Final Report - Automated Seat Belt Adjuster

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Revised Abstract

This project develops a functional prototype of a visual sensor and actuator mechanism combination in order to allow automatic adjustment of the seat belt D-ring for different sizes of occupants in consumer vehicles. Our goal is to allow occupants of much larger height and BMI ranges to comfortably, autonomously, and safely reconfigure their seatbelt locations to provide much needed comfort. Following the development of a mechanism, the team has created plans to program the actuator controller to accept input from the visual sensor system regarding the anthropometry of the occupant in order to reposition the shoulder belt to its optimal location.

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Project Introduction, Background, and Information Sources

Currently, car seat belt fits are standardized based on the measurements of the “standard male” - someone standing at 5’9”, with a BMI of approximately 25 [1]. While typical built in D-ring adjusters allow for some variability, this range remains much too small to accommodate for those moderately smaller or larger than this body type. Seat belt codes necessitate that this range covers from the 5th to 95th percentile of height and BMI ranges [2], but this still leaves an entire 10% of the population without a safe solution (as well as a lack of comfort for all those bordering these ranges). Additionally, the amount of people with mobility and health issues incapable of operating built in adjusters brings this range down even further. Our project aims to provide a solution for those fitting into these marginalized categories.

Sponsor Research Background & Context

In order to understand the fundamental design problem motivating this project, it is also important to discuss our sponsors. This project was proposed by Dr. Kathleen D. Klinich and Dr. Byoung-Keon Daniel Park of the University of Michigan Transportation Research Institute. Dr. Klinich has many years of experience in research surrounding the protection of occupants in motor-vehicle crashes, and has recently focused on wheelchair transportation safety issues and autonomous vehicles. Dr. Park’s research involves biomechanical and parametric modeling of human anatomy across a broad range of populations.

Automated Wheelchair Tiedown and Occupant Restraint System

In 2021, Dr. Klinich and Dr. Park worked on a project that would employ both of their skill sets in an evaluation of an automated wheelchair tiedown and occupant restraint system (AWTORS) on volunteer participants who used their wheelchairs as car seats. This system involved the docking and anchoring of the wheelchair as well as an automated occupant restraint system. Our sponsors helped develop an automated seatbelt donning system for the occupant restraint portion of the AWTORS that would rotate the seatbelt into position over the person in the wheelchair. One of the main outcomes evaluated throughout their testing was the quality of the resulting seat belt fit for the participants after the automatic adjustments were made. In order to evaluate the fit qualitatively, a measurement called shoulder belt score was applied after donning occurred. Figure 1 displays four different shoulder belt fits classified qualitatively and by their corresponding shoulder belt score.

Fit	Touching neck	Inboard	Centered	Outboard
Photo				
SBS	-39	0	30	82

Figure 1: Demonstration of post-donning seat belt fit range for AWTORS testing with qualitative description of fits and corresponding shoulder belt score values (SBS) in millimeters [3]

These seat belt fit outcomes demonstrate four reference fits which acted as points of comparison for the outcomes of each automatic seat belt adjustment carried out. The shoulder belt score is a measurement defined in a previous study, which Dr. Klinich contributed to, looking at the effects of driver characteristics on seat belt fit. In this study, the shoulder belt score is defined as the location of the inner edge of the belt relative to the torso centerline at the height of the suprasternale landmark in millimeters [4] (See Appendix A for location of the suprasternal notch). This relationship can be visualized in Figure 2 below:

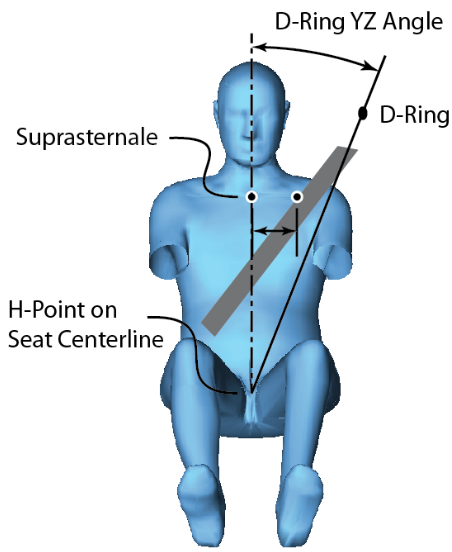


Figure 2: Diagram of standard car seat posture and visualization of shoulder belt score measurement [5].

Using this definition, our sponsors and their team of researchers were easily able to classify and quantify the quality of a seat belt fit after adjustment.

A major factor that was determined to affect shoulder belt score was the seat belt D-ring positioning. As such, a fixture was added to the testing vehicle that allowed the D-ring to be adjusted laterally, vertically, and fore-aft.

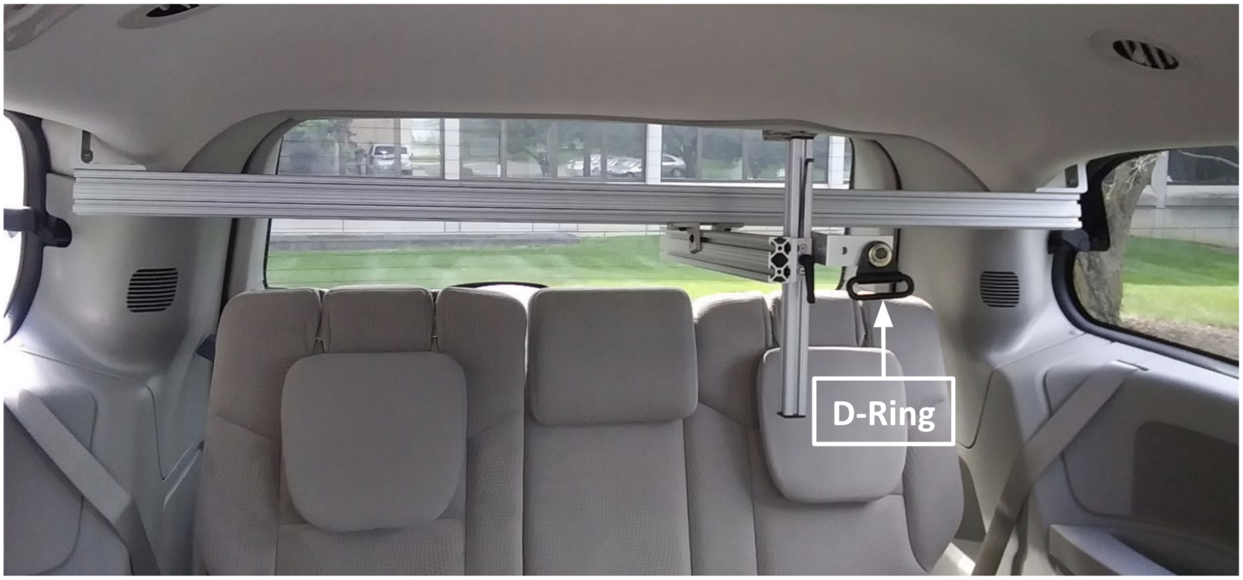


Figure 3: Fixture to allow vertical, lateral, and fore-aft adjustment of D-ring location. Picture taken from original development of the AWTORS [6].

Using this fixture to adjust the D-ring positioning, a D-ring location that corresponded to the optimal shoulder belt score was found. Then, automated restraint tests were conducted in this optimal location, as well as in scenarios where the d-ring was moved slightly from optimal. Noting the role that D-ring location had in creating a good shoulder belt fit and the difficulty and tedium involved with manually adjusting it for each trial (especially when switching between participants in manual and power wheelchairs with large shoulder height differences), our sponsors felt it would be beneficial to have a system that would automatically adjust the location of the D-ring.

Visual Sensing and Human Modeling

When envisioning how such a system might look, our sponsors also noted that it would be necessary to have a visual sensing system of some kind to inform the control of the mechanism. As such, including a visual sensing system became an important consideration for our sponsors. When consulting with Dr. Klinich and Dr. Park, they suggested that an XBOX Kinect camera could be used for this purpose [7]. This was due to Dr. Park's prior research which involved this camera system.

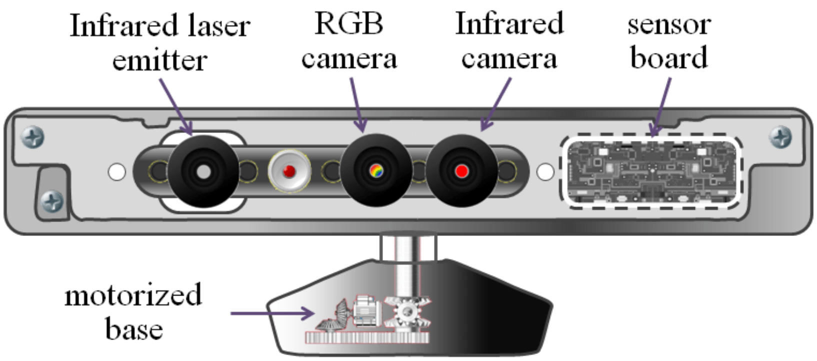


Figure 4: Diagram of XBOX Kinect V1 Camera with major components Labeled [8].

The system works by projecting a speckled pattern of infrared rays onto a scene from the laser emitter which is then captured by the infrared sensor at the same time that a standard 2D image of the scene is captured. Resulting from this process is a 3D point cloud representation of the scene where each point has RGB values as well as a depth value associated with it (where depth is the distance from the camera to that point in space)[9]. This 3D point cloud representation of a scene can be visualized in Figure 5 below which is taken from Dr. Park's research on in-vehicle occupant head tracking.

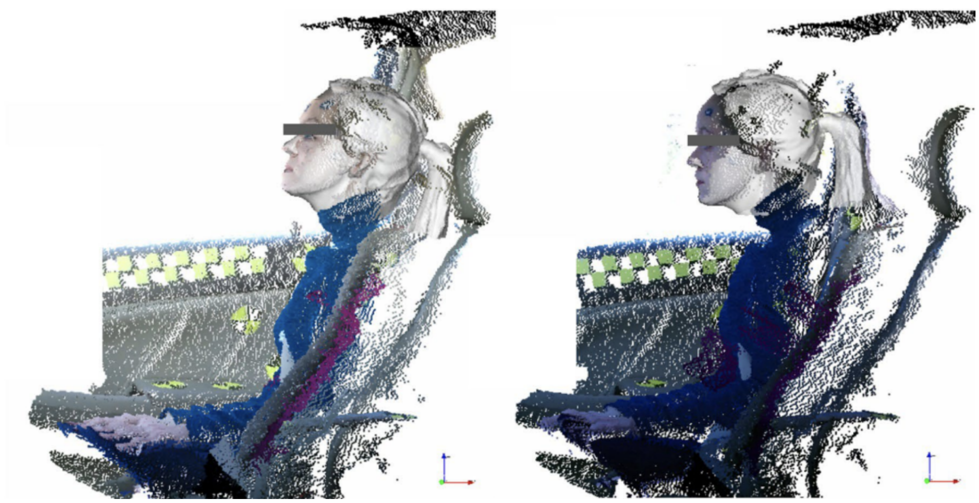


Figure 5: Kinect 3D point cloud with RGB data (colored) overlaid on detailed head scans taken with a hand-held infrared scanner (white) [10].

This capability of the Kinect had an application in the automated wheelchair tiedown system; a major factor that the AWTORS needed to account for was the variation in posture of disabled people in wheelchairs as compared to non-disabled occupants. To account for this, Dr. Park used Kinect depth imaging in combination with human shape models that he previously helped develop to assess and characterize the differences in seated posture between someone in a wheelchair and someone of similar stature in a standard vehicle seat. This process involved two key components - Kinect depth imaging and human shape models.

Humanshape.org is a product of prior research by Dr. Park and other researchers at UMTRI. It is a human avatar generation software based on statistical analysis of laser scans of hundreds of men and women taken at UMTRI. Within this software, 3D models of male and female figures can be scaled by inputting standard anthropometric dimensions, such as stature, body mass index (BMI), and age to represent a large range of body sizes [11].

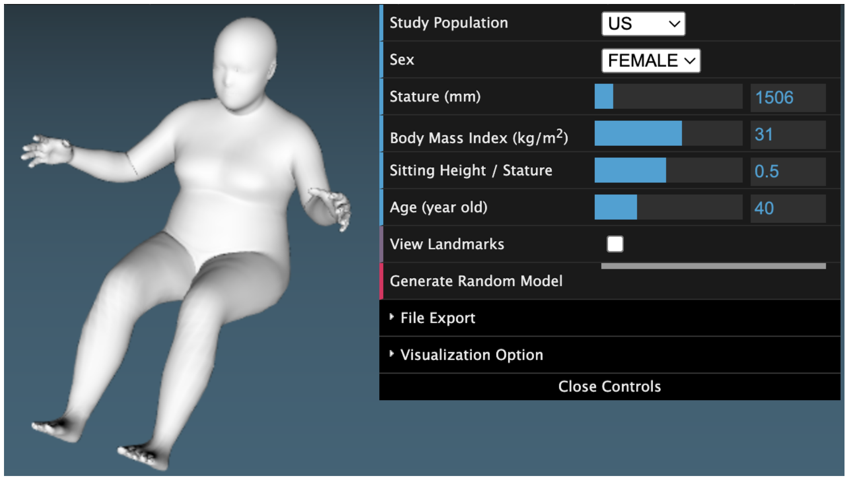


Figure 6: Example of a human shape model generated on humanshape.org. Standard anthropometric dimension selection interface is also displayed [12].

In order to evaluate the posture of disabled occupants for the AWTORS, Dr. Park took scans of them using the Kinect, generated an avatar using the occupants anthropometric measurements, then manipulated the avatar to match up with the 3D point cloud visualization [13]. The end result of this process was a human shape model that reflected the wheelchair posture of the participant. This result is pictured in Figure 7 Below.

Figure 7: Example of AWTORS occupant seated posture modeled using Kinect 3D point cloud data in combination with avatar generated using humanshape.org [3].

Having this posture-accurate model made it possible to simulate optimal belt fit according to each individual occupant and apply it to the docking station set up and control strategy for the donning system.

Formulation of The Fundamental Design Problem

All of these prior research projects and outcomes carried out by our sponsors and UMTRI are critical information sources for our project that prefix our report and contextualize our design problem. Comfort can better be quantified using the shoulder belt score, and this measure, in turn, can be improved through adjustment of the D-ring. But, adjusting the D-ring manually is tedious and impractical for many populations such as the elderly and obese. As such, an automated system that can adjust the D-ring would be highly beneficial. Moreover, having a visual sensing system that can capture an occupant in 3D and give recommendations to the controller and actuating mechanism based on their body shape would enable accessibility and comfort for vehicle occupants of a large range of body shapes and sizes. Given this, the fundamental problem driving this project is: can we develop a system that automatically provides a comfortable seat belt fit to vehicle occupants of all shapes and sizes? An extension of this problem is: can the system provide this fit using their body shape determined from a 3D scan as an input?

This project has many potential solutions, but the success of this project is dependent on a few important factors. First, our system aims to provide a large range of adjustability within which occupants with a broad range of height and BMI can be provided a comfortable fit. Secondly, we want our mechanism to provide accessibility to limited mobility occupants. Additionally, we want our mechanism to be able to achieve particular shoulder belt scores, within a specific range, if directed to do so given an occupant's body shape. Naturally, this implies the need for our input based on classification of occupant shape using the Kinect or other visual sensing systems and human shape models to be accurate enough; we want our sensing system to be capable of determining an occupants shape and size and provide that accurately as an input to the adjustment mechanism. If these criteria are met by our final solution, then we can say that the project was a success.

Design Process

In order to produce a working prototype this semester, our team has considered various design processes with the goal of finding a process most closely tailored to the goals of our project. Following our research, we utilized a ***linear***, ***stage-based***, and ***problem-oriented*** design process to best allow us to reach these goals. The specifics and reasoning behind our chosen process are laid out below.

In researching design processes, we were able to narrow them down by thinking of what we hope to gain from the process. Systems V models [14] are rigid and complex, with an emphasis on rigorous verification and validation that is overall better suited for larger scale projects with larger time constraints. Design thinking processes [15], on the other hand, can utilize extreme amounts of iteration and feedback, and spend a large amount of time in the ideation phase, slowing down progress in the initial stages of concept creation. However, certain aspects from each, such as taking a very structured approach and placing an emphasis on concept generation, at least initially, are two aspects we deem important. Utilizing a combination of the two, along with certain aspects from the ME450 suggested design process [16], allowed us to create a process that is best suited for our specific project, seen in Figure 8 below.

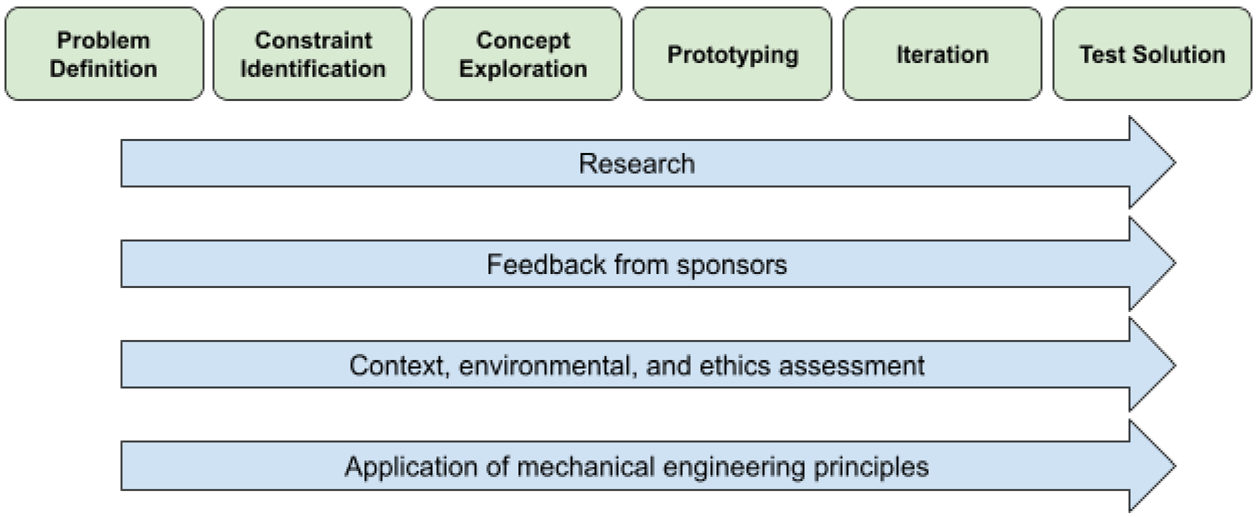


Figure 8: Our Design Process

Our design process resembles Systems V models in that it attempts to remove uncertainty early by placing a strong emphasis on problem definition, constraints, and continual research. This benefits us by removing uncertainty and decreasing additional project costs that would have been incurred had sufficient research not been done. It resembles design thinking processes in that concept exploration is a huge part of our design process and sets us up for success for the entire rest of the process. Certain aspects from the ME450 design process have also been adapted, such as problem definition and context / ethics assessments, to ensure our project remains sustainable in all facets. Aside from the decisions we made backed by existing models, we also chose to place an emphasis on actively searching for feedback in addition to researching all aspects of the design throughout the semester. This commitment to gaining outside knowledge during the process will enable us to iterate and make informed design decisions, without getting roped into too cyclic of a process that would ultimately slow us down in the long run.

This model can be additionally defined as a stage-based process [17], as opposed to activity based, as it emphasizes major landmarks (or stages), and doesn't focus on the day-to-day or specific activities that are needed to progress through the process. This will allow for us to work based on the morphological dimensions of design, giving structure to our process and not forcing us to complete specific activities when they could pose more of an inconvenience than a help. Keeping our process generally linear and problem-oriented will also eliminate the need for excessive rework, and so long as we keep well structured, will enhance the efficiency and timing of our project to ensure we can produce something functional, while also staying within the scope of the class.

Design Context

Stakeholder Analysis

Stakeholders take an important role in our project; their preferences and ideas shape the direction the project is headed. For example, we will be surveying our target customers and changing our design based on their feedback; based on whether the device is too clunky, too difficult to operate, too time consuming, etc. Here is a list of our stakeholders (also seen graphically in Figure 9 below):

- **Primary:** UMTRI, Elderlies and disabled, Drivers and passengers, Ride sharing companies, Microsoft, Actuator and controller manufacturers, labor markets
- **Secondary:** Established car manufacturers, Research facilities, Seat belt companies and other competitors
- **Tertiary:** Government (Department of transportation), Media, Skeptics, Competitors' investors

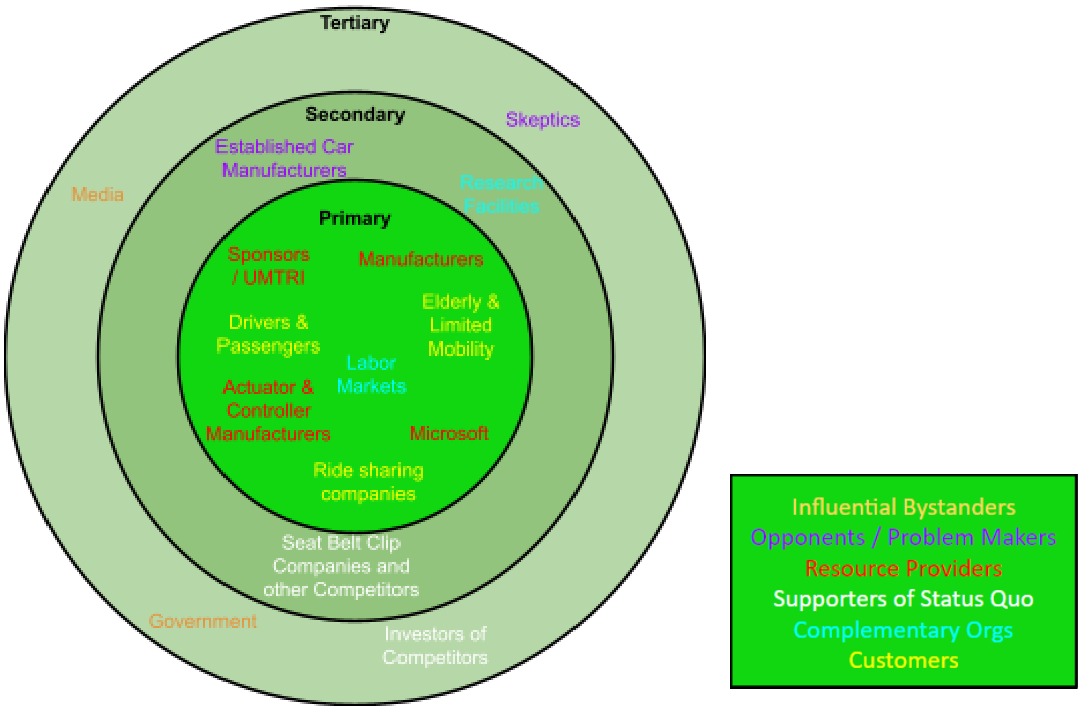


Figure 9: Stakeholder map

Our main customers and beneficiaries include the elderly, the disabled, ride sharing companies, and average vehicle users. The automated seat belt adjuster aims to make their vehicle experience more comfortable and safer, and their feedback contributes heavily to our decision making. Other stakeholders that will benefit from our project include manufacturers of our product or other materials that are required for our project. There are potential job opportunities and economic benefits if the product turns out to be successful. Some main stakeholders that will be negatively impacted by our project include seat belt companies who are beneficiaries of the status quo, competing organizations who are also trying to develop automated seat belt adjusters, and car manufacturers. Some tertiary stakeholders, who are least affected by our project and have the least influence over it, include Government, Media, Skeptics, and Competitors' investors. A noteworthy tertiary stakeholder would be the department of transportation, since our project involves seat belts, which is a major safety concern. There can potentially be regulations for our finished product in the future. We also have to consider the engineering standard for seat belts: 49 CFR § 571.209 - Standard No. 209 [16]; Seat belt assemblies, which describes how a seat belt should behave and includes specifications on certain factors, such as how much force a seat belt should withstand.

Social, Economic, and Environmental Impact

The automated seat belt adjuster aims to fit the majority human body shape and focuses heavily on inclusivity. Our project sponsors, Dr. Klinich and Dr. Park, place a large emphasis on social impact as opposed to profit or other priorities. As a research group associated with the University, they are primarily concerned with forging technology that will benefit the general population. We believe that this emphasis will benefit our product design process, because this decision has led to less firm deadlines on producing a profitable product, and functionality will be able to take the front seat initially as opposed to other factors like cost or profitability. Along the lines of benefiting the general population, our team is also determined to minimize the environmental impact of the project by choosing to work with recyclable material and avoiding 3D printing parts. We aim to achieve a product life of 10+ years under weekly use, which would ensure a more sustainable nature in our automated seat belt adjuster.

Our personal ethics align very similarly to those expected of us in these professional settings, and there is a mutual respect amongst all parties involved in this project; The sponsors are being very helpful and trusting of our abilities, and we respect them for being available and willing to assist us when necessary. Amongst team members, there is the same level of respect and trust in each other's abilities. We respond to the end users needs in order to accomplish our project, but even though listening to the customer's problems guides our design, we ultimately have the final say in design choices.

Additional considerations regarding the implications of our design were also important to consider. Should automated seat belt adjusters become normalized or sought after by a large portion of society, large automotive companies may look into ways to make them built into new vehicles as opposed to being just add-on products. Half-way solutions such as increasing the range of seat belt D-rings and making them adjustable with buttons that are easily accessible in place of current methods may also appear more. While our design hopes to be a functional and useful type of add-on product, the implications for automotive companies extend beyond this.

Intellectual Property

Since our project is a research project under the University of Michigan Transportation Research Institute, Intellectual property is not a major focus. However, potential patents on future designs will become necessary. Integration of our design with previously patented and regulated designs for seatbelts/seatbelt housings/connections are also important factors that need to be reviewed further into the project.

Benchmarking

Benchmarking is a process of measuring the performance of a design and comparing it against those of other similar products or designs that are popular in the industry. It clarifies what features are already available in the current marketplace, provides a baseline for a new product's engineering specifications, and opens the door to identifying areas for improvement.

We are unable to find similar research on the topic of **automated seat belt adjuster**, so we will be benchmarking our design with other **manual seat belt adjusters** on the market. Currently, there are 3 main seat belt products on the market that assist with the adjustment of the shoulder belt position: Standard seat belt D-ring, Seat belt adjuster clip, and Seat belt extender.

Figure 10: Standard seatbelt

1. Standard seat belt D-ring: This is the standard seat belt that is built into every vehicle and are all the same across the world. As mentioned before, the standard D-ring in a seat belt does not have enough range of motion to accommodate for a percentage of human body shapes, which is one of the main reasons that formed our current project. The standard seat belt aims to accommodate the body shape of the 5th to 95th percentile, and it struggles to meet on the extreme end of both sides. It also only have a 24 to 48 degrees XZ range of motion and a 19 to 39 degrees YZ range of motion.To achieve a better performance than the standard D-ring, our automated seat belt adjuster aims to accommodate the body shape of the 5th to 98th percentile, and double the range of motion: 12 to 60 degrees XZ range of motion and 9 to 49 degrees YZ range of motion.

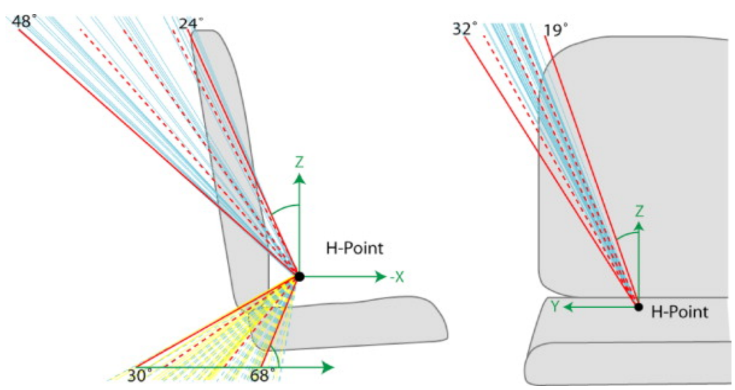


Figure 11: Seat belt range of motion

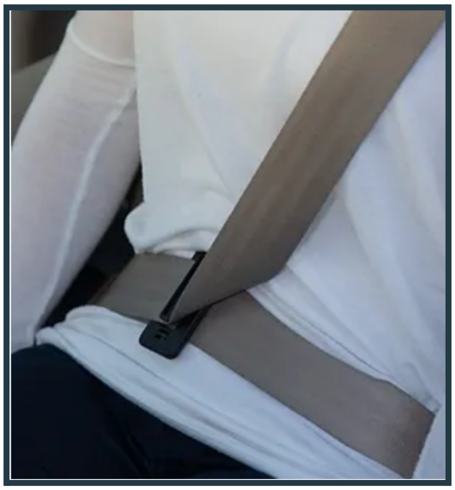


Figure 12: Seat belt adjuster clip

2. Seat belt adjuster clip: This is a commonly sold device that helps the passenger adjust their shoulder belt position. The product works by clipping the shoulder belt and the waist belt together as shown in the left image, and the passenger can adjust the shoulder belt by simply sliding the adjuster clip left and right. This device only has one degree of freedom (Left to right), and since it requires manual adjustment, there is no guarantee that the passenger is able to adjust the seat belt to the best or safest position. To achieve a better performance than the seat belt adjuster clip, our automated seat belt adjuster aims to offer a wider range of motion, more degrees of freedom, better position locating with the help of Kinect sensor, and a complete automated adjustment to accommodate for the elderly and disabled.

Figure 13: Seat belt extender

3. Seat belt extender: This is a device that aims to help the passengers who are larger in size and unable to fit in a standard seat belt strap. The product consists of a seat belt buckle with a certain length of strap and a clip at the end, which would connect to the original seat belt buckle installed in the vehicle, thus a seat belt extender. This device is unsafe and only recommended by the department of transportation if the passenger is unable to fit into a standard seat belt. The seat belt extender only accommodates for bigger body size, and does not have any effect on the shoulder belt position compared to previous devices.To achieve a better performance than the seat belt extender, our automated seat belt adjuster aims to achieve both accessibility and automatic position adjustment.

The cost, safety, and range of motion / adjustability comparisons between these products in comparison to our expected ranges are seen below.

