Digital Beam Attenuator

Final Report

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Abstract

Current research in the field of medical physics has offered insight into the benefits of dynamically attenuating X-Ray beams during computed tomography (CT) scans. Attenuation can be accomplished by placing a device between the X-Ray beam and the patient that changes in thickness as different portions of the patient are scanned; the beam attenuation changes proportionally as the thickness changes. Beam attenuation allows researchers and doctors to tailor CT dosage to the specific thickness of the body being scanned. This attenuation improves image quality and both doctor and patient safety. To test this technique, our client has created a hand-actuated wedge prototype and requires a method to mechanically actuate the prototype during a CT scan. This actuator must be accurate and precise, as the motor-controlled wedge position changes attenuation levels. Additionally, the device must be small enough to fit on the current CT, not impede CT motion, and must be scalable to be used with future smaller versions of the wedge prototype. For the final design, a M Drive 23 Plus Linear Actuator was attached to an individual wedge in order to linearly actuate the wedge within the prototype housing. The actuator used has a constant acceleration and moved with approximately 10,173 **μ**steps per mm. Testing demonstrated this motor satisfied the velocity, position, and force requirement set for each wedge within our product design specifications, but at 56.4 mm in width it is too wide to actuate multiple wedges. In the future we would like to implement a smaller motor in order to actuate all the wedges of the prototype, as well as investigate hydraulics as a possible actuation design alternative.

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Background

Client Description

Dr. Charles Mistretta is a Professor of Medical Physics and Radiology for the University of Wisconsin School of Medicine and Public Health [11]. His group was responsible for the development of digital subtraction angiography (DSA); his current research interests include the development of 4-dimensional DSA technology and digital beam attenuation (DBA) in X-Ray computed tomography (CT) scanning [16]. Dr. Mistretta is also an Affiliate Professor in the Biomedical Engineering department and holds a research partnership with the University of Wisconsin Biomedical Engineering Center for Translational Research [11]. Dr. Mistretta has published work in numerous peer-reviewed journals and has generated 33 US patents as a result [16].

Timothy Szczykutowicz is a doctoral degree student in the Department of Medical Physics at the University of Wisconsin – Madison. He is a student of Dr. Mistretta's and is working on the digital beam attenuator project. Some of his current work pertains to calculating the level of attenuation required to produce quality, clear images and to determining how to reconstruct the image after attenuation has dynamically altered the intensity of X-Ray photons. Siemens, a global electrical engineering company, is funding the DBA project and has also provided an Artis Zeego Multi-Axis C-Arm CT scanner to use in DBA research. Siemens hopes to integrate DBA into next generation CT scanners to improve image quality and lessen the adverse effects of radiation exposure.

Our clients have proposed that we actuate the current DBA prototype to demonstrate the effectiveness and feasibility of the design. The purpose of this design is to determine the optimum method for actuating the prototype wedges and to design a simple system using that optimum method that actuates a single wedge.

X-Ray Computed Tomography

Until the later part of the 20th century, the primary method of imaging in medical diagnostics was X-Ray radiography. This method projects X-Rays from a generator that pass through the desired object (in medical circumstances, the patient), and are detected by a detector opposite the source [6]. The variation in density and composition of the patient would correspond to the black and white contrast in the final X-Ray image [12].

In 1979, the Nobel Prize in Physiology for Medicine was awarded to Allan M. Cormack and Godfrey N. Hounsfield for their "development of the computer assisted tomography [12]." The limitation that traditional X-Ray imaging posed was its inability to produce three-dimensional images. With the advent of X-Ray computed tomography, three-dimensional images could be produced, a breakthrough that would greatly improve diagnostic radiology.

Figure 1: A conventional CT machine developed by General Electrics Healthcare. Source: http://www.flickr.com/photos/gehealthcare/3359124523/in/set-72157615371237798/

The X-Ray CT employs a point-source X-Ray generator that projects X-Rays in a fan-shaped array through the patient [6]. Figure 1 shows a conventional CT machine; the patient is inserted into the round opening and the scanning procedure commences. The X-Rays are detected by a detector on the opposing side [6]. A schematic of the relative positions of the patient, the X-Ray beam generator, and the

X-Ray detector is shown in Figure 2. The number of X-Rays that pass through the patient are detected and used to construct planar images. This method is repeated at multiple planes around the axis of revolution of the subject being scanned in order to produce image "slices"[6]. These slices are then compiled to produce a three-dimensional image, allowing what would traditionally be generated as pixels in a two-dimensional scan to be generated as three-dimensional voxels [6]. These three-dimensional reconstructions are then used by a variety of medical personnel for diagnoses. The benefits of this type of imaging include the ability to perform procedures with real time visual streaming and the non-invasiveness of the overall procedure [17]. The method, however, also carries the disadvantage of increased lifetime cancer risk for the patient due to exposure to high intensity X-Ray beams [17]. In addition, there are certain qualitative drawbacks to the current method of computed tomography, the most notable being low image quality caused by the lack of beam attenuation.

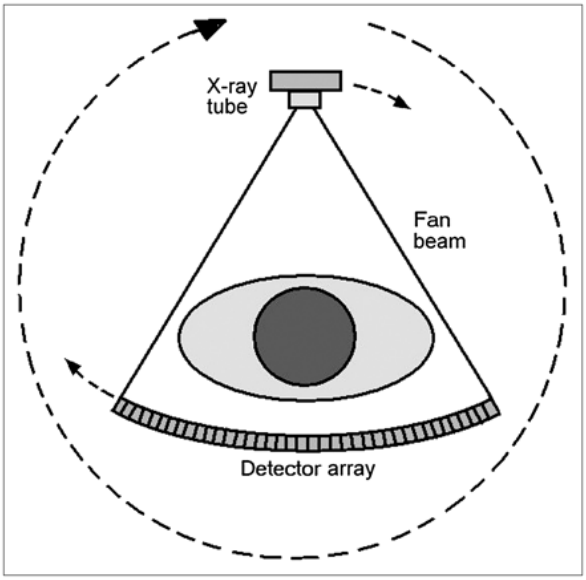


Figure 2: Schematic of a point-source-generated fan shaped X-Ray beam with a patient positioned between the beam source and the detector. No beam attenuation exists in this model. Source: http://tech.snmjournals.org/content/35/3/115.full

Current Methods

One current shortcoming of X-Ray computed tomography is the use of a uniform incident beam despite the fact that the transmission through the patient varies significantly due to the geometry of the patient. This results in a number of different problems. One problem is that a low, non-uniform signal-to-noise ratio can be a result of a non-attenuated, uniform beam; if the signal-to-noise ratio is too low or is non-uniform, a grainy and substandard image is produced [5]. Also, because the beam is of a constant intensity, a sub-optimal distribution of X-Ray scatter occurs. If the beam were to be continually attenuated to account for the density and composition of the subject, fewer X-Rays would scatter, consequently resulting in a clearer final image [5]. Finally, are significantly higher doses than necessary are administered to some regions and insufficient doses are administered to others.

