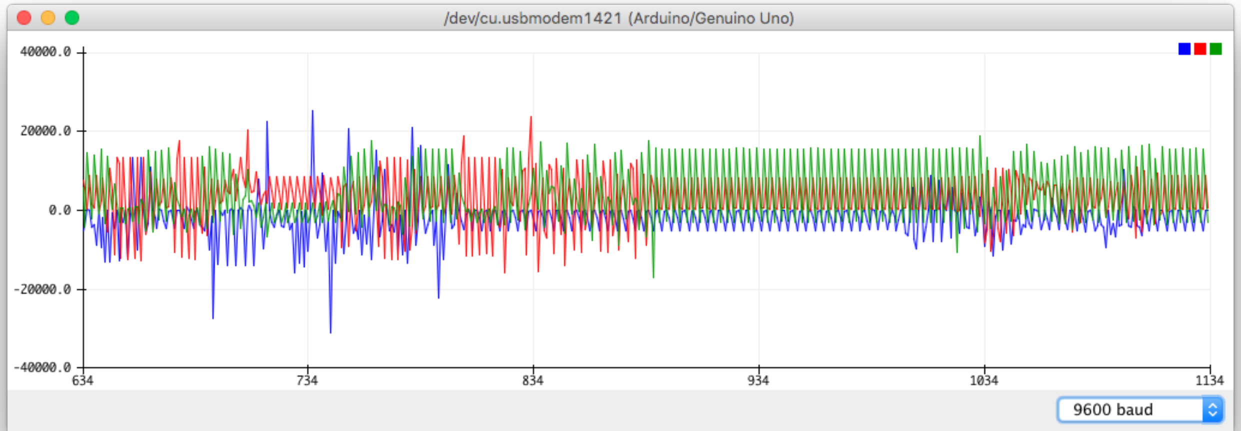


Figure 127: Noisy output of the FLORA sensor at rest

The UCTronics accelerometer produced output with a consistent offset on one axis (Figure 128). While this offset could have been compensated for digitally through data manipulation, the team was not confident in this sensor's reliability or the consistency in this error.

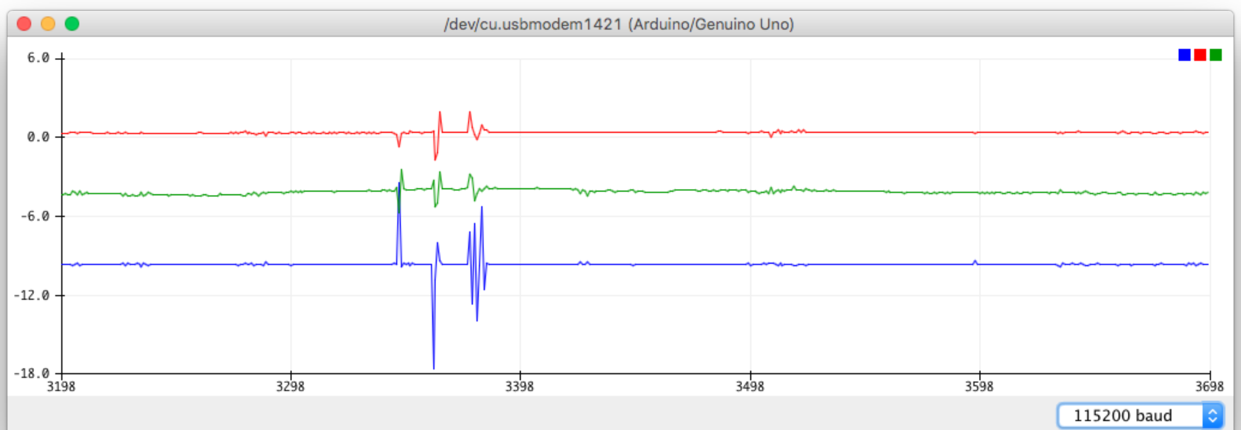


Figure 128: Output of the UCTronics sensor. The green and red lines should be equal at 0. The blue axis is in the vertical direction and sits approximately at the expected -10 m/s^2. The data spikes correspond to movement of the sensor.

The Velleman accelerometer performed the best of the three. It had the least noisy data and all three axes responded as expected to the imposed stimuli (Figure 129). Based on this information, the team decided to pursue the Velleman accelerometer for further testing and abandon the other two. After testing each sensor with the Arduino serial plotter, the team switched to a Processing script (available in Section 10.4) to collect and save the outputted data.

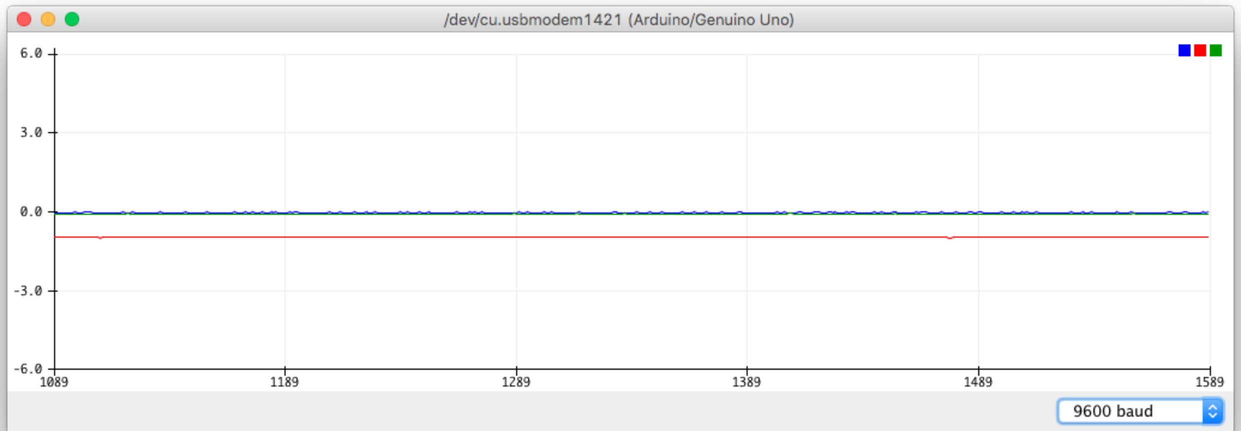


Figure 129: Smooth output of the Velleman sensor at rest. The red (vertical) axis sits approximately at the expected -1g.

8.0.2 Vehicular Testing

We needed to understand the response of accelerometer to a disturbance on the road as felt through a vehicle with suspension. In order to accomplish this, the accelerometer had to be tested inside a vehicle traveling at a repeatable speed and going over a repeatable bump. The team used a 2009 Honda Pilot as the test vehicle. Of all the vehicles the team had access to for testing, this vehicle most closely resembled the form factor and size of an ambulance (although this is, of course, a crude approximation). In order to test repeatedly, the team needed a stretch of quiet road on campus where we could work without risk of being disturbed by other drivers or pedestrians. Lot 1F (Figure 130, 131) met these criteria, and thus was used as our test site.