Table 1: Comparison of automatic seat belt adjuster with the standard seat belt system and manual seat belt adjuster in the current market

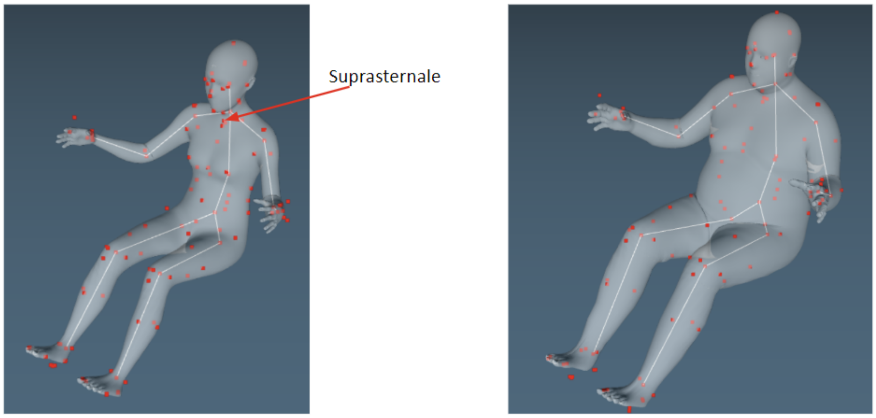
	Automated Seat belt adjuster	**Standard Seat belt D-ring**	**Seat belt adjuster clip**	**Seat belt extender**
Price	~ 1000$	N/A (built in)	~ 10$	~ 20$
Safety	Safe	Safe	Unsafe	Unsafe
Range of motion (XZ)	12 to 60 degrees	24 to 48 degrees	N/A	N/A
Range of motion (YZ)	9 to 49 degrees	19 to 39 degrees	20 to 30 degrees	N/A

As can be seen, be it safety issues or lack of range of motion, these cheap “solutions” fail to accurately solve our design problem. Additionally, none are capable of autonomous movement and require mobility that some users may not have.

User Requirements and Engineering Specifications

Inclusivity is an important aspect of the design problem as our design solution must be usable by a large variety of people. As our target demographic is individuals with mobility issues, which include disabled people and elderly people, we must first acknowledge that these issues can happen to anyone. To address this crucial aspect of the design problem, it is imperative that specific user requirements encompass the principles of inclusivity. With this in mind, our chosen requirements and specifications are laid out individually in brief paragraphs below, and summarized together in a chart at the end of this section. Requirements are presented in order of diminishing priority - those of foremost importance are listed first. This was based upon which are absolutely necessary, such as range of BMI and height to accurate visual data, as well as which respond to the implementation of our design solution, such as installation system to affordability. The first four requirements take priority, as their fulfillment constitutes a successful project. All have been translated into appropriate and correlated specifications, which are laid out in the table at the end of this section.

One such user requirement is to accommodate a wide range of BMI and heights. Current seat belt adjustment devices allow a very minimal range based around only the “typical” user - a 5’9 male with a BMI of 25 [1]. This requirement was specified by our sponsor, and is important in that the vast majority of users don’t fit this stature. For this design solution, we will try to make our product suitable for individuals with BMI values ranging from **18** through **40** and heights of **5 feet** to **6 feet** tall. Code 49 CFR § 571.209 - Standard No. 209 specifies that current seat belt assemblies accommodate from the lower end of 5th percentile of adult females to the upper bound of 95th percentile of adult males. We can identify this weight range to be approximately 103 pounds to 215 pounds, which can be converted to their respective BMI range of 20.2 to 29.2 [18]. This design requirement allows us to not only respond directly to the problem statement by better accommodating a much wider range of vehicle users, but also adhere to this specification established by the sponsor. Given that our primary design goal is to cater to a diverse range of users, this requirement takes top priority.



Age: 40 years, Sex: Female
Height: 5'0", BMI: 18

Age: 40 years, Sex: Male
Height: 6'0", BMI: 40

Figure 14: BMI and Height Range for Users - Our range of adjustability attempts to cover everything from 5'0", 18 BMI females to 6'0", 40 BMI males

Aside from adjustability requirements, another relevant user requirement is that the solution product must be easy for individuals with mobility issues to use. Ultimately, the user must interact with the product in order to adjust the seat belt shoulder strap, whether through contact with the product itself or a remote that controls the product. So, the corresponding engineering specification is that the design solution must have less than 2 interactable, moving parts. For example, if the adjuster were to use an external power source such as a battery, the actuator may need to be switched on before usage. The product itself may have multiple moving parts in order to operate, but can only be activated and controlled by the user by these 2 parts. This requirement is supplemental in achieving inclusivity and also takes utmost priority.

For the automatic seat belt adjuster to move the shoulder belt strap to the optimal position, we must record and utilize accurate imaging data. There are termed landmark points on the human body that can be used in calculating the shoulder belt score.The most important landmark is named the suprasternale, which is pointed out in Figure 14, can be defined as the deepest point in the hollow of the suprasternal notch lying at the middle of the anterior-superior border of the sternal manubrium, as also seen in Figure A1 and A2 [19-21], which is explained in Appendix A. Once the location of the suprasternale has been determined, we must measure a certain distance away from this landmark in order to calculate the optimal shoulder belt score for the user. Although this distance can be measured directly on a horizontal axis, it may be more accurate to calculate the shoulder belt score by measuring along a reference axis created by two landmarks. Because one landmark is already occupied by the suprasternale, the other landmark would ideally be located on the end of the user's shoulder, such as the axilla anterior left, shown in Figure A3 [21]. The utilization of this newly created axis will provide a more accurate measurement of the distance away from the suprasternale. Therefore, we have detailed an engineering specification of detecting at least 2 major landmarks on the user's body. We have determined that locating more landmarks will perpetually yield more accurate reference axes, which results in a more optimized and personalized shoulder belt score.

The shoulder belt score differs depending on the BMI, height, and other measurable characterizations of the human body shape. Though calculating these particular scores is important, we must come within a small range of that score value when positioning the shoulder belt. This range of proximity is dependent on the type of visual sensor that we use to measure and record data. Some differing properties of visual sensors, such as point cloud systems, may include the number of points generated in a certain, specified region, set distance between the generated points, and resolution of the generated points. Although using a high quality sensor can give accuracy to the degree of millimeters, it may be more feasible in terms of adjuster mechanical movement to aim for a precision within 2 centimeters. However, a missed distance in centimeters can be the difference that causes the shoulder belt to be in contact with the user's neck or positioned at the wrong location on the user's shoulder that results in bone dislocation in the event of a vehicular accident. The actual value again depends on the specifications of the visual sensor model, but it will be better in terms of safety to keep the proximity range of the shoulder belt score to be in millimeters.

Many of the current D-ring models that hold the seat belt are immovable or can only be adjusted vertically, as seen in Figure 15, which limits the range of motion.

Figure 15: Current standard D-ring height adjusters [23-24]

This vertical movement is operated through usage of the push button apparatus in order to shift the entire D-ring system, or by tilting the D-ring upwards or downwards. Due to this limited range of motion, passengers are only able to adjust their shoulder belt up to a certain degree. Some positions on the users' shoulders may remain inaccessible or can only be temporarily reached. One method of increasing the range of motion is to apply both vertical motions of the push button and D-ring simultaneously. Another method comes from increasing the degrees of freedom of the D-ring to allow for better shoulder belt positioning for more passengers. For example, adding horizontal movement to the D-ring will increase the current degree of freedom by a value of 1. However, this may require excess modifications to the car pillar that the D-ring holder is attached to as its width is not suitable for this type of additional movement. One method of increasing the degrees of freedom may come from axial movement. This axial movement will not be applied to the D-ring itself, but from the shoulder belt strap. The axes of rotational movement have the naming conventions of roll, yaw, and pitch as seen in Figure 16.

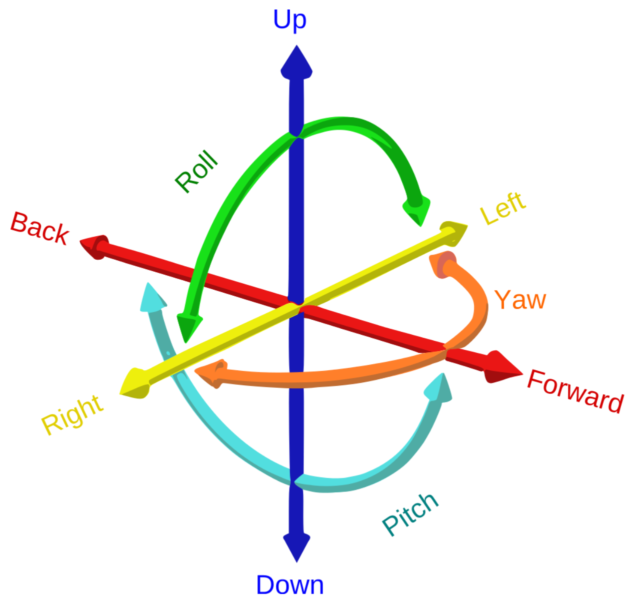


Figure 16: Axes of the 6 degrees of freedom [25]

The most prevalent axis of rotational movement that can be applied to the shoulder belt strap is rotation around the Y-axis or normal axis, also known as the roll axis. This rotational motion can allow for the shoulder strap to be shifted horizontally, albeit to only a certain extent. Despite this, incorporating rotational movement allows us to work well within the constraints of the dimensions of the D-ring holder pillar. It must be noted that the additional range of motion regarding vertical only movement is of higher importance than increasing the degrees of freedom. The addition of axial movement will only be explored once the vertical movement issue has been resolved.

Many options were given in terms of which visual sensors to use to record and utilize visual data. Our sponsors have previous research and work experience with the XBOX 360 Kinect sensor, which itself has a RGB camera and depth sensor in order to capture the scene in front of it. Though released in 2010, the XBOX 360 Kinect is one of the best point-cloud system based sensors in the current market in terms of accuracy and price. Its respective specifications can be found in Appendix B, Table B1 [26]. However, to accomplish reliable one dimensional motion, simpler visual sensors that record a two dimensional scene can be utilized. These visual sensors can be accompanied by real-time multi-person human pose detection libraries such as OpenPose [27]. In order to justify using an automatic seat belt adjuster, the adjuster must not fall too far behind manual methods of positioning the shoulder belt in terms of speed. We have determined that the visual sensor must be able to collect and send visual data to our adjuster within a **4 second time frame** to achieve adequate speed.

The design of our automatic seat belt adjuster also prioritizes safety and convenience without compromising driver visibility. The integrated visual sensor can be installed on the front dashboard, and will have to be positioned to ensure that it does not obstruct the driver's field of view or impede their ability to operate the vehicle safely. Code 49 C.F.R. 393.60(e)(1)(ii) specifies that “devices with vehicle safety technologies must be mounted not more than 216 mm

(8.5 inches) below the upper edge of the area swept by the windshield wipers and not more than 175 mm (7 inches) above the lower edge of the area swept by the windshield wipers” [28]. We must comply with this code in order to ensure that the sensor's location falls well within this range, allowing it to effectively monitor the seat belt position and make adjustments as needed while also ensuring the driver's field of view remains unaffected.

The automatic seat belt adjuster must be compatible with the existing car models as it is an aftermarket product. There are no federal regulations regarding the dimensions of the B-pillar of vehicles, in which is the pillar the seat belt assembly would affect as seen in Figure 17, or the dimensions of the passenger seats. However, there must be no breach of structural integrity to the pillars or the passenger seats. The Federal Motor Vehicle Safety Standard states such regulations regarding the B-pillar and passenger seats, must abide by strength and durability regulations, written in codes FMVSS No. 216 and FMVSS No. 208 [29-30]. We can ensure that the adjuster itself is adjustable so that it will be **installable for at least 75%** of all vehicles by utilizing extendable and retractable installment parts.

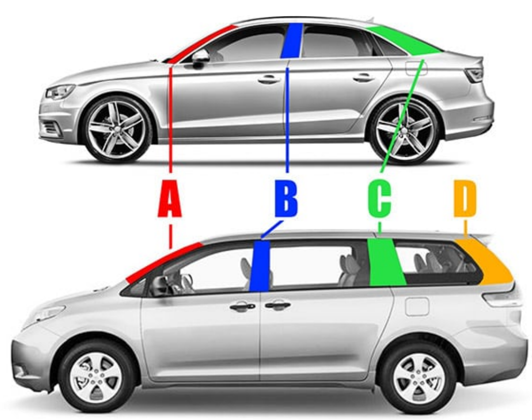


Figure 17: Naming conventions and locations of the pillars in a car [31]

As a supplement to the compatibility requirement, the seat belt adjuster must be easy to install as it must not affect the integrity of the vehicles’ pre-existing components or systems. To meet the requirement for easy installation, we must design simplicity in mind. The adjuster will incorporate a **maximum number of three installment parts**, which includes the mounting of the visual sensor. This deliberate choice not only streamlines the installation process but also aligns with the goal of enhancing compatibility with a wide range of existing vehicle models. In addition to ease of installation, we have considered the power source for the seat belt adjuster. It has the flexibility to be powered either internally or through an external power source. To further facilitate installation, we have given consideration to wire routing when utilizing the automobile auxiliary power outlet so that there is no need for complex wiring configurations during installation. The power source wiring must run through the floor of the vehicle’s front row so as to not impede the passengers field of view or freedom of movement. Furthermore, the external power source must be easy to replace and installed in a location of easy accessibility.

This flexibility of installation not only adheres to our compatibility requirements but also provides a user-friendly and versatile solution.

The design of the automatic seat belt adjuster requires sustainability by avoiding the excessive use of 3D-printed parts. This not only reduces waste associated with additive manufacturing but also mitigates concerns related to the brittleness of such components. While 3D printed plastic parts typically have advantages in terms of energy efficiency, waste production, and transportation, resulting in lower carbon emissions compared to machined metals, mass production of this product using metal manufacturing would ultimately result in reduced carbon emissions. Metal parts are stronger and more durable, which would require less frequent manufacturing compared to plastic parts as they are relatively weaker and may necessitate more frequent maintenance. The adjuster will be manufactured with durable materials and construction methods to ensure a longer lifespan. With an estimated usage that spans the lifetime of the vehicle of approximately 10 years, this adjuster will contribute to a more eco-friendly environment.

Finally, the product must be affordable in order to promote inclusivity. The cost of manufacturing can not be determined at the moment but there are some purchasable components that are integral to the design solution. Such parts include the Intel Realsense or the XBOX 360 Kinect as the visual sensor, an Arduino to collect visual data and control the adjuster, a motor to control an actuator, and wires and breadboard to connect the components. The price of these components are organized in Table 2:

Table 2: Price of components

Component	**Price ($)**
Intel Realsense	272 - 499 [32]
XBOX 360 Kinect	36.99 [33]
Arduino	14.70 - 53.80 [34]
Motor	~20 [35]
Wires	~15 [36]
Breadboard	~10 [37]
Total	368.69 - 634.79

This price will increase as the metal component manufacturing costs become clear. These costs will include manufacturing, transportation, and waste. With these costs in mind, the final cost to manufacture the automatic seat belt adjuster must be less than $1000.

Our requirements along with their connected specification are summarized in Table 3 below.

Table 3. Requirements and Specifications for Automated Seat Belt Adjuster Design

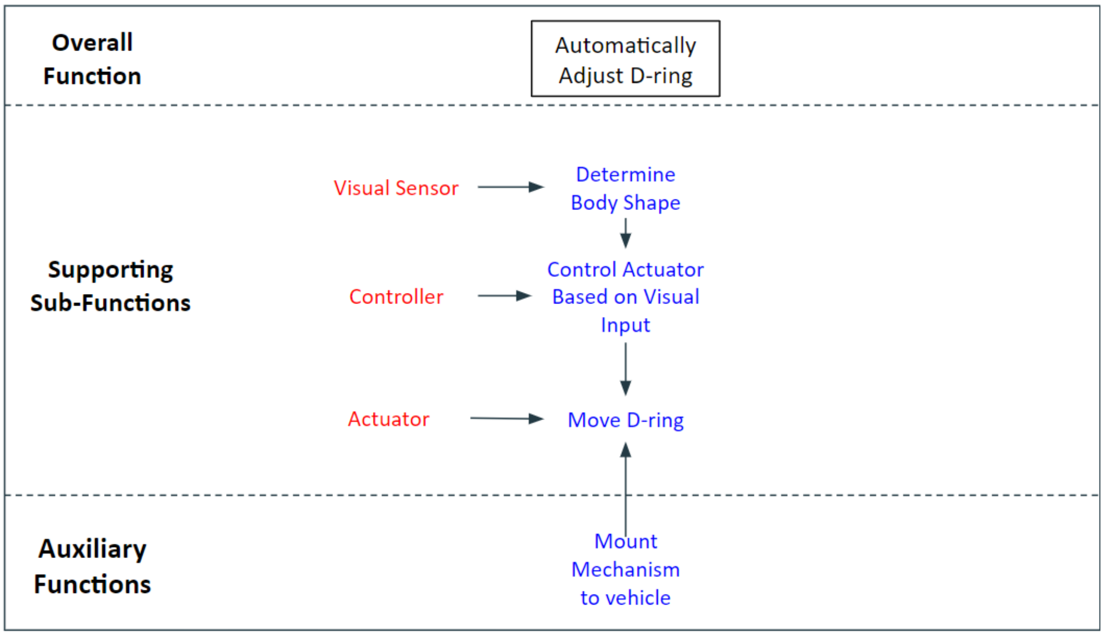
Requirement	Specification
Provide enhanced range for seat belt users based on height and BMI	Provide for: 18 ≤ BMI ≤ 40 5’0” ≤ Height≤ 6’0”
Easy for individuals with mobility issues to operate	< 2 moveable parts
Ensure accurate imaging data	Detect ≥ 2 major landmarks on body of passenger
Achieve comfortable shoulder belt placement	Shoulder belt score of 22 ± 2 cm is accurately obtained
Adjustable D-ring location	Position the D-ring component through an increased vertical range of motion Provide ≥ 1 degrees of freedom
Utilize visual sensor and library	Time from point cloud measurement to adjuster < 4 seconds
Safety	Follow Code 49 C.F.R. 393.60(e)(1)(ii) regarding front windshield visibility Follow Codes FMVSS No. 216 and FMVSS No. 208 regarding structural integrity of B pillar and car seats
Easy to install	＜3 installment parts External battery, lighter outlet, USB cable
Compatibility	Compatible with ＞75% of vehicles
Sustainable	Avoid PLA/3D printed parts Last ≥ 10 years under weekly use
Affordable	Cost to produce ＜$1000

In summary, each component of our design comes with various limitations that we must call out. The justification behind these requirements has been presented, and specifications for each have been created. As seen, each of these specifications is both quantified and verifiable. No other specs beyond these are seen as necessary, as our requirements address all problems and feasibility issues with the design. In proceeding through our design process, these requirements and specs will be referred to many times to ensure we produce a design that is both functional and efficient.

Concept Generation

In accordance with our design process, following the completion of problem definition and constraint identification, we begin our concept generation stage. We start off this concept generation process with functional decomposition of our design problem. This method helps identify all the factors that need to be considered during concept generation, and breaks down the overall problem into smaller sub functions that can assist our team in generating a wider variety of solutions.

Table 4: Functional decomposition chart of automated seat belt adjuster



Based on the result of the functional decomposition, we identified our supporting sub-functions, which include determining body shape, control actuator based on visual input, move D-ring, and an auxiliary functions being the installation of the mechanism to vehicles. We also identified that a visual sensor, a controller, and actuators are needed. With these sub-functions in mind, we proceed in our concept generation with a morphological chart, which includes different methods or materials that can be used to achieve the corresponding sub-functions.

Table 5: Morphological chart of sub-functions

Sub-Function	**Solutions**			
Determine Body Shape	Kinect V1	Kinect V2	RGB Camera	Thermal Camera
Control Actuator Based on Visual Input	Arduino	Raspberry Pi	Pneumatic Controller	ESP32
Move D-ring	Electric Linear Piston	DC Motor	Pneumatic Piston	Winch
Installation method	Clamp on B-pillar	Screw into Ceiling Liner	Strap onto passenger seat	Window Suction Cup

A morphological chart enables the solutions that we came up with to be listed clearly and provides a structure for considering alternative combinations. The 4 sub functions were produced - image processing, controller, actuator, and installation, and various combinations of each were used to create many different concept designs. With this morphological chart in mind, we started the brainstorming process and generated as many concepts as possible, regardless of the feasibility. Described below are 5 of the main concepts generated in the process. Many of the other concepts we produced can be found in Appendix C, in which design heuristics are also used and will be demonstrated.

Concept 1

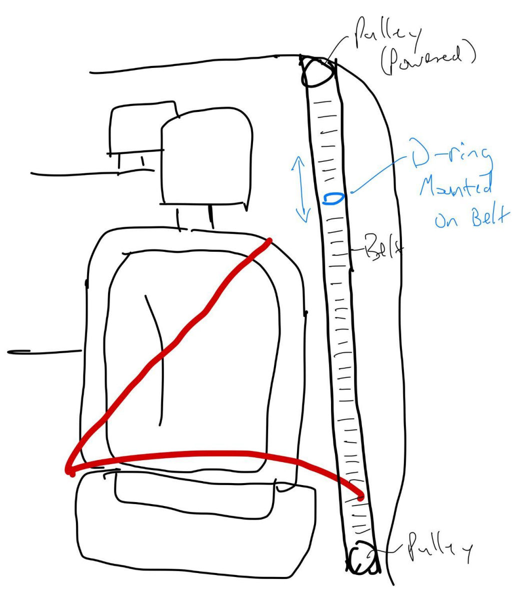


Figure 18: Concept 1 design

The first concept involves a pulley driven by a DC motor mounted to the roof of the vehicle, and a second pulley mounted to the floor of the vehicle between the driver seat and side of the car. The belt connects the 2 pulleys, and the D-ring is connected to the belt itself. As the pulleys are powered on and move, the belt would also move accordingly, as well as the D-ring attached on the belt, thus achieving the goal of adjusting the D-ring. This concept has 1 degree of freedom.

Concept 2

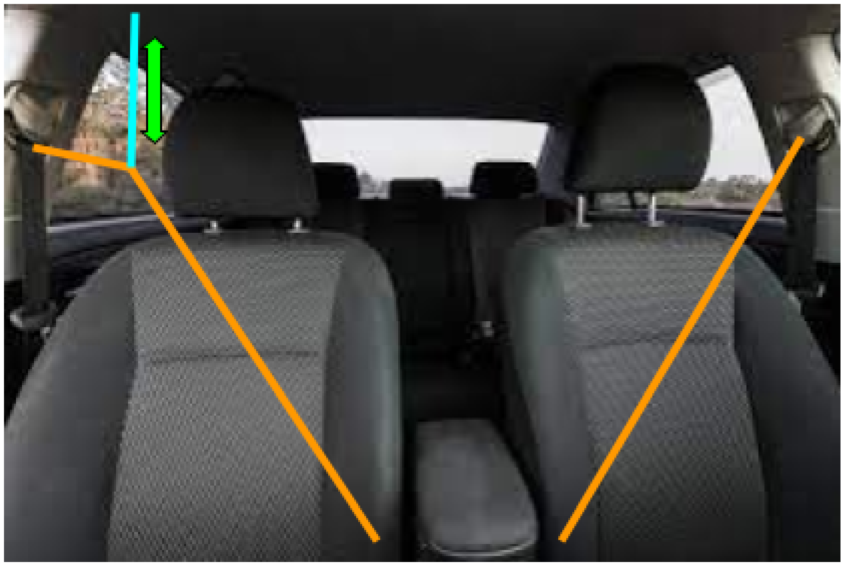


Figure 19: Concept 2 design

The second concept involves adding an additional belt to the vehicle. The new seat belt will be attached to the ceiling of the vehicle, which is shown as the light blue strip in the figure above (the original seat belt is depicted as orange). This new belt is designed to move vertically up and down to adjust the original seat belt shoulder position, as seen in image. The right side is the current standard seatbelt design, the left side is the concept 2 design, which includes a teal ceiling adjuster. This concept has 1 degree of freedom.

Concept 3

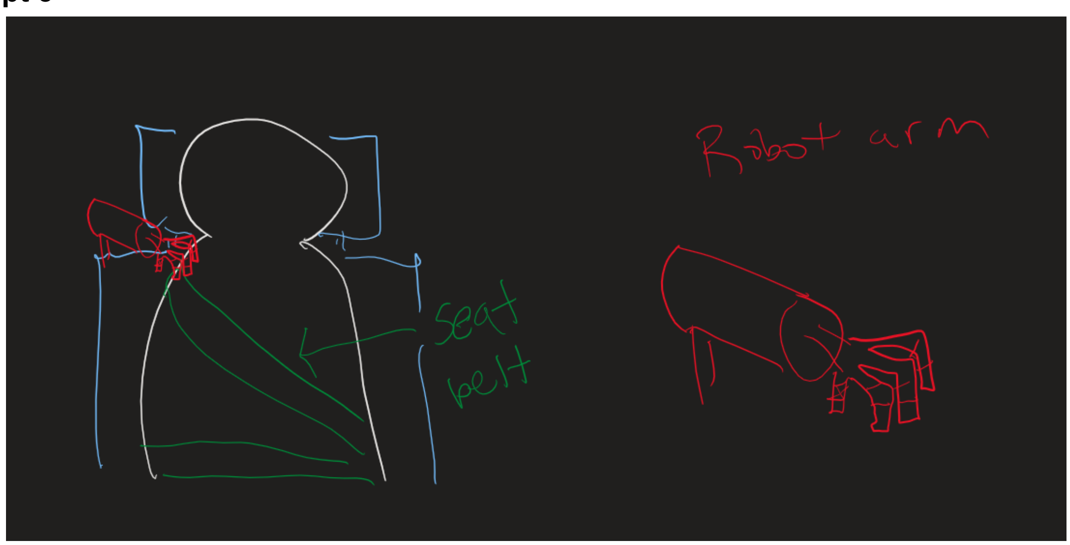


Figure 20: Concept 3

The third concept involves a robot arm placed behind the car seat. Once the passenger sits down in the vehicle and straps in the seat belt, the robot arm can automatically reach out and adjust the shoulder belt based on the position data received from the visual sensor. Although complicated, the robot arm will have a wide range of motion and is able to perform a much more detailed adjustment compared to other concepts.

Concept 4

Figure 21: Concept 4

The fourth concept follows a different train of thought compared to previous concepts. Instead of designing an add-on device to the vehicle's seat belt, concept 4 focuses on enhancing the existing seat belt D-ring adjuster design to provide a greater range of motion in the vertical Z-axis. Simply by expanding the adjustable range for the D-ring, the seat belt can accommodate a much wider range of passenger body shapes. The current range of standard seat belt D-ring adjustability is marked as yellow in the figure, and a potential improved range is marked in purple.This design is relatively simple while having flexibility, and has 1 degree of freedom.

Concept 5

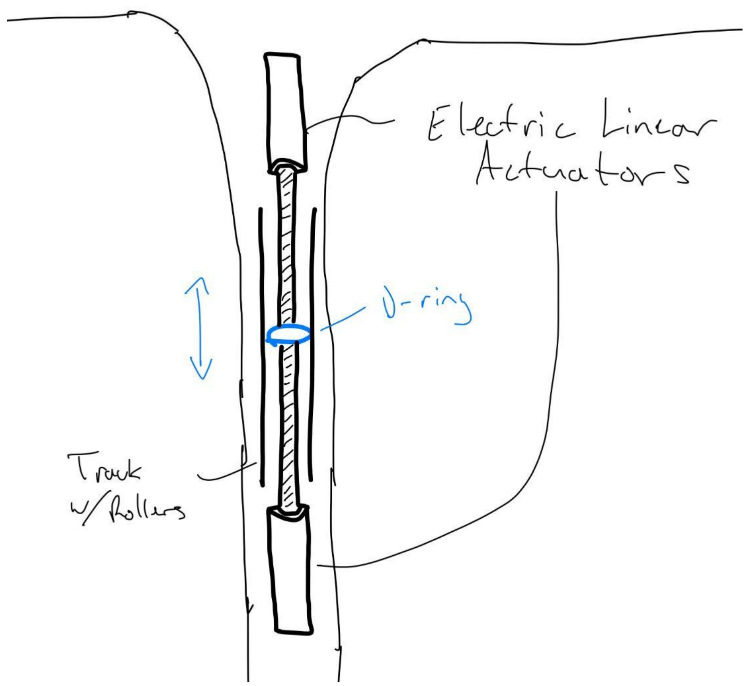


Figure 22: Concept 5

The fifth concept consists of 2 electric linear actuators and a track with rollers that the D-ring is attached to. This device will be mounted on the B-pillar (Figure drawn from the perspective of the driver side seat). A visual sensor would be placed to the right of the frame on the dash. The electric linear actuators are mounted above and below the D-ring and fixed to either side. This design has 1 degree of freedom, as actuators extend or retract the D-ring is moved up or down. Seat belt not depicted but would be threaded through D-ring (blue ellipse).

Concept Selection Process

Throughout the concept generation process, the array of designs created was intended to be exhaustive and include as many potential solutions as possible. For this reason, it was necessary to find certain criterias that would allow us to narrow down the range of potential solutions to a smaller number such that we could carry out focused concept selection techniques and determine an alpha design.

Concept Screening Criterias

The first criteria used was to place an emphasis on designs adjusting the D-ring as a means of moving the seat belt. This criteria was used both to address a requirement given to us by our sponsors, as well as reduce the amount of infeasible and overly complicated ideas. While the creative aspect of our concept generation process allowed us to widen our perspectives and produce some very out of the box designs, many of these failed to acknowledge this requirement and were therefore removed.

The second screening criteria was to place a greater emphasis on simplicity. Creating ideas such as fully rotational or double armed mechanisms, while holding potential to solve the issues at hand, are much more difficult to build and prototype than our other ideas. Ideas like this push the problem outside the scope of this class and our capabilities, and were therefore removed as well.

The third and final criteria we used to narrow down our designs was screening concepts based on whether they utilized 1 or 2 dimensional movement. As further research proves below, a 1-dimensional mechanism will be able to fulfill our height and BMI range requirements, and so was ultimately the preferred type of design - based on both ability and ease of construction.

Range of Adjustability - Criteria 3

It was made clear by our sponsors early on that an important metric that should inform our design selection is the overall range of adjustability of the D-ring needed for the range of occupant sizes we aim to accommodate [11]. To accomplish this, preliminary analysis of seatbelt range for human models generated on humanshape.org was conducted using SOLIDWORKS. It was determined through consultation with Dr. Klinich and Dr. Park that minimizing the complexity of the motion of the design would be ideal as it would lead to more accurate and programmable control of the mechanism [13]. Given this, tertiary analysis was focused on determining if a shoulder belt score of 22 mm could be achieved for occupants ranging from a small female (5’0”, BMI:18) to a large male (6’0”, BMI:40) with purely vertical D-ring adjustment, and if so, what the maximum vertical range necessary to accomplish this specification.