X-Ray beam attenuation is one of the methods currently used to address these problems. X-Ray beam attenuation is defined as a reduction in X-Ray intensity; this reduction occurs after the X-Rays have been generated. One way to attenuate X-Ray beams is by using X-Ray tube modulation. Concern about the amount of X-Ray exposure due to the high intensity beams necessary for diagnostic resolution led to the development of modulation of the X-Ray tube. This modulation is achieved by

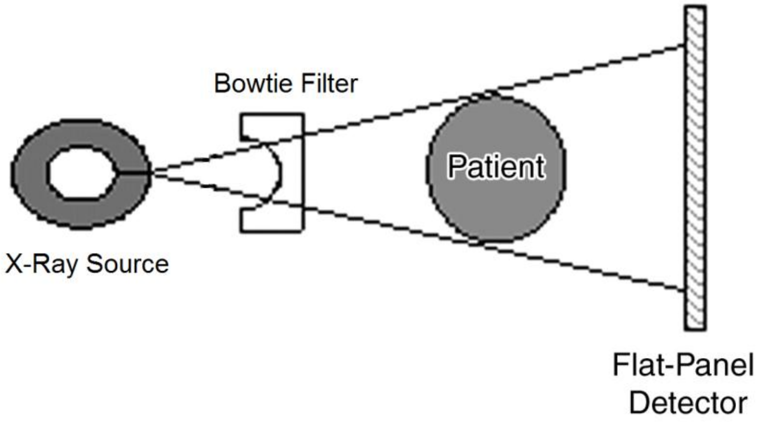


Figure 3: Schematic of a point-source-generated fan shaped X-Ray beam with a bowtie filter positioned between the beam source and the patient. Passive beam attenuation exists in this model. Source: [4]

controlling the current in the X-Ray tube based on the necessary X-Ray beam intensity. The beams are either modulated based on preprogrammed predictive algorithms, or on continuous real-time feedback adjustments. This is the primary method of accounting for the high dosage of X-Rays that patients are exposed to without compromising the quality of the final images [7]. Aside from this, a passive method, shown in Figure 3, is also used in point-source-generated fan shaped X-Ray beam CT machines. A component called a "bowtie filter" (similar in shape to a bowtie) attenuates the X-Ray beams to a greater degree nearer to the outer edges of the X-Ray fan and less at the center of the bowtie, which corresponds to the areas of the patient with the greatest thicknesses. This accounts for the average shape in the human form and, besides X-Ray tube modulation, is one of the few methods of reducing X-Ray dosage during a CT scan.

Problem Motivation

The existing methods of X-Ray beam attenuation are not ideal because these methods do not dynamically attenuate the intensity of the X-Ray beam over the entire fan-shaped X-Ray projection. The X-Ray tube modulation modifies the intensity of the entire X-Ray beam produced, which creates a constant X-Ray beam that does not compensate for the varied thicknesses throughout the patient [7]. Bowtie filter attenuation of X-Ray beam intensity can account for the varied thicknesses of the patient but does not actively attenuate the intensity of the X-Ray beam produced from the X-Ray source [7]. Instead, the bowtie filter passively attenuates X-Ray beams after the beams have been generated. As these methods are limited in scope and not ideal, some patient regions receive unnecessarily high dosages of X-Ray radiation during CT scans [7]. This can result in excess X-Ray scatter which interferes with X-Ray detection, resulting in a non-uniform signal-to-noise ratio, and a grainier, lower resolution image [6]. These high X-Ray dosages are also thought to increase the long-term risk of developing cancer or other radiation-induced complications [17].

Digital beam attenuation will combine the X-Ray beam intensity modification of X-Ray tube modulation and the geometry-based X-Ray beam attenuation of the bowtie filter to improve current X-Ray beam attenuation. DBA will increase the signal-to-noise ratio and thus improve image quality and also decrease the X-Ray dose administered to a patient, making the system safer for patients and doctors.

Current Prototype

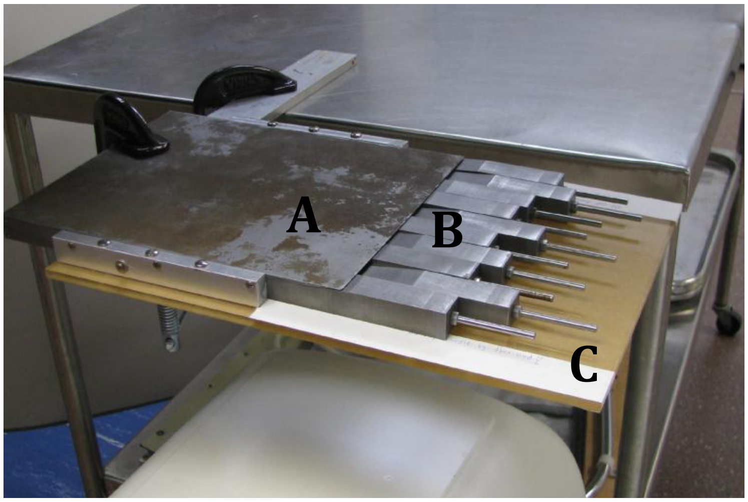


Figure 4: The current DBA prototype consists of a solid top wedge (A), ten solid steel hand-actuated wedges (B), and a Plexiglas baseboard (C). It is pictured here mounted to a table. Source: Timothy Szczykutowicz

The current prototype for the DBA project was fabricated prior to the semester based on specifications laid out by our client. The prototype can be seen in Figure 4. Detailed drawings of the prototype can be found in Appendix A. The prototype consists of ten steel wedges and one solid steel upper wedge-shaped plate mounted to a Plexiglas base. The wedges are 17.5 mm in width,10 cm in length, and have a mass of 275 g each. The entire prototype is hand-actuated.

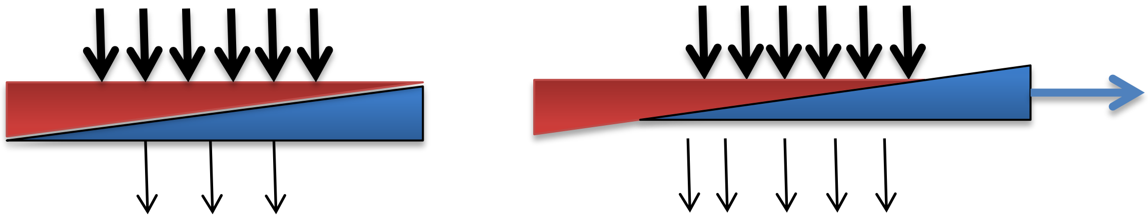


Figure 5: Beam attenuation using wedge prototypes. Source: Katherine Lake

Figure 5 demonstrates how beam attenuation can be achieved using the current prototype. The movable prototype wedges are represented in blue and the fixed top wedge in red. X-Rays from the X-Ray beam generator first pass through the top wedge and are attenuated to a degree that depends on the combined thickness of the two wedges. As the bottom blue wedge slides to the right, as seen in the rightmost drawing, the overall thickness decreases and less attenuation occurs, so a greater intensity of X-Ray beams are allowed through.