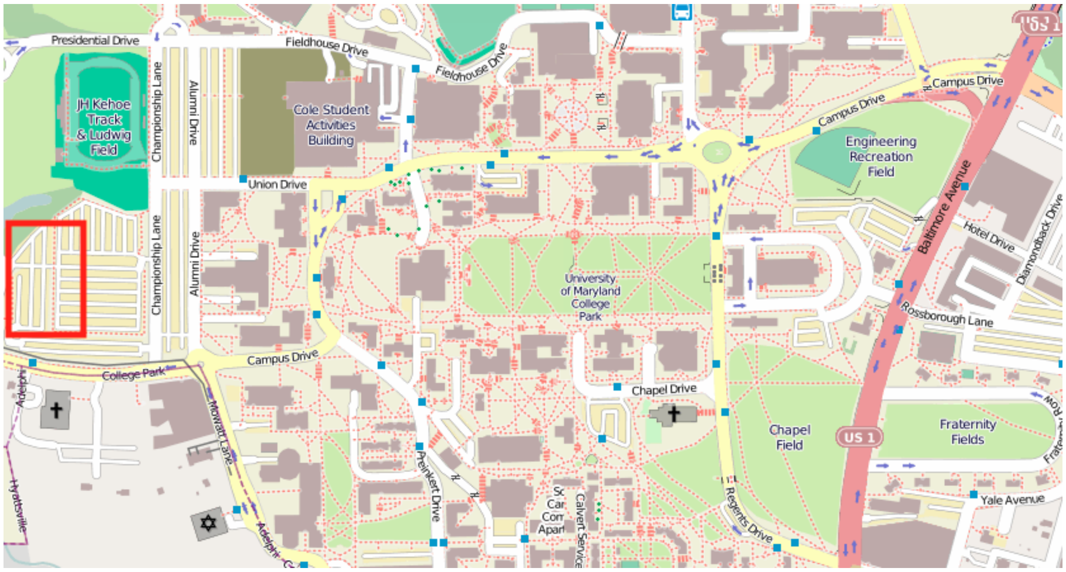


Figure 130: TerpNav map of campus with Lot 1F highlighted

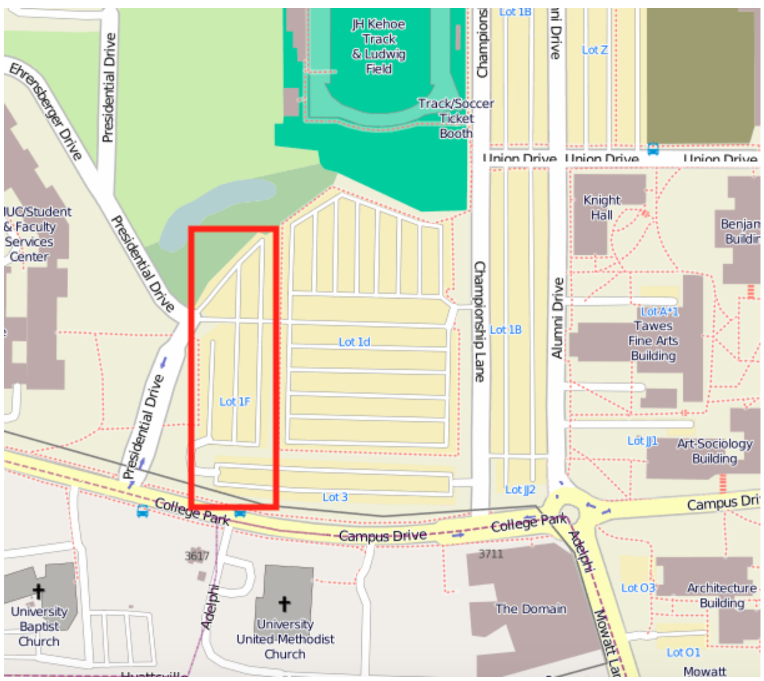


Figure 131: TerpNav map of campus with Lot 1F highlighted

The length of this lot restricted the maximum speed we could safely test at. After some short tests, we determined that 20mph was a speed that could be easily and safely achieved within the given stopping distance constraints. The parking lot surface is in good condition and lacking in any meaningful potholes. To create a repeatable disturbance, the team used an 8' long piece of 2x4 lumber placed perpendicular to the path of the car (Figure 132).

Figure 132: Photo of the car rolling over the wood 2x4

With the basic test layout now defined, the team had to affix the accelerometer to the car. We originally wanted to mount the accelerometer on the dashboard of the car (Figure 133) but adhesion issues made this impractical.

Figure 133: Photo of Arduino and Sensor on Car Dashboard

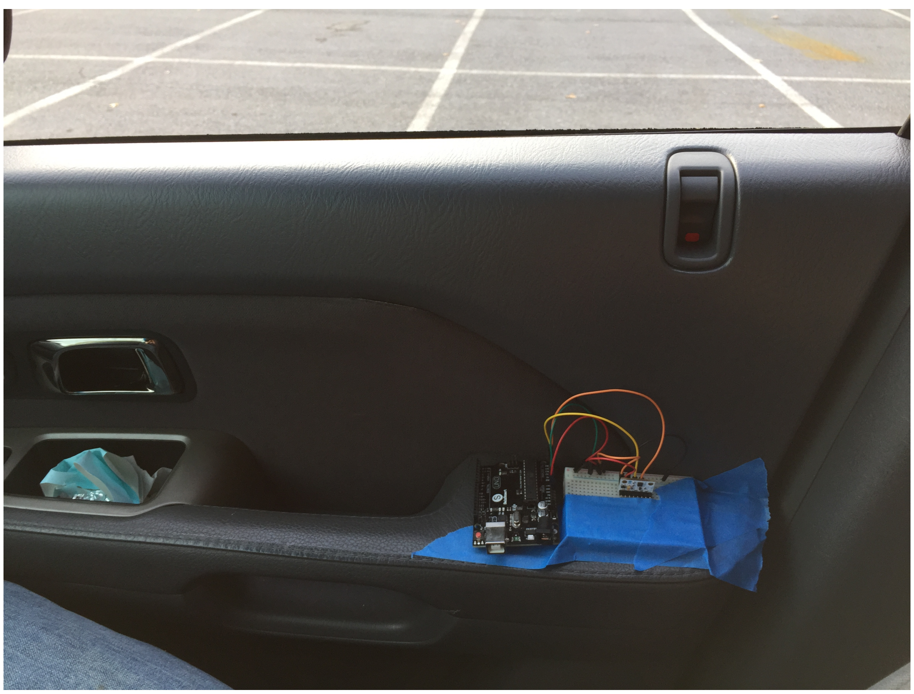


Figure 134: Photo of Arduino and Sensor Mounted on the Passenger Side Arm Rest

We relocated the sensor circuit to the passenger side arm rest (Figure 134) and attempted to secure it there. Our basic tests showed that the padding and other material in that region had too much flexibility, causing the sensor to bounce erroneously and not follow the movement of the vehicle.

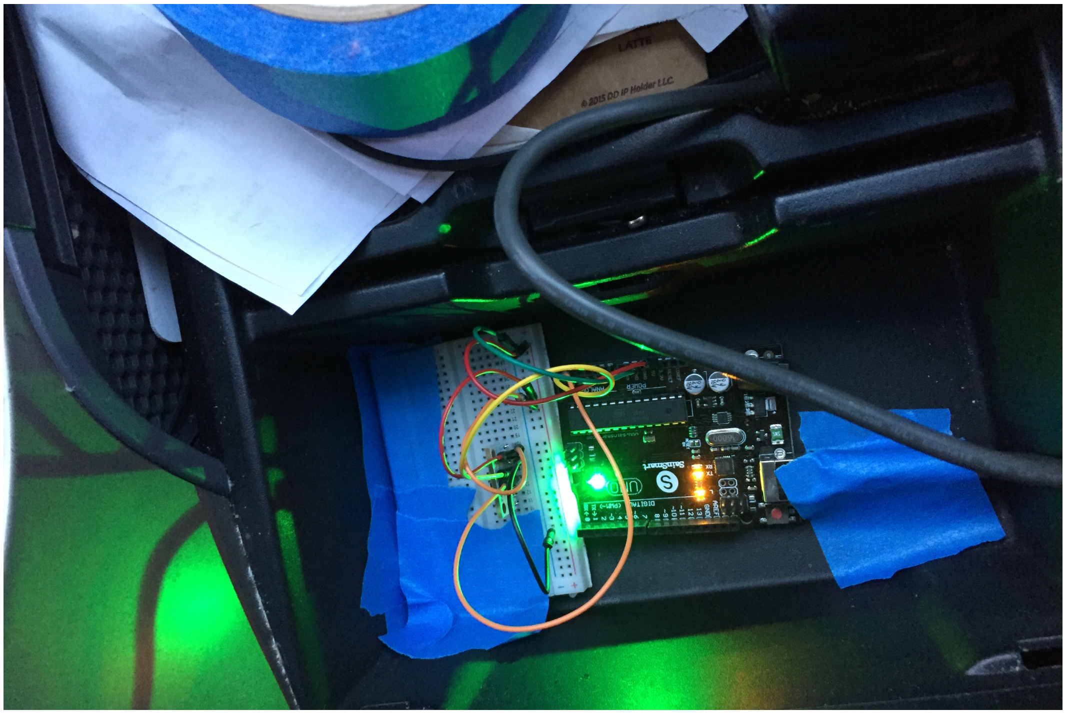


Figure 135: Photo of Arduino and Sensor Mounted in the center console

The sensor circuit was then mounted inside the center console of the vehicle. This spot, with a removable cup holder insert, had a flat, smooth, rigid surface that could be more easily adhered to. The sensor measures three axes (labeled on the device). In this configuration, the X axis was along the forward direction of the car, the Y axis in the vertical direction, and the Z axes to the left/right (Figure 136).