Empirical D-ring Location Data Collection

In order to isolate a vertical range of motion of the D-ring, it was necessary to determine a standard reference location of the D-ring with respect to the passenger seat in the other two axes of motion (fore-aft, and inboard-outboard). Such a reference location is not standardized between different car models, and so empirical measurements were required to characterize this. The car used for these measurements was a Subaru sedan that came standard with a manual D-ring adjuster. The goal with these measurements was to determine a reference fore-aft and inboard-outboard position of the D-ring in reference to the car seat such that we could create a CAD model where the D-ring is constrained to move only in the vertical direction while maintaining those standard reference positions (see Appendix D for description of measurement process and how values were derived). The resulting reference values are described in Table 6 below:

Table 6: Empirically derived reference values for the Fore-aft and Inboard-outboard location of the D-ring

Inboard Distance from D-ring to Centerline of Car Seat Headrest (mm)	Fore Distance from D-ring to Forward Face of Car Seat Headrest (mm)
243	3.97

These reference values could now be used to define our D-ring position in a CAD model in order to evaluate whether pure vertical adjustment of the D-ring would be sufficient for our design.

Human Shape Model SOLIDWORKS Analysis

Two SOLIDWORKS assemblies were created, each with a human shape model representing either extreme of our desired occupant size range placed in a front car seat model. Next, the values from Table 6 were used to define the outboard placement of the model D-ring with respect to the car seat model centerline and the aft placement of the model D-ring with respect to the forward face on the car set model headrest. The model D-ring was then mated to a vertical wall using parallel mate such that it was constrained to move only vertically while maintaining the reference distances in the other perpendicular axes of motion. Once the D-ring was constrained, a reference curve was created which spanned from the D-ring model to the seat belt latch and which referenced points on the front side of the human model to account for the curvature the seatbelt would have when placed over a real occupant. Figure 23 below provides a visualization of all of these components of the model:

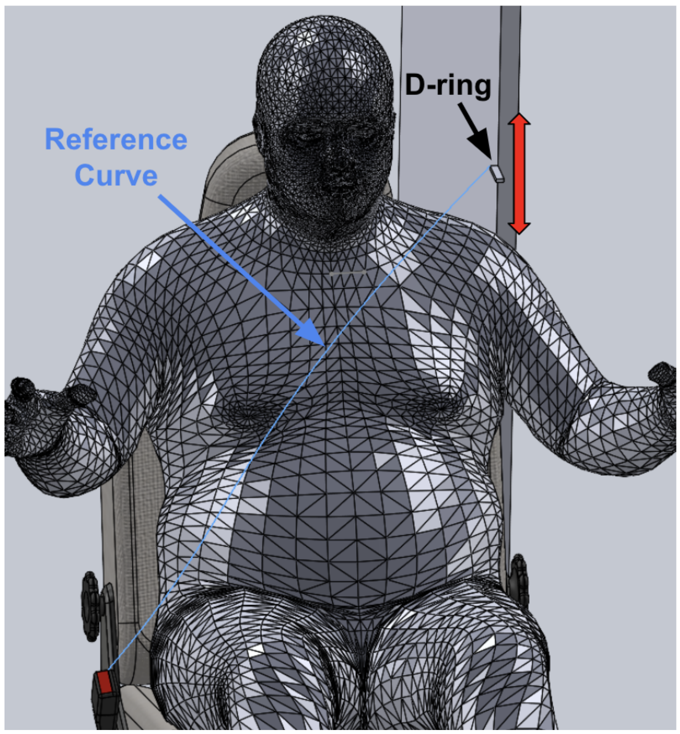


Figure 23: Large male SOLIDWORKS assembly with model D-ring and reference curve labeled.

As can be seen in Figure 23, the D-ring is the only component that can be moved and it is constrained to move vertically. Since the reference curve uses a point on the D-ring as an endpoint, its overall shape changes when the D-ring is moved up or down. Ultimately, we wanted to be able to move this model D-ring and determine the resulting shoulder belt score. As such, a horizontal line representing the shoulder belt score was drawn on the model from a point representing the suprasternale landmark such as in Figure 2. Then, the D-ring was adjusted up/down while viewing the whole model head-on until the reference curve intersected the rightmost point of the shoulder belt score line. Once this position was reached we could then measure the vertical distance of the D-ring from the bottom of the attachment wall and associate that measurement with the shoulder belt score referenced. Our specification for shoulder belt score is 22 ± 20 mm; from initially observing the effect of moving the D-ring on the reference curve it was clear that increasing the height of the D-ring corresponded to a smaller shoulder belt score. As such, we determined that the maximum range of adjustability needed for the D-ring would be between the vertical position corresponding to a shoulder belt score of 42 mm on the small female model, and the vertical position corresponding to a shoulder belt score of 2 mm on the large male model. We also wanted to determine the range of adjustability needed to encompass the ideal shoulder belt scores on each model only (22 mm) for future testing purposes. A front view of each model with D-ring location corresponding to the ideal shoulder belt score is shown in Figure 24 below:

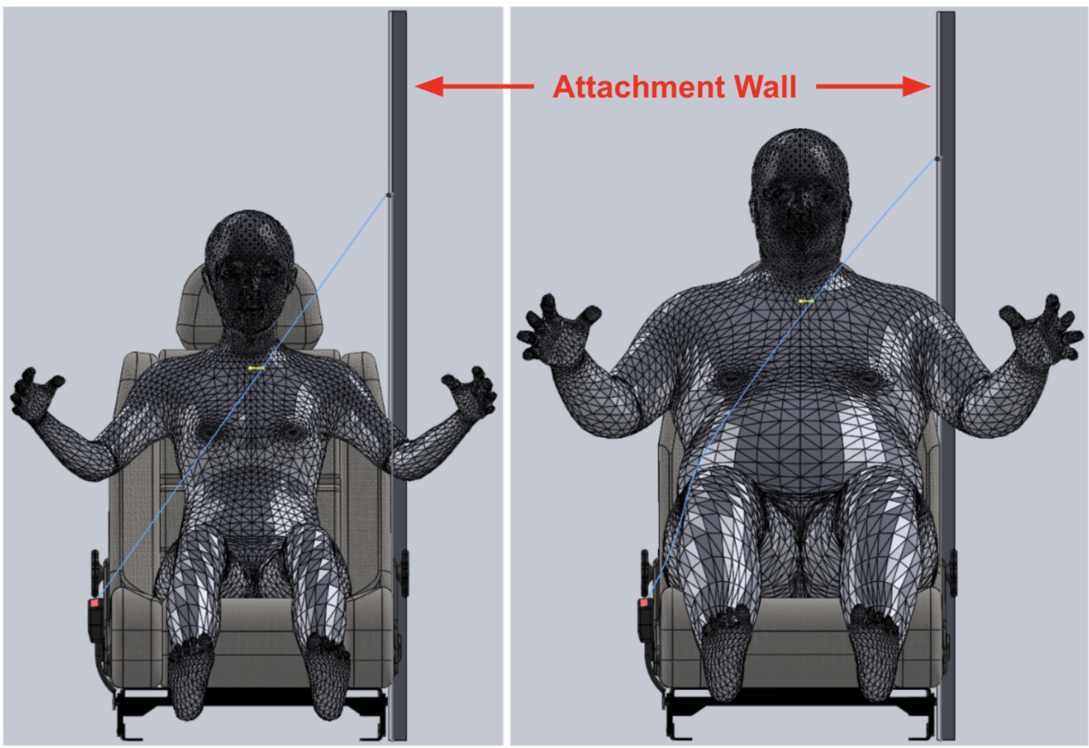


Figure 24: SOLIDWORKS car seat assemblies with small female (left) and large male (right) human models where D-ring vertical position corresponds to the ideal shoulder belt score of 22 mm (shoulder belt score line shown in yellow). See Appendix E for detailed description of human shape model characteristics.

Using this framework, measurements were taken for both the ideal shoulder belt score locations as well as the upper and lower bounds described previously. The height measurements were taken as the vertical distance from the D-ring to the bottom of the adjustment wall shown in Figure 24. Then, these heights were compared - the differences represented the range necessary to adjust between the scenarios referenced (see Appendix E for all measurements and derivation of final range). Table 6 below describes the derived range of vertical adjustability.

Table 7: Vertical range of adjustability needed to achieve specified ideal shoulder belt score (22 mm) for specified occupant size range (5' tall female with BMI of 18 to 6' tall male with BMI of 40)

Range of Adjustability Needed to Achieve Ideal Shoulder Belt Score (in)	Range of Adjustability Needed to Achieve Ideal Shoulder Belt Score Including Uncertainty (± 20 mm) (in)
2.64	7.57

Since our maximum range of adjustability needed to theoretically achieve a comfortable fit for our specified range of occupant sizes is 7.57 inches, we determined that it was feasible to create a design which only incorporated vertical motion (one degree of freedom) and that could achieve this necessary range of vertical adjustability. This allowed us to rule out the remaining designs that had more than one degree of freedom and designs that had linear motion but in a non-vertical axis of motion. Doing so left us with 5 remaining designs that incorporated purely vertical motion. These 5 designs are described below in **Table 8**.

Table 8: 5 selected designs

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Linear Actuators Design

This design consists of 2 electric linear actuators and a track with rollers that the D-ring is attached to. This device will be mounted on the B-pillar (Figure drawn from the perspective of the driver side seat). A visual sensor would be placed to the right of the frame on the dash. The electric linear actuators are mounted above and below the D-ring and fixed to either side. This design has 1 degree of freedom, as actuators extend or retract the D-ring is moved up or down. Seat belt not depicted but would be threaded through D-ring (blue ellipse).

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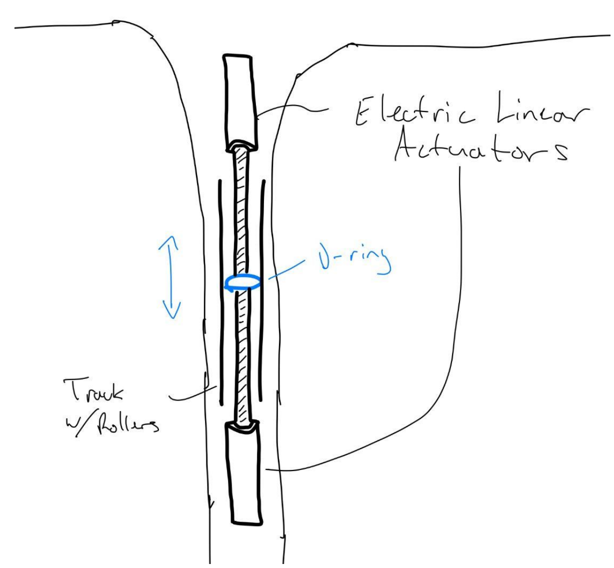

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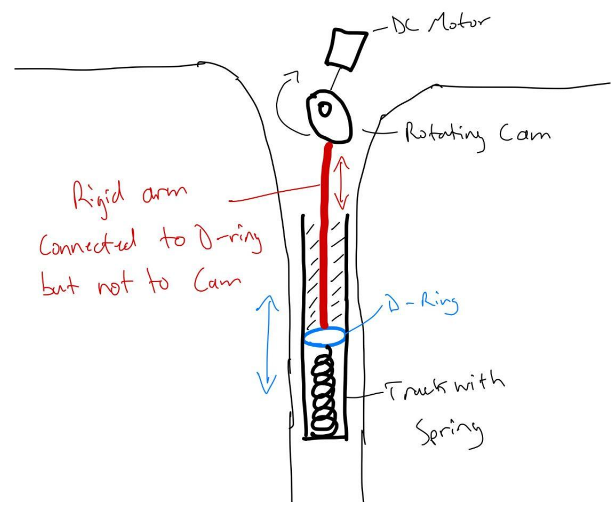
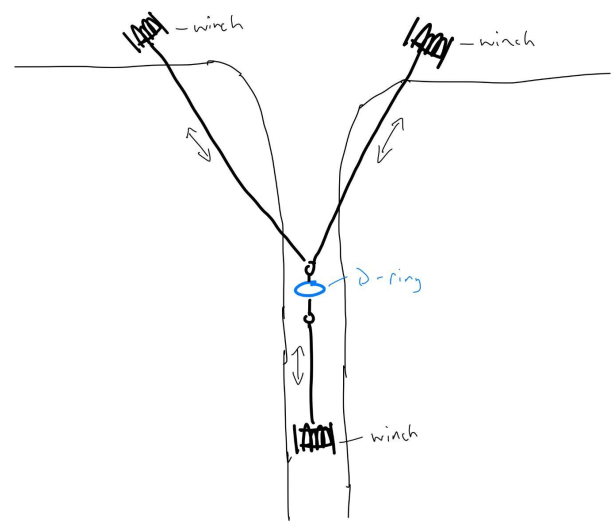
Rotating Cam Design In this design, a rotating cam is engaged with a rigid arm that is constrained vertically by a track (mounted to B-pillar). The D-ring is attached to one end of the rigid arm and is also engaged with the track on rollers. The other end of the arm is not connected with the cam, so when the cam rotates it pushes the rigid arm down along with the attached D-ring. On the other side of the D-ring there is a spring which compresses or extends as the cam rotates.	
Winches Design In this design, 3 winches are mounted on the B-pillar side of the vehicle, there will be 2 winches on top of the D-ring, which are mounted at a certain angle above the B pillar. The other winch is located below the D-ring. Strings connect the winches and the D-ring. By turning one or multiple winches, the D-ring can be adjusted across 2 degrees of freedom.	

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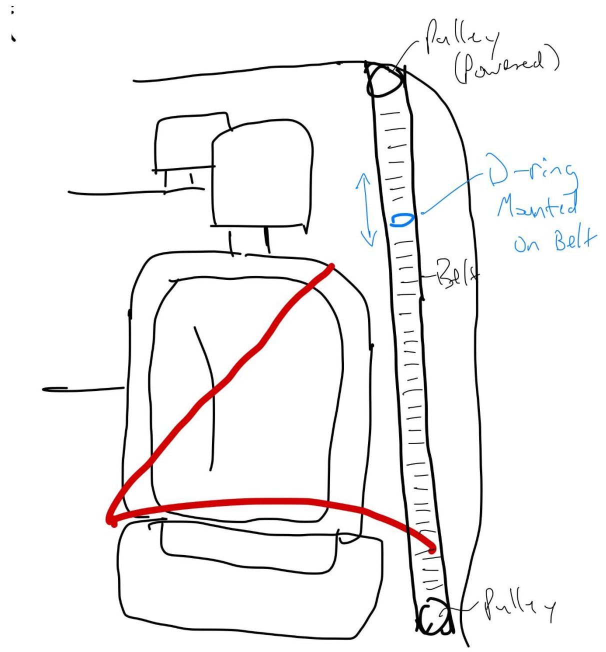
<td>Belt & Pulley Design

This design involves a pulley driven by a DC motor mounted to the roof of the vehicle, and a second pulley mounted to the floor of the vehicle between the driver seat and side of the car. The belt connects the 2 pulleys, and the D-ring is connected to the belt itself. As the pulleys are powered on and move, the belt would also move accordingly, as well as the D-ring attached on the belt, thus achieving the goal of adjusting the D-ring.</td>
<td>
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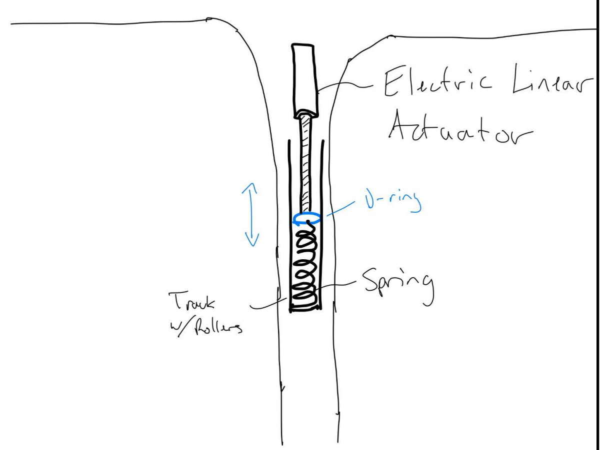
<tr>
<td>Actuator/Spring combo Design

Similar to the 2 electric linear actuators design, this actuator/spring combo replaces the bottom actuator with a spring. A track is mounted to the B-pillar, in which the D-ring is engaged with the track with rollers. An electric linear actuator is mounted above the D-ring. The spring mounted underneath the D-ring provides a resistive force to the actuator pushing it up when the actuator retracts.</td>
<td>
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Concept Evaluation

After screening the initial concepts based on the criteria listed above, we were able to translate the user requirements for our top 5 concepts into scoring categories utilized in a Pugh chart. The two highest priority requirements include range and sensitivity. The range category incorporates the achievable range of adjustability of the shoulder belt and the D-ring location. The design concepts were graded by how efficiently they can achieve the same range of motion with their respective actuation systems. For example, actuation systems such as the rotating cam were assigned a lower score due to requiring a larger cam in order to achieve the same range of motion that of a linear actuator. The sensitivity category describes the accuracy at which the shoulder belt position can be achieved. If we were to fulfill an proximity range of ± 2 cm, each design concept must use actuators and controllers that are able to move the D-ring and shoulder belt in intervals of millimeters or any magnitude less than centimeters. As these requirements are specified as highest priority, their respective weights reflect their importance by having the highest value of 5.

As the automatic seat belt adjuster is catered to individuals who may have mobility issues such as disabled or elderly people, we must ensure that the design concepts are simple. Simplicity ensures lower probability of failure and less complicated methods of maintenance. Additionally, simplicity poses less challenges for the users in terms of interaction. The simplicity category includes grading aspects such as number of parts, complexity of actuation system, and utilization of simple machines. As inclusivity is also an important aspect of the design solution, we have decided to give this category a weight of 4.

An automatic seat belt adjuster that uses a visual sensor and converting its output data in order to position a shoulder belt requires a multi-step process as opposed to the process of manually adjusting the shoulder belt. We have determined that the adjusting system must collect data and send its data to the controller and actuator within a 4 second time frame in order to achieve adequate speed. We have compared the stroke length, rotational speed, and mechanical advantages of each actuation system. Speed is a moderately important category, which has a weight value of 3.

The automatic seat belt adjuster must be compatible with a wide range of vehicle models for installation. This category similarly considers the simplicity aspects of the design concepts, such as the number of parts, but also examines the sizes of each actuation system. Since this category is of lower priority, we have given this a weight a 2.

We have determined that affordability is a low priority user requirement as stated previously. It is more important to cover a wide range of user profiles and achieve an accurate shoulder belt score than to account for the price required to purchase parts, manufacture, and maintain. The significance of this category is reflected in its weight, which is a value of 1.

The pugh chart in its entirety can be seen in table 9 below, and indicates the **Linear Actuator** design as the most suitable design choice.

Table 9: Pugh Chart

Category	Weight	Linear Actuators	Rotating Cam	Winches	Belt & Pulley	Actuator / Spring Combo
Range	5	5	2	2	3	4
Sensitivity	5	5	3	3	2	4
Simplicity	4	4	2	4	3	3
Speed	3	4	2	3	3	4
Installability	2	3	1	1	3	3
Affordability	1	2	3	2	4	3
Score total		**86**	44	54	56	73

Chosen Design

Our selected concept was built off of the **linear actuator** design chosen using our pugh chart. Following the identification of this design as the superior concept, we further iterated on it in order to maximize its potential to satisfy all design requirements. The initial concept is seen again in figure 25 prior to being updated.

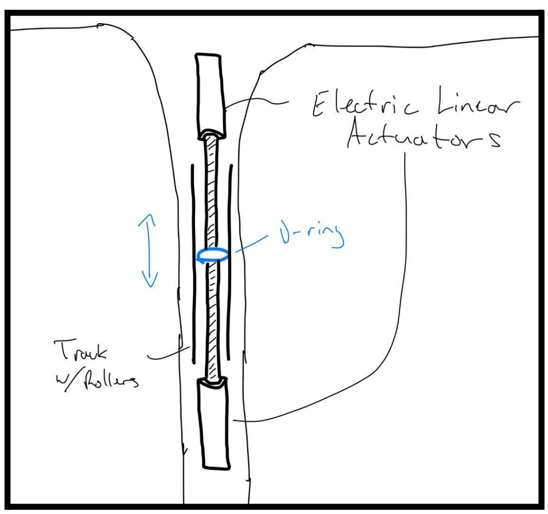

Figure 25: Selected “alpha” design of linear actuators, prior to iteration

Design Justification and Specifications

Our selected design is built off of this double linear actuator concept. Following initial analysis of the concept, it was determined that one linear actuator would be sufficient in that employing a second actuator **could not** be utilized to add additional range of motion with the use of a rigid D-ring attached between the two. Additional early-stage iteration was done in determining potential methods by which one-dimensional motion could be assured. These changes are reflected in our first CAD prototype of the mechanism portion of our model, seen below.

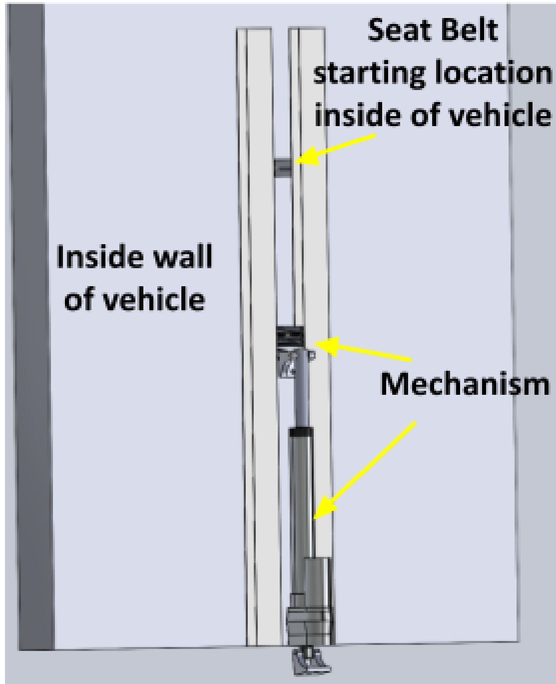

Figure 26: Preliminary CAD model of selected prototype (mechanism only)

In this model of the mechanism portion of our design, a secondary D-ring is attached rigidly to a linear actuator and located between two H-bars that guide its motion. The seat belt of the vehicle would come out of the vehicle B or C pillar as normal, based on if the occupant was in the front or back seat of the car, and would then be guided through the second D-ring attached to the actuator within our mechanism to adjust its height. The actuator would then be controlled using the photo sensor subsystem of our design to move the D-ring up or down. The H-bars provide restraints on the motion of the D-ring and actuator and are useful in providing additional durability to the system as it operates. A closer look at the interaction between the D-ring and H-bars can be seen in figure 27 below.

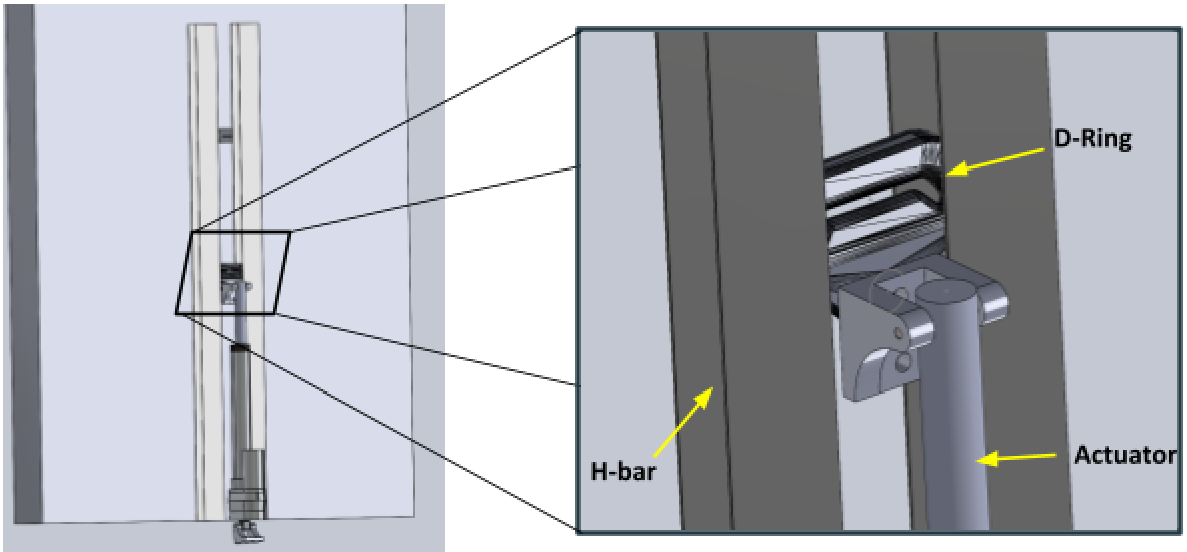

Figure 27: Close up look at mechanism

Inclusion of Photo-Processing and Controller Subsystems

While our team has placed a priority on ensuring we are able to produce a working mechanism capable of fulfilling the range of motion we specified in a durable and controllable way, the photo-processing and controller subsystems of the project cannot be overlooked. While the exact processing tools are still being researched by our team, the relative location and size of these tools relative to our mechanism has been approximated, and is demonstrated below in figure 28.

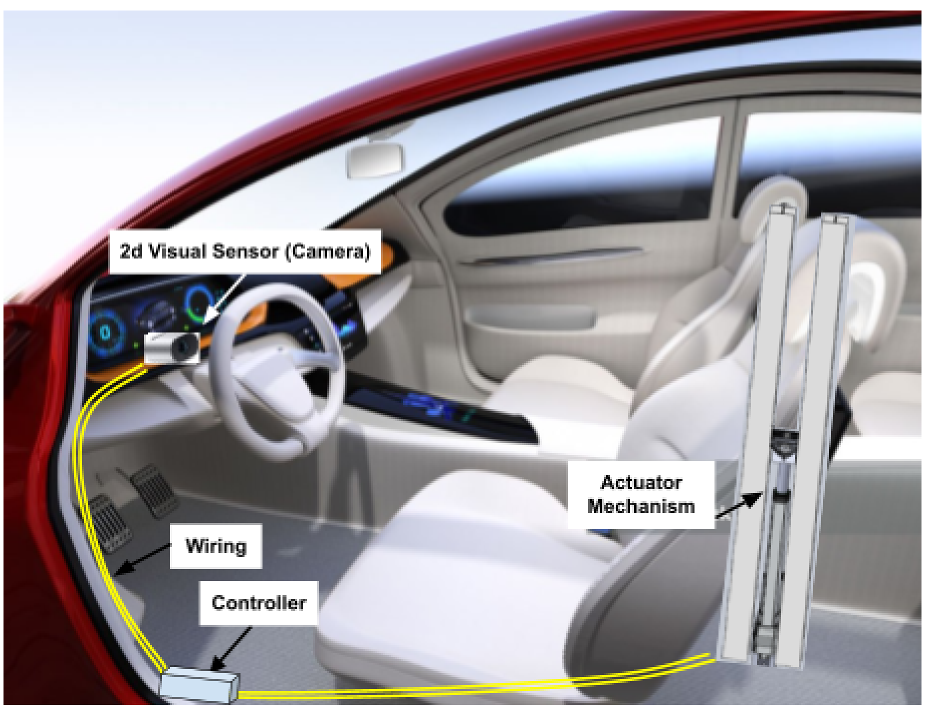

Figure 28: Interaction between visual sensor and actuator mechanism within vehicle.

Iterative Bill of Materials
While our selected concept remains subject to change as we perform more analysis into its capabilities, we have produced a rough bill of materials based on the essentials of the initial design. The components listed are only what we have finalized as major components for construction of the mechanism. Additional screws and wiring components will need to be assessed and added as we iterate on the prototype.

Table 10: Bill of materials

Part No.	Part Title	Material	Dimension	Supplier	Quantity	Price	Notes
1	D-ring	Zinc Plated Steel	1.875” x 2.75”	McMaster-Carr	1	$9.79	Capable of fitting seat belt inside slot
2	H-bar	Aluminum	0.05” x 1.724” x 3’	McMaster-Carr	2	$13.74 each	May be milled down based on engineering analysis
3	Linear Actuator	Alloy-steel shaft, aluminum alloy housing	16.1” x 3.82” x 2.05” package, extended length 26.4”	Amazon	1	$42.99	Various sizes available from 2” to 18” extension - 10” satisfies requirements with safety factor of approx. 1.25
4	Seat Belt Restrainer	Plastic Polyester	Dependent on model	Amazon	1	$6.99	None
5	Controller	Arduino	Dependent on model	Amazon	1	$14.70 - 53.80	Arduino Model dependent on pin usage

While initial designing on CAD has been performed already by various team members, we have chosen to omit assigning roles in further designing, purchasing, and machining tasks until our design has been analyzed and the final design has been chosen. Additionally, until our design has been finalized we have omitted the inclusion of screws and attachment mechanisms, as they are subject to change. However, we have begun initial analysis of determining the type of screw, nut, bolt, etc that will be necessary to attach each component to each other.

Early Manufacturing Plans
While there remains much iteration necessary prior to the development of a marketable product, various components can begin to have plans created for their manufacture. The D-ring purchased for our design, while remaining essentially intact, will require a slot for placing the seatbelt within it. This can be accomplished using a mill. The H bars, following additional analysis on their feasibility, may also need their length of 3 feet shortened to accommodate smaller vehicles, should there still be a great enough range of adjustability when these lengths are reduced. Holes for screws in the H bars for potential mounting purposes (to the actuator and potentially the vehicle itself) will also need to be researched, but will be easily done using a mill

to provide for precision and clean drilling of the holes. As our design develops and more specific nuances are addressed, our team's manufacturing plans will become more intricate and exact, however our initial analysis leads us to believe that additional manufacturing beyond the assembly of pre-existing parts will likely be minimal and limited to use on the mill.

Engineering Analysis

With the framework of our chosen design laid out, our team took time to carefully conduct analysis for all components in order to narrow down and select specific parts and materials for a final design. This process involved looking at each user requirement-engineering specification pair we set, determining what constituent parts of our chosen design would be contributing to the goal of the specification, then conducting rigorous analysis in order to determine what that specific part would need to achieve quantitatively.