Design Requirements

As the client has developed a prototype, the final design shall utilize the current device. The final design shall be hydraulically or electrically controlled; this decision shall be made based on an analysis of which system is more scalable, accurate, and efficient. This semester the final design shall actuate a single wedge.

Each wedge shall operate independently of other wedges and the wedges shall be able to actuate to a pre-determined position within a maximum movement increment of 1 mm. The wedges shall have a minimum stroke length of 4 cm; that is, the wedges must translate a minimum of 4cm linearly. Following the completion of the scan, a report of wedge position over time shall be generated for every wedge. The wedges shall move at a minimum speed of 15 mm/s.

The wedges shall be flush with the base plate and any neighboring wedges. This requires that the wedges are actuated linearly along the pitch of the wedge so each wedge slides at the same angle as the base plate.

The actuation method used shall be scalable so that in future iterations, it can be incorporated into a smaller version of the prototype. In addition, the actuation method shall be sufficiently scalable in order to control greater numbers of wedges.

Design Alternatives

Prior to building and testing a chosen design, two actuation systems were identified: electrical actuation and hydraulic actuation. Our team identified the benefits and drawbacks of each potential system alternative to determine which system to pursue. Hydraulic systems are often smaller and more scalable than electrical systems but have the drawback of being more difficult to integrate into an all-electrical CT scanner and also require a position feedback system, potentially decreasing the accuracy of the system and requiring calibration [18]. Some electrical systems are available with integrated position feedback and are therefore more precise and simpler to control, but electrical systems can also be larger and become significantly more expensive as the motor size decreases [18].

Our team decided to first investigate electrical control systems. Three potential motor alternatives were identified and evaluated. Each alternative utilized a precise control mechanism, moderate speed, and adequate scalability into a smaller size. The three alternatives are outlined in detail below.

Linear Servomotors

Linear Servomotors are high precision linearly actuating motors that use a type of DC motor with a built-in feedback system [3]. The built-in feedback system provides precise details about the position of the linear actuating arm [3]. This motor is available in widths ranging from 16mm to several hundred millimeters and is widely available on the commercial market; this demonstrates that linear servomotors are scalable and can be used in future smaller prototypes. An example of a Firgelli Linear Servomotor can be seen in Figure 6. The motor can be controlled by its specific commercial controller or any custom microcontroller. Consequently, a linear servomotor can be programed using its specific software as well as using any programming language that can program a microcontroller. By using linear servomotors, we eliminate the requirement for an outside position control system and also eliminate the need to translate rotational motion into linear motion.

Figure 6: Linear Servomotor from Firgelli Technologies Inc. This motor is 16mm in width, the stroke length is 140mm, and the maximum force generated is 30N. Source: www.firgelli.com

Step Motors

Step motors are brushless, electric motors that rotate based on the activation of electromagnetic teeth in the motor [2]. Electromagnetic teeth are arranged around a central gear-shaped core [2]. The rotation of the gear-shaped core is produced by the attraction of an electromagnetic tooth at a programed position [2]. The activation of the electromagnetic teeth is controlled by an electric pulse; one pulse activates one tooth at the appropriate position [2]. The speed of the motor is regulated by the frequency of the electric pulses and the step frequency is controlled by which tooth of the stepper motor is energized [2]. The size of a step motor can vary from 6 millimeters to several centimeters in diameter [9] [2]. Two examples of step motors can be seen in Figure 7.

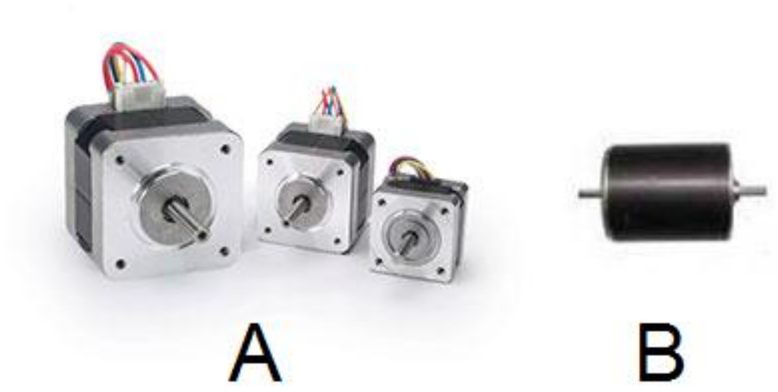


Figure 7: A and B show step motors from different manufactures. Step motor housing design is highly variable. (A) step size of these motors is 7 degrees. Source: http://wintechprecision.com/StepMotors.aspx (B). step size of this motor is 180 degrees, Source: http://www.micromo.com

The design of a step motor is such that it produces rotational motion. To produce linear motion, the motor must be used with a lead screw or rack and pinion system. Although step motors do not incorporate a feedback mechanism, they can be controlled precisely if the size and torque output are carefully matched to the application. High precision can be achieved by using several methods. One method is to use a step motor with a smaller step size (fewer steps per revolution) or a motor that supports microstepping [2]. Another method is using more precise gears or threads to translate the rotational motion into linear motion [2]. An array of limit switches could also be used to more precisely control the motor.

Brushless DC Motors

Brushless DC motor's rotation is the result of a magnetic field that exists between the permanent magnet in the core of the motor and the electromagnets surrounding the core [1]. As the polarities of the electromagnets change based on the input current, the permanent magnet rotates due to the effect of the magnetic force [1].The major difference between brushless DC motors and other types of DC motors is that brushless DC motors have a lower wear cost because there is no physical contact of the moving parts in the motor [1]. Compared to step motors, brushless DC motors are controlled by a continuous DC current [1]. Consequently, only the operation time length of the motor can be controlled and the degree of rotation cannot be controlled directly. Generally, brushless DC motors are inexpensive and vary in size. Brushless DC motors are also readily commercially available. As brushless DC motors also produce rotational motion, to translate that motion into linear actuation rack and pinion or lead screw systems must be used. Limit switches can also be used to allow for a more precise controlling mechanism.

Design Matrix

To determine which design alternative is best suited for our final design, our group conducted a comparative examination between the three motor alternatives using a design matrix (Table 1). The design matrix provided a quantitative analysis of how well each design alternative adhered to the proposed design requirements. The seven categories assessed in the motor design matrix were accuracy and precision, size, scalability, speed, cost, the control mechanism, and the extent of fabrication required. Based on the point allotments shown in the matrix below, if our group chooses to prototype an electrical system, linear servomotors will be pursued as a component of our final design prototype.

Table 1: Motor Design Matrix. The maximum possible point values are indicated in the parentheses in the row headings. The linear servomotors scored highest and will be used if an electrical prototype is constructed.