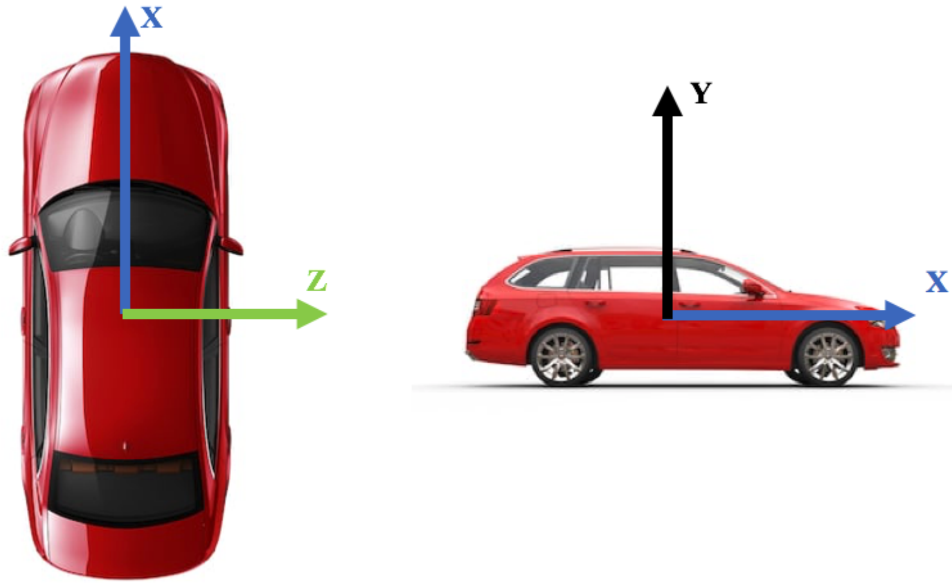


Figure 136: Diagram showing the axes of car

This position and orientation of the sensor was used for each vehicle test. 10 trials were performed, each with the car traveling at 20mph over the same distance and hitting the wood at the same spot.

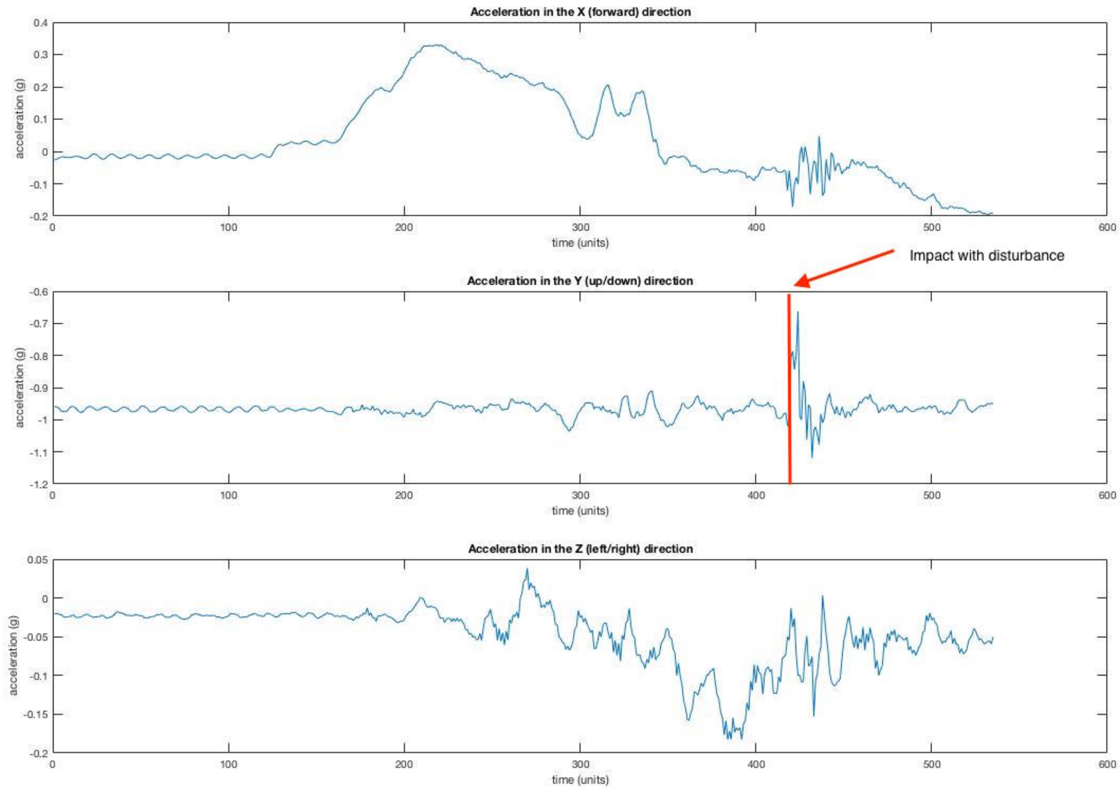


Figure 137: Three axis output of the accelerometer from one trial; data is shown with a 5 point moving average.

The MATLAB code used to generate Figure 137 can be viewed in Section 10.5. The impulse from the bump is clear in the data gathered (Figure 137). This will be the most important data for directly countering vertical impulses from the road. It is also easy to visualize the forward acceleration of the vehicle in the x acceleration plot (Figure 137). With this data in hand, we could have our final system compensate against the inertia frame of the accelerating ambulance, further improving the stability of our robot. The noise in the Z direction can likely be attributed to the loose mounting of the sensor in the breadboard and the breadboard to the car, vibrating with the movement of the vehicle. Note that the axes of each plot are scaled independently and do not have equal scales. The motion in the Y direction is much more pronounced than the disturbance in the Z direction. For the final design, the accelerometer will need to be rigidly affixed to the ambulance to avoid some of these issues.

The second round of testing was very similar to the first in set up, consisting the same sensors and orientation. It consisted of driving over 3 main obstacles: predefined numbers of wood 2x4"s; potholes of known depth; and a *flâneurian schema*, (*i.e.,* one consisting of driving around town without a preset destination in order to capture variation in the response to road conditions). For the present number of pine boards, one, two and three boards were selected for separate trials, respectively.

In Figure 138, the response of the acclerometer over a course of about 6 minutes is shown. After smoothing, we found that the max acceleration variation was on the order of 0.6 g. This figure is the most illustrative, as within those 6 minutes many potholes, speed bumps and other mundane road obstacles were driven over, with their responses recorded.