Enhanced Range of Adjustability and Comfortable Shoulder Belt Placement
The user requirements of achieving enhanced range of adjustability and a comfortable shoulder belt placement are intertwined in purpose; providing a comfortable shoulder belt placement for a given occupant is important, but it can only be achieved given that the D-ring has enough range of adjustability to accommodate that specific occupant. As such, the part of our design that influences both of these specifications is the part responsible for the physical motion of the D-ring: the linear actuator. More specifically, the stroke length of the linear actuator which corresponds to the range of movement of the D-ring is the factor which determines if both of these specifications can be achieved.

The human shape model d-ring adjustability analysis detailed in the design selection section was effective in allowing us to translate our engineering specifications into a metric that could be applied to actuator selection (see Appendix D-E). The main goal with this analysis was to translate the range of occupant sizes (defined using height and BMI) to a linear distance in which the actuator stroke must encompass. An alternative method we considered was to empirically derive the range of adjustability by having one of us sit in a car seat and manually lift and lower the seat belt. The simulation alternative was chosen because the human shape model database allowed us to most accurately model occupants at either end of our specified range [12].

As described previously, empirical measurements were taken to constrain a reference D-ring location relative to the seat in the fore-aft and inboard-outboard directions (see Appendix D). The next step was to consolidate and constrain the CAD models. The greatest limitation of this method was the physics of the reference curves we used to simulate the seat belt over the occupant models. The curves were constructed by connecting points on the belt buckle and D-ring and then defining reference points on the occupants body through which the curve would travel. These contact points were determined qualitatively by referencing frontal wheelchair occupant pictures taken in our sponsors research. Occupants in the study had a variety of body shapes, and reference pictures were selected based on how closely the occupant resembled the human shape model. This comparison is shown for the large male case in Figure 29 below.

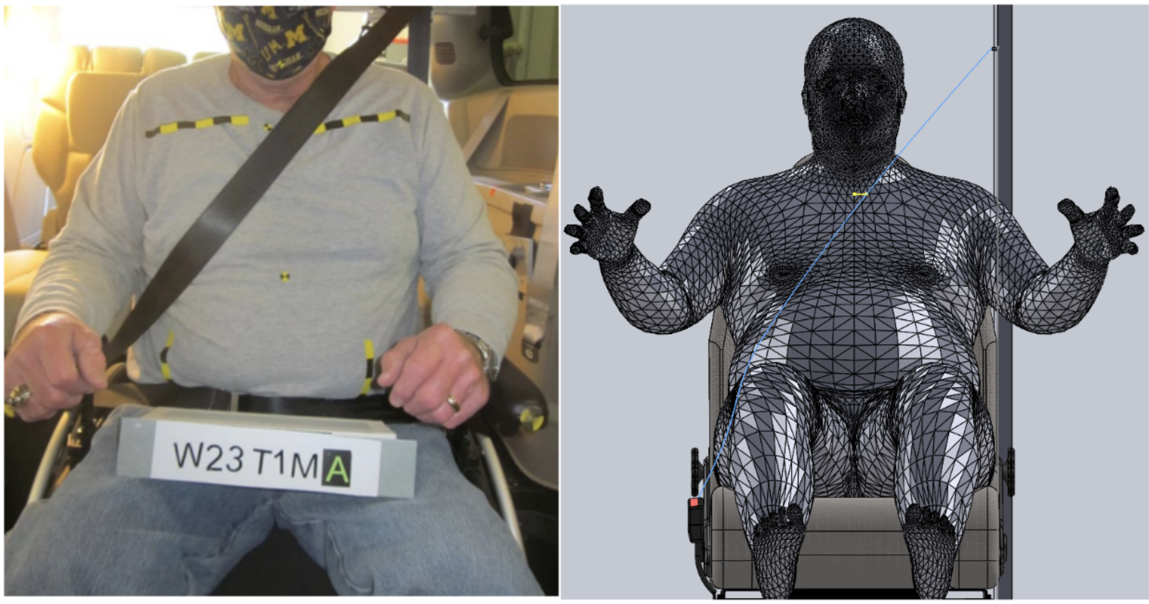

Figure 29: Comparison of SOLIDWORKS model with reference curve to frontal picture of similarly sized occupant in Automated Wheelchair Tiedown and Occupant Restraint System study for defining of points on human model through which reference curve travels [3]

Despite how close in size the occupant is, their body shape is not exactly the same, meaning that the reference curve is still an approximation. However, this approximation was deemed to be satisfactory for this analysis. Table 11 below gives an overview of the metrics derived from this analysis, where the D-ring height was measured after aligning the reference curve with the shoulder belt score sketch (shown in yellow in figure 29).

Table 11: Results from CAD human shape model D-ring adjustability analysis

Occupant	Small Female D-ring Lower Bound (5', 18 BMI)	Large Male D-ring Upper Bound (6', 40 BMI)
Shoulder Belt Score (mm)	42	2
D-ring Height from bottom of attachment Wall (mm)	944.1393	1136.4117
Necessary Range of Adjustability	192.2724 mm ≈ **7.5698 in**	

As can be seen from these results, the specification for our occupant range (shoulder belt score of 22 ± 2cm) was used in combination with the specification for our occupant size range (small female to large male) through this analysis to derive a range of adjustability necessary to meet both specifications. Provided this range, we were then able to assert that <u>the linear actuator chosen must have a stroke length greater than or equal to approximately 7.57 inches.</u>

While having an actuator that can physically reach the position necessary to achieve our specified shoulder belt score is paramount, it cannot do so without a control system that can command its actuation. As such, as part of meeting the shoulder belt score requirement we included selection of the control system. Due to the similarity of our actuation system to that of our shared previous experience in ME 350, we decided to use an Arduino Uno in combination with an L298N Dual H-bridge motor driver. Additionally, we need to get an AC-DC 12 V power supply. The Arduino Uno was chosen due to its robustness and our familiarity with it. The L298N was chosen due to its ability to interface between the arduino and DC motor powering the linear actuator. Moreover, the L298N has a built-in 5 volt regulator. This allows us to establish the 5 V operating voltage for the Arduino without needing to use resistors to reduce voltage from the power supply.

Ensure Accurate Imaging Data

In order to calculate the shoulder belt score, major landmarks of the human body must be identified and utilized. The most important landmark needed to calculate the shoulder belt score is the suprasternale point. The visual sensor as well as the library used to identify the landmarks must be able to capture the upper torso of the user. However, there may be cases in which the suprasternale is not enough to calculate the shoulder belt score. In these cases, there must be other indicators or reference points of the human body that are captured by the visual sensor and its respective data sent to the controller. These landmarks include the shoulder left and right and the center head point. The visual library used to identify these landmarks will be OpenPose. OpenPose is a real-time multi-person human pose detection library that has the capability to jointly detect the human body, foot, hand, and facial keypoints on single images [27]. Although this software is able to track the human structure in real-time, it can also detect keypoints through a still image. Since the automatic seat belt adjustment will be performed a single time by the user, preferably before the vehicle starts moving, a still image may be preferred in order to save energy consumption. The simplest way to see whether the engineering specification can be accomplished will be by examining the specifications of the OpenPose software. According to the developers of OpenPose, the software is capable of detecting a total of 135 key points simultaneously [27]. However, this specification refers to identifying the landmarks on multiple people while the automatic seat belt adjuster only needs single person capability. Figure 1b labels the major key points that it can detect on each human model.

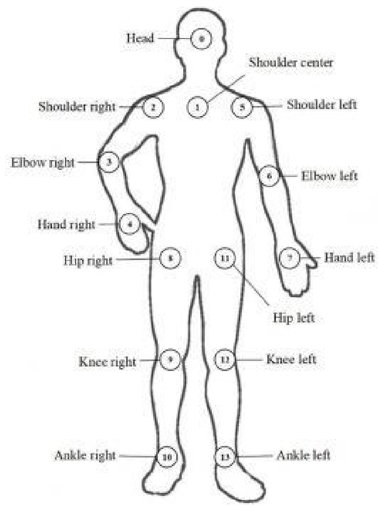

Figure 30: OpenPose major landmark identification capability [27]

This figure shows that for each individual, OpenPose can identify and track 14 major landmarks. As stated before, the process of automatic seat belt adjuster only concerns the key points located on the upper torso of the human body. The only limitation of this analysis is that we are unable to determine any accuracy issues that the software might have. Still, if the landmarks are in the vicinity of the desired and predicted locations on the human model, we can account for those discrepancies through code.

Utilize Visual Sensor and Library

The automatic seat belt adjuster to be competitive with the manual adjusting method through means of accuracy and comfortability. One way to quantify comfortability is through the speed of the automatic seat belt adjuster system. The engineering specification for this requirement currently states that the time from the visual sensor measurement to the adjuster must be less than 4 seconds. To further elaborate this specification, we have determined that this time limit must be the time from the visual sensor capturing the scene to when the adjuster moves one millimeter. We have also further defined this process through four individual steps. The first step involves a visual sensor, in which we identified as a webcam as these types of visual sensors are the most accessible through availability and cost. Additionally, the usage of webcam has been recommended by our sponsors as they also have experience with webcams in their studies. Then the scene captured by the webcam will be sent to the library of OpenPose. This software will be able to convert the scene into readable visual data for our third step mechanism, the controller. We have identified this controller to be the Arduino as again, these types of controllers are the most accessible and cost efficient. The final stage consists of the linear actuator, in which will move the D-ring one millimeter. Although this step will be most accurately timed through empirical testing, once the system has been built, we can easily calculate the total runtime of this system considering the specifications of each technology.

The time it takes for a webcam to capture a single image is dependent on its shutter speed or exposure time. If we were to use a still image for this adjuster process, an average webcam has an average exposure time of 1/30 or approximately 0.034 seconds according to models found on Amazon. We have chosen the webcams with the slowest shutter speeds in order to accommodate the different types of webcams we may use. If we choose to capture a video of the human model, the equation to calculate the runtime becomes:

$$Total\ Runtime\ =\ \frac{Number\ of\ Frames}{Frame\ Rate}$$

Equation 1: Calculation of total runtime of capturing a video through a webcam

According to the webcam models sold on Amazon, the average webcam has a capture rate of 45 frames per second. The video time needed to capture the scene will be close to that of a still image. The number of frames that it takes to capture an accurate scene can be considered as one frame as the subject will be still and the scene will be stationary. However, we can account for extraneous factors such as webcam shake by determining the needed frames to be 25 frames, much larger than the theoretical need. Therefore, we have calculated the total webcam runtime to be .56 seconds.

The second step consists of OpenPose receiving the visual scene from the webcam and then identifying and visualizing the major landmarks on the human model. This runtime is dependent on the graphics card specification of the computer or laptop used. There are studies done on the runtime for capturing individual and multiple models using OpenPose. The study we have used to calculate the runtime of this step uses a computer that has a 1080 Ti graphics card, an outdated graphics card. Their measurements are shown in Figure 31.

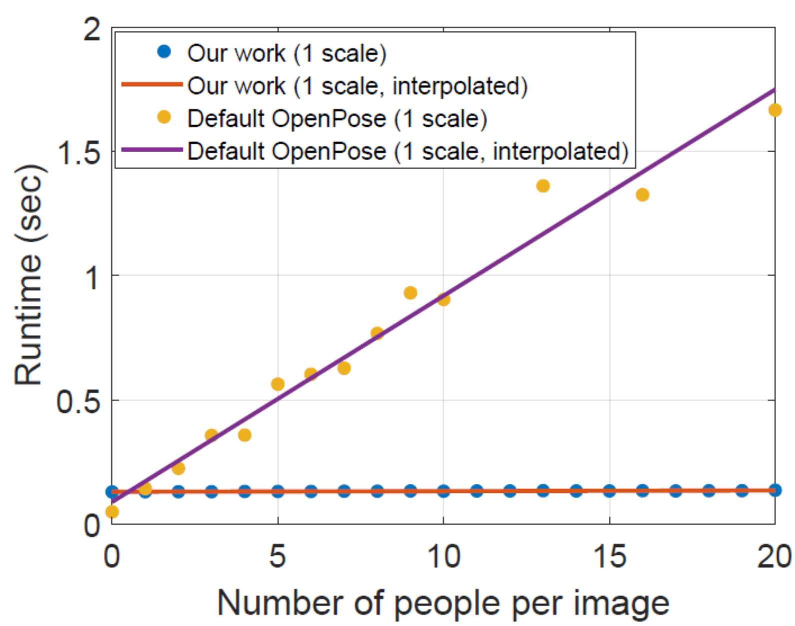

Figure 31: Research study showing the runtime of OpenPose in identifying and visualizing the major landmarks on human models

Though this study shows time measurements with multiple human subjects and measurements with improvements they made with code, we are most interested in the Default Open pose model of one person per image. Their experiment shows that the total runtime for one human model through OpenPose is approximately 0.14 seconds. The limitation of this analysis is that we will have computers that have a different graphics card, but we can safely assume that this runtime will be under a second as the used graphics card is outdated and many modern computers have better specifications.

The third step consists of the Arduino controller receiving and processing the visual data from OpenPose and executing code. This runtime is dependent on the type of connection it has to OpenPose and the processing speed of the Arduino. The simplest connection we can use between OpenPose and the Arduino will be that of serial communication. Utilizing a bluetooth and other wifi communication will be prone to error and longer runtimes. We have used the Arduino Uno as the benchmark of this analysis as it is one of the most common controllers used and it is one that the project group has the most experience with. The Arduino Uno uses a USB 2.0 interface for communication with a computer and this type of connection supports a maximum data transmission speed of 480 Mbps. However, it is difficult to calculate this total runtime as the Arduino is largely dependent on the code it is executing and the necessary input and output pins used. We have empirically tested a simple DC motor circuit as the linear actuator also uses a DC motor to actuate. Figure 1h shows the board that we have used to simulate these tests.

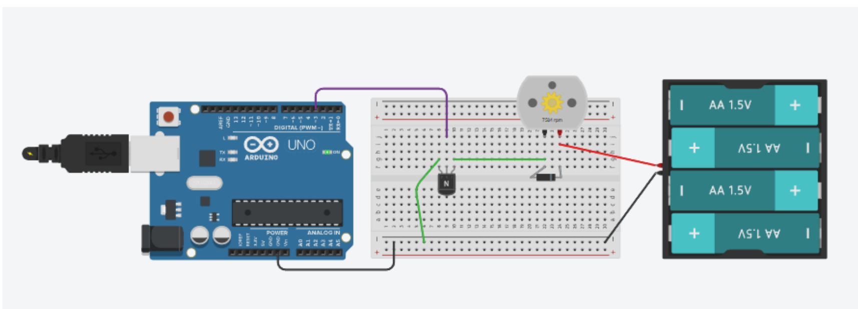

Figure 32: Simple DC motor board experiment

The average runtime to get the motor to start actuating was approximately 0.5 seconds. The limitation of this experiment is that the connections and pins used for our seat belt adjuster will be different from this simple DC motor board. To account for the additional pin connections and the different code execution, we have given a time frame of 1.5 seconds for this step as the time to process visual data will be increased.

The final step of this process will be the linear actuator moving a distance of one millimeter. This step is dependent on the travel speed of the linear actuator. The linear actuator that we will be using for our design has a travel speed of 0.4 inches per second or 10 millimeters per second. We can simply use a ratio comparison to calculate the runtime for the actuator moving one millimeter in Equation 2.

$$\frac{10\,mm}{1\,s} = \frac{1\,mm}{x\,s}$$

Equation 2: Calculation for total runtime of linear actuator moving a distance of 1 millimeter

From this calculation, we can approximate the runtime of the last step to have a value of 1/10 or 0.1 seconds. We have increased the allowed runtime of this step to be 0.2 seconds to account for the friction that the motor and actuator will have to overcome to start moving.

If we were to calculate the total runtime of the entire four step system, we would have to add the runtime of each step. From this, we can estimate that the time it takes for the webcam to capture a scene to moving the actuator to be 1.874 seconds for a still image and 2.4 seconds for a video or multiple frame scene.

Safety

There are several vehicle codes that the seat belt adjuster must abide by in order to be available for commercial use. These codes are largely concerned with the safety of the passengers as well as the structural integrity of the vehicles. Since the seat belt assembly is a large component of safety precautions, adding any mechanisms or equipment affecting the seat belt performance must be compliant with the code requirements.

The first code that we are concerned with is 49 C.F.R. 393.60(e)(1)(ii). This code specifies not only the mounting parameters of safety equipment, but also the amount of windshield that must not be covered by safety equipment. The safety equipment that is affected by this code will be the visual sensor or webcam that we will be using. The webcam must be able to capture the upper torso of the passenger subject in order to locate and identify the major landmarks. This gives us the option to mount the webcam on the front dashboard of the vehicle, or directly on the windshield as long as it is mounted not more than 216 mm below the upper edge of the area swept by the windshield wipers and not more than 175 mm above the lower edge of the area swept by the windshield wipers as stated previously in the user requirements section. However, both options will cause the webcam a small area of the front windshield. In order to calculate the percentage of windshield covered, we must know the area of the windshield as well as the frontal area of the webcam. We have taken the average lengths and heights of the largest webcams. The average dimensions of these webcams are approximately 1.65” x 1.65”. Additionally, the average surface area of a standard windshield is approximately 59” x 31.5”. From there we can create a ratio shown in Equation 3 to get a percentage of 1.5%.

$$Percentage\ Covered\ =\ \frac{Area\ of\ webcam}{Area\ of\ windshield} \times\ 100\%$$

Equation 3: Calculation of percentage of front windshield covered by webcam

The second code that we must follow is FMVSS No. 210, which consists of regulations following seat belt assembly anchorages. Abiding by this code as this is dependent on the screws and fasteners used in the build design. This code will be best evaluated by empirical testing once the build design prototype has been completed. If a certain type of fastener does not abide by the code regulations, we will have to change the types of fasteners by utilizing different materials, such as stronger metals, in the assembly.

The third code that we must follow is FMVSS No. 209. A certain regulation in this code that we must follow is that the reaction force of the strap in the retractor must be larger than 1N when under 7N force. This is to ensure that the strap will not simply snap under tension when the vehicle is going through an impact collision. Similarly, this analysis will be best examined under empirical testing once the build design has been produced. However, we can run simulations to determine the reaction force of the seat belt strap. Through this simulation, we were able to identify a resultant force of approximately 2N. The limitations of this simulation comes from the material properties of the adjuster assembly, namely the wood and fastener components. The types of fasteners used in the current assembly is dependent on code FMVSS No. 210 so we have determined to use fasteners made of conventional steel. Additionally, the wooden part of the build material in which the H-bars are attached do not have available properties on Solidworks, in which the simulation was performed. However, we were able to give certain parameters to this material, in which we have determined to have the elastic modulus, Poisson's Ratio, and yield strength of oak wood.

The final vehicle safety code in which the seat belt must abide by comes from FMVSS No. 208. This code mostly refers to the passenger safety standards in regards to a frontal impact collision. The following section explains the manual calculations in which we determined the force affecting the D-ring performance.

Force Analysis on D-ring

Since our chosen design is meant to incorporate an OEM three point seat belt assembly and modify passenger vehicles, it was important that our non-OEM components not hinder the ability of the overall seat belt assembly to comply with federal motor vehicle safety standard No. 209 detailing seat belt assembly regulations and No. 208 detailing occupant crash protection demands. The primary non-OEM component in question that is a concern is the linear actuator. As such, ensuring that the load bearing capacity of the linear actuator is sufficiently high so as to allow the whole assembly to meet the regulations, was the final step necessary to select a specific actuator. As per our chosen design description, the seat belt webbing will route through a secondary D-ring which itself is rigidly attached to the actuator rod. Additionally, this driven D-ring is constrained in the fore-aft and inboard-outboard directions by two H-bars. As such, we assume that the only force acting on the actuator is the vertical tension force from its interface with the seat belt webbing. This is visualized in Figure 33 below:

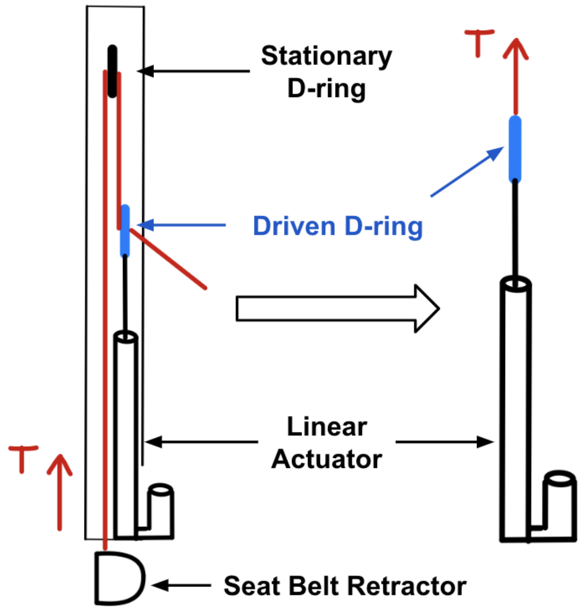

Figure 33: Diagram of linear actuator integration with seat belt assembly and free body diagram of actuator displaying vertical tension force.

There are two scenarios for which this tension force needed to be evaluated - dynamic and static loading. Dynamic loading would occur during actuation of the mechanism. Since our design is intended to automatically adjust prior to operation of the vehicle and not during driving, it was assumed that the maximum dynamic load that would need to be supported by the actuator is the baseline tension created by the retractor to maintain a snug seat belt fit. Friction forces due to contact between the D-ring and H-bars and gravitational forces were assumed to be negligible. Baseline retractor tension was determined from FMVSS No. 209. According to this standard, an emergency locking retractor, *"shall exert a retractive force not less than 1 N and not more than 7 N under zero acceleration when attached to a strap or webbing that restrains both the upper torso and the pelvis"*[41]. Since we assumed that this retraction force acts completely and purely vertically on the actuator as in **Figure 33**, we can therefore conclude that the selected actuator must have a dynamic load capacity greater than 7 N.

The static load requirement for the linear actuator was determined in accordance with FMVSS No. 208. Section 5.1 details the 30 mph frontal barrier crash test. Initially, we conducted analysis based on the mass of the occupant, acceleration they experienced, and corresponding resultant force on the D-ring based on seat belt angle. However, our sponsor Dr. Klinich provided feedback on this analysis indicating that our final static force value seemed far too low. She advised us to simplify the analysis by just taking into account the load limiting force for the seat belt retractor [42]. One major criteria for adherence to the frontal crash test is that the occupant (or crash test dummy) must meet a set of injury criteria [43]. Dr. Klinich told us that typical seat belt assemblies have load limiters set at 4500 - 7000 N in case of high acceleration such as in the frontal crash test to prevent head injuries and rib injuries to the elderly. What this means is that tension is completely released from the seatbelt, and by extension, the linear actuator when the load exceeds this threshold. Assuming again that this tension force is applied vertically and completely to the actuator, we can then conclude that the actuator must be able to withstand a static load of at least 7000 N in order to comply with occupant crash protection regulations, and by extension, our safety specification.

Linear Actuator Selection
Initial selection and purchase of the linear actuator was based solely on the stroke length requirement derived using CAD analysis above. This purchase was expedited before force analysis was conducted due to it being necessary to measure and dimension the physical actuator for use in construction of the final design CAD model. As such, force analysis was done recursively and left us with unsatisfactory results. The dynamic and static maximum load of our selected actuator is 1500 N (see Appendix F for actuator specs). This meets the dynamic load safety requirement of 7 N, but is well short of the static load safety requirement of 7000 N. Upon further research, it was determined that a linear actuator with a load capacity of 7000 N was on the order of hundreds of dollars to purchase, and would therefore not be realistic to incorporate into a prototype for this class. As such, we decided to proceed with our purchased actuator and develop a build design incorporating it, noting that a higher load capacity actuator would need to be substituted in a final design.

Final Design

Our final design for this project comes as a culmination of the various engineering analyses and concept iterations we produced. A detailed representation of our final build design is seen below in CAD. Utilizing the chosen concept design, we have iterated to include fasteners and other changes that respond to the results of our engineering analyses above. The assembly is seen below in Figure 34.

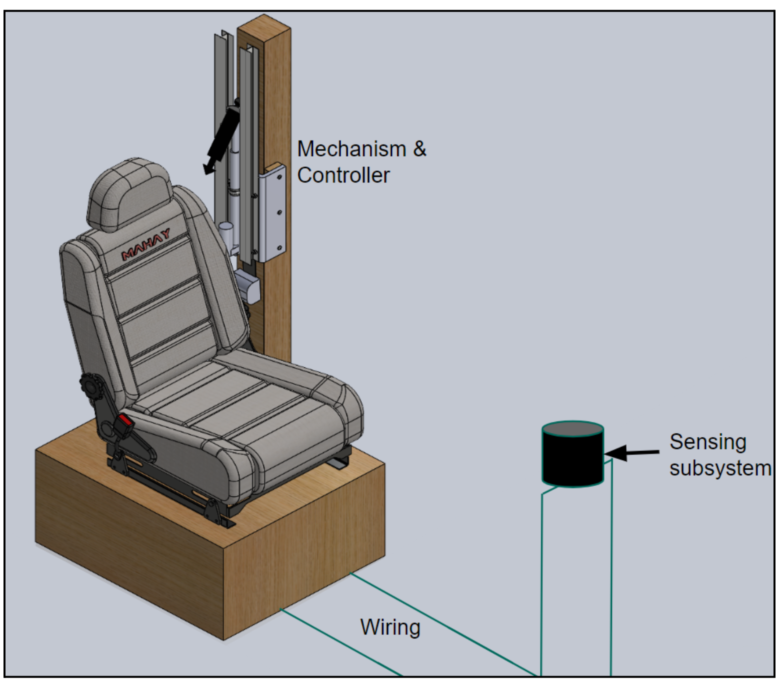

Figure 34: Final Design CAD Assembly

The assembly consists of 3 subsystems - a mechanism, controller, and sensing system. Most important of these is the mechanism - powered by the linear actuator from our chosen design concept, it enables vertical movement of the driven D-ring without manual adjustment using input from the controller. This mechanism subsystem is exploded below for better visualization of its components.

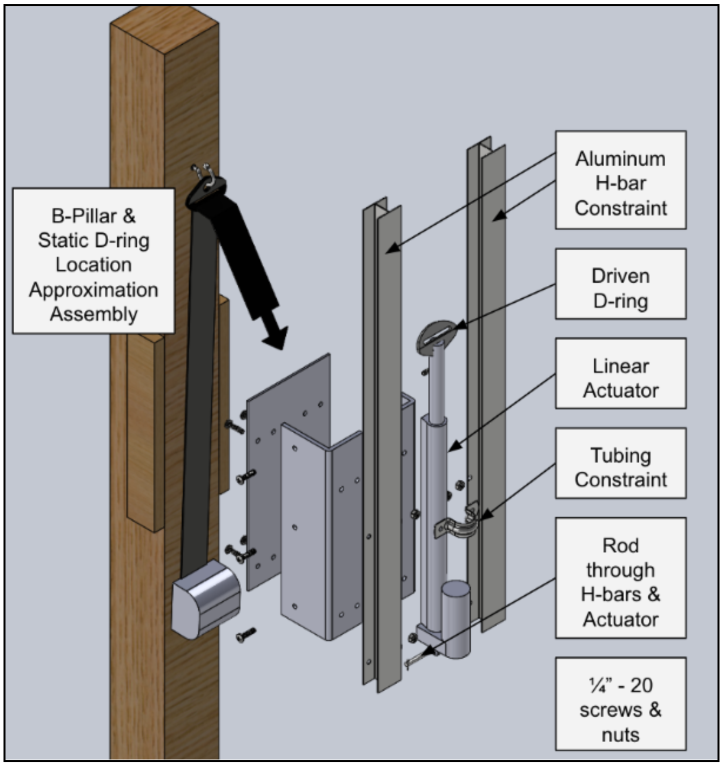

Figure 35: Mechanism Subsystem - Exploded View

In this final mechanism design, the linear actuator is used to power the driven D-ring. The actuator is constrained to Z-axis movement by the H-bars on either side. These H-bars and the actuator are jointly attached using screws and a routing clamp to a metal plate, which mimics a mounting contraption used to connect the design to a vehicle's B-pillar. The H-bar and actuator are also connected by a steel rod at their base, further confining their motion and providing additional restraints preventing the detachment of the actuator in the event of a "crash". The fasteners used are symmetrical across the actuator.

This mechanism is further utilized in the assembly by being positioned in a location that mimics the location of it within a vehicle. Using some of the analysis from concept selection in determining whether 1-dimensional motion would prove to be enough for our design, we were able to locate the placement of current seat belt D-rings in vehicles. Using this, an assembly using the car seat, seat belt, and optimal placement of the mechanism and "D-ring" was constructed.

Utilizing a wooden 4x4” and a realistic car seat, this assembly hopes to be capable of testing the feasibility and effectiveness of our mechanism in a less costly and more open environment than had it been installed directly into a vehicle. This assembly will allow for basic analysis and testing of the design concept, including verification of how different sized people interact with the design and how various forces affect the durability of the mechanism. Additional images of this mechanism subsystem can be found in Appendix G.

Beyond the mechanism subsystem, controller and photo sensing components are also important to our final design. The controller subsystem consists of the use of an Arduino Uno and L298N motor controller connected to a 12 volt power supply. This control system is then connected to our linear actuator via the motor controller and to a computer via a USB-B cable connected to the arduino port (see Appendix J for wiring diagram) . These components can be programmed to accept input from external sources and output code that moves the actuator to specific positions. Taking in values given to them by the photo sensing system regarding the occupant’s height, they can then effectively move the D-ring to the location of optimal shoulder belt score. This subsystem is utilized in our build design and pictured in figure 37 below.

The third and final subsystem is the photo sensing and processing subsystem. Making use of a simple webcam located in the same position as a vehicle dashboard, images of the occupant will be sent to OpenPose programming to quantify the shoulder height of the occupant. This will then be sent to the controller system’s input.

Additional considerations on the **manufacturing** and specifications of **materials** are presented in the **Build Design section** below, where the mechanism and controller subsystems mimic those of the final design and are detailed further.

Build Design

Due to constraints in time and resources throughout the course of this project, a build design consisting of the mechanism and controller subsystems was produced in place of a completely functional finalized design. While research has been done in this report detailing the uses of OpenPose software and the Kinect sensor within this report, producing working models of these components is outside the scope of this project. In creating a final design, the location of the sensor has been determined and was pictured in the CAD assembly in Figure 34 above. However, more detailed specifications are yet to be determined and are outside the scope of this report.