Criteria	**Brushless DC Motors**	**Step Motors**	**Linear Servomotors**
Accuracy and Precision (20)	10	14	18
Size (20)	17	17	15
Scalability (20)	15	15	12
Speed (15)	13	13	12
Cost (10)	7	6	9
Control Mechanism (10)	4	5	8
Extent of Fabrication (5)	2	3	5
Total (100)	**68**	**73**	**79**

Accuracy and Precision

As the position of the wedge determines the level of attenuation of an X-Ray beam, accurate and precise position measurements of wedge position are vital to ensuring proper beam attenuation and as a result, this category represented 20 points out of a total of 100 points in the motor design matrix. Brushless DC motors require external position control mechanisms and so received a score of 10 points. Step motors also require external position control feedback systems but step motors move in fixed-length steps and so received a higher score of 14 out of 20 points. Linear servomotors are readily available with integrated position feedback systems and so require no external position feedback system, making them a more accurate and precise solution than brushless DC motors or step motors; because of this, linear servomotors received the highest score of 18 points.

Size

The second category used to evaluate motor alternatives, size, was equally as important as accuracy and precision and so was allotted 20 possible points. This category assessed the dimensions of the components that would be located directly next to the wedges. Brushless DC motors and step motors are both available as small as 6mm in diameter and as this is significantly smaller than the wedge width, both brushless DC motors and step motors received 17 out of 20 points in this category. Linear servomotors found were a minimum of 16mm in width, which is considerably larger than the brushless DC motors or step motors available, and so received a slightly lower score of 15 points.

Scalability

Scalability was equally as important as accuracy and precision and size and so was also allotted 20 possible points. For our device, the design scalability refers to the ability to create the prototype on a smaller scale using similar components. Brushless DC motors and step motors are both available as small as 6mm, but are available from a limited number of manufacturers at those smaller sizes and so both brushless DC motors and step motors received a score of 15 points. Linear servomotors identified during research had minimum widths of 17mm, which is considerably larger than the smallest brushless DC motors or step motors and so linear servomotors received a lower score of 12 points.

Speed

The speed category was used in assessing the speed of each motor design and represents how quickly the wedge can be translated horizontally across the prototype platform. This category was allotted 15 points because, although significant, it is less of a determining design characteristic. In systems that use brushless DC motors and step motors, the speed can be altered by changing gear ratios but is limited by the motor's speed itself and so both systems received a score of 13 points. Linear servomotors have integrated gearing ratios and so operate at fixed speeds and so received a slightly lower score of 12 points.

Cost

Another important category was the cost of the system. This category received a possible 10 points because maintaining a low cost during the prototyping phases is important to ensure the availability of funds for design iteration. In this category, step motors received the lowest score of 6 points and brushless DC motors received the second-lowest score of 7 points. This is because as both step motors and brushless DC motors scale to smaller sizes, both options become significantly more expensive. Linear servomotors received the highest score of 9 points out of a possible 10, because our client already owns linear servomotors our group could use to control a prototype.

Control Mechanism

Another category equally as important as cost was the control mechanism used to control the motors. The control mechanism category was allotted 10 possible points. Linear servomotors received the highest score of the three systems in this category, 8 points, as servomotors identified are easy to use and come with vendor software that immediately allows a user to begin controlling the motor. This makes it much easier to focus on the custom programming linear servomotors would require. Additionally, linear servomotors do not require an outside position control mechanism and so would be simpler to control and integrate into the final design. Both step motors and brushless DC motors would require an outside position control mechanism and custom circuit design and so received lower scores in the control mechanism category. Step motors are controlled in fixed-length steps and it is simpler to control step motor position than it is to control brushless DC motor position, and so step motors received a slightly higher score of 5 points. Brushless DC motors received the lowest score of 4 points out of a possible 10 because of the system's complexity and the significant effort required to develop the prototype.

Extent of Fabrication

The final category assessed was the extent of fabrication required to actuate the prototype. As this category is less important to our client, it was allotted 5 possible points. Brushless DC motors would require control circuit development, a position control mechanism, and custom software programming and thus received the lowest score in this category, 2 points. Step motors are simpler to control due to their use of steps but would also require control circuit development, a position control mechanism, and custom software programming and so received the second lowest score of 3 points. Linear actuators can be purchased with off-the-shelf control circuits that contain vendor position control software and so would require a small amount of software programming to fabricate, and so received a perfect score of 5 points.

Final Design

Using the design matrix, we decided that the most efficient electric control of the wedges could be achieved using linear servomotors. However, the UW-Madison Computed Tomography lab donated an M-Drive 23 Plus Linear Actuator stepper motor, so that was used to actuate the final design this semester. In future semesters, linear servomotors could be used to actuate more than one wedge and should be investigated further.

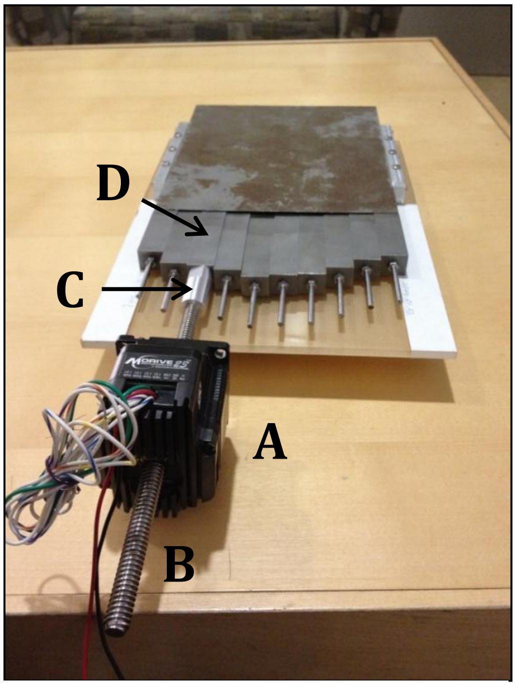


Figure 8: The final design using the M Drive 23 Plus Linear Actuator (A) to actuate a single wedge within the prototype. The Linear Actuator uses a leadscrew (B) and an adapter (C) to actuate one wedge (D). Source: Katherine Lake.

The final design, as shown in Figure 8, is comprised of the M-Drive Plus 23 Linear Actuator, a movable wedge and a connecting adapter. The linear actuator has a stroke length of 10 cm and uses a lead screw to translate rotational motion into linear motion. The control board is integrated into the motor and it is controlled using a serial port and terminal software provided by the manufacturer [15]. The motor is 56.4 mm in width, which does not satisfy the width design criteria of less than 17.5 mm, but as a different type of actuator will be used in future semesters and therefore that particularity can be overlooked [15]. The motor is produced in two smaller widths; the M Drive Plus 14 Linear Actuator is 35.55 mm in width and the M Drive Plus 17 Linear Actuator is 42.7 mm in width, making both alternative models too wide for our use [13],[14].