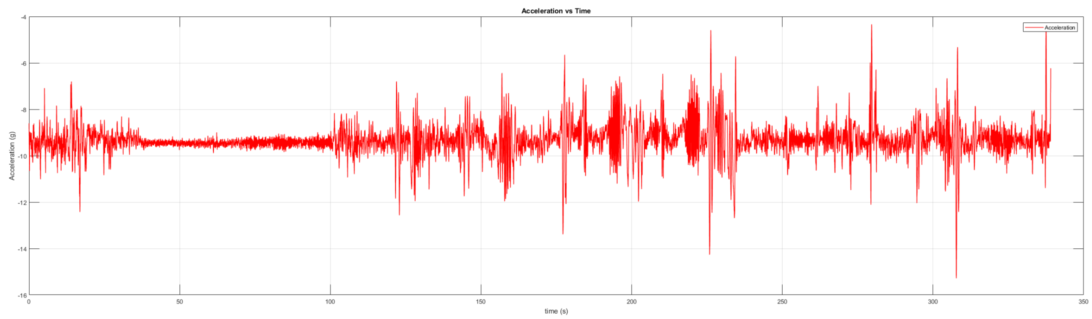


Figure 138: *flâneurian schema*

The specifications for our motor are intrinsically linked to the expected response of the cabin of the ambulance under input from the road. The cabin's response is of such importance to our motor choice that it characterizing the aforementioned response was the purpose of our initial prototype. From this testing, we were able to employ numerical integration techniques within MATLAB to translate acceleration-time data into specification requirements for our motor.

The relationship between acceleration, velocity and position is as follows:

$$v(t) = \int_{t_i}^{t_f} a(t)dt$$

$$y(t) = \int_{t_i}^{t_f} v(t)dt$$

where

$a(t)$ = acceleration

$v(t)$ = velocity

$y(t)$ = vertical position

t_i = the time at the beginning of the cabin's response to a bump

t_f = the time at the terminus of that response.

Using numerical integration techniques within MATLAB, we were able to determine that maximum displacement of the cabin over all of our tests was 0.133 meters in 0.127 seconds. Empirical confirmation of these results was achieved through a non-rigours video analysis of the cabin, using the obstacles as reference length scales.

A full compendium of our trials and their responses can be found in Section 10.6.

9 Updated Product Design Specifications

9.1 Product Design Specification (PDS)

Product Title

- Vibration dampening medical robot mount.

Purpose

- To provide the care of a medical robot in a mobile ambulance.

New or special features

- Allows use of medical robot in an ambulance.
- Small; takes up little space in an ambulance.
- Reduces vibration damage to medical robot.
- Maintains accuracy of medical robot sensors.
- Improves/Maintains patients trust in procedures.

Competition

- Camera stabilization systems for car chase scenes/film making.
- Gun stabilizers on helicopters, tanks and other moving vehicles.
- None of the existing solutions satisfy the needs this product addresses

Intended market

- We will sell direct to medical research labs of which there are just shy of 20 in the DMV area.
- Secondary market will be to ambulance manufacturing companies. 2069 ambulances were manufactured by Ford alone last year. [34]

Need for product

- User survey has shown customer interest in this concept; over 70 percent of people surveyed expressed willingness to receive mobile medical care from a robot.

Relationship to existing product line

- This is a new concept. No other products currently exist.

Market demand

- In 2015 there were 15.7 million ambulance responses with transport to a medical facility. This number is continuously growing. [35]
- There are 22 medical research labs in the united states that would be interested in this product. [10]

Price

- We anticipate selling this medical robot mount at a price no greater than fifteen thousand US dollars. [36]

Functional performance

- Allows medical robot full range of movement.
- Accounts for torques and forces.
- Sturdy enough to withstand vibration and impacts during ambulance commute.
- Secures medical robot firmly in place.
- Dampens vibration transmitted to robot from ambulance.
- Takes up minimal space in ambulance when not in use.

Physical requirements

- Volume not to exceed 2 ft^3.
- Weight not to exceed 50lbs.
- Shape triangular but must be within volume constraints.
- Texture smooth and anti-bacterial (or easy to clean).
- Power input must not exceed 125 Volt-AC with maximum of 15A. [30]

Service environment
These characteristics look at the environment the robot will be placed in. Even though many ambulances are insulated and temperature controlled [30], it is important that the mount remain functional and not degrade while the ambulance is parked or otherwise not in use.

- Mount material should be structurally stable from -30°F to 120°F. [37]
- Mount material should be structurally stable in 0% to 100% relative humidity.
- Mount material should be anti-bacterial and easily sterilized.

Life-cycle issues

- Mount mechanism must not exhibit structural failure for minimum 5 years.

Human factors

- No sharp corners or edges that could injure any of the users.
- Installation of mount must be simple and straightforward.
- System should maintain or improve human Trust
- System should not interfere with the haptic feedback relied upon by the operator

Corporate constraints

- Must be in the market in five years time because the average ambulance lasts 3-4 years. [32]
- Manufacturing will be contracted to suppliers.
- Will use trademark Hold My Robot.
- Must conform to ASME code of ethics. [12]

Legal requirements

- No toxic materials to be associated with manufacturer. [15]
- Robot and mount cannot exceed 50lbs. [38]
- Materials must be FDA compliant and OSHA compliant for use inside an ambulance. [38]

9.2 Group Sign Off

Brian Bock

Luxi Huang

Ashley Ollech

Nathan Orwig

Saul Schaffer

Greg Turlik

10 Appendix

10.1 UCTronics Accelerometer Code

Below is the code used with the UCTronics accelerometer.

```
/*
 * Library: https://github.com/bolderflight/MPU9250
Basic_I2C.ino
Brian R Taylor
brian.taylor@bolderflight.com

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   FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT,
   TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR
   THE USE OR OTHER DEALINGS IN THE SOFTWARE.
*/
/*
 * Updated by Ahmad Shamshiri on July 09, 2018 for Robojax.com
 * in Ajax, Ontario, Canada
 * watch instrucion video for this code:
For this sketch you need to connect:
VCC to 5V and GND to GND of Arduino
SDA to A4 and SCL to A5
```

```
S20A is 3.3V voltage regulator MIC5205-3.3BM5
*/

#include "MPU9250.h"

// an MPU9250 object with the MPU-9250 sensor on I2C bus 0 with address 0x68
MPU9250 IMU(Wire,0x68);
int status;

void setup() {
  // serial to display data
  Serial.begin(115200);
  while(!Serial) {}

  // start communication with IMU
  status = IMU.begin();
  if (status < 0) {
    Serial.println("IMU initialization unsuccessful");
    Serial.println("Check IMU wiring or try cycling power");
    Serial.print("Status: ");
    Serial.println(status);
    while(1) {}
  }
}

void loop() {
  // read the sensor
  IMU.readSensor();
  // display the data
  Serial.print(IMU.getAccelX_mss(),6);
  Serial.print("\t");
  Serial.print(IMU.getAccelY_mss(),6);
  Serial.print("\t");
  Serial.println(IMU.getAccelZ_mss(),6);
  Serial.println();
  delay(200);
}
```