Built with the final design goals in mind, our team's build design allows for verification and analysis to be accomplished despite not containing a photo sensing system, with only minor modifications made (to reduce price). The build design almost exactly replicates the final design, however uses a cheaper linear actuator that does not allow for feedback control that would be necessary in a truly autonomous system. This build design with the replaced actuator can be seen, fully assembled, in Figure 36 below. The Arduino and controller subsystem is also pictured in Figure 37.

Figure 36: Build Design Assembly

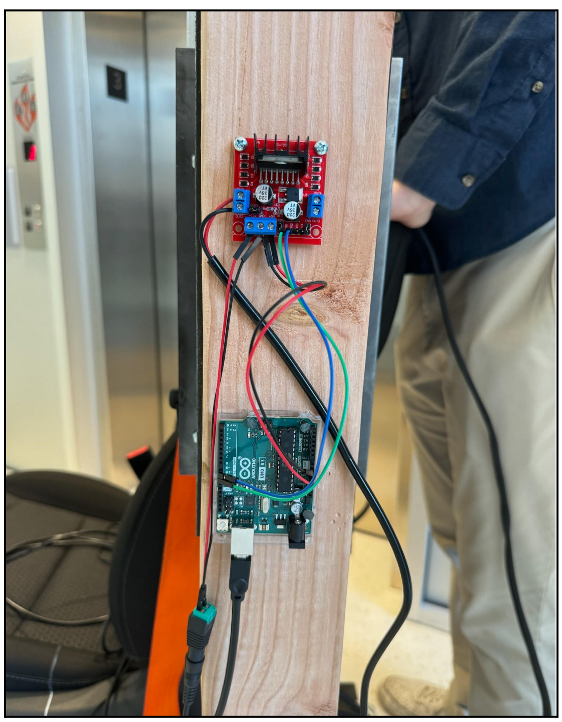

Figure 37: Controller Subsystem

Materials and Parts
For our build design, we produced a comprehensive bill of materials including components necessary for our mechanism, controller, and assembly as a whole. This bill of materials mimics that of the final design with two alterations: a cheaper actuator has been selected without a potentiometer, and the sensing system is excluded entirely. Prices and vendors are laid out for each part here in Appendix H.

Also, as denoted in the bill of materials, various components used were sourced in-house from UMTRI, including various additional screws, nuts, and the chair setup (used in previous research).

Manufacturing Plans
Machining was important to our design primarily in that we needed to tailor the components we bought to be able to fasten to each other. This consisted of creating holes for screws and the metal rod and bending the metal plate purchased to attach the mechanism to the 4x4”. Parts requiring holes for screws include the H-bars, metal rod, and metal plate.

For the screws: Use a 17/64" drill bit to create clearance holes in the metal plate and H-bars. This can be accomplished on the mill using clamps to hold down each component. First, use the edge finder to datum each piece and then measure out the exact location. This exact location will not matter too much as long as it is precisely the same for each component in relation to each other (for alignment purposes). Clearance holes are preferred as the materials are thin and nuts will be used, so tapping is unnecessary.

For the hole for the rod: These can be slightly less accurate than for the screws and will need to accommodate the 6mm diameter rod to ensure the actuator is locked to the H-bars. This can be accomplished on the mill with the use of a 7mm drill bit (to provide clearance while not allowing for too much wiggle room - again, this does not need to be violently locked in place as that will only create unnecessary tension).

Tolerancing was important in this process in order to align and create the holes. Making sure the spaces between them were the same enabled our design to fit together without excessive stress on any components. Tolerancing was less important in the bending of the metal plate.

Beyond the heavy machinery required to create precise holes in our metal components, additional wood drilling was used attaching the mechanism, arduino, and seat belt to the 4x4, as well as the 4x4 to the chair assembly. Finally, the driven D-ring and actuator were welded together to provide for rigid motion between them.

Engineering drawings for this build design are deemed irrelevant - the vast majority of components are not to be altered and are represented using CAD files found on McMaster that have very high tolerances already. The sole use for these drawings would be for hole creation in aligning the screws; this process was accomplished with the help of UMTRI professionals and didn’t call for these drawings to be made.

Build and Final Design
As mentioned prior, our build design omits the photo sensing subsystem of the final design. Despite this, it still demonstrates a number of important concepts. The first of these is that, along with the engineering analysis proving its force bearing capabilities, an autonomously controlled D-ring is feasible. Second, it demonstrates proof of concept and provides a foundation for future teams to use should they be able to produce the photo sensing subsystem. Our build design is also extremely useful in that it can be used to verify all of the requirements of the final design excluding those relating specifically to photo sensing and processing. The engineering analysis and verification plans we have done and come up with are to be applied to this build design. The similarities between it and the eventual conception of a full design or something non-OEM will be similar enough to provide verification and assurance of the ability of the design to function. This is demonstrated in the following section, particularly related to requirements regarding the mechanism and controller subsystems, such as comfortability, safety, and range of adjustability.

Description of Verification and Validation Approach

Verification and validation are important final steps in the design process. Verification confirms whether specific parts of the final design matches the critical user requirements/engineering specifications set at the beginning. Validation confirms whether the final prototype addresses the original problem statement and creates a satisfactory value for the user. Verification plans will be provided for the following 6 critical user requirements:

- Provide enhanced range of adjustability for seat belt users based on height and BMI
- Achieve comfortable shoulder belt placement
- Ensure accurate imaging data
- Adjustable D-ring location
- Utilize visual sensor and library
- Safety

Due to delay in material shipping and UMTRI requiring our prototype to be disassembled for other uses following the design expo, only some of the verification plans have been carried out to their fullest extent. However, remaining test methods are labeled clearly and improved based on the feedback from our stakeholders, and can be carried out in the future following our descriptions.

Enhanced Range of Adjustability

For this user requirement, the engineering specification details the final design to be able to accommodate users with $18 \leq BMI \leq 40$ and 5’0” ≤ Height≤ 6’0”. The selected test method is user testing, where participants with a wide range of body shapes will be invited to test out the automated seat belt adjuster. This method is selected because the automated seat belt adjuster is a product designed for the general public, and having a variety of body shapes to physically test out the prototype can ensure there are no unforeseen factors that the simulations done during testing phase did not cover. The ideal situation would be testing the final prototype on participants with BMI near both extremes. However, a major limitation in this method is that it is relatively difficult to guarantee people with said body types will join the user testing, so several alternatives are considered. Replacing human users with mannequin or dummy models can allow customizable body shapes, but can be relatively expensive compared to the scope of this project. Having test subjects wear bigger clothing or stuffing items such as pillows in their clothes can simulate a user with bigger body size, which is a viable alternative that can be executed. A minimum of 20 subjects will participate in the user testing, with 5 trials each. Our sponsor from UMTRI believed this verification to be the most crucial one, as it is the center focus of the project, and their feedback will be important as we help them to iterate beyond a build design in the future.

For our build design, although we were able to empirically test the product on varying types of people according to their heights, we were unable to verify all the different heights included in our range. Therefore, we were only able to verify the accommodation of various specific heights. Our additional verification plan for the build design would be to have two people matching low end metrics and high end metrics both sit in the seat and see if the shoulder belt score of 22 can be achieved. If the proper fit for these two users can be satisfied, we can assume that the fits for the other heights in this range can also be satisfied.

Achieve Comfortable shoulder belt placement

For this user requirement, the engineering specification details the final design should be able to achieve a shoulder belt score of 22 ± 2 cm accurately. The user testing from the previous requirement (Enhanced Range of Adjustability) is extended to verify this requirement. After the participants are in the car seat with the automated seat belt adjuster activated, the visual sensor will activate and measure the shoulder belt score before and after the adjustment, as intended in the design. A ruler will also be used to physically measure and calculate the shoulder belt score before and after the adjustment, acting as a comparison to the visual sensor data. As above, a minimum of 20 subjects will participate in the user testing, with 5 trials each.

There are three general fits that characterize the positioning of the shoulder belt on the user. The first position is called inboard, in which the shoulder belt is positioned too closely to the user's neck. In this position, the user can be severely injured by the seat belt itself as in a vehicular accident, the shoulder belt will come into direct contact with the user's neck. The second position is centered, in which the optimal shoulder belt score has been achieved. The final position is outboard, in which the shoulder belt is too far away from the user's optimal shoulder belt score, and closer to the arms. In this position, the seat belt will not be able to properly function in safely supporting the user in a vehicular accident. The shoulder belt has the potential to slip off the shoulder of the user, creating a circumstance as if the user were not to be using a seat belt at all. The following table shows a demonstration of the measured result of the shoulder belt score for the automated seat belt adjuster.

			
SBS	2	22	58
Fit	Inboard	Centered	Outboard

Table 12: Visual representation of the different extremes of shoulder belt positioning

The shoulder belt score for an average 6ft white male ranges from a low score of 2, which is too close to the neck, to 58, which is too far off towards the shoulder. This demonstrates that the prototype is capable of providing a wide range of shoulder belt scores to accommodate different body sizes and can accurately achieve the desired score for at least one subject. Additional testing on other body sizes could be conducted in similar ways, but could not be completed within our time constraints.

Ensure accurate imaging data

For this user requirement, the engineering specification details the visual sensor and image analysis system should be able to detect ≥ 2 major landmarks on the body of any passenger. The selected test method is inspection, since it is relatively straightforward for us to identify the 2 major landmarks detected if our selected image processing software, OpenPose, is working as intended. The 2 major landmarks chosen are the suprasternale point and the shoulder center.

Such a test consists of taking pictures of different users in the car seat with the seat belt on, then verifying that OpenPose can detect at least 2 body landmarks, which are necessary to calculate the shoulder belt score. Additionally, we can also have the users wear different sets of clothing, with differing colors and volume size, to ensure that the landmark detection is reliable and consistent. As the photo processing subsystem was not part of our build design, this could not be reasonably conducted within the scope of our abilities.

Adjustable D-ring location

For this user requirement, the engineering specification details that the final design should increase the vertical range of motion of the D-ring component compared to the provided OEM standard D-ring in a vehicle. The selected test method is an experiment/physical test, since we can easily distinguish the difference in range of motion by physically measuring both products. The experiment will be conducted with 2 different types of measuring devices: a ruler and a tape measure, measuring the distance between the highest and lowest points for each D-ring adjuster. An assumption made here is that most vehicles built in standard D-ring have a similar vertical range of motion. To decrease the potential of inaccuracies, a minimum of 5 trials will be conducted on both adjusters, and the same experiment will be repeated on 3 different standard passenger vehicles that are currently available for this project.

Again, due to limitations in the time we had the assembly available to us, this test could not be run. However, the range of adjustability visually was proven to be much much greater than that of current adjusters, leading us to conclude with great confidence that this requirement can be verified with minimal additional testing.

Utilize visual sensor and library

For this user requirement, the engineering specifications detail that the time from point cloud measurement to adjuster should be less than 4 seconds, which is the process between the visual sensor begins collecting data and the actuator initiates movement. The 4 second time period is set based on stakeholder feedback, specifically from our sponsors. The selected test method is an experiment/physical test, where a timer will be used to record the elapsed time of the entire process. This method is chosen due to its simplicity in execution and accuracy of the result. The timer will trigger as the visual sensor starts to process the initial body shape of the person, and ends when motion is detected on the actuator.

While the build design did not have the photo processing subsystem as part of it, this experiment was conducted on time from user input of height to motion of the actuator to attempt to verify that a time of under 4 seconds is at least feasible for the final design. This experiment was repeated with 10 trials. The estimated time for the entire process including photo processing was approximately 2.5 seconds. The average time recorded for the half of the process available to us was 1.6 seconds. This verifies that it is at least possible should the photo processing process take under 2.4 seconds. This can be verified following conception of the photo processing subsystem in the same way.

Safety

For this user requirement, the engineering specifications detail multiple safety standards issued by the department of transportation that the product is involved with: Code 49 C.F.R. 393.60(e)(1)(ii) regarding front windshield visibility, Codes FMVSS No. 208, 209, 210, Frontal impact FoS >2. The standard vehicle crash test involves a 30 mph crash test, which would be unrealistic and extremely difficult to replicate for the current type prototype given our scope. Instead, a separate force analysis on the D-ring was applied, detailed in the Engineering Analysis section. The specifications of this test were given to us by our sponsors. However, the subsequent force analyses and the windshield visibility test were performed theoretically and were calculated manually or through software simulations.

For the windshield visibility verification test, we can set the visual sensor in its installation position, in addition to its respective installation components. Although the visual sensors themselves do not impede the passenger's or driver's field of vision and ability to operate the vehicle properly, the inclusion of the installation components may cover specific areas of the windshield that the driver may deem necessary, even if the total area of the windshield covered is still under 2%.

For the seat belt assembly verification test, we were able to simulate a force of 7N acting on the strap in the retractor in Solidworks. We were able to determine that the subsequent reaction force of the strap was approximately 2N, which was greater than the minimum required magnitude of 1N.

Similarly, for the seat belt anchorage verification test, we had attempted to simulate the force generated by a 30mph frontal impact test, but were unable to yield accurate results as this specific test was dependent on the bolts and fasteners used in the design solution assembly. These bolts and fasteners consist of certain thread counts and materials, which the Solidworks library did not have.

Validation

The above verification plans are mostly composed of experiments/physical tests that can provide concrete evidence that the corresponding engineering specifications are met. However, validation plans should still be implemented to consider the automated seat belt adjuster as a whole, with all the mentioned engineering specifications presented simultaneously. Since the product is designed for the general public to use, user testing and demonstration are essential to validating the final prototype. The goal of this project, which is defined at the beginning, is to "allow occupants of much larger height and BMI ranges to comfortably, autonomously, and safely reconfigure their seatbelt locations to provide much needed comfort". To validate this goal, our major focus will be on setting up multiple user testings with the help from our sponsors from University of Michigan Transportation Research Institute (UMTRI), who have the resources and experience in these types of events. Dr.Klinich has worked with many volunteer participants in her research, and we hope that with her connections, we can invite participants with a wide range of body shapes to test out the automated seat belt adjuster, as mentioned above in the verification plans.Test subjects can provide valuable feedback on the general experience and success of the device. We aim to obtain user feedback from different demographics to find common-ground issues. Three key points that are focused on in the feedback are user experience/easy to use, comfort, and safety concerns. The automated seat belt adjuster can be further improved in the near future based on the response from our stakeholders.

For the enhanced range for seat belt users based on height and BMI requirement, the validation test would consist of having many different users with various body shapes and types to use the automatic seat belt adjuster and after, have them fill out a survey asking them if the shoulder belt placement was comfortable after it is adjusted to a shoulder belt score of 22. If there is a considerable number of complaints that come from a similar or equal body shape and type demographic, we would be able to adjust the shoulder belt placement for that group through the extension or retraction of the linear actuator.

For the accurate imaging data requirement, the validation test would require installing the final design solution into a realistic environment, which would be inside of the vehicles. This test would require that the final design be placed in different types and models of vehicles, each having different colors present in the scene captured by the visual sensor. Additionally, the users inside the vehicle and on the passenger or driver seat would be wearing various different colored clothing in order to adequately test the accuracy of the visual sensor. Each trial would determine whether the visual sensor was able to detect and identify the major landmarks on the users needed to calculate the shoulder belt score and begin the seat belt adjustment process.

For the comfortable shoulder belt placement requirement, the validation test would consist of the same process as its verification test, except we would have users fill out a survey or questionnaire asking them if the resulting fit from each trial was comfortable. They would have to determine whether the shoulder belt was too close or too far away from their neck and if there is a considerable amount of concerns from a specific user group, we would again be able to adjust the shoulder belt placement for that group through the extension or retraction of the linear actuator.

For the adjustable D-ring location requirement, the validation test would also be placed in a realistic environment, which is inside of a vehicle. This test would also go hand-in-hand with the compatibility requirement as we would have to ensure that the H-bars and its installation parts would fit within the space between the B-pillar and the vehicle seats. However, this validation test is to check whether the linear actuator is able to extend to its fullest length without any obstruction from the vehicles' interior structures. Once we validate that the D-ring is able to move vertically throughout its entire range through the means of the linear actuator, we can ensure that the product is able to perform properly in enhancing the range of adjustability.

For the utilization of a visual sensor and library requirement, we would have users give feedback on how comfortable they were in waiting for the adjustment process to begin and finish. This test would compare the total runtimes of the automatic seat belt adjuster and having the users manually adjust the shoulder belt themselves and allowing them to determine if the automated process took too long to be considered equivalent to or better than the manual process.

For the safety requirements, our first validation test would consist of empirically testing the frontal impact test through the sled test using a dummy. We would have to ensure that the linear actuator does not malfunction or become displaced from the assembly after the crash. The subsequent force codes can be validated through using a durability testing machine to exert the required forces and tension. These validation tests are required to determine that the structural integrity of the final design is reliable and durable. Any failure in passing these would first result in reevaluating the fasteners used in the product and the materials of the H-bars and linear actuator before reconsidering the design itself.

A summary of the validation tests and verification tests can be found in the table in Appendix I.

Problem Analysis and Iteration

The initial prototype of our alpha design consisted of the H-bar, D-ring component, linear actuator, shoulder belt strap, seat buckle restrainer, and car seat. From there, we positioned the H-bar system at the standard distance away from the individual car seat as described in Appendix E. Through this set-up, we were able to initially verify three top priority user requirements and their respective engineering specifications.

The first user requirement states that the design solution must provide an enhanced range of adjustability for seat belt users based on their height and BMI. This can be verified by either using test subjects or manufactured dummy models of users at both extreme ends of the height and BMI ranges. The specification states that this range is between 18 and 40 for BMI and between 5’0” and 6’0” for height. Before this form of empirical testing, we can perform quicker theoretical tests through modeling software. We have already created a CAD model of the aforementioned system as described in Appendix E. However, we must empirically test this system to account for environmental factors such as friction between the D-ring component and the H-bar and to observe whether the shoulder belt is adequately in contact with the users’ shoulders. These tests allow us to better understand the dynamics between the D-ring component and the H-bar, and can lead to additional testing on ways to reduce friction between these components should they prove to inhibit the range or functionality of our design.

The second high priority user requirement states that the design solution must achieve comfortable shoulder belt placement. The corresponding specification establishes a ±2 cm accuracy range within the shoulder belt score. The quickest method in verifying this specification is to empirically test the actuator assembly without a controller. First, we will set a target shoulder belt score and figure out the activation time required for the actuator to move the shoulder belt a set distance, such as 1 cm. Then, we can set the shoulder belt initial position at an arbitrary point on the user’s shoulder and measure the distance it is from the target shoulder belt score. From there, we can figure out the activation time required to move that measured distance difference. When the actuator stops after its activation time, we will be able to determine whether its actual position is within the specified range of ±2 cm from the target shoulder belt score. Not only will this test allow us to verify the chosen design solution’s capability to achieve the user requirement and specification, but it will also help us identify the effects of environmental factors such as friction between the D-ring component and H-bar and the sensitivity of the linear actuator due to its torque. Such factors are incorporated into the dynamics between the linear actuator and D-ring component and dynamics between the D-ring component and H-bar. However, this empirical test could be further enhanced through the introduction of a controller, such as an Arduino. The Arduino will be able to automatically calculate the required activation time for each arbitrary initial shoulder belt position. This will cut down on the time required to manually calculate such values, which in turn allows us to collect more data. More data will provide means to pinpoint a standardized accuracy range that our chosen design solution yields.

The final verifiable user requirement is one that states that the design solution must incorporate a system with an adjustable D-ring location. Sush positioning of the D-ring component is defined by the vertical displacement relative to the B-pillar or z-axis of the vehicle. We are attempting to offer an increased vertical range of motion when compared to the standard D-ring assemblies issued in current vehicle models and such new assemblies may utilize the unused space on the B-pillar. However, in order to verify the chosen design concept's ability to adjust the D-ring location, we simply need to establish vertical movement of the D-ring component, through activation of the linear actuator. We can use the same test in the aforementioned empirical testing procedure that does not utilize a controller in order to get quick results. The H-bars will represent the B-pillars of the vehicle and its length will be determined according to the full usable length of the B-pillars. Such lengths will subtract more material from the B-pillars, so we must make sure that this does not change the structural integrity of the vehicle and adheres to code FMVSS No. 216. From there can easily verify that the operational vertical movement can translate to 1 degree of freedom as the movement is only relative to a singular axis. This test explores the dynamic relationship between the combination of the D-ring and linear actuator, and the H-bar.

Discussion

Problem Definition

Defining our fundamental design problem was one of the most difficult and strenuous parts of our design process. Looking back, one question that should have been explored in much greater depth was that of who would be the primary/target beneficiaries and users of the final realized version of our design. This question was primarily tackled in our early design process through interviews with our sponsors at UMTRI. As our perception of the project developed, we got to a point where it was necessary to make a decision on the target implementation of the device - should it be made for wheelchair users and implemented in accessible vehicles, or should it be made for passengers of typical cars with mobility restrictions? The decision to pursue the latter option was made after speaking with our sponsors and determining that an application in a general car would be more feasible to design and build within the scope of this project's timeline. However, upon completion of our build and testing with users at the design expo, it became more apparent that some key aspects of the system may not be as appealing or beneficial to the people the design was intended for. Namely, our design still requires users to reach over and pull the seat belt webbing over their shoulder and buckle it into place. As such, if a passenger had the ability to do that, they likely would also have the ability to operate a manual D-ring adjuster. Furthermore, this realization also partially contradicted one of the user requirements we defined (easy for individuals with mobility limitations to operate). Reflecting on this, it would have been a good idea to further explore the question of the target users of our design. To explore this consideration further, we would conduct further interviews with our sponsors, but also conduct interviews with users in both populations - wheelchair users, and mobility impaired normal car users. This way we could gauge which application the idea was best suited for and tailor our design process and related user requirements accordingly.

Incorporating a visual sensor to act as input for the automatic system was a central aspect of the initial design proposal and was a critical component of our problem definition. A question related to this that we would have explored further given additional time and resources was how would different kinds of visual sensors be incorporated into a mechatronic system, and what techniques could be used to process the visual information? Our idea of the role that the visual sensor would play in the greater system was purely qualitative in the problem formulation stage of our process. We envisioned using a Kinect sensor based purely off input from our sponsor Dr. Park who had experience working with that sensor. However, his prior work using the Kinect did not incorporate real time processing of the data/computer vision techniques that we later deduced would be required to integrate the Kinect into an autonomous system. Accordingly, given additional time and resources we would conduct more in-depth research into the viability of 3D depth sensors like the Kinect as well as RGB cameras in the context of an autonomous mechatronic system. This research would involve consideration of existing research projects or developed products in industry that involve this type of system. Furthermore, we would seek the advice of professors in the robotics department whose research and experience is related to perception in automatic applications such as self-driving cars, and overall autonomous system design using visual sensors.

Design Critique

Despite the difficulties in formulating the design problem, we were able to settle on a problem that we felt was feasible to design our project around. The true strengths of our final design lie in its ability to satisfy the user requirements and specifications related to adjustability and comfort. The analysis we did in CAD using the human shape models ultimately led to an effective choice of the stroke length of our actuator. Having a sufficiently large stroke length allowed us to satisfy three of our major user requirements - enhanced range of adjustability, comfortable shoulder belt placement, and adjustable D-ring position. All of the specifications corresponding to these requirements were verified empirically on our build design as discussed previously. This was a major strength of our final design as it encompasses the component of our design problem which aims to provide greater comfort and accessibility to the users. Another strength of our design was the level of thought and detail put into the Initial CAD model and manufacturing plans, and the translation of these efforts into the mechanical build. Our build design prototype was manufactured and assembled with little to no mishaps or incongruencies thanks to the meticulous visualization and plan set forth preceding assembly.

Unfortunately, our design also had several weaknesses, most of which were discovered through the prototype building process. While our purchased linear actuator excelled in meeting the adjustability and comfort requirements it had a fatal flaw - the lack of position feedback. We initially purchased the linear actuator based on its relatively low price compared to other similar products and its overall stroke length. Moreover, we needed to have the physical actuator in order to make measurements that would inform components of our final design CAD model. Unfortunately, this proved to be a premature action, and we should have spent more time researching existing arduino projects using similar actuators before purchasing. In our later research, we discovered that there are two primary types of electric linear actuators available for purchase, those with built in feedback and those without. We had purchased the latter option with no position feedback, but with only limit switches. Typically, the feedback actuators are manufactured with a built in linear potentiometer in the shaft or rotary potentiometer or encoder in the base before or after the transmission gears. The feedback components are then wired allowing connection within a circuit. Our actuator had no positional feedback, and thus could only be controlled using a feedforward strategy, dependent on the limit switch. This is visualized in Figure 38 below:

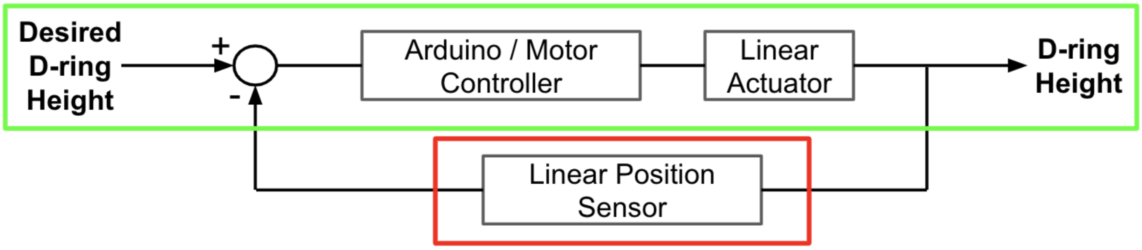

Figure 38: Simplified block diagram of the control system. The linear actuator is the plant being controlled. Linear position sensor is missing from the system so the system is limited to a feedforward functionality (boxed in green).

Due to a lack of feedback, the actual position of the D-ring corresponding to the actuator's extension/retraction could not be accurately measured. As a result, the best solution we were able to come up with to develop a proof of concept for the design expo was estimating the position of the actuator based on actuation time and empirical measurements we took of the total amount of time to go from fully retracted to fully extended and vice versa. The most significant consequence of having no feedback was that there was no way for the prototype to actuate autonomously; movement instructions had to be hard coded and prompted manually with input on the Arduino IDE from the user. In order to remedy this problem and improve the design to be capable of autonomous function, it is absolutely necessary to incorporate a position feedback sensor into the design. The most simple way to do this would be to replace the current linear actuator with a new one that has built in feedback. The type of linear actuator used in our design is a common product manufactured by various companies generally for the purpose of solar panel tracking. As such, our actuator shares its form factor with many other comparable linear actuators that have built-in feedback and thus could be swapped out with minimal to no modification of the surrounding architecture.

Another fix for this problem would be to purchase and attach a linear potentiometer to the linear actuator in a way that the extension/retraction of the actuator would correspond directly to that of the potentiometer. Through research, we found that this would be feasible using the linear variable displacement transducer displayed in Figure 39.

Figure 39: Visualization of how a linear variable displacement transducer could be connected to our linear actuator.

As can be visualized from the figure, this type of linear travel sensor could be attached to the mounting holes on either end of the linear actuator so that the two components are side by side. With this configuration the sensor is narrow enough that it could fit inside the adjacent H-bar and mount on the bottom connecting rod of our mechanism (rod shown in Figure 34). Then, the connecting wires could easily be connected to any of the analog pins on the arduino. The main concern with this strategy would be price - these linear sensors cost hundreds of dollars which is more expensive than purchasing a new linear actuator with built-in feedback.

Another area of weakness of our design is the ease of use in terms of operating the system like a normal seat belt assembly in order to strap yourself in before automatic adjustment occurs. We found during initial testing and operation of our prototype that there was a much higher than expected amount of friction resistance when trying to pull the seat belt webbing out and over your body from the adjustable D-ring. We determined that this was caused by two factors.

The first factor was that the further fore H-bar rail was restricting the movement of the seatbelt as it was being pulled in the fore and inboard direction simultaneously upon the initial extension required to buckle yourself in (see Appendix D for diagram of vehicle axes). During our final building process we noticed this interference and decided to use an angle grinder to cut off the innermost half of the H-bar in the area that the D-ring was able to move in. This solved the interference issue with the webbing and significantly decreased the overall friction associated with pulling the seat belt out. For future modifications/iterations of the design, this could be modified by either making this cut before assembly using a table saw or mill.

The second factor contributing to this resistance issue was the driven D-ring (see Figure 33). The issue with the D-ring that we ordered and incorporated into our assembly is two-fold; the slot through which the webbing feeds was too wide allowing too much vertical play of the webbing leading to shifting and bunching of the webbing when pulled forward. This had the effect of a large increase in friction and meant that you had to pull the seat belt out along the inboard direction without pulling it forward at all or else it would get caught and stuck. The second issue with the D-ring was that it was welded onto the linear actuator shaft and thus was incapable of rotating in the pitch direction (see Figure 16) like D-rings in normal vehicles. We were warned about the importance of having the D-ring rotate in this fashion by our sponsors, but in the limited time we had to build the prototype our only option was welding.

In order to fix these problems with the driven D-ring, two main modifications can be made. For the gap width, it would be simple to purchase a more OEM-accurate D-ring to be used as the driven D-ring. The McMaster part we used as the driven D-ring is compared to the OEM part used in most cars below in Figure 40:

McMaster D-ring **OEM D-ring**

Figure 40: McMaster D-ring used in build design prototype assembly compared to a D-ring design found in many OEM cars.

As can be seen from the figure, the slot design of the OEM D-ring is significantly more optimized for the seat belt application, being narrower and having curved edges to eliminate bunching. Our main reason for choosing the McMaster part for our build design was that it was easily machinable and made of steel that we could weld to the actuator. In hindsight, the design should definitely be modified to incorporate an OEM D-ring such as in Figure 40 as the driven D-ring in order to minimize bunching. Moreover, instead of welding the driven D-ring directly to the linear actuator shaft, we would modify the design to have a swivel mounting point welded to the shaft, and then the D-ring bolted loosely to the swivel mounting point such that it could rotate in the pitch direction when the webbing is pulled in the fore or aft direction.

Risks

One challenge that we have encountered in our design process came from the method in which the range of adjustability can be enhanced. There were a wide variety of solutions that were included in our concept generation stage, but we had agreed that choosing the simplest solution would not only streamline the manufacturing process, but also decrease the chance of failure during the adjustment process. Therefore, we have decided to focus on one degree of motion in the vertical axis to increase the range of adjustability. This would also ensure that there would only be one component, such as the actuator, that would be controlling the movement of the shoulder belt and D-ring. Less moving components would also decrease the possibility of mechanical failure, but also decrease the need for extensive maintenance during usage.