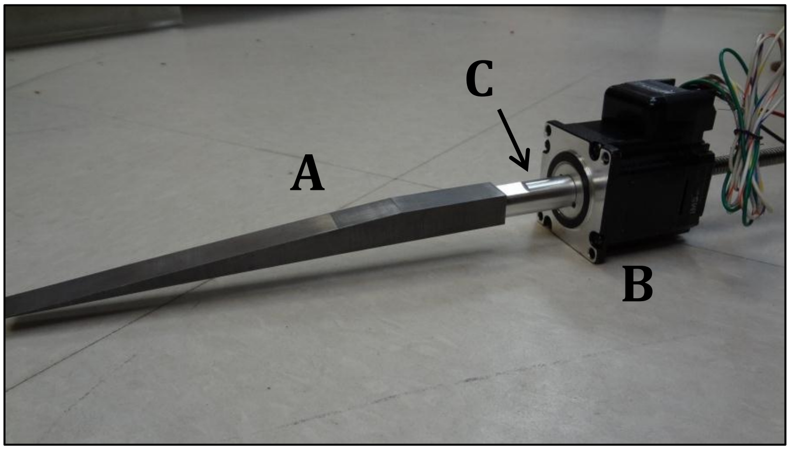


Figure 9: The motor attached to a single wedge outside of the prototype housing. The wedge (A) is attached to M Drive Plus 23 Linear Actuator (B)via a connector piece (C). Source: Katherine Lake

Figure 9 shows the final prototype removed from the housing. The M-Drive 23 Plus linear actuator is connected to the wedge with an adapter and can drive the wedge a 10 cm stroke at an initial linear velocity of 25 mm/s [15].

The linear actuator was chosen based on the design criteria. Since this project is large enough to be continued in the following semesters, the final design did not satisfy all design requirements. However, the final design for this semester was created to satisfy most of the requirements, and it is scalable for the future semesters.

Figure 10: M Drive Plus Linear Actuators with leadscrews and integrated controllers, as used in the final design. Source: (Schneider Electric n.d.)

The linear actuating motor that is used for our final design is the M Drive 23 Plus Linear Actuator from Schneider Electric, as shown in Figure 10. This motor is a stepper motor which is driven by electromagnetic force caused by the circuit inside of the motor. Stepper motors are brushless, electric motors that rotate based on the activation of electromagnetic teeth in the motor [2]. Electromagnetic teeth are arranged around a central gear-shaped core [2]. The rotation of the gear-shaped core is produced by the attraction of an electromagnetic tooth at a programed position [2]. The activation of the electromagnetic teeth is controlled by an electric pulse; one pulse activates one tooth at the appropriate position [2]. The speed of the motor is regulated by the frequency of the electric pulses [2]. The size of a step of the M Drive 23 Plus Linear Actuator is 1.8 degrees [15]. The M Drive 23 Plus Linear Actuator is able to translate rotational motion into linear motion by keeping the motor fixed and adding a leadscrew adaptor on the rotational screw. The stroke length is 10cm, which is dependent on the rotational core that is installed in the motor. This core can be replaced if a longer stroke length is needed.

Based on the datasheet and preliminary testing on the motor, the movement characteristics satisfy most of the design requirements. The initial linear velocity of the motor is 25 mm/s , which is much smaller than the required 15 mm/s [15]. The maximum stroke length is 10 cm. This length depends on the leadscrew that is used as the rotational core of the motor [15]. Since the leadscrew can be selected based on length and threading, the movement characteristics can be adjusted accordingly. Finally, the minimum movement increment of M Drive 23 Plus Linear Actuator is 7.5×10-5 mm. This indicates the motor is very precise. The reason is that the motor is able to move in micro-steps [15]. One regular step can be composed of 256 micro-steps, and there are 200 regular steps in one revolution. Therefore, there are 51,200 micro-steps within one revolution [15]. This movement increment is very precise, and it is able to satisfy the required maximum 1 mm movement increment.

Testing

A Test Plan was developed and carried out to better examine the properties of the M-Drive 23 Plus Linear Actuator. The Test Plan can be found in Appendix C. As stated in the Test Plan, testing included a scalability analysis, positional accuracy and precision testing, and velocity testing. Calculations to determine the forces due to static friction on the wedge were also performed.

Scalability Analysis

Scalability, in terms of our design, refers to the ability to use similar motion control techniques on a physically smaller prototype. As stated in the requirements, our client wishes to scale the prototype down by using a greater number of smaller wedges; the ideal number of wedges, n = 1240, represents the number of detector elements within the system. To perform the scalability analysis, the width of the current wedge, 17.5mm, was compared to the width of the M-Drive 23 Plus Linear Actuator and then to the width or diameter of two other types of small linear motors and stepper motors. It was found that, as the M-Drive 23 Plus Linear Actuator has a width of 54.6 mm, this actuator is a poor choice for actuating more than one wedge [15]. As the M-Drive 23 Plus Linear Actuator is over three times the width of one wedge, significant positional offsetting would be required to properly actuate all ten wedges. If the prototype wedges were made smaller, the M-Drive 23 Plus Linear Actuator could not be used to easily actuate all wedges.

Micromo, a company that produces micro motors and actuators for use in medical devices, offers two alternatives that demonstrate motor-based wedge control is a scalable design. Micromo offers micro linear motors 12.5mm in width and stepper motors 6-12mm in diameter [8],[10]. Additionally, the stepper motors can be purchased with custom length lead screws; this means any stroke length can be used [8]. Both motor options are possibilities for actuating many wedges in a smaller-scale device.

Positional Accuracy and Precision Testing

As the motor used to drive the wedge will require precise positional accuracy and precision, these qualities of the M-Drive 23 Plus Linear Actuator were tested determined to compare the actual motor characteristics to the characteristics given in the datasheet. Our client wishes to send the wedge to multiple positions during the scan, which makes it necessary to have accurate wedge positioning at all times. Precision is important because the wedge must achieve a precise position to correctly attenuate the X-Ray beam.

First, the programming capabilities of the device were examined. The device encoder uses a ‘Move Absolute’ command that can be used to send the wedge to a precise and accurate position each time. This position is not dependent on previous wedge positions and would be a useful tool when moving between positions without re-calibrating the relative wedge position at a zero position before each movement. This command was then used during testing to ensure the motor moved to the same place each time and that any discrepancies in movement distance would be explained by skipped µsteps.

Positional accuracy and precision were tested by moving the motor to 500,000 µsteps and measuring the actual distance traveled. The wedge was tested while resting on a flat surface but not within the prototype to allow for easier measurement of the distance travelled. To prevent against measurement accuracy caused by accidental wedge movement, the distance measured was the distance between the adapter and the actual motor; this distance was determined entirely by leadscrew movement and therefore was the actual distance travelled by the wedge. Nine trials were used and the distance values averaged to determine the average number of microsteps the motor rotated per millimeter the wedge travelled. The experimental values found can be found in Table 2 and a graph of the experimental values can be found in Figure 11.