10.2 Velleman Accelerometer Code

Below is the code used with the Velleman accelerometer.

```
#include <Adafruit_MMA8451.h>
```

```
/******************************************************************************
MMA8452Q_Basic.ino
SFE_MMA8452Q Library Basic Example Sketch
Jim Lindblom @ SparkFun Electronics
Original Creation Date: June 3, 2014
https://github.com/sparkfun/MMA8452_Accelerometer

This sketch uses the SFE_MMA8452Q library to initialize the
accelerometer, and stream values from it.

Hardware hookup:
  Arduino --------------- MMA8452Q Breakout
    3.3V ---------------   3.3V
    GND  ---------------   GND
  SDA (A4) --\/330 Ohm\/-- SDA
  SCL (A5) --\/330 Ohm\/-- SCL

The MMA8452Q is a 3.3V max sensor, so you'll need to do some
level-shifting between the Arduino and the breakout. Series
resistors on the SDA and SCL lines should do the trick.

Development environment specifics:
   IDE: Arduino 1.0.5
   Hardware Platform: Arduino Uno

This code is beerware; if you see me (or any other SparkFun employee) at the
local, and you've found our code helpful, please buy us a round!

Distributed as-is; no warranty is given.
******************************************************************************/
#include <Wire.h> // Must include Wire library for I2C
#include <SFE_MMA8452Q.h> // Includes the SFE_MMA8452Q library

// Begin using the library by creating an instance of the MMA8452Q
//  class. We'll call it "accel". That's what we'll reference from
//  here on out.
MMA8452Q accel;

// The setup function simply starts serial and initializes the
//  accelerometer.
void setup()
{
  Serial.begin(9600);
  Serial.println("MMA8452Q Test Code!");
```

```
  // Choose your adventure! There are a few options when it comes
  // to initializing the MMA8452Q:
  //  1. Default init. This will set the accelerometer up
  //     with a full-scale range of +/-2g, and an output data rate
  //     of 800 Hz (fastest).
  accel.init();
  //  2. Initialize with FULL-SCALE setting. You can set the scale
  //     using either SCALE_2G, SCALE_4G, or SCALE_8G as the value.
  //     That'll set the scale to +/-2g, 4g, or 8g respectively.
  //accel.init(SCALE_4G); // Uncomment this out if you'd like
  //  3. Initialize with FULL-SCALE and DATA RATE setting. If you
  //     want control over how fast your accelerometer produces
  //     data use one of the following options in the second param:
  //     ODR_800, ODR_400, ODR_200, ODR_100, ODR_50, ODR_12,
  //     ODR_6, or ODR_1.
  //     Sets to 800, 400, 200, 100, 50, 12.5, 6.25, or 1.56 Hz.
  //accel.init(SCALE_8G, ODR_6);
}

// The loop function will simply check for new data from the
//  accelerometer and print it out if it's available.
void loop()
{
  // Use the accel.available() function to wait for new data
  //  from the accelerometer.
  if (accel.available())
  {
    // First, use accel.read() to read the new variables:
    accel.read();

    // accel.read() will update two sets of variables.
    // * int's x, y, and z will store the signed 12-bit values
    //   read out of the accelerometer.
    // * floats cx, cy, and cz will store the calculated
    //   acceleration from those 12-bit values. These variables
    //   are in units of g's.
    // Check the two function declarations below for an example
    // of how to use these variables.
    printCalculatedAccels();
    //printAccels(); // Uncomment to print digital readings

    // The library also supports the portrait/landscape detection
    //  of the MMA8452Q. Check out this function declaration for
    //  an example of how to use that.
    printOrientation();
```

```
    Serial.println(); // Print new line every time.
  }
}

// The function demonstrates how to use the accel.x, accel.y and
//  accel.z variables.
// Before using these variables you must call the accel.read()
//  function!
void printAccels()
{
  Serial.print(accel.x, 3);
  Serial.print("\t");
  Serial.print(accel.y, 3);
  Serial.print("\t");
  Serial.print(accel.z, 3);
  Serial.print("\t");
}

// This function demonstrates how to use the accel.cx, accel.cy,
//  and accel.cz variables.
// Before using these variables you must call the accel.read()
//  function!
void printCalculatedAccels()
{
  Serial.print(accel.cx, 3);
  Serial.print("\t");
  Serial.print(accel.cy, 3);
  Serial.print("\t");
  Serial.print(accel.cz, 3);
  Serial.print("\t");
}

// This function demonstrates how to use the accel.readPL()
// function, which reads the portrait/landscape status of the
// sensor.
void printOrientation()
{
  // accel.readPL() will return a byte containing information
  // about the orientation of the sensor. It will be either
  // PORTRAIT_U, PORTRAIT_D, LANDSCAPE_R, LANDSCAPE_L, or
  // LOCKOUT.
  byte pl = accel.readPL();
  switch (pl)
  {
```

```
  case PORTRAIT_U:
    Serial.print("Portrait Up");
    break;
  case PORTRAIT_D:
    Serial.print("Portrait Down");
    break;
  case LANDSCAPE_R:
    Serial.print("Landscape Right");
    break;
  case LANDSCAPE_L:
    Serial.print("Landscape Left");
    break;
  case LOCKOUT:
    Serial.print("Flat");
    break;
  }
}
```

10.3 FLORA Accelerometer Code

Below is the code used with the FLORA accelerometer.

```
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_LSM9DS0.h>
#include <Adafruit_Sensor.h> // not used in this demo but required!

// i2c
Adafruit_LSM9DS0 lsm = Adafruit_LSM9DS0();

// You can also use software SPI
//Adafruit_LSM9DS0 lsm = Adafruit_LSM9DS0(13, 12, 11, 10, 9);
// Or hardware SPI! In this case, only CS pins are passed in
//Adafruit_LSM9DS0 lsm = Adafruit_LSM9DS0(10, 9);

void setupSensor()
{
  // 1.) Set the accelerometer range
  lsm.setupAccel(lsm.LSM9DS0_ACCELRANGE_2G);
  //lsm.setupAccel(lsm.LSM9DS0_ACCELRANGE_4G);
  //lsm.setupAccel(lsm.LSM9DS0_ACCELRANGE_6G);
  //lsm.setupAccel(lsm.LSM9DS0_ACCELRANGE_8G);
  //lsm.setupAccel(lsm.LSM9DS0_ACCELRANGE_16G);
```

```
  // 2.) Set the magnetometer sensitivity
  lsm.setupMag(lsm.LSM9DS0_MAGGAIN_2GAUSS);
  //lsm.setupMag(lsm.LSM9DS0_MAGGAIN_4GAUSS);
  //lsm.setupMag(lsm.LSM9DS0_MAGGAIN_8GAUSS);
  //lsm.setupMag(lsm.LSM9DS0_MAGGAIN_12GAUSS);

  // 3.) Setup the gyroscope
  lsm.setupGyro(lsm.LSM9DS0_GYROSCALE_245DPS);
  //lsm.setupGyro(lsm.LSM9DS0_GYROSCALE_500DPS);
  //lsm.setupGyro(lsm.LSM9DS0_GYROSCALE_2000DPS);
}

void setup()
{
#ifndef ESP8266
  while (!Serial);   // will pause Zero, Leonardo, etc until serial console opens
#endif
  Serial.begin(9600);
  Serial.println("LSM raw read demo");

  // Try to initialise and warn if we couldn't detect the chip
  if (!lsm.begin())
  {
    Serial.println("Oops ... unable to initialize the LSM9DS0. Check your wiring!");
    while (1);
  }
  Serial.println("Found LSM9DS0 9DOF");
  Serial.println("");
  Serial.println("");
}

void loop()
{
  lsm.read();

  Serial.print("Accel X: "); Serial.print((int)lsm.accelData.x); Serial.print(" ");
  Serial.print("Y: "); Serial.print((int)lsm.accelData.y); Serial.print(" ");
  Serial.print("Z: "); Serial.println((int)lsm.accelData.z); Serial.print(" ");
  Serial.print("Mag X: "); Serial.print((int)lsm.magData.x); Serial.print(" ");
  Serial.print("Y: "); Serial.print((int)lsm.magData.y);   Serial.print(" ");
  Serial.print("Z: "); Serial.println((int)lsm.magData.z); Serial.print(" ");
  Serial.print("Gyro X: "); Serial.print((int)lsm.gyroData.x); Serial.print(" ");
  Serial.print("Y: "); Serial.print((int)lsm.gyroData.y);  Serial.print(" ");
```

```
  Serial.print("Z: "); Serial.println((int)lsm.gyroData.z); Serial.println(" ");
  Serial.print("Temp: "); Serial.print((int)lsm.temperature); Serial.println("
     ");
  delay(200);
}
```