The biggest challenge that we had encountered was how to integrate the visual sensor in the automatic adjusting process, specifically how to gather the visual data and process it so that it outputs readable data for the controller to process and use to mechanically move the actuator. Our group had limited knowledge in how visual sensors operated and less so on the data being outputted and utilizing that data. Through meetings with our sponsors and hearing about their past experiences with visual sensors, they were able to suggest solutions such as incorporating already made programs such as Open-Pose, that come with their own user interface and image data processing to help with the design process. Also, they were able to suggest specific visual sensors such as the XBOX Kinect, in which they have much experience with, to use in our design solution.

A risk that is associated with the end-user of our final design is potential inaccuracies in adjusting the shoulder belt to its proper position. Such causes of this inaccuracy may come from mechanical failure of the linear actuator. Although there is only one moving component that controls and moves the D-ring and shoulder belt, which reduces overall potential failure, any small problem with the actuator will exacerbate improper seat belt placement on the user's shoulder, relevant to the shoulder belt score and suprasternale. Another cause of inaccuracy may come from issues with the visual sensor. Since the visual sensor and its capabilities is dependent on the colors that can be identified in the scene, if the clothes of the user were to be too similar to that of the seat belt in the vehicle, the visual sensor may have a difficult time trying to distinguish between the two colors. Inaccuracies in the shoulder belt placement will inevitably lead to personal injuries in the aftermath of a vehicular accident. Additionally, if there is too much dependency on the reliability and accuracy of the seat belt adjusting technology, the users will not be able to identify any issues with the adjuster itself and have the required maintenance carried out in order to fix it.

Reflection

Creating a design capable of fulfilling all of the requirements and specifications laid out above requires planning, understanding of different methods and analyses, and the ability to act them out correctly and efficiently. Recognizing where our lapses in knowledge lie was crucial to ensuring we were capable of this.

There are a number of techniques that we can use to verify and validate the specs laid out. Firstly, our knowledge of mechanical engineering principles and the design process will serve as the background to our analysis. Having all taken core classes within the engineering school at Michigan, these classes will provide us with much of the understanding needed. Subjects such as materials, controls, and circuits, and technical skills such as working with Solidworks and design iteration, will be instrumental in verifying technical requirements can be met. This includes confirming adjustability ranges can be met, as well as ensuring feasibility of design when connecting our chosen photo processing sensors to any potential mechanisms created. Controls and circuit knowledge will especially play a large role in drawing a link between the photo sensors and the rest of the design, as their location within the vehicle will likely need to be chosen separately to ensure the best possible measurements can be taken, in accordance with research done by our sponsors. Requirements relating to cost, sustainability, and number of moving parts are all easily measurable, and can be found through analysis of the cost and material properties of each of the components in consideration.

Our largest gap in understanding comes from the Kinect sensors themself, as image processing and the “2.5” dimensional characteristics of the sensor are two components we are almost entirely unfamiliar with. Making sure we are capable of assessing the abilities of the sensor will be crucial to the design’s functionality. A second foreseen difficulty is ensuring sustainability. Electronic components are sometimes difficult to analyze, and environmental sustainability is a much more complex topic than it might first appear.

However, we have identified a number of resources that will enable us to find any information we currently don’t have, to better respond to these challenges. Firstly, utilizing online resources such as the University of Michigan library can help fill in any informational gaps left by our mechanical engineering classes. We will also utilize the resources found here to prepare for the next steps in information gathering. For information on Kinect sensors and seat belt location, our sponsors have a wealth of knowledge and research relevant to what we hope to accomplish, and so turning to them when necessary will be important for us when working in this area. Issues in the concept generation stage, such as trouble with finding a solution that is both feasible and effective, while still accomplishing all the specifications laid out, can be solved through the use of ideation methods and iterative prototyping. Attribute listing, morphological analysis, and utilizing design heuristics to make changes that fulfill all of these criteria are also very helpful tools that will push us to create the best design we can. Finally, to create a functional prototype towards the end of this design process, finding the resources and materials needed will be aided by a combination of past experience in purchasing technical items for X50 design classes, speaking with our sponsors to see what hardware they have available, and seeking assistance from online resources and industry experts that might better understand our needs.

Of course, it is likely that additional problems will come up as we proceed along our designing journey. However, between our prior knowledge and experience, and the help of our sponsors and other resources discussed above, we feel confident that we can address the vast majority of complications that arise.

The public health, safety, and welfare factor is the most relevant factor when considering the design of our final solution as it must adhere to several vehicle safety codes such as the frontal impact test, windshield area coverage, and the anchor and installation standards. Additionally, the goal of our project that was established at the beginning was to accommodate as wide a range of people as possible, including people with mobility issues such as the elderly and people with disabilities as the automated seat belt adjuster can make transportation through vehicles more accessible to them and benefit their daily lives.

In terms of global context, as this project pertains to application to vehicles, our problem solution can be one that can be applicable to the majority of vehicles as the automated seat belt adjuster is designed to mount on the B-pillar in a vehicle, which is a common feature structure that is included in nearly every vehicle around the world. Also, since there are people with mobility impairments that exist everywhere, this design provides a solution to a global issue.

Most of the social impacts associated with this project comes from usage of the device. Since the automatic seat belt adjuster enhances safety, it could lead to a reduction in injuries and fatalities in car accidents, while improving overall public safety. However, there may be cases of malfunctions or improper adjustments which could compromise safety, leading to accidents or injuries. Additionally, the introduction of an automatic seat belt adjuster will promote a cultural shift towards proper usage of seat belts. However, this may cause dependency on technology which decreases focus on individual responsibilities for personal safety.

Some potential economic impacts associated with this project come from manufacturing and usage. As this product is one of the first of its kind, if not the first, the manufacturing and maintenance of automatic seat belt adjusters can contribute to job creation and economic growth in the automotive industry. Accurate and proper seat belt placement can reduce the number of personal injuries caused by accidents, which in turn reduces the number of insurance claims. On the other hand, if the automatic seat belt adjuster is inaccurate and displays inconsistencies with proper belt placement, it will have an opposite effect. In terms of disposal, there are some economical benefits that can be identified, such as repurposing of materials and components. Metal components such as the H-bars and fasteners can be melted and repurposed in the future. Furthermore, the Arduino and motor controller can be removed from the product individually and reused for other projects should they not be damaged during their times of usage. However, it is important to keep in mind that our build and final designs were created with the main purpose of validating the proof of concept and less so about the integration into current vehicles.

Two basic tools that we have used to characterize the potential societal impacts of our design include the stakeholder map and life-cycle costing estimation. As described previously, the stakeholder map divides the people who could be impacted by our design into groups dependent on influence level. For the life-cycle costing estimation, we have utilized a software called CES Eco-Audit. Through inputting the required materials and their respective manufacturing processes, we can estimate the economical and energy costs of the manufacturing process as a whole. From there, we can estimate the energy costs of the use stage of the product's life-cycle by inputting the product lifespan, power consumption, and usage habits related to the product. In addition to these considerations, we are able to input the transportation means of the materials and product. This factor is dependent on the transportation type, distance traveled, and the dimensions of the package used when transporting the product.

Though there were many cultural and stylistic differences between each team member, we were able to identify our similarities and let those characteristics influence the approach our team took throughout the project. Our similarities and differences became more evident as the development of the project progressed, so it became increasingly easier and clearer in dividing the work according to each member's strengths. For example, all team members took ME-250 and 350 that provided relevant experience to complete the project. Such experiences include Solidworks modeling skills, coding background for the Arduino controller, and manufacturing knowledge. These experiences allowed us to utilize Solidworks for concept generation and concept selection, choose the Arduino as the preferred controller for our project, and perform necessary manufacturing processes for prototype development. One significant difference between our members was ownership of a car. Those who were in possession of a car had a better understanding of the interior design and functionality of the vehicle and were able to input more valuable information pertaining to our initial designs and iterations. Therefore, the ones without possession of a car were able to ask questions that challenged the notions of the generated concepts and further enhance the understanding of vehicle structure and equipment integration for all members.

There were evident power differences with our sponsor that influenced our design processes and final design as not only did they act as people of authority, but also as clients. In our meetings with our sponsors, they were able to give us specific requirements such as our targeted demographic and utilization of a visual sensor, but also allowed us to ask questions on how to approach the problem in terms of user needs or specific details of the product that must be featured in order to ensure client satisfaction. In this manner, the sponsors gave a lot of freedom in defining the problem ourselves through meetings and our own analysis. Additionally, the sponsors from UMTRI have much experience working with vehicle safety, specifically with seat belt safety for passengers in wheelchairs, which provided great insight for this project.

A significant ethical dilemma that we faced in the design of our project was regarding the visual sensor and its collected data. Some users may be uncomfortable with the utilization of a visual sensor, such as a camera, in order to operate the automatic seat belt adjuster. If a picture were to be taken of the users' faces and upper torsos, they would have a reasonable concern that their privacy may be invaded. One suggestion that we have offered as a solution to this problem was the usage of real-time video capturing as there would be no need to take a picture and store its respective visual data to the controller. The seat belt adjuster would only move according to the current scene captured on the visual sensor and would stop operating once the process is finished. However, another concern that arose from this issue was that the video itself could be recorded and stored, which would again lead to concerns about unauthorized access to personal data. One way to mitigate these concerns would be to only utilize the color information captured and identified by the visual sensor and controller to operate the product. This was the reason why a bright orange seat belt was used in the build design of our project. Although certain landmarks of the user's body are needed to calculate the shoulder belt score, the suprasternale and even the shoulder ends are located below the face of the user, so there may not even be a need to capture the head and face of the user with a visual sensor.

As members who not only possess vehicles but can use them on a daily basis in the future, our group agrees that user privacy is an important aspect that we must consider when implementing our product. At the University of Michigan, there are guidelines that we must follow regarding respectful behavior towards others. It is universal knowledge that users will expect a certain degree of privacy, especially if they are in an environment such as their own vehicle. Basic common courtesy and our personal ethics coincide with the professional standards set forth by the University of Michigan. It is both considerate and respectful to observe and comply with the privacy expectations established by the university. On the other hand, the professional ethics expected by a future employer will depend on the industry, company values, and specific job responsibilities. However, our belief in expectation of privacy overlaps with an employer's general codes of conduct regarding integrity, confidentiality, and compliance with company policies and legal regulations.

The stakeholder analysis and ecosystem map can be seen in Figure 9 in our previous section, Design Context.

Project Plan

Our team produced a detailed project plan in order to accomplish our goal of creating a ***semi-functional prototype*** by the end of the semester. Tasks have been assigned leaders and are discussed in more detail following the created schedule. A visual representation of our project timeline can be found in Appendix K**.**

We believe that this was a realistic schedule that enabled us to succeed, by setting internal deadlines and placing an emphasis on both research and refinement. While this was a hefty project, we believe it remained generally within the scope of the class to produce a semi-functional prototype by the end of this semester

Recommendations

One recommendation was formulated when we were empirically testing the automated seat belt adjuster on certain users. We had observed that the shoulder belt was not in contact with the user's shoulder for individuals over a certain height. As the linear actuator extended towards its full length, it would subsequently raise the D-ring in which the distance between its point of contact with the shoulder belt and the optimal shoulder belt position on the user's shoulder would also increase. This caused the shoulder belt to hover over the user's body, absent of any contact with any point along the user's shoulder. Our recommendation to combat this issue is to move the H-bars and their respective installation points further behind the user's passenger seat and not on the vehicle's B-pillar as initially designed. As this issue only pertains to taller users, shorter users will not be affected by this installation change as the shoulder belt will continuously be in contact with the user's shoulder as the linear actuator retracts.

In order to address the challenge of determining the method in which to increase the range of adjustability, it may be worthwhile to explore the other axes of motion, namely axial movement. As seen in Figure 16, this most applicable axial movement would be along the pitch axis. This may require another form of actuation to achieve, but it may further increase the range of adjustability as well as offer a solution to the issue with no shoulder belt contact for taller users. The shoulder belt would be wrapped around an object such as a cylinder located near the D-ring, which would be at its final optimal height for the user. Such axial movement will most likely require retraction into the seat belt assembly's retractor or means of decreasing the shoulder belt length coming out of the D-ring, which will increase the tension in the shoulder belt itself.

The incorporation of the visual sensor in this project was unfortunately unexplored due to time constraints. We would recommend reintroducing the concept of using the XBOX Kinect sensor as it allows for a certain degree of depth perception. This feature will help in determining whether the shoulder belt is in contact with the user's shoulder, while still using the needed color detection capability. Approaching this design problem with the intention of using the XBOX Kinect sensor should only be considered with knowledge of the point cloud system as well as incorporating a means to move the D-ring in the fore and aft axes. The depth perception capability of the Kinect can only be utilized properly with the mechanical capabilities of the design solution to move forward and backwards relative to the B-pillar and the H-bars.

Alternatively, we also believe that the perception task necessary for our current 1 DOF mechanism can be accomplished using an RGB camera as we had planned to use in our final design. Using this approach may be a simpler task. Both 2D images and 3D point cloud input information would need to be processed using computer vision techniques in order to classify the seatbelt's location and relative position compared to the passenger in order to provide the arduino with a control input. Given that our current design was verified to achieve the range of shoulder belt scores aimed for, and that the shoulder contact could be remedied by backwards movement of the mechanism, we believe that the 2D perception task is the more appropriate approach.

Firstly, a simple RGB camera is much easier to integrate into the mechatronic system and communicate with due to it being less complex than a sensor like a Kinect. Next, the perception task of locating the seatbelt's position in space relative to that of the occupant is very similar to monocular object detection tasks in the context of self-driving cars - a well researched and developed perception task with a multitude of open source solutions online. Monocular object detection is the process of detecting and classifying objects within images captured using a single visual camera. An example of an approach to this task that could be adapted from a self-driving car application would be to train a convolutional neural network on a test set of images of occupants in our build design prototype with the seat belt on, validate the model using a validation set, and then use that trained model to predict and locate the seat belt from images in real time and predict the current shoulder belt score to give to the arduino as a control input. This model could be trained using google cloud to access a graphical processing unit remotely, and the program could be written in python. This python code could then communicate with the Arduino code development environment in real time using object oriented programming.

Overall, programming the computer vision task and integrating that functionality with the arduino control loop in real time will be the most challenging, but most necessary action required to actualize our final design. There is not an easy way to tie all the components of our final design together into a consolidated autonomous system, but this computer vision framework is our best recommendation.

Conclusion

Our project focuses on bringing comfortability, safety, and autonomous ability to seat belts for those incapable of finding comfort with existing D-ring adjusters. It is built off of the research started by Dr. Klinich and Dr. Park, and hopes to respond to a lack of seat belt adjustability seen in many current vehicles. In accordance with this problem, we have prioritized addressing these needs in the creation of requirements and specifications related to adjustability range, ease of use, and safety. In order to verify these design requirements can be met, our team used a solid understanding of numerous engineering principles and analytical methods, particularly those relating to mechanical engineering and controls. While our past coursework and experience provided a solid foundation in these respects, challenges still presented themselves in understanding Kinect sensors better and addressing sustainability concerns. However, our team was prepared and able to seek out knowledge in order to bridge these knowledge gaps, through the use of the Michigan library, our sponsors, and the utilization of various ideation methods and iterative prototyping.

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Bios

ANDREW SHEFFIELD

Andrew is a senior studying Mechanical Engineering at the University of Michigan. Hailing from Grosse Pointe Woods, Michigan, Andrew's love for designing began at a very young age. Ever since he received his first lego set in elementary school, he has been interested in designing. His interest in mechanical engineering stems jointly from this as well as from a strong enjoyment of physics, which he found while taking multiple physics classes at GP North High School.

At Michigan, he has started to steer towards a career in the automotive industry, and has already explored two internship opportunities with Stellantis. Looking forward, he hopes to continue growing his passions for engineering and automotive long into the future. He also hopes to continue his academic studies with a masters in engineering at some point in the near future, and perhaps an MBA further down the road. Outside of school and his career, Andrew also loves playing and watching soccer, and is an avid premier league fan. He also has two younger, twin brothers who currently each attend Indiana and Bucknell, studying business and economics, respectively.

AUSTIN CHOU

Austin is a senior studying Mechanical Engineering at the University of Michigan. Born in California and raised in Taiwan, Austin grew up in a bilingual environment and went to a bilingual highschool that follows the American curriculum. His interest in mechanical engineering began when his friends asked him to join them to start a First Robotics Team together for their highschool. Under the team mentor and peers' influence, he found enthusiasm in designing and building the robot, and acted as vice team captain for 3 years.

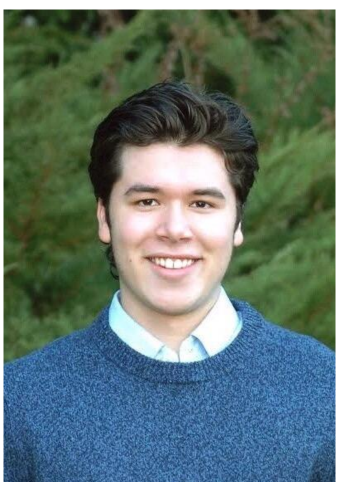
At the University of Michigan, Austin took an interest in robotics and dynamic systems. He had two internships during college at Hiwin Corp and OSA Corp. As an intern in Hiwin Corp, he worked with robotics arms and had experience with engineering clients. At OSA Corp, he designed engineering models and utilized the information from the courses in college. He hopes to continue his passion in mechanical engineering by completing a masters degree in the near future.

DAVID KIM

David is a senior studying Mechanical Engineering at the University of Michigan. Born in New Jersey, David has taken an early interest in engineering, which led him to attend a magnet high school, where he specialized in an engineering major. From there, David was first exposed to the machine shop, where he learned how to use the water-jet, CNC mill, laser cutter, and 3D printer. With these machines, David was able to pursue several projects and teams that involved building robots for competitions.

At the University of Michigan, David was able to translate those early interests into a pursuit of advanced study and career. He was able to further apply his knowledge at an internship at Mozzign Corporation, where he was able to work with Arduinos, pressure sensors, and the Unity software. Outside of academics, David is an avid supporter of Tottenham Hotspurs, a soccer team in the premier league. He also enjoys time outdoors with friends and golfs whenever possible with his dad.

EDDIE POMIANEK



Eddie is a senior studying Mechanical Engineering and concentrating in Robotics at the University of Michigan. Originally from Weston, Massachusetts, Eddie grew up with a love for cars - going to car shows every year and working on cars since before he could drive. He would also attend First robotics competitions in Boston with his father who was a judge which sparked his interest in robotics. He chose to pursue mechanical engineering to pursue his passion for cars hoping to one day design performance systems. Along the way he rediscovered his love for robotics and hopes to merge the two passions in his career.

Eddie had an internship at Technip Energies two summers ago where he developed infrastructure for and installed a network of PID temperature controllers for a pilot plant research project, as well as wrote a program for remote communication with the controllers. He joined the Biomechanics Research Lab as a research assistant under Dr. Ashton-Miller this past summer and has been working there since. He hopes to continue his passion for research by pursuing a PhD after graduating with his Bachelors. Eddie has four brothers and no sisters and enjoys outdoor rock climbing and skiing with them whenever home.

Appendix

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Appendix A: Human Anatomy for User Requirement

The jugular (or suprasternal) notch is the midline notch on the superior border of the manubrium, in which the manubrium is the broad upper part of the sternum of mammals, with which the clavicles and first ribs articulate [38-39]. The suprasternal notch describes the valley-like area in which the suprasternale is located. While the suprasternale is usually a term used to describe structures or features that are situated above the sternum, we are utilizing the term in locating the center point in which the shoulder belt score is calculated from.

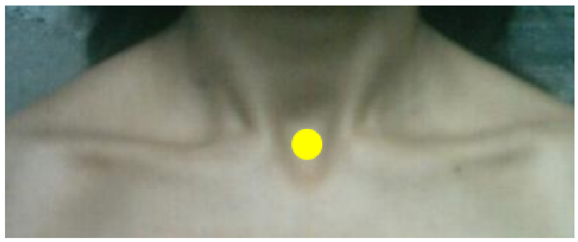


Figure A1: Location of Suprasternal Notch [20]

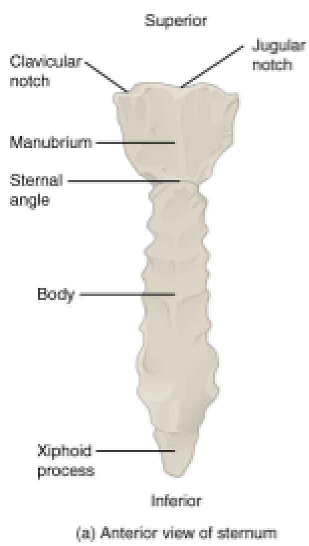


Figure A2: Anterior view of sternum [21]

The axilla is a term for the armpit or the underarm area, which is a pyramid-shaped area located between the upper part of the arm and the chest. When referring to the axilla anterior left, we are specifically referring to a reference point located within the left armpit's front or anterior aspect.

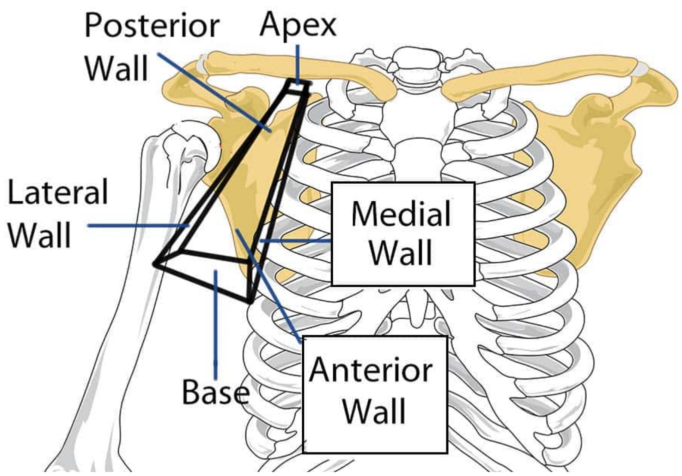


Figure A3: Anterior view of the right axilla region [22]

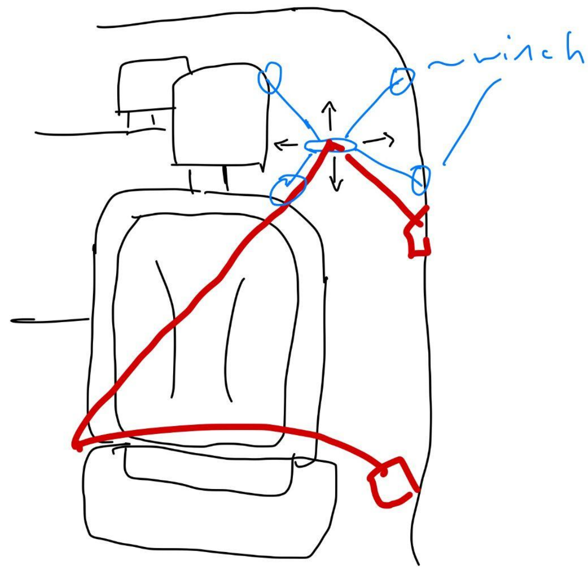
Appendix B: XBOX 360 Kinect Specification

Features	Depth Sensor Color Depth	Frame Rate (Hz)	Resolution (Pixels)	RGB Camera Color Depth
RBG Camera Depth Sensor	11-bit	9 - 30	640 x 480 - 1280x1024*	8-bit
Practical Tracking Range (m)	Extended Tracking Range (m)	Color Filter Array	Horizontal Angular Field of View (degrees)	Vertical Angular Field of View (degrees)
1.2 – 3.5	0.7 – 6	Bayer	57	43

Table B1: General Specifications for XBOX 360 Kinect [24]

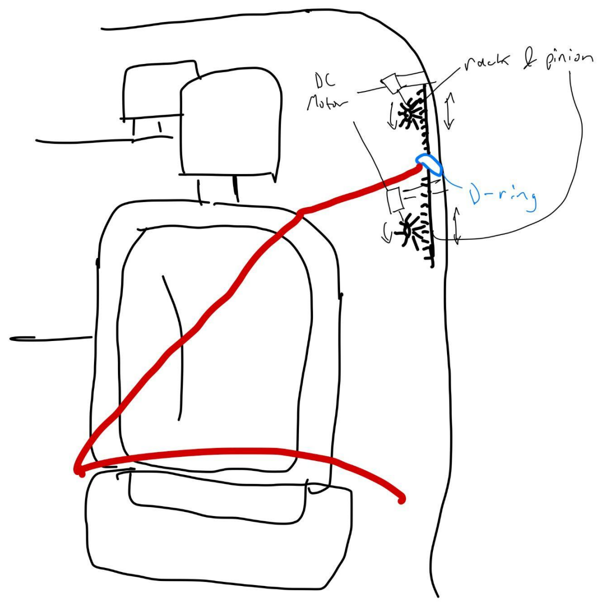
*Resolution is dependent on the applied frame rate. The lower the frame rate, the higher the achieved resolution.

Appendix C: Concept Generation

CONCEPT #1 This concept designs a device that uses four motor-driven winches to move the d-ring in the center. In the figure the 4 winches are depicted as light blue, and the oval shape in the middle represents the D ring. This design is inspired by the michigan stadium camera, which is suspended by four large cables that are connected to each corner of the upper stadium, and each is extended or retracted to adjust the position of the camera. 2 Degree of freedom Figure drawn from front view of car driver seat (perspective of the Kinect sensor)	
CONCEPT #2 Instead of building around the D-ring, this concept completely removes the shoulder belt from the standard seat belt, and instead adds a new horizontal belt around the chest area (depicted as the orange horizontal line in the figure). The automated adjuster would then build around the newly added "Chest belt". This design would remove the problem of having an optimal shoulder belt score and ideally provide more comfort than having a shoulder belt touching the passenger's neck. 1 Degree of Freedom	

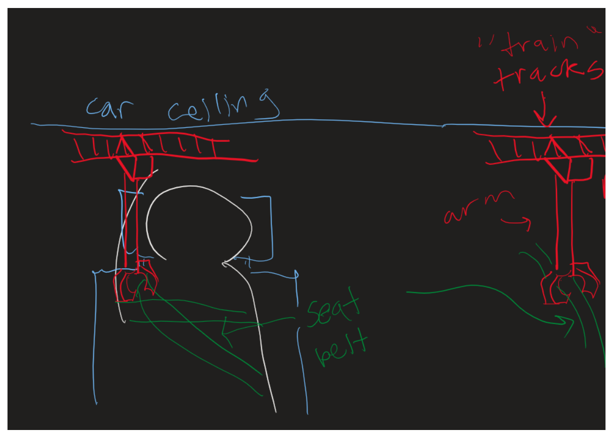
CONCEPT #3
This concept involves a rack and pinion mounted on the B-pillar where the pinion is driven by a DC motor. Two of these mechanisms are placed on the pillar with the D-ring being attached to the end of the rack of each mechanism. Movement of motors simultaneously moves the D-ring vertically.

1 degree of freedom



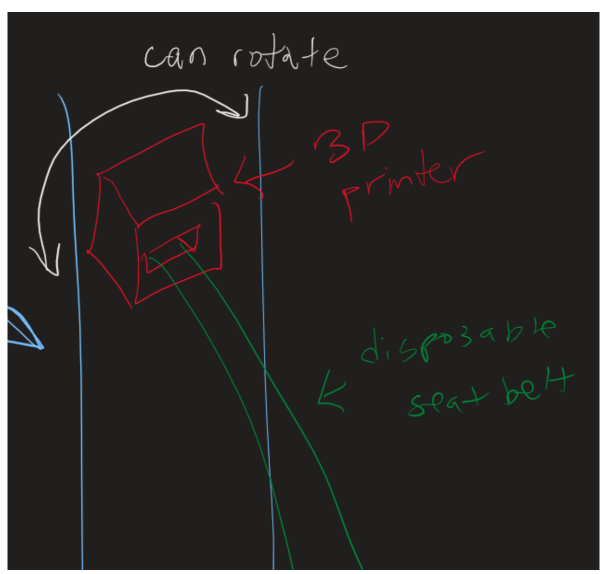
CONCEPT #4
This concept involves a claw hand attached to a railing system mounted on the ceiling of the vehicle. Similar to the robot arm concept, the robot arm would adjust the shoulder belt based on the input data from the visual sensor, and the railing system on the ceiling would allow horizontal movement.

2 degrees of freedom



CONCEPT #5
This concept designs a device that is added onto the current D-ring of a standard seat belt, which would allow the D-ring to rotate and adjust the shoulder belt position. This will add an extra degree of freedom and allow more adjustability

2 degrees of freedom



<table>
<tr>
<td>CONCEPT #6
Similar to the design concept 2 discussed in the report, instead of having the new seat belt attached to the ceiling, this design puts the new seat belt under the current seatbelt, which would adjust the shoulder belt position by contracting and pulling the shoulder belt. This employs the design heuristic of repositioning.

1 degree of freedom</td>
<td></td>
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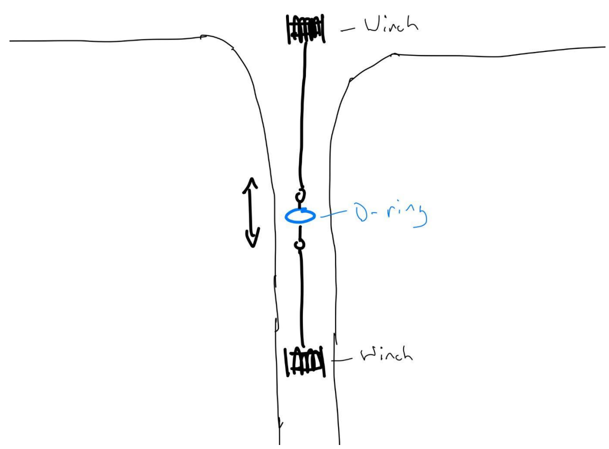
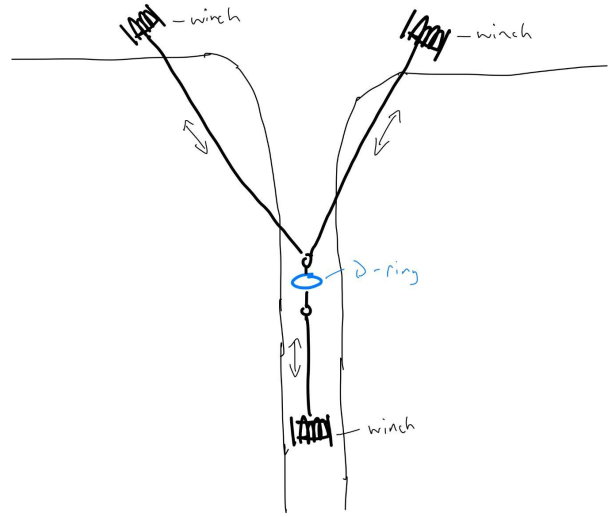
<tr>
<td>CONCEPT #7
This design draws inspiration from a standard roller coaster seat belt, which will replace the current standard seat belt in a vehicle. This design provides more safety and more comfort with equal position and force distribution on both shoulders.