Table 2: Experimental Values and Datasheet-Provided Values for the M-Drive 23 Plus Linear Actuator

Value	Experimental	Actual
µsteps per mm	10173 µsteps	10078 µsteps
Standard Deviation	9.72 µsteps	N/A
Percent Error	.93%	1%

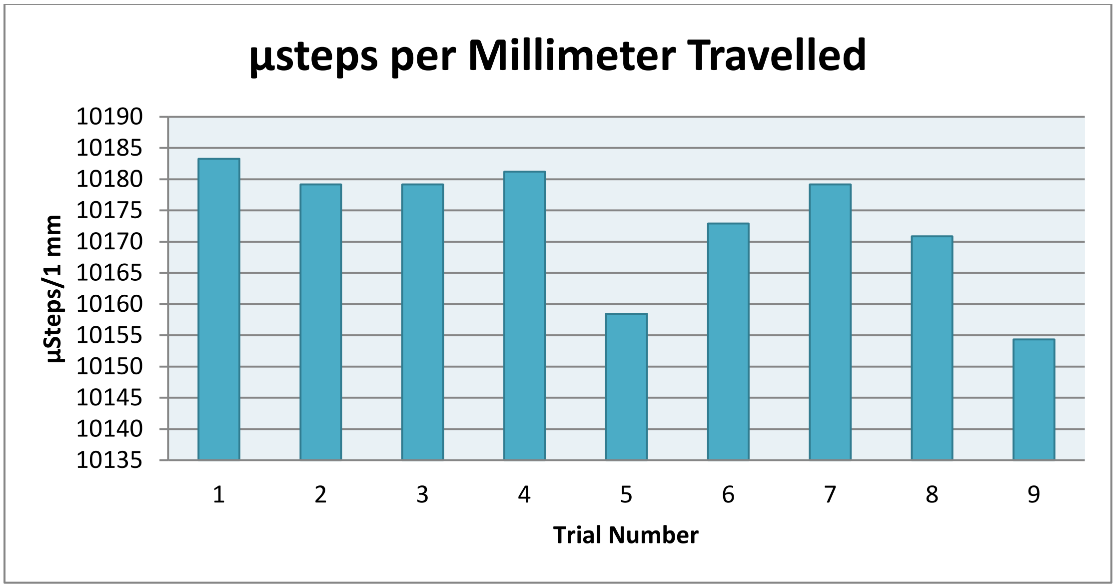


Figure 11: Steps/Distance Traveled Graph showing the number of steps traveled per mm in each trial.

As the calculated experimental value of 10173 µsteps/mm is within one percent of the actual value as given in the datasheet, it was determined that the motor is capable of highly accurate positioning. The small standard deviation of 9.72 µsteps is indicative of the motor's precision; a small standard deviation demonstrates that the motor position was close to the mean position each trial.

Velocity Testing

Velocity testing was performed to determine if the minimum velocity of the wedge met both the velocity given in the M-Drive 23 Plus Linear Actuator datasheet and the client's minimum velocity requirement of 15 mm/s. As the wedge was accelerating at a constant rate, velocity was approximated by timing how long was required for the wedge to traverse a given distance. Experimental points were taken at distances n = 20 mm to n = 70 mm; distances smaller than n = 20 mm were not considered because a stopwatch was used to time the wedge and smaller distances could not be measured accurately. Ten velocity trials were used at each distance. The average velocity for each trial was calculated and the average velocity for each distance was then determined. A velocity vs. time graph using the experimental data can be found in Figure 12.

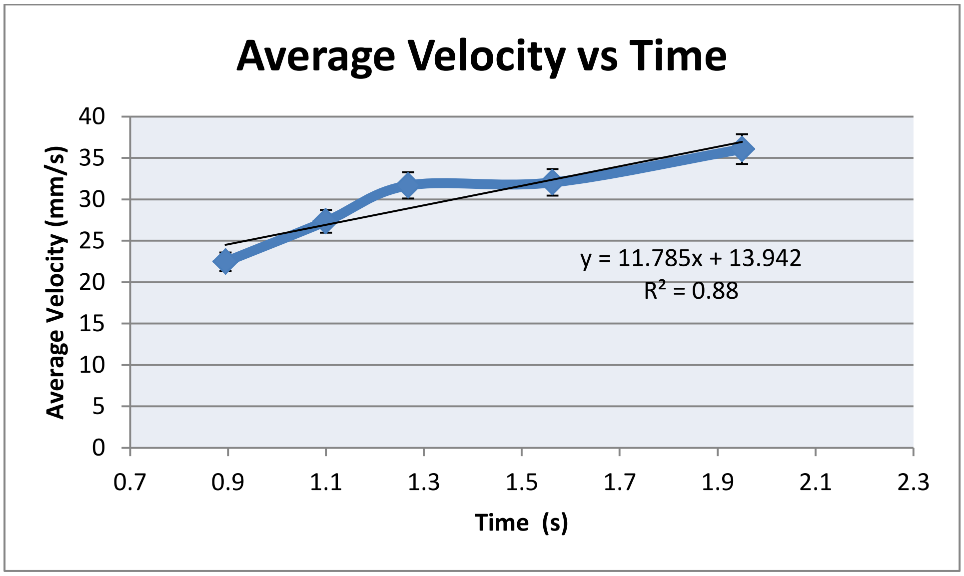


Figure 12: Average Velocity vs. Time Graph. A linear regression was used to calculate the estimated acceleration as a = 11.78mm/s^2. The R^2 value is .88.

A linear regression was used to calculate the estimated wedge acceleration. The estimated acceleration was found to be 11.78 mm/s^2. The error bars on the figure show one standard deviation of error. The minimum average velocity calculated was 22.5 mm/s at n = 20mm, which is larger than the minimum velocity requirement of 15 mm/s. This indicates the chosen M-Drive 23 Plus Linear Actuator meets the client requirements.

Force Testing

To better estimate the forces on the wedge, a simple free body diagram was created to model the force required to overcome static friction between the wedge and the Plexiglas base. This model assumed no rotational torque along the long axis of the wedge and that friction only exists along the long axis of the wedge. The free body diagram is shown in Figure 13.

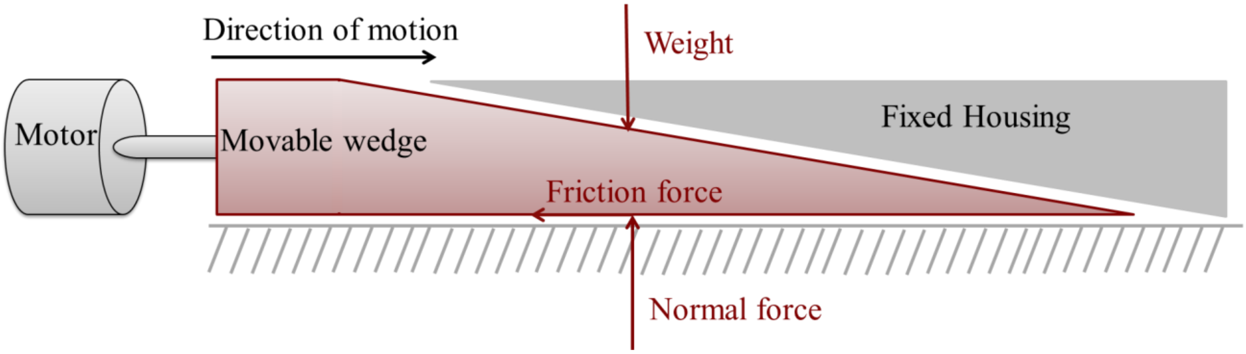


Figure 13: Free Body Wedge Diagram. Only the normal force, friction force, and weight were used in force calculations.