10.4 Processing Code

```
import processing.serial.*; // add the serial library
import java.util.Date;
Serial myPort;
PrintWriter output;

void setup() {
    size(400, 400);
  printArray(Serial.list());
  myPort = new Serial(this, Serial.list()[7], 9600);
  myPort.clear();
  output = createWriter("ENME_472_proto"+month()+"-"+day()+"
     "+hour()+"-"+minute()+"-"+second()+".csv"); //Create CSV with the current
     time as it's filename");
}

int xpos = 0;

void draw () {
if (myPort.available () > 0) {
String inString = myPort.readStringUntil('\n');
if (inString != null) {
inString = trim(inString);
String[] voltages = splitTokens(inString, ","); // Split at the tab character
println(voltages);
if (voltages.length==3){
  output.println(voltages[0]+","+voltages[1]+","+voltages[2]);
  //println("it works");
}

  }
 }
 }


void keyPressed() { // when any key is pressed, stop saving the data
```

```
  output.flush(); // flush the excess data
  output.close(); // close the data file
  exit();
}
```

10.5 MATLAB Code

This section contains the MATLAB code used to plot the accelerometer data.

```
clear all
close all
% Read the CSV and separate the data
theData = csvread("ENME_472_proto10-31 18-39-10fixed.csv")
theX=theData(:,1)
theY=theData(:,2)
theZ=theData(:,3)


%%%% Moving Mean %%%%
smoothingFactor=5;

Xsmooth=movmean(theX,smoothingFactor)
Ysmooth=movmean(theY,smoothingFactor)
Zsmooth=movmean(theZ,smoothingFactor)


%plots
subplot(3,1,1);
plot(Xsmooth)
xlabel ("time (units)")
ylabel ("acceleration (g)")
title ("Acceleration in the X (forward) direction")

subplot(3,1,2);
plot(Ysmooth)
xlabel ("time (units)")
ylabel ("acceleration (g)")
title ("Acceleration in the Y (up/down) direction")


subplot(3,1,3);
plot(Zsmooth)
xlabel ("time (units)")
ylabel ("acceleration (g)")
```

```
title ("Acceleration in the Z (left/right) direction")

figure
hold on
plot(Xsmooth)
plot(Ysmooth)
plot(Zsmooth)
xlabel ("time (units)")
ylabel ("acceleration (g)")
title("Acceleration in three directions")
legend("Acceleration in the X (forward) direction","Acceleration in the Y
   (up/down) direction","Acceleration in the Z (left/right) direction")

hold off
```

10.6 Additional Data Collected

This section contains the plots of additional accelerometer testing trials, including driving over predefined numbers of Pine 2x4" planks as well as measured as well as potholes of measured depth. The selected graphs were only a subset of the data collected, and these represent the best of the trials that were conducted.

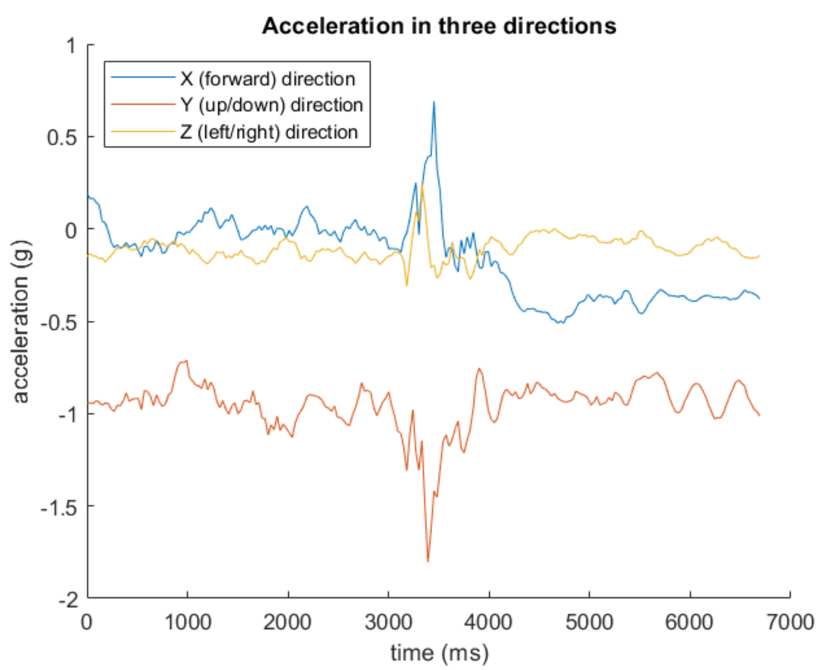

Figure 139: Accelerometer Data while Driving Over 3.5" Deep Pothole"

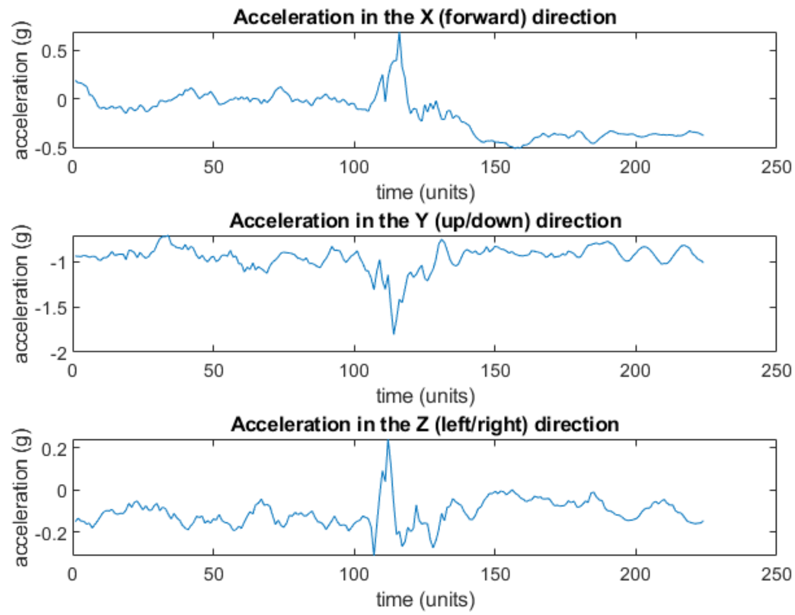

Figure 140: Accelerometer Data while Driving Over 3.5" Deep Pothole"

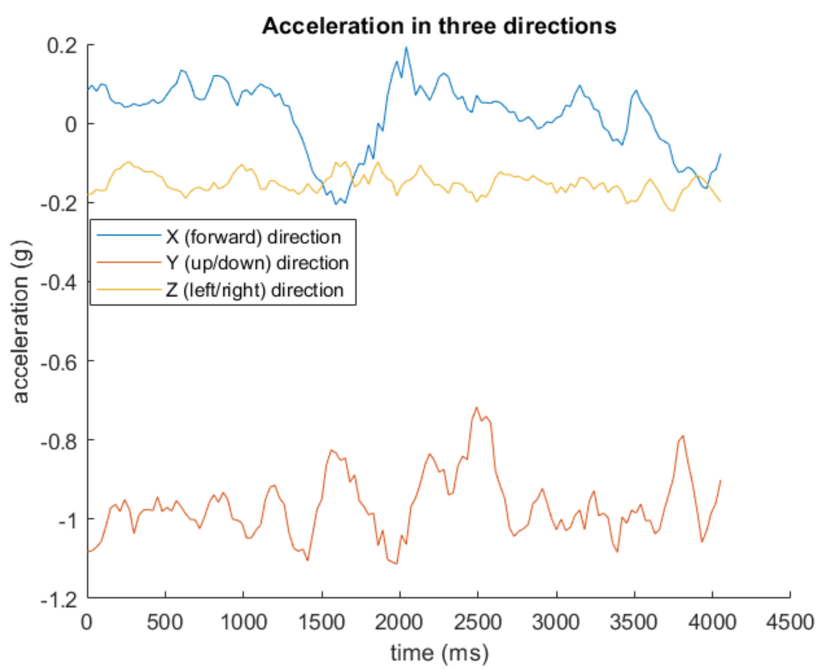

Figure 141: Accelerometer Data while Driving Over 4.2" Deep Pothole"