0 degree of freedom</td>
<td></td>
</tr>
<tr>
<td>CONCEPT #8
This design involves two winches mounted on the top and bottom of the D-ring on the B-pillar. The D-ring will be attached with a string onto both winches. These winches will be motor powered and can retract the string in order to adjust the D-ring. Seat belt not depicted but would be threaded through D-ring (blue ellipse)

1 degree of freedom</td>
<td>
</td>
</tr>
</table>

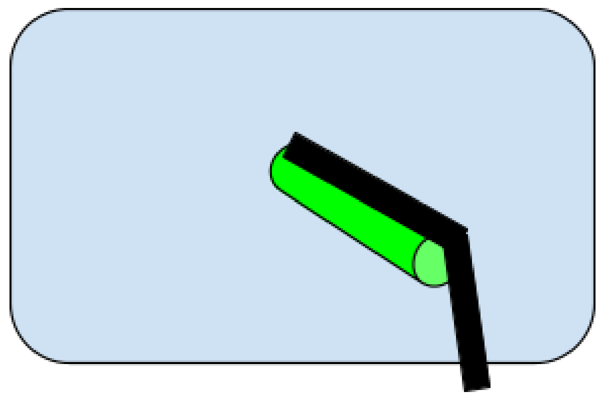
CONCEPT #9
Using design heuristics, concept #9 is an improved version of concept #8, where 3 winches will be used instead of 2. As shown in the figure, there will be 2 winches on top of the D-ring, which are mounted at a certain angle on the B pillar. This allows a wider range of motion and an extra degree of freedom.

2 degrees of freedom



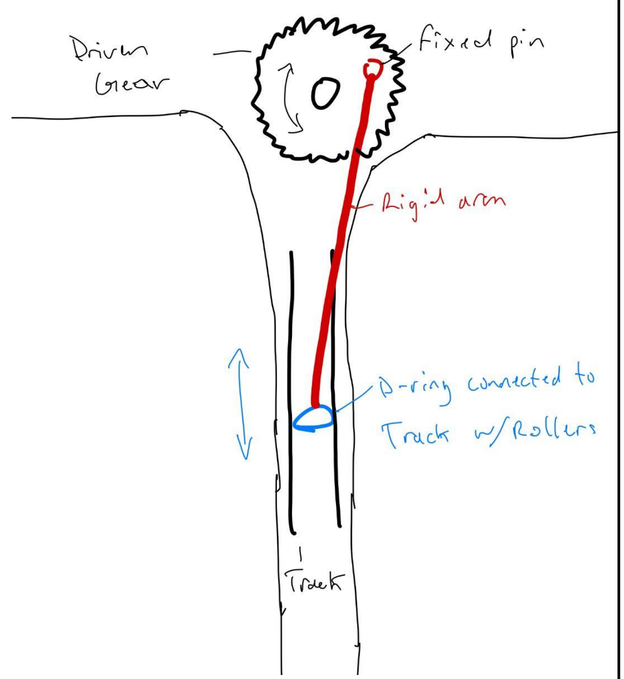
CONCEPT #10
This concept involves adding an arm extending from the side of the car that the seat belt runs through. This arm will be stiff enough to stay in place and allow for 3D adjusting. Green arm in the image comes out of the side of the car at the seat belt start and guides it to a new position before being draped over the shoulder of the user.

0 degrees of freedom



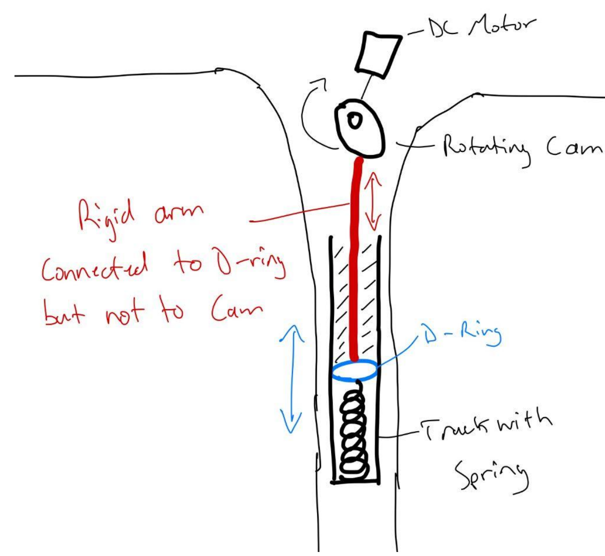
CONCEPT #11
This concept involves a gear mounted on the upper part of the B-pillar and driven by a DC motor. A rigid arm is fixed to a point on the outer part of gear with a pin, and the other end is attached to the D-ring, which is engaged with rollers on a track mounted on the B-pillar. As the gear rotates, the D-ring moves vertically. Seat belt not depicted but would be threaded through D-ring (blue ellipse)

1 degree of freedom



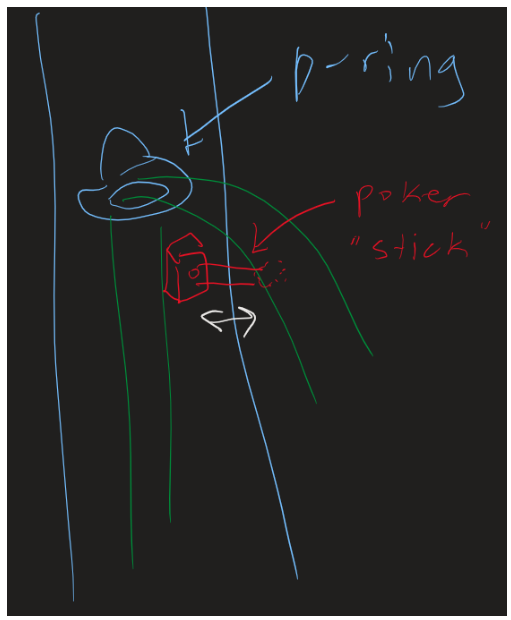
<table>
<tr>
<td>CONCEPT #12
Using design heuristics, concept 12 is based on the idea behind concept 11. In this design, a rotating cam is used instead of a gear, and it is engaged with a rigid arm that is constrained vertically by a track (mounted to B-pillar). The D- ring is attached to one end of the rigid arm and is also engaged with the track on rollers. On the other side of the D-ring there is a spring which compresses or extends as the cam rotates.

1 degree of freedom</td>
<td>



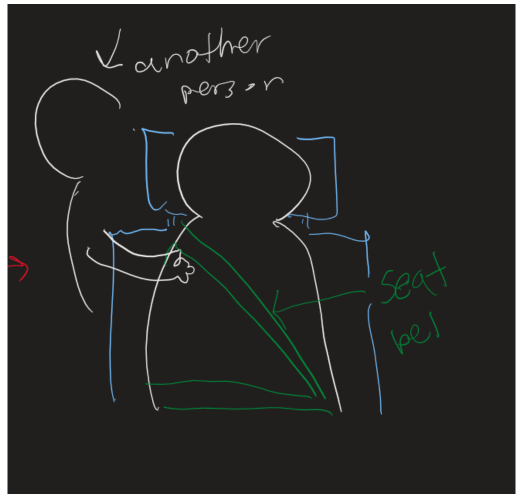
</td>
</tr>
<tr>
<td>CONCEPT #13
This concept designs a device that is mounted under the D-ring on the B-pillar. Instead of adjusting the D-ring itself, the device extrudes a stick that pushes the shoulder belt in one direction, which would then adjust the belt’s position.

1 degree of freedom</td>
<td>



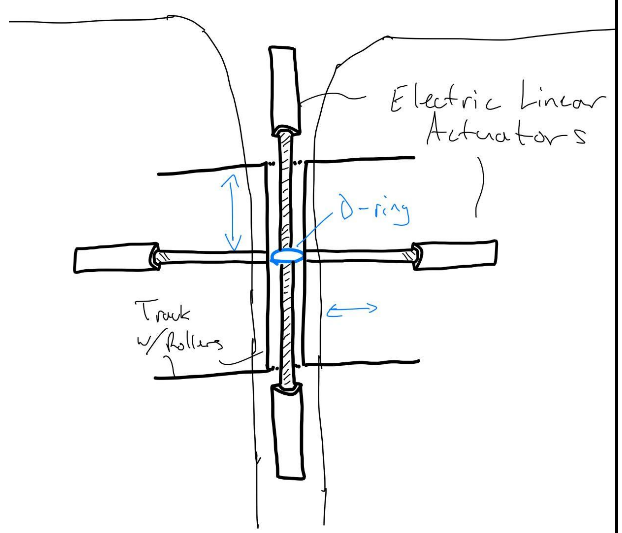
</td>
</tr>
</table>

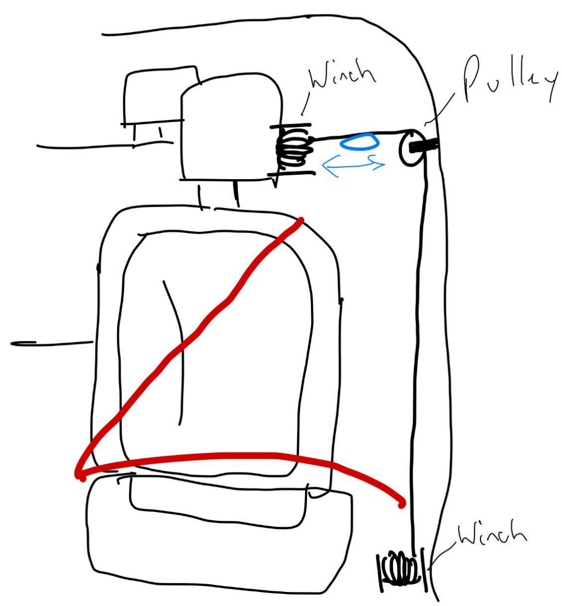
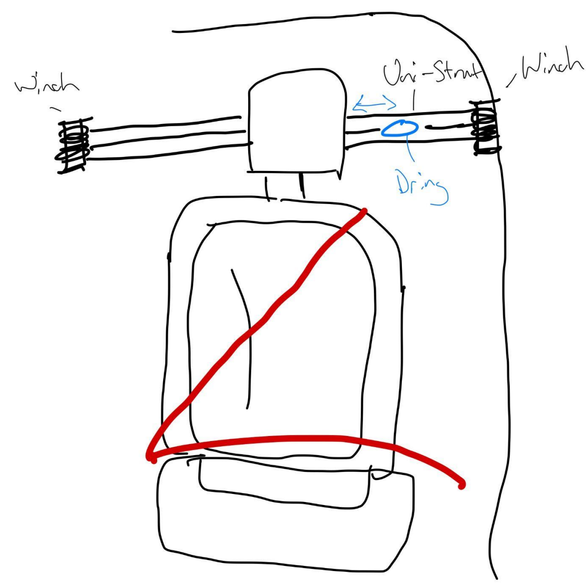
CONCEPT #14
This concept involves hiring another person as the passenger's personal seat belt adjuster, which can ensure the shoulder belt is adjusted to the best position with a wide range of motion.

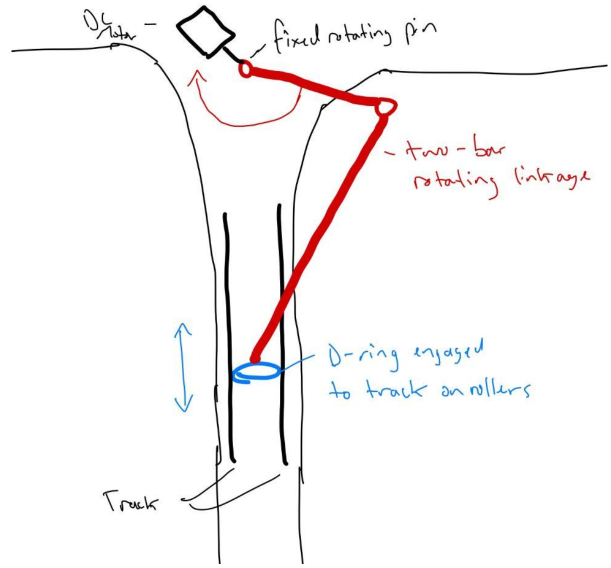
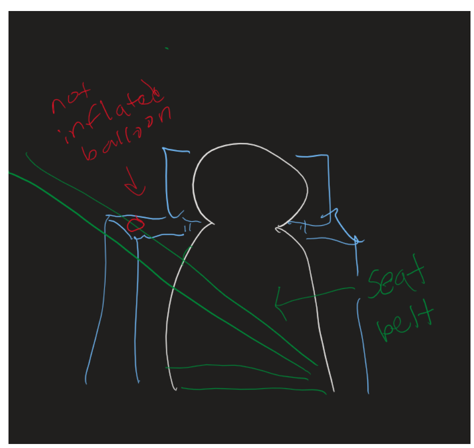


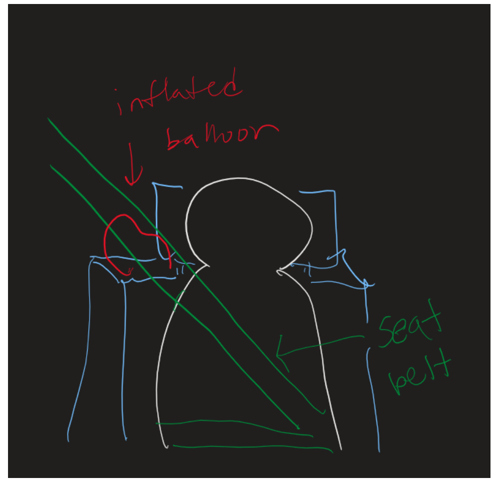
CONCEPT #15
This design involves a horizontal track that is mounted to the windows. 2 electric linear actuators are mounted on either side of the B-pillar on the window. A vertical track which includes two more electric linear actuators on either side of the D-ring is engaged with the horizontal tracks underneath it such that the entire vertical assembly can move side to side as the horizontal actuators extend/retract.

2 degrees of freedom



CONCEPT #16 This design involves a motorized winch mounted to the headrest, while another one is mounted to the floor next to the vehicle seat. Each winch is attached to one end of the D-ring. The floor winch cable is passed over a pulley that is mounted on the B-pillar resulting in horizontal motion of the D-ring. 1 degree of freedom	
CONCEPT #17 This concept involves a unistrut beam mounted horizontally behind the headrest, spanning from the B-pillar on one side of the vehicle to the other. A motorized winch is mounted on both ends of the beam and cables attached to both sides of the D-ring. This will allow the D-ring to move horizontally across the beam when the winch is turned on. 1 degree of freedom	

CONCEPT #18 This design consists of a two bar linkage rotation to translation system powered by a dc motor. The D-ring is attached to the end of the second link with a pin, as shown in the figure. As link one rotates around the fixed point, D-ring translates up and down. The D-ring is engaged with rollers on a track mounted on the B-pillar. 1 degree of freedom	
CONCEPT #19 Microorganisms will be placed onto the shoulder belt of each assembly. These microorganisms can be controlled either through thermal or moisture influence. The environmental factors such as temperature or moisture will differ according to the users' optimal shoulder belt scores. 6 degrees of freedom	
CONCEPT #20 This concept places an inflatable material such as a balloon on the shoulder portion of the passenger seat. This inflatable material will expand and move the shoulder belt due to this expansion. Ideally, this material will not inflate linearly as a set shape, but will create organic 3-dimensional forms. 6 degrees of freedom	

	inflated balloon seat belt

Appendix D: Empirical D-ring Measurement Process

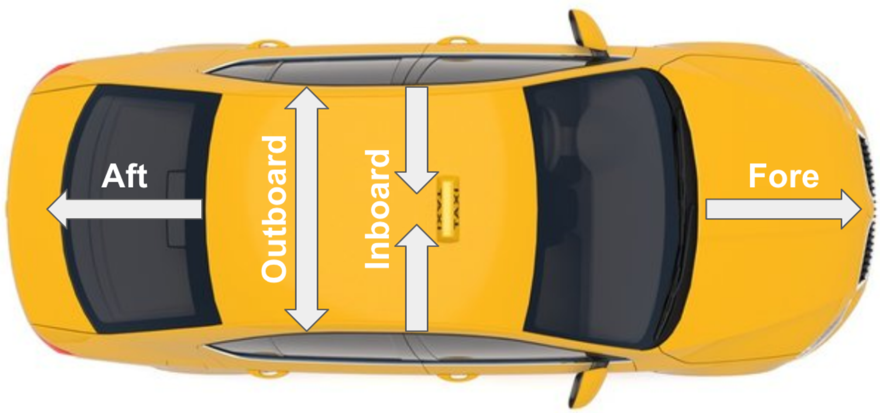


Figure D.1: Top down schematic of generic car with description of relevant measurement axes

Six total measurements were taken and are described in Table D.1 below. The measurements with D-ring adjuster in both extreme positions were then averaged to get values representative of the average D-ring height. Then the resulting averages for fore-aft distance were averaged with each other to get a fore distance between d-ring and forward headrest that represents the average D-ring height as well as the average fore-aft location for seat adjustment.

Table D.1: Measurements taken on Subaru (all measurements made with measuring tape)

	Inboard Distance from D-ring to Centerline of Seat Headrest (in)	Fore Distance from D-ring to forward face of headrest when seat is in furthest forward location (in)	Aft Distance from D-ring to Forward face of Headrest when seat is in furthest aft location (in)	Averaged Fore Distance from D-ring to Forward Face of Headrest between extreme seat positon
D-Ring - adjuster Highest setting	9.25	5	-4.375	
D-ring - adjuster lowest setting	9.875	4.75	-4.75	
Averaged Value Converted to mm	**242.8875**	-115.8875	123.825	**3.96875**

Picture examples of measurements:

Figure D.2: Inboard Distance from D-ring to centerline of seat headrest with D-ring adjuster in highest setting (Left) and in lowest setting (right)

Figure D.3: Aft Distance from D-ring to forward face of seat headrest

Appendix E: Human Shape Model D-ring Vertical Adjustment Analysis using SOLIDWORKS

Table E.1: Metrics used to generate each human model from humanshape.org

	Occupant Height (mm)	Occupant BMI (kg/m^2)	Sitting Height / Stature	Age (Years)
Small Female	1524	18	0.52	40
Large Male	1829	40	0.52	40

Table E.2: Values measured using SOLIDWORKS analysis and final range of adjustability derived

	Small Female D-ring Lower Bound (22mm+20mm)	Large Male D-ring Upper Bound (22mm-20mm)	Small Female D-Ring Desired Location	Large Male D-Ring Desired Location
Shoulder Belt Score (mm)	42	2	22	22
D-ring Height from bottom of attachement Wall (mm)	944.1393	1136.4117	991.03399	1058.036
Range of adjustability without uncertainty (mm)			**67.00201**	
Range of Adjustability with uncertainty (mm)	**192.2724**			
Range of Adjustability converted to Inches	**7.569779528**		**2.637874409**	

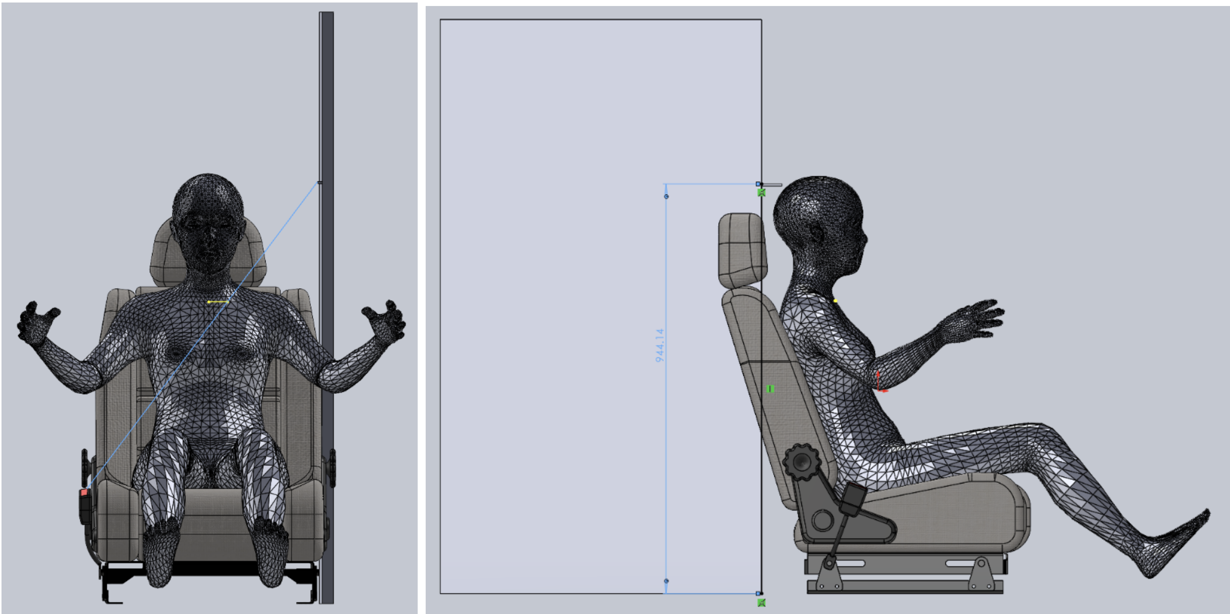


Figure E.1: Small female model wth shoulder belt score of 42 mm. Front veiw (left) shows reference curve alignment and side view shows subsequent D-ring height measurement (944.1393 mm) [40].

Seat model downloaded from grabcad.com:
https://grabcad.com/library/seat-belt-amsafe-1/details?folder_id=452738

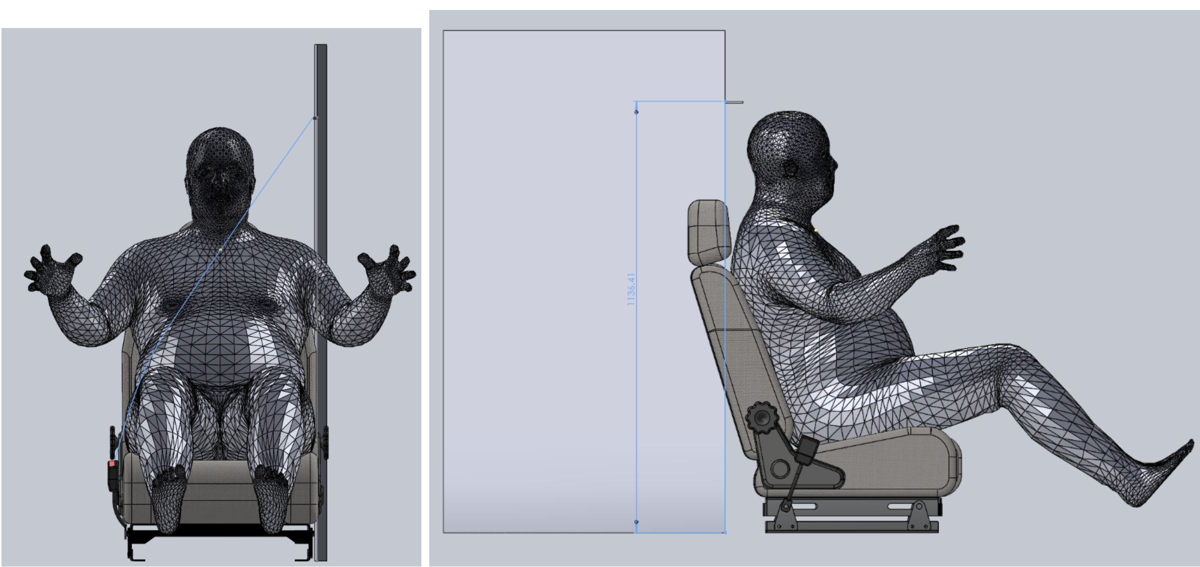
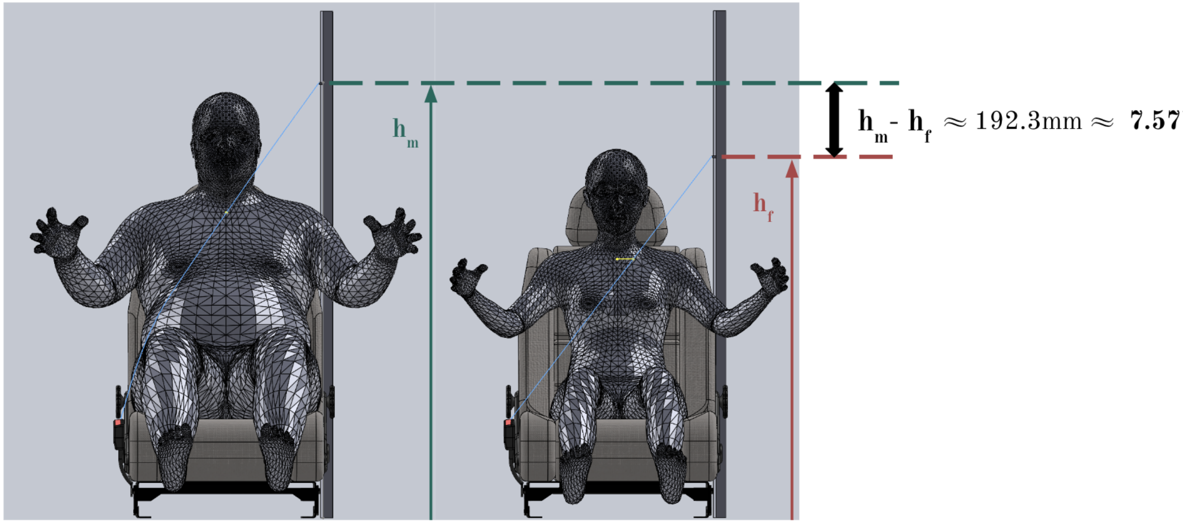


Figure E.2: Large male model wth shoulder belt score of 2 mm. Front veiw (left) shows reference curve alignment and side view shows subsequent D-ring height measurement (1136.4117 mm) [40].

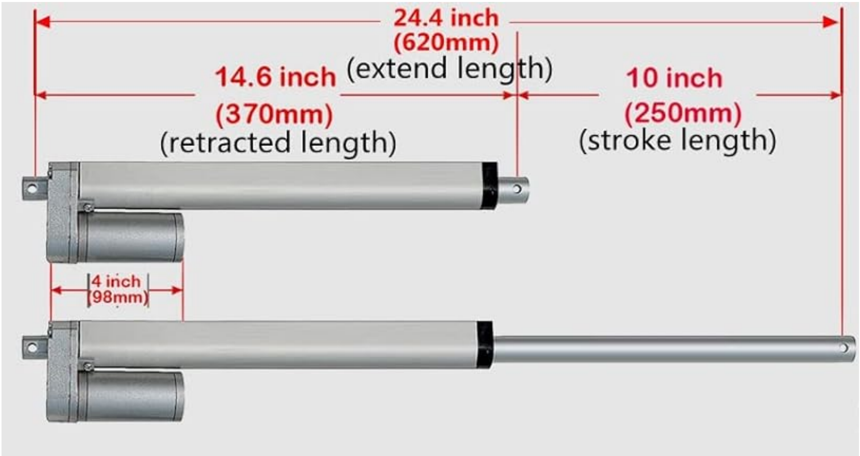


Occupant:	Large Male	Small Female
Height	6 ft	5 ft
BMI	40 kg/m^2	18 kg/m^2
SBS	2 mm	42 mm

} Human shape models shown were generated using these metrics

Figure E.3: Large male model wth shoulder belt score of 2 mm. Front veiw (left) shows reference curve alignment and side view shows subsequent D-ring height measurement (1136.4117 mm) [40].