Using a known coefficient of static friction $\mu_s = 0.4$ between the 275g steel wedge and the Plexiglas base, the force required to move the wedge was calculated at F = 1.08 N. This calculation can be used in the future to determine the amount of force required to move the wedge.

Future Work

As the digital beam attenuator project will be continued through future semesters, considerable additional work remains. The prototype and wedge actuation mechanisms require iteration and refinement as the design continues to evolve. Eventually, Siemens USA hopes to integrate the digital beam attenuator device into an Artis Zeego C-Arm CT Scanner, but future works in the next several semesters include improving wedge actuation, modifying the prototype, and improving testing procedures.

Wedge Actuation

As the current design only actuates one wedge, in the future all wedges should be actuated with smaller actuators. As outlined during the scalability analysis, smaller stepper motors or linear motors can be purchased and used to actuate all ten wedges. Before doing so, we intend to investigate hydraulics as an alternative source of actuation. One study suggests that small-scale precise control systems are better implemented using hydraulics [18]. To prototype hydraulics we will meet with Erick Oberstar, the head of the Mechatronics lab at UW-Madison, to discuss hydraulic systems.

The M-Drive 23 Plus Linear Actuator currently actuates the wedge from one fixed position to another and accelerates linearly. We hope to actuate the wedge such that it will move in a sinusoidal fashion, as requested by our client for testing purposes, by developing a sinusoidal motion algorithm for future control systems.

Prototype Modification

The current prototype contains ten wedges and each wedge is 17.5 mm in width. In the ideal DBA case, 1240 wedges would be used; one wedge per detector element. Future prototypes should be made with greater numbers of wedges in order to reduce the number of detector elements per wedge, but further prototypes cannot increase proportionally in width; that is, the wedges must increase in number and decrease in width. Therefore, the prototype should be scaled and a greater number of smaller wedges should be used to maximize DBA's impact on the image. We hope to design and build a smaller prototype that uses a greater number of independently-actuated wedges in the coming semesters.

Testing Procedures

Currently, velocity testing uses a stopwatch to time the wedge as it travels from one fixed distance to another. Although this method produced consistent results, the testing system is inherently flawed because it uses hand-controlled stopwatches to measure time. However, as the encoder does not include a clock mechanism, no other simple measurement system exists for the M-Drive 23 Plus Linear Actuator. In the future, any actuation mechanism should have a timing device integrated into the circuit. This will allow for more precise velocity testing as well as for time-based wedge positioning during the scan.

Bibliography

[1] Condit, Reston. "Brushed DC Motor Fundamentals." *Microchip Technology.* January 26, 2004. http://ww1.microchip.com/downloads/en/AppNotes/00905a.pdf (accessed September 13, 2011).

[2] Condit, Reston, and Douglas W. Jones. "Stepping Motors Fundamentals." *Microchip Technology.* January 26, 2004. http://ww1.microchip.com/downloads/en/AppNotes/00907a.pdf (accessed September 13, 2011).

[3] Figrelli Technologies, Inc. "L16 Series Datasheet." *L16 Series.* 2011. http://www.firgelli.com/Uploads/L16_datasheet.pdf (accessed September 17, 2011).

[4] Gupta, Rajiv et al. "Flat-Panel Volume CT: Fundamental Principles, Technology, and Applications." *RadioGraphics*, 2008: 2009-2022.

[5] Kak, A.C., and Malcom Slaney. *Principles of Computed Tomographic Imaging.* IEEE Press, 1988.

[6] Ketcham, Richard. *X-Ray Computed Tomography (CT).* February 1, 2011. http://serc.carleton.edu/research_education/geochemsheets/techniques/CT.html (accessed September 29, 2011).

[7] McCollough, Cynthia H., Michael R. Bruesewitz, and Jr,James M. Kofler. "CT Dose Reduction and Dose Management Tools: Overview of Available Options." *RadioGraphics*, 2004.

[8] Micromo. "2-Phase Stepper Motors." *Micromo: Micro Motion Solutions.* June 8, 2011. http://www.micromo.com/datasheets/Stepper%20Motors/ADM_0620_PCS.pdf (accessed December 7, 2011).

[9] Micromo. *Micro Drive Solutions.* 2011. http://www.micromo.com (accessed September 29, 2011).

[10]Micromo. "QUICKSHAFT Technology." *Micromo: Micro Motion Solutions.* 2011. http://www.micromo.com/datasheets/Linear%20Motors/LM_0830-01_MIN.pdf (accessed December 7, 2011).

[11] Mistretta, Charles. *Mistretta, Charles A.* August 19, 2011. http://www.engr.wisc.edu/bme/faculty/mistretta_charles.html.

[12] Nobel Prize. *Physiology or Medicine 1979 - Press Release.* n.d. http://www.nobelprize.org/nobel_prizes/medicine/laureates/1979/press.html (accessed October 12, 2011).

[13] Schneider Electric. "M Drive Plus 14 Linear Actuator Datasheet." *Schneider Electric.* n.d. http://imshome.com/downloads/datasheets/MLM14.pdf (accessed December 12, 2011).

[14] —. "M Drive Plus 17 Linear Actuator Datasheet." *Schneider Electric.* n.d. http://imshome.com/downloads/datasheets/MLM17.pdf (accessed December 12, 2011).

[15] —. "M Drive 23 Plus Datasheet." *Schneider Electric.* n.d. http://imshome.com/downloads/datasheets/MLM23.pdf (accessed December 7, 2011).