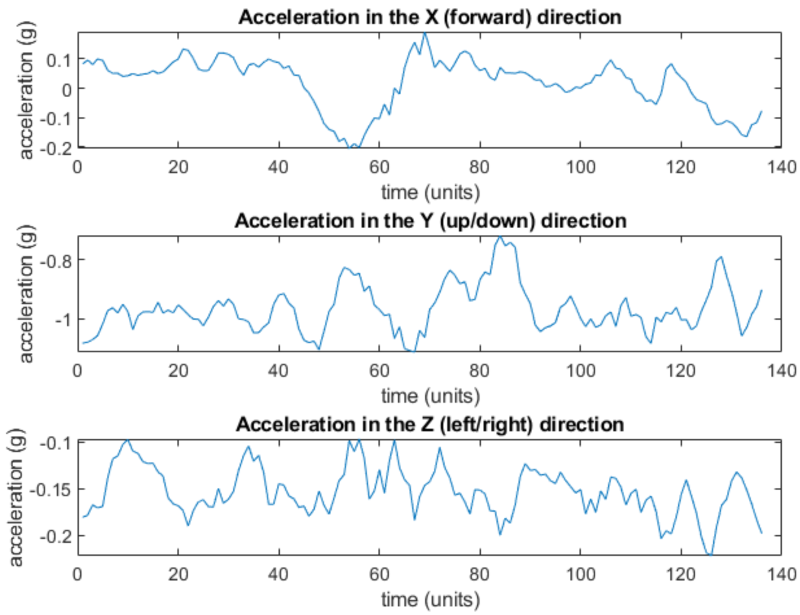

Figure 142: Accelerometer Data while Driving Over 4.2" Deep Pothole"

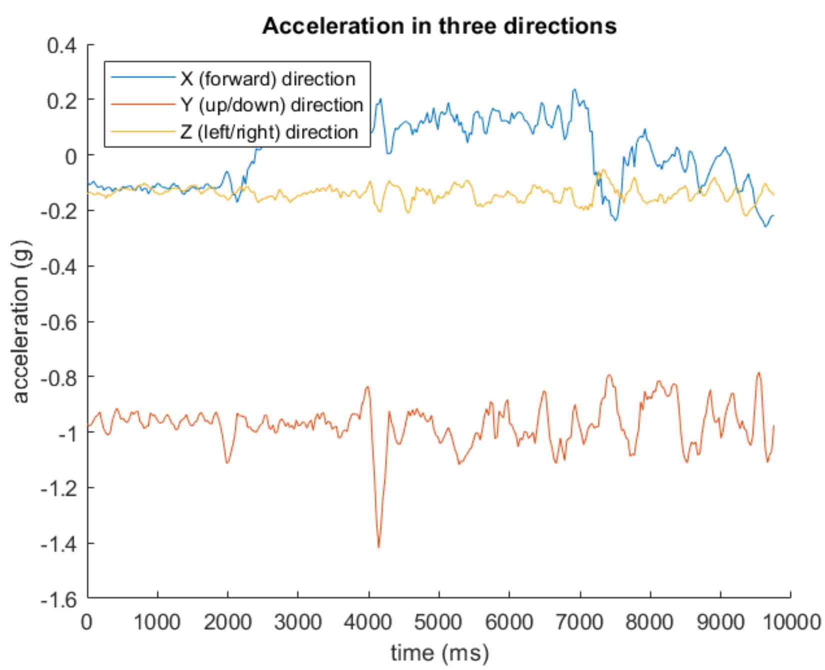

Figure 143: Accelerometer Data while Driving Over 5.7" Deep Pothole"

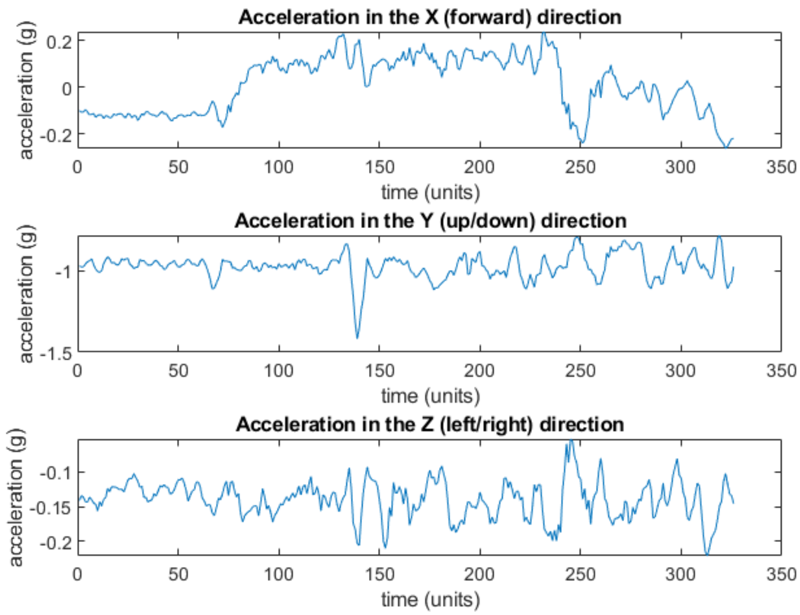

Figure 144: Accelerometer Data while Driving Over 5.7" Deep Pothole"

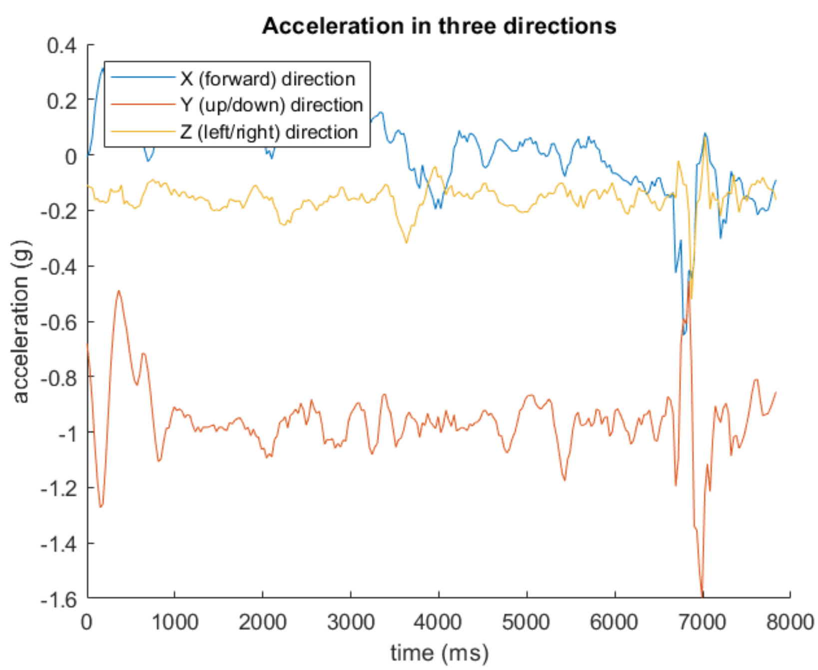

Figure 145: Accelerometer Data while Driving Over One 2X4"