Appendix F: Linear Actuator Specifications



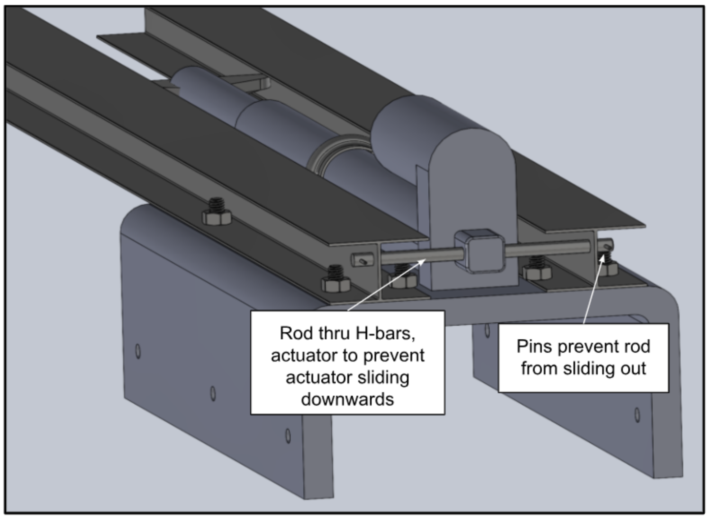
RATED LOADS (LBS) N	STROKE LENGTH (MM)	TYPE	VOLT	RETRACTED LENGTH (MM)	EXTENDED LENGTH (MM)
330 lbs(1500N)	50	NW-1500-12	12V	155	205
	100	NW-1500-12	12V	205	305
	150	NW-1500-12	12V	260	410
	200	NW-1500-12	12V	320	520
	250	NW-1500-12	12V	370	620
	300	NW-1500-12	12V	420	720
	350	NW-1500-12	12V	470	820
	400	NW-1500-12	12V	550	950
	450	NW-1500-12	12V	600	1050

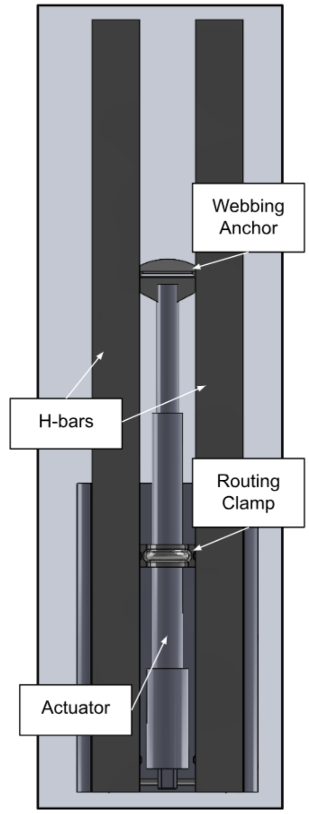
Specifications

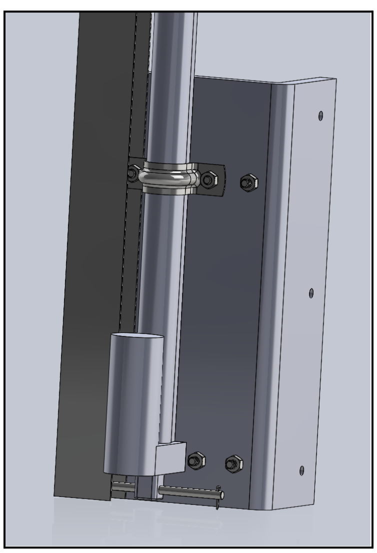
Stroke Length	10"/250mm
Retracted Length	370mm
Extended Length	620mm
Input Voltage	12V DC
Max Push Load	1500N/330lbs
Max load	150KG/330lbs
Max Pull Load	1000N/264lbs
Travel Speed	0.22 in/sec (5.7 mm/s)

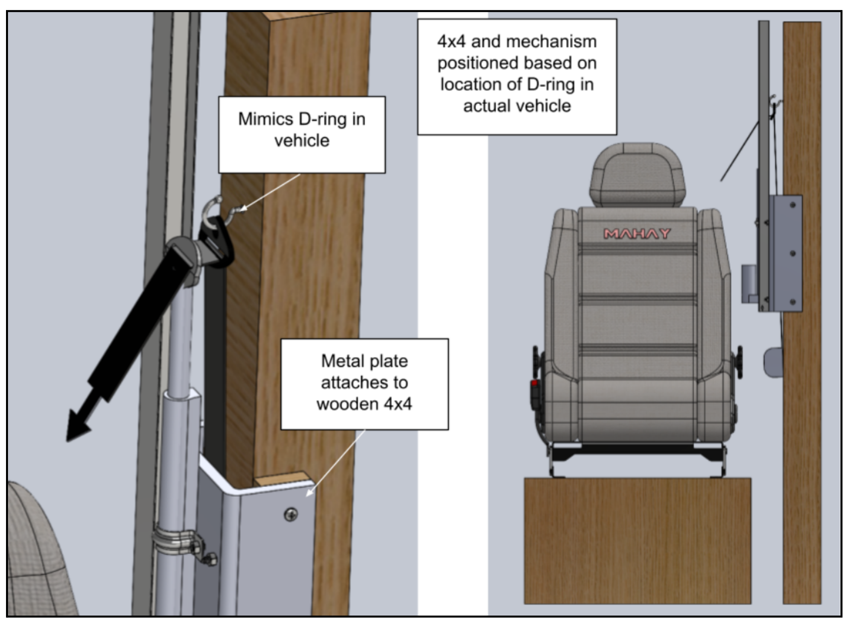
Duty Cycle	20%
Material	Aluminum alloy
Color	Silver grey
Operation temperature	-26°C~+65°C
Protection Class	IP54
No-load current	0.8A
Max load current	3A

Appendix G: Mechanism Assembly CAD









Appendix H: Build Design Bill of Materials

Part No.	Item	Quantity	Source	Catalog Number	Contact	Price
1	Eco-worthy 12 Volt 10 Inch Linear Actuator	1	Amazon	N/A	amazon.com	$45.57
2	3 Point Retractable Seat Belt	1	OEM Seatbelts	N/A	oemseatbelts.com	$85.95
3	Webbing Anchor	1	McMaster - Carr	3648T95	mcmaster.com	$9.79
4	Routing Clamp	1	McMaster - Carr	8874T44	mcmaster.com	$4.16
5	6mm Dia. Steel Rod	1	McMaster - Carr	6103N432	mcmaster.com	$17.50
6	H-Bar (6 foot)	1	McMaster - Carr	4558T52	mcmaster.com	$22.90
7	Steel hex nuts	8	McMaster - Carr	95462A029	mcmaster.com	Machine shop
8	¼” Philips Head Screws (1”)	14	McMaster - Carr	94836A423	mcmaster.com	Machine shop
9	Wood 4x4” 8 foot	1	McMaster - Carr	N/A	Homedepot.com	$12.85
10	UMTRI Chair Setup	1	UMTRI	N/A	kklinich@umich.edu	$0
11	Metal Plate 12x12”	1	Alro	N/A	alro.com	$40.28
12	Arduino Uno Rev3	1	Arduino	ATmega328P	amazon.com	$24.84
13	3M Arduino UNO USB Type A/B Data Sync Cable	1	Amazon	N/A	amazon.com	$7.99
14	L298N Dual H-Bridge Motor Controller Board	1	Amazon	L298N	amazon.com	$9.99

15	Universal AC/DC Adapter Power Supply	1	SoulBay	N/A	amazon.com	$14.43
16	Qunqi 400 tie Point Experiment Mini Breadboard	1	Qunqi	N/A	amazon.com	$5.99
17	EDGELEC 120pcs 50cm Breadboard Jumper Wires Assorted	1	EDGELEC	N/A	amazon.com	$13.99

Appendix I: Verification and Validation Table

Requirement	Specification	Verification Test	Validation Test
Provide enhanced range for seat belt users based on height and BMI	Provide for: $18 \leq BMI \leq 40$ 5'0" ≤ Height≤ 6'0"	Build design - Have a person matching low end metrics and high end metrics both sit in seat and see if SBS of 22 can be achieved	Build design - Have the two users fill out a survey asking them if the shoulder belt placement was comfortable after it is adjusted to SBS 22
Ensure accurate imaging data	Detect ≥ 2 major landmarks on body of passenger	Final Design - Take pictures of different users in the car seat with belt on, then verify that OpenPose can detect at least 2 body landmarks	Final Design - Have different users with various types of clothing be captured by the visual sensor in a vehicle environment to test the validity and reliability of the sensor
Achieve comfortable shoulder belt placement	Shoulder belt score of 22 ± 2 cm is accurately obtained	Final Design - Perform adjustment task on multiple users of different sizes, multiple times, and empirically measure SBS at final adjusted position to determine whether it is within error bounds consistently	Final Design - Same process as verification except have users fill out survey/questionnaire asking them if the resulting fit from each trial was comfortable
Adjustable D-ring location	Position the D-ring component through an increased vertical range of motion Provide ≥ 1 degrees of freedom	Final Design - Comparison between the range of adjustability between the standard seat belt assemblies with the final design	Final Design - Place the product in a vehicle environment and make sure that the full vertical range of the actuator and D-ring is achievable
Utilize visual sensor and library	Time from point cloud measurement to adjuster < 4 seconds	Final Design - Determine the total run time of the adjustment process by having the seat belt adjuster move according to arbitrary seat belt scores and measuring the total time	Final Design - Have users give feedback on comfortability in waiting for the adjustment process to begin and finish

Safety	Follow Code 49 C.F.R. 393.60(e)(1)(ii) regarding front windshield visibility Follow Codes FMVSS No. 216 and FMVSS No. 208 regarding structural integrity of B pillar and car seats	Build Design - The 30 mph frontal impact test was not achievable. The subsequent force analyses were theoretical and were calculated manually and through software simulations.	Final Design - Empirically test the frontal impact test through the sled test using a dummy. The subsequent force codes can tested using a durability testing machine to exert require forces and tension

Appendix J: Build Design Wiring Diagram and Arduino Code

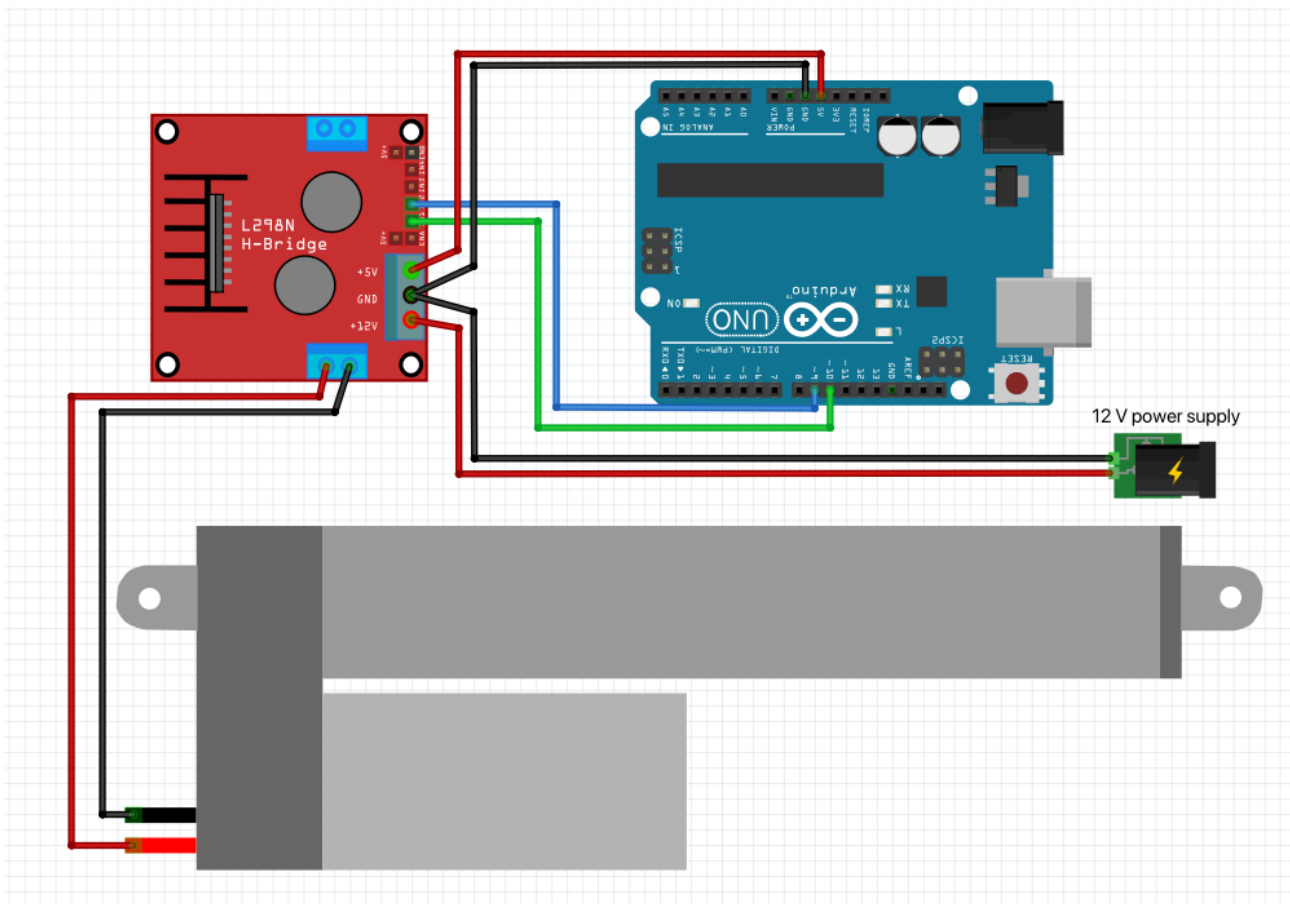


Figure J.1: Wiring diagram for build design. Usb-B connector is attached to the port on right side of Arduino and connected to serial port on a laptop.

Arduino Code:

```
const int Extend = 10;
const int Retract = 9;
const int delayTime = 5000;
const int timeout = 28000;

int currentPosition = 0;

void setup() {
  pinMode(Extend, OUTPUT);
  pinMode(Retract, OUTPUT);
  Serial.begin(9600);
}

int readIntegerInput(const char* prompt) {
```

```
  Serial.println(prompt);
  while (!Serial.available()) {}
  String inputString = Serial.readStringUntil('\n');
  int value = inputString.toInt();
  Serial.print("Debug: Read value: ");
  Serial.println(value);
  return value;
}

void moveActuator(int direction, unsigned long moveTime) {
  unsigned long startTime = millis();

  if (direction == 1) {
    Serial.println("Retracting actuator...");
    digitalWrite(Retract, HIGH);
    digitalWrite(Extend, LOW);
  } else if (direction == 2) {
    Serial.println("Extending actuator...");
    digitalWrite(Extend, HIGH);
    digitalWrite(Retract, LOW);
  }

  while (millis() - startTime < moveTime) {
    delay(10);
  }

  Serial.println("Stopping actuator...");
  digitalWrite(Extend, LOW);
  digitalWrite(Retract, LOW);
}

void controlActuator(int a, int b) {
  Serial.println("Debug: Inside controlActuator function");
  Serial.print("Input Height in Feet: ");
  Serial.println(a);
  Serial.print("Input Height in Inches: ");
  Serial.println(b);
  Serial.print("The Current Position Is: ");
  Serial.println(currentPosition);

 if (currentPosition == 1) {
    if (a == 5 && b == 6) {
      moveActuator(2, timeout / 2);
    } else if (a == 5 && b == 0) {
```

```
    } else if (a == 6 && b == 0) {
      moveActuator(2, timeout);
    } else if (a == 5 && b == 1) {
      moveActuator(2, timeout/12);
    } else if (a == 5 && b == 2) {
      moveActuator(2, 2*(timeout/12));
    } else if (a == 5 && b == 3) {
      moveActuator(2, 3*(timeout/12));
    } else if (a == 5 && b == 4) {
      moveActuator(2, 4*(timeout/12));
    } else if (a == 5 && b == 5) {
      moveActuator(2, 5*(timeout/12));
    } else if (a == 5 && b == 7) {
      moveActuator(2, 7*(timeout/12));
    } else if (a == 5 && b == 8) {
      moveActuator(2, 8*(timeout/12));
    } else if (a == 5 && b == 9) {
      moveActuator(2, 9*(timeout/12));
    } else if (a == 5 && b == 10) {
      moveActuator(2, 10*(timeout/12));
    } else if (a == 5 && b == 11) {
      moveActuator(2, 11*(timeout/12));
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }

  } else if (currentPosition == 4) {
    if (a == 5 && b == 6) {
      moveActuator(2, 5*(timeout/12));
    } else if (a == 5 && b == 0) {
      moveActuator(1, timeout/12);
    } else if (a == 6 && b == 0) {
      moveActuator(2, 11*(timeout/12));
    } else if (a == 5 && b == 2) {
      moveActuator(2, 1*(timeout/12));
    } else if (a == 5 && b == 3) {
      moveActuator(2, 2*(timeout/12));
```

```
    } else if (a == 5 && b == 4) {
      moveActuator(2, 3*(timeout/12));
    } else if (a == 5 && b == 5) {
      moveActuator(2, 4*(timeout/12));
    } else if (a == 5 && b == 7) {
      moveActuator(2, 6*(timeout/12));
    } else if (a == 5 && b == 8) {
      moveActuator(2, 7*(timeout/12));
    } else if (a == 5 && b == 9) {
      moveActuator(2, 8*(timeout/12));
    } else if (a == 5 && b == 10) {
      moveActuator(2, 9*(timeout/12));
    } else if (a == 5 && b == 11) {
      moveActuator(2, 10*(timeout/12));
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }

  } else if (currentPosition == 5) {
    if (a == 5 && b == 6) {
      moveActuator(2, 4*(timeout/12));
    } else if (a == 5 && b == 0) {
      moveActuator(1, 2*(timeout/12));
    } else if (a == 6 && b == 0) {
      moveActuator(2, 10*(timeout/12));
    } else if (a == 5 && b == 1) {
      moveActuator(1, 1*(timeout/12));
    } else if (a == 5 && b == 3) {
      moveActuator(2, 1*(timeout/12));
    } else if (a == 5 && b == 4) {
      moveActuator(2, 2*(timeout/12));
    } else if (a == 5 && b == 5) {
      moveActuator(2, 3*(timeout/12));
    } else if (a == 5 && b == 7) {
      moveActuator(2, 5*(timeout/12));
    } else if (a == 5 && b == 8) {
      moveActuator(2, 6*(timeout/12));
```

```
    } else if (a == 5 && b == 9) {
      moveActuator(2, 7*(timeout/12));
    } else if (a == 5 && b == 10) {
      moveActuator(2, 8*(timeout/12));
    } else if (a == 5 && b == 11) {
      moveActuator(2, 9*(timeout/12));
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }

  } else if (currentPosition == 6) {
    if (a == 5 && b == 6) {
      moveActuator(2, 3*(timeout/12));
    } else if (a == 5 && b == 0) {
      moveActuator(1, 3*(timeout/12));
    } else if (a == 6 && b == 0) {
      moveActuator(2, 9*(timeout/12));
    } else if (a == 5 && b == 1) {
      moveActuator(1, 2*(timeout/12));
    } else if (a == 5 && b == 2) {
      moveActuator(1, 1*(timeout/12));
    } else if (a == 5 && b == 4) {
      moveActuator(2, 1*(timeout/12));
    } else if (a == 5 && b == 5) {
      moveActuator(2, 2*(timeout/12));
    } else if (a == 5 && b == 7) {
      moveActuator(2, 4*(timeout/12));
    } else if (a == 5 && b == 8) {
      moveActuator(2, 5*(timeout/12));
    } else if (a == 5 && b == 9) {
      moveActuator(2, 6*(timeout/12));
    } else if (a == 5 && b == 10) {
      moveActuator(2, 7*(timeout/12));
    } else if (a == 5 && b == 11) {
      moveActuator(2, 8*(timeout/12));
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
```

```
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }

  } else if (currentPosition == 7) {
    if (a == 5 && b == 6) {
      moveActuator(2, 2*(timeout/12));
    } else if (a == 5 && b == 0) {
      moveActuator(1, 4*(timeout/12));
    } else if (a == 6 && b == 0) {
      moveActuator(2, 8*(timeout/12));
    } else if (a == 5 && b == 1) {
      moveActuator(1, 3*(timeout/12));
    } else if (a == 5 && b == 2) {
      moveActuator(1, 2*(timeout/12));
    } else if (a == 5 && b == 3) {
      moveActuator(1, 1*(timeout/12));
    } else if (a == 5 && b == 5) {
      moveActuator(2, 1*(timeout/12));
    } else if (a == 5 && b == 7) {
      moveActuator(2, 3*(timeout/12));
    } else if (a == 5 && b == 8) {
      moveActuator(2, 4*(timeout/12));
    } else if (a == 5 && b == 9) {
      moveActuator(2, 5*(timeout/12));
    } else if (a == 5 && b == 10) {
      moveActuator(2, 6*(timeout/12));
    } else if (a == 5 && b == 11) {
      moveActuator(2, 7*(timeout/12));
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }
```

```
} else if (currentPosition == 8) {
  if (a == 5 && b == 6) {
    moveActuator(2, 1*(timeout/12));
  } else if (a == 5 && b == 0) {
    moveActuator(1, 5*(timeout/12));
  } else if (a == 6 && b == 0) {
    moveActuator(2, 7*(timeout/12));
  } else if (a == 5 && b == 1) {
    moveActuator(1, 4*(timeout/12));
  } else if (a == 5 && b == 2) {
    moveActuator(1, 3*(timeout/12));
  } else if (a == 5 && b == 3) {
    moveActuator(1, 2*(timeout/12));
  } else if (a == 5 && b == 4) {
    moveActuator(1, 1*(timeout/12));
  } else if (a == 5 && b == 7) {
    moveActuator(2, 2*(timeout/12));
  } else if (a == 5 && b == 8) {
    moveActuator(2, 3*(timeout/12));
  } else if (a == 5 && b == 9) {
    moveActuator(2, 4*(timeout/12));
  } else if (a == 5 && b == 10) {
    moveActuator(2, 5*(timeout/12));
  } else if (a == 5 && b == 11) {
    moveActuator(2, 6*(timeout/12));
  } else {
    Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
    Serial.print("Input Height in Feet: ");
    Serial.println(a);
    Serial.print("Input Height in Inches: ");
    Serial.println(b);
    Serial.print("The Current Position Is: ");
    Serial.println(currentPosition);
    return;
  }

} else if (currentPosition == 2) {
  if (a == 5 && b == 6) {

  } else if (a == 5 && b == 0) {
    moveActuator(1, 6*(timeout/12));
  } else if (a == 6 && b == 0) {
    moveActuator(2, 6*(timeout/12));
```

```
    } else if (a == 5 && b == 1) {
      moveActuator(1, 5*(timeout/12));
    } else if (a == 5 && b == 2) {
      moveActuator(1, 4*(timeout/12));
    } else if (a == 5 && b == 3) {
      moveActuator(1, 3*(timeout/12));
    } else if (a == 5 && b == 4) {
      moveActuator(1, 2*(timeout/12));
    } else if (a == 5 && b == 5) {
      moveActuator(1, 1*(timeout/12));
    } else if (a == 5 && b == 7) {
      moveActuator(2, 1*(timeout/12));
    } else if (a == 5 && b == 8) {
      moveActuator(2, 2*(timeout/12));
    } else if (a == 5 && b == 9) {
      moveActuator(2, 3*(timeout/12));
    } else if (a == 5 && b == 10) {
      moveActuator(2, 4*(timeout/12));
    } else if (a == 5 && b == 11) {
      moveActuator(2, 5*(timeout/12));
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }
  } else if (currentPosition == 9) {
    if (a == 5 && b == 6) {
      moveActuator(1, timeout / 12);
    } else if (a == 5 && b == 0) {
      moveActuator(1, (timeout*7)/12);
    } else if (a == 6 && b == 0) {
      moveActuator(2, (timeout*5)/12);
    } else if (a == 5 && b == 1) {
      moveActuator(1, timeout/2);
    } else if (a == 5 && b == 2) {
      moveActuator(1, (timeout*5)/12);
    } else if (a == 5 && b == 3) {
      moveActuator(1, timeout/3);
    } else if (a == 5 && b == 4) {
```

```
    moveActuator(1, timeout/4);
  } else if (a == 5 && b == 5) {
    moveActuator(1, timeout/6);
  } else if (a == 5 && b == 8) {
    moveActuator(2, timeout/12);
  } else if (a == 5 && b == 9) {
    moveActuator(2, timeout/6);
  } else if (a == 5 && b == 10) {
    moveActuator(2, timeout/4);
  } else if (a == 5 && b == 11) {
    moveActuator(2, timeout/3);
  } else {
    Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
    Serial.print("Input Height in Feet: ");
    Serial.println(a);
    Serial.print("Input Height in Inches: ");
    Serial.println(b);
    Serial.print("The Current Position Is: ");
    Serial.println(currentPosition);
    return;
  }

} else if (currentPosition == 10) {
  if (a == 5 && b == 6) {
    moveActuator(1, timeout / 6);
  } else if (a == 5 && b == 0) {
    moveActuator(1, timeout);
  } else if (a == 6 && b == 0) {
    moveActuator(2, timeout);
  } else if (a == 5 && b == 1) {
    moveActuator(1, (timeout*7)/12);
  } else if (a == 5 && b == 2) {
    moveActuator(1, timeout/2);
  } else if (a == 5 && b == 3) {
    moveActuator(1, (timeout*5)/12);
  } else if (a == 5 && b == 4) {
    moveActuator(1, timeout/3);
  } else if (a == 5 && b == 5) {
    moveActuator(1, timeout/4);
  } else if (a == 5 && b == 7) {
    moveActuator(1, timeout/12);
  } else if (a == 5 && b == 9) {
    moveActuator(2, timeout/12);
  } else if (a == 5 && b == 10) {
```

```
  moveActuator(2, timeout/6);
} else if (a == 5 && b == 11) {
  moveActuator(2, timeout/4);
} else {
  Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
  Serial.print("Input Height in Feet: ");
  Serial.println(a);
  Serial.print("Input Height in Inches: ");
  Serial.println(b);
  Serial.print("The Current Position Is: ");
  Serial.println(currentPosition);
  return;
}
} else if (currentPosition == 11) {
if (a == 5 && b == 6) {
  moveActuator(1, timeout / 4);
} else if (a == 5 && b == 0) {
  moveActuator(1, timeout);
} else if (a == 6 && b == 0) {
  moveActuator(2, timeout);
} else if (a == 5 && b == 1) {
  moveActuator(1, (timeout*2)/3);
} else if (a == 5 && b == 2) {
  moveActuator(1, (timeout*7)/12);
} else if (a == 5 && b == 3) {
  moveActuator(1, timeout/2);
} else if (a == 5 && b == 4) {
  moveActuator(1, (timeout*5)/12);
} else if (a == 5 && b == 5) {
  moveActuator(1, timeout/3);
} else if (a == 5 && b == 8) {
  moveActuator(1, timeout/12);
} else if (a == 5 && b == 7) {
  moveActuator(1, timeout/6);
} else if (a == 5 && b == 10) {
  moveActuator(2, timeout/12);
} else if (a == 5 && b == 11) {
  moveActuator(2, timeout/6);
} else {
  Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
  Serial.print("Input Height in Feet: ");
  Serial.println(a);
  Serial.print("Input Height in Inches: ");
  Serial.println(b);
```

```
  Serial.print("The Current Position Is: ");
  Serial.println(currentPosition);
  return;
}
} else if (currentPosition == 12) {
if (a == 5 && b == 6) {
  moveActuator(1, timeout / 3);
} else if (a == 5 && b == 0) {
  moveActuator(1, timeout);
} else if (a == 6 && b == 0) {
  moveActuator(2, timeout);
} else if (a == 5 && b == 1) {
  moveActuator(1, (timeout*3)/4);
} else if (a == 5 && b == 2) {
  moveActuator(1, (timeout*2)/3);
} else if (a == 5 && b == 3) {
  moveActuator(1, (timeout*7)/12);
} else if (a == 5 && b == 4) {
  moveActuator(1, timeout/2);
} else if (a == 5 && b == 5) {
  moveActuator(1, (timeout*5)/12);
} else if (a == 5 && b == 8) {
  moveActuator(1, timeout/6);
} else if (a == 5 && b == 9) {
  moveActuator(1, timeout/12);
} else if (a == 5 && b == 7) {
  moveActuator(1, timeout/4);
} else if (a == 5 && b == 11) {
  moveActuator(2, timeout/12);
} else {
  Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
  Serial.print("Input Height in Feet: ");
  Serial.println(a);
  Serial.print("Input Height in Inches: ");
  Serial.println(b);
  Serial.print("The Current Position Is: ");
  Serial.println(currentPosition);
  return;
}
} else if (currentPosition == 13) {
if (a == 5 && b == 6) {
  moveActuator(1, (timeout*5)/12);
} else if (a == 5 && b == 0) {
  moveActuator(1, timeout);
```

```
} else if (a == 6 && b == 0) {
  moveActuator(2, timeout);
} else if (a == 5 && b == 1) {
  moveActuator(1, (timeout*5)/6);
} else if (a == 5 && b == 2) {
  moveActuator(1, (timeout*3)/4);
} else if (a == 5 && b == 3) {
  moveActuator(1, (timeout*2)/3);
} else if (a == 5 && b == 4) {
  moveActuator(1, (timeout*7)/12);
} else if (a == 5 && b == 5) {
  moveActuator(1, timeout/2);
} else if (a == 5 && b == 8) {
  moveActuator(1, timeout/4);
} else if (a == 5 && b == 9) {
  moveActuator(1, timeout/6);
} else if (a == 5 && b == 10) {
  moveActuator(1, timeout/12);
} else if (a == 5 && b == 7) {
  moveActuator(1, timeout/3);
} else {
  Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
  Serial.print("Input Height in Feet: ");
  Serial.println(a);
  Serial.print("Input Height in Inches: ");
  Serial.println(b);
  Serial.print("The Current Position Is: ");
  Serial.println(currentPosition);
  return;
}
} else if (currentPosition == 3) {
if (a == 5 && b == 6) {
  moveActuator(1, timeout/2);
} else if (a == 5 && b == 0) {
  moveActuator(1, timeout);
} else if (a == 5 && b == 7) {
  moveActuator(1, (timeout*5)/12);
} else if (a == 5 && b == 1) {
  moveActuator(1, (timeout*11)/12);
} else if (a == 5 && b == 2) {
  moveActuator(1, (timeout*5)/6);
} else if (a == 5 && b == 3) {
  moveActuator(1, (timeout*3)/4);
} else if (a == 5 && b == 4) {
```

```
      moveActuator(1, (timeout*2)/3);
    } else if (a == 5 && b == 5) {
      moveActuator(1, (timeout*7)/12);
    } else if (a == 5 && b == 8) {
      moveActuator(1, timeout/3);
    } else if (a == 5 && b == 9) {
      moveActuator(1, timeout/4);
    } else if (a == 5 && b == 10) {
      moveActuator(1, timeout/6);
    } else if (a == 5 && b == 11) {
      moveActuator(1, timeout/12);
    } else {
      Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
      Serial.print("Input Height in Feet: ");
      Serial.println(a);
      Serial.print("Input Height in Inches: ");
      Serial.println(b);
      Serial.print("The Current Position Is: ");
      Serial.println(currentPosition);
      return;
    }
    } else {
    Serial.println("Debug: No condition matched. Invalid input or unexpected state.");
    Serial.print("Input Height in Feet: ");
    Serial.println(a);
    Serial.print("Input Height in Inches: ");
    Serial.println(b);
    Serial.print("The Current Position Is: ");
    Serial.println(currentPosition);
    return;
  }
}

void loop() {
  int a, b;
  bool invalidInput = false;

  while (true) {
    Serial.print("Enter initial position: ");
    while (!Serial.available()) {}

    currentPosition = Serial.parseInt();

    if (currentPosition >= 1 && currentPosition <= 13) {
```

```
      break;
    } else {
      invalidInput = true;
    }
  }

  if (invalidInput) {
    Serial.println("Invalid input for initial position. Please enter 1, 2, or 3.");
    invalidInput = false;
  }

  while (Serial.available()) {
    Serial.read();
  }

  Serial.print("Enter height in feet (5 or 6): ");
  while (!Serial.available()) {}
  a = Serial.parseInt();

  if (a != 5 && a != 6) {
    Serial.println("Invalid input for feet. Please enter 5 or 6.");
    return;
  }

  while (Serial.available()) {
    Serial.read();
  }

  Serial.print("Enter height in inches (0 to 12): ");
  while (!Serial.available()) {}
  b = Serial.parseInt();

  if ((a == 5 && (b < 0 || b > 12)) || (a == 6 && b < 0)) {
    Serial.println("Invalid input for inches. Please enter a valid value.");
    return;
  }

  controlActuator(a, b);

  delay(5000);
}
```

Appendix K: Project Timeline