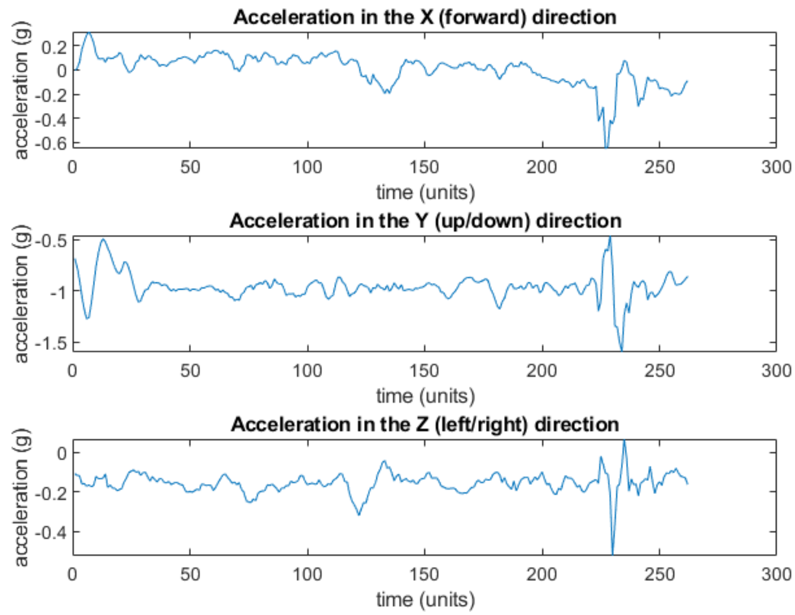

Figure 146: Accelerometer Data while Driving Over One 2X4"

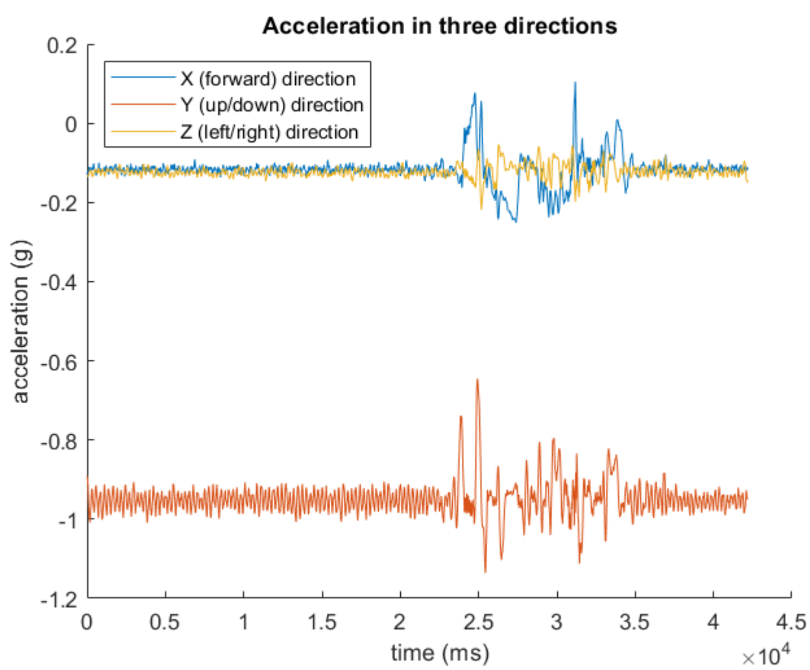

Figure 147: Accelerometer Data while Driving Over Two 2X4"s

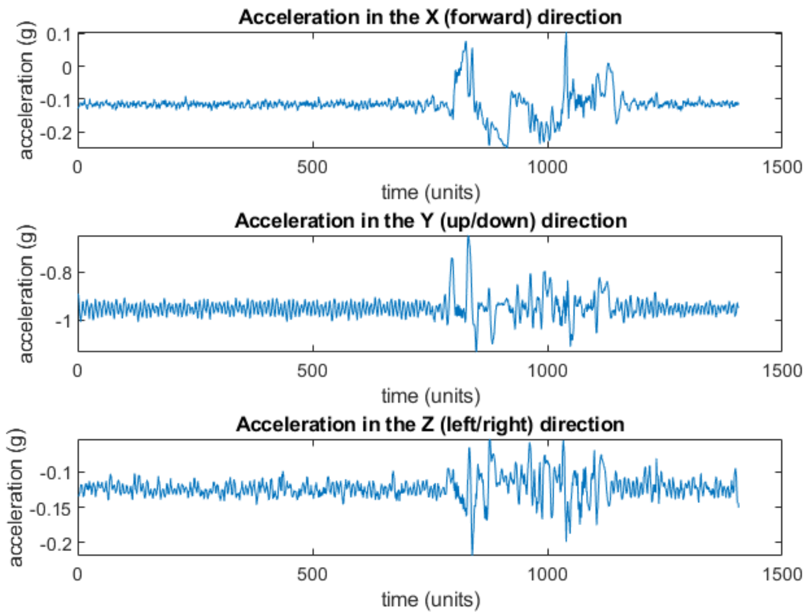

Figure 148: Accelerometer Data while Driving Over Two 2X4"s

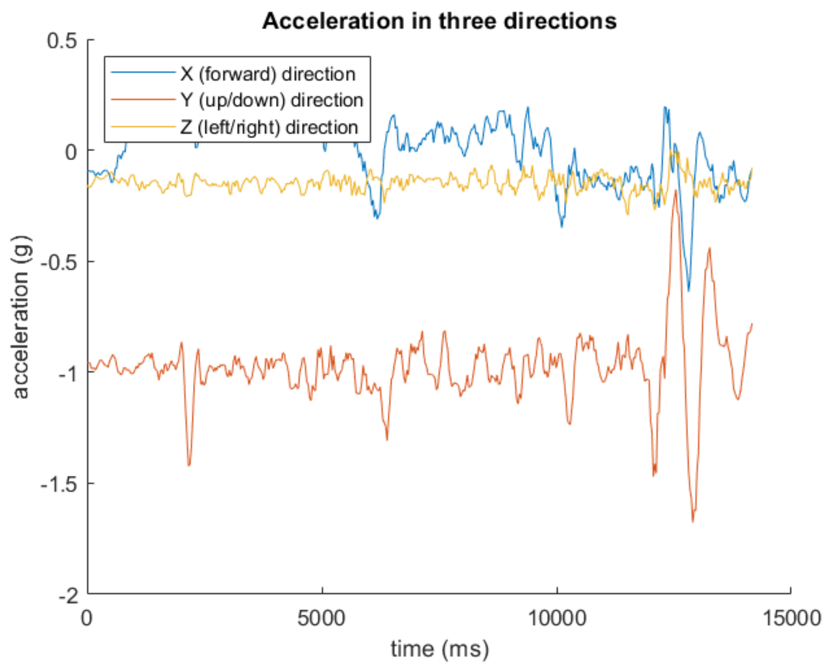

Figure 149: Accelerometer Data while Driving Over Three 2X4"s

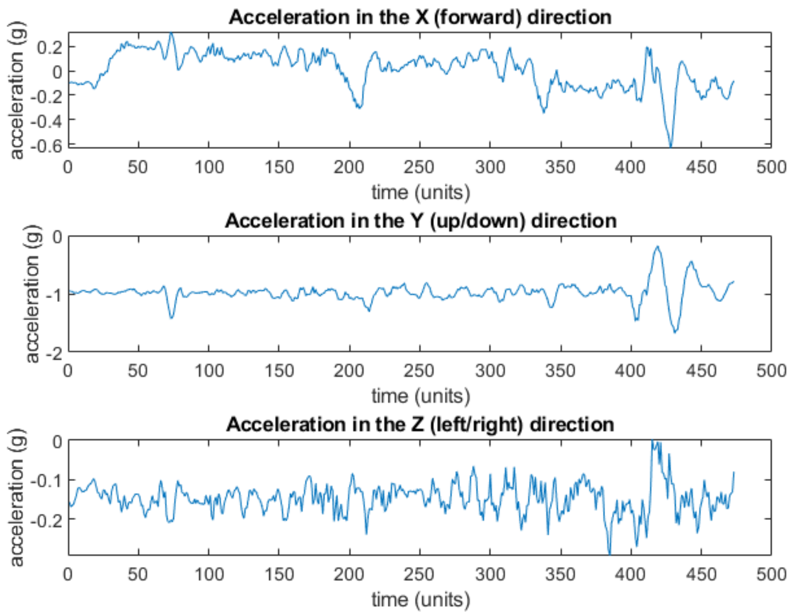

Figure 150: Accelerometer Data while Driving Over Three 2X4"s

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