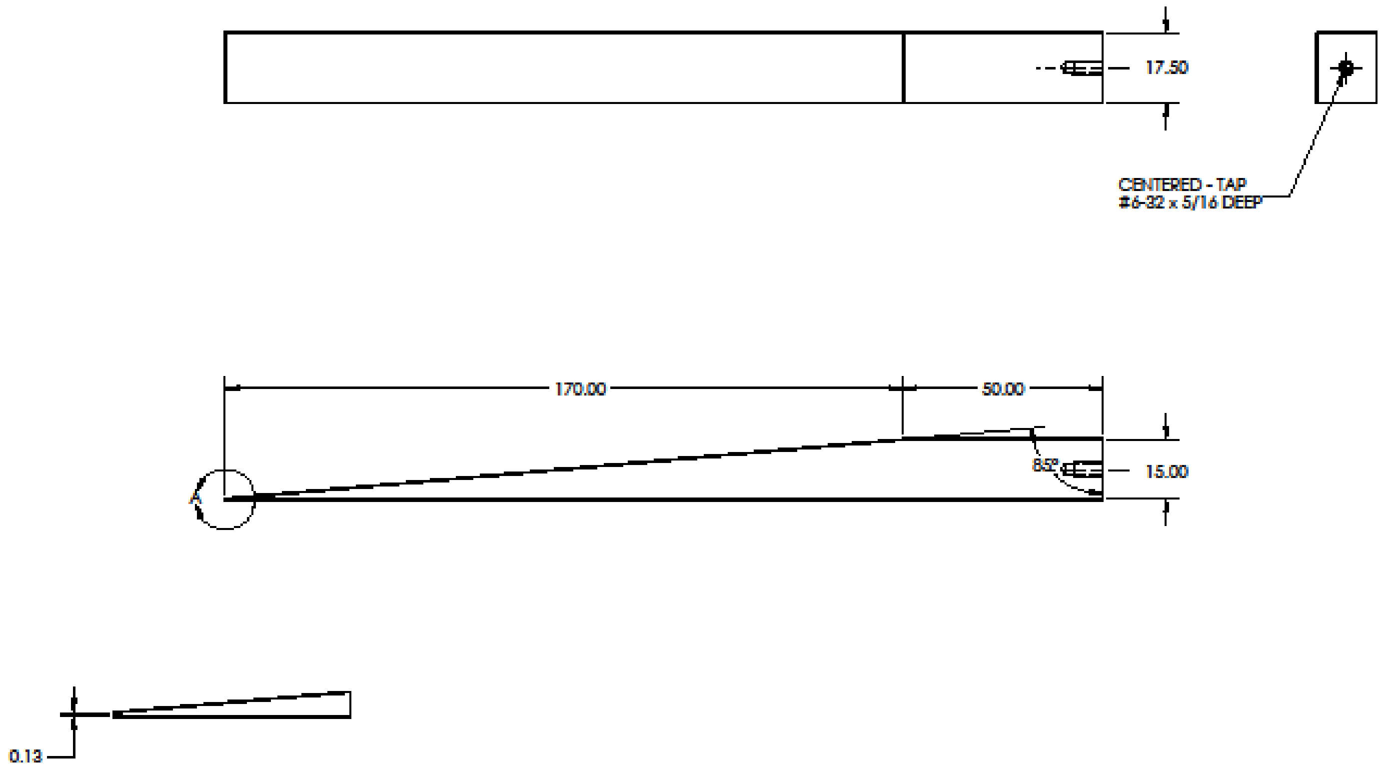
[16] System, The Board of Regents of the University of Wisconsin. *Dr. Charles Mistretta.* 2011. https://www.radiology.wisc.edu/people/facultyContent.php?vaultID=69.

[17] U.S. Food and Drug Administration. *Computed Tomography (CT).* November 09, 2010. http://www.fda.gov/Radiation-EmittingProducts/RadiationEmittingProductsandProcedures/MedicalImaging/MedicalX-Rays/ucm115317.htm (accessed September 29, 2011).

[18] Xia, Jicheng, and William K. Durfee. "Analysis of Small-Scale Hydraulic Systems." *IEEE Trans. Mechatronics*, 2011.

Appendix A

Appendix A, made up of the following five pages, consists of technical drawings of the prototype provided to the team by Erick Oberstar. These technical drawings are detailed schematics of the prototype.



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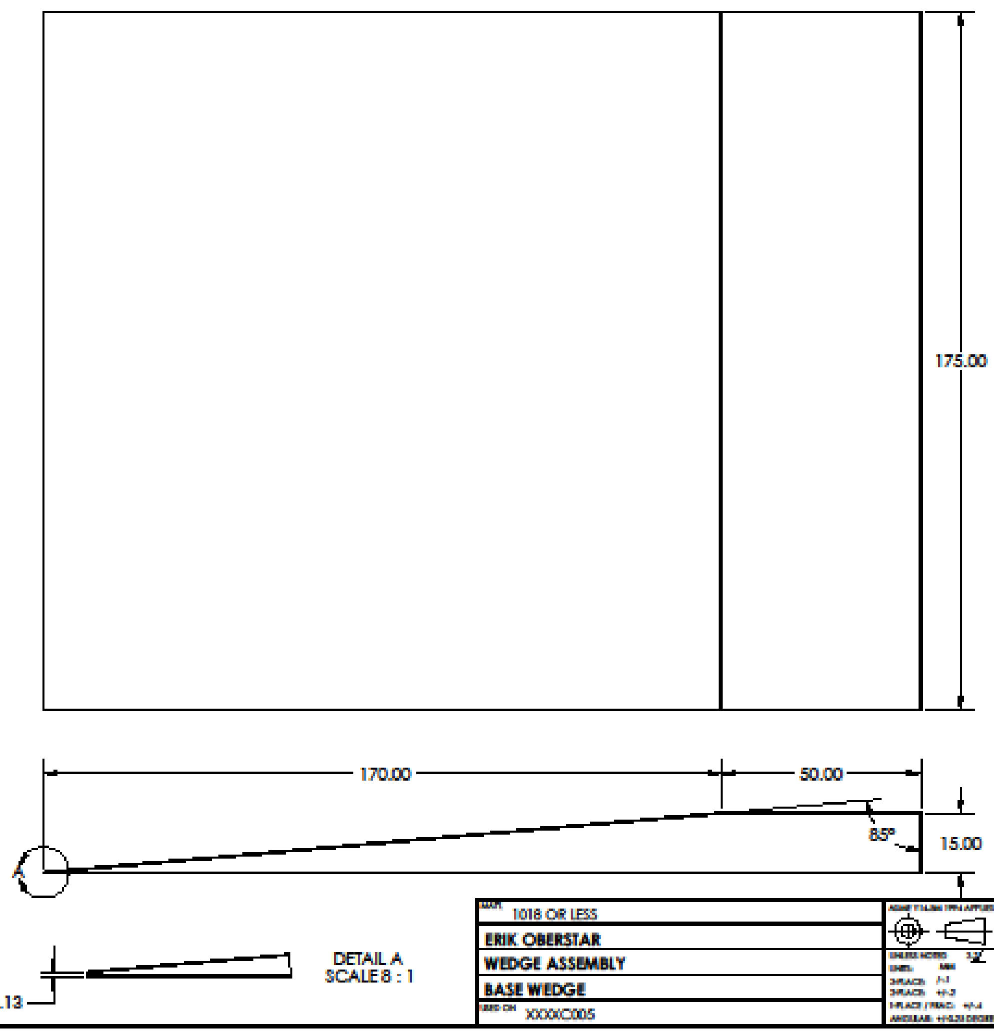
ERIK OBERSTAR		DRAWN GMG	
WEDGE ASSEMBLY	UNLESS NOTED UNITS: MM	CHK'D -	
FINGER WEDGE	3-PLACE: +/-.1 2-PLACE: +/-.2	APPR'D -	NO REQ'D 10 / DWG NO XXXX B 002 / REV -
USED ON XXXC005	1-PLACE / FRAC: +/-.4 ANGULAR: +/-0.25 DEGREES	SCALE 1:1	SHEET 1 OF 1

DRAWN WITH SolidWorks Office 2007



MAT'L 1018 OR LESS

ERIK OBERSTAR

WEDGE ASSEMBLY

BASE WEDGE

USED ON XXXXC005

ASME Y14.5M-1994 APPLIES

UNLESS NOTED

UNITS: MM

DATE 2-25-10

DRAWN GMG

CHK'D -

APPR'D -

SCALE 1:1

PHYSICAL SCIENCES LABORATORY

UNIVERSITY OF WISCONSIN

(608-877-2200)

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DWG NO XXXX B 001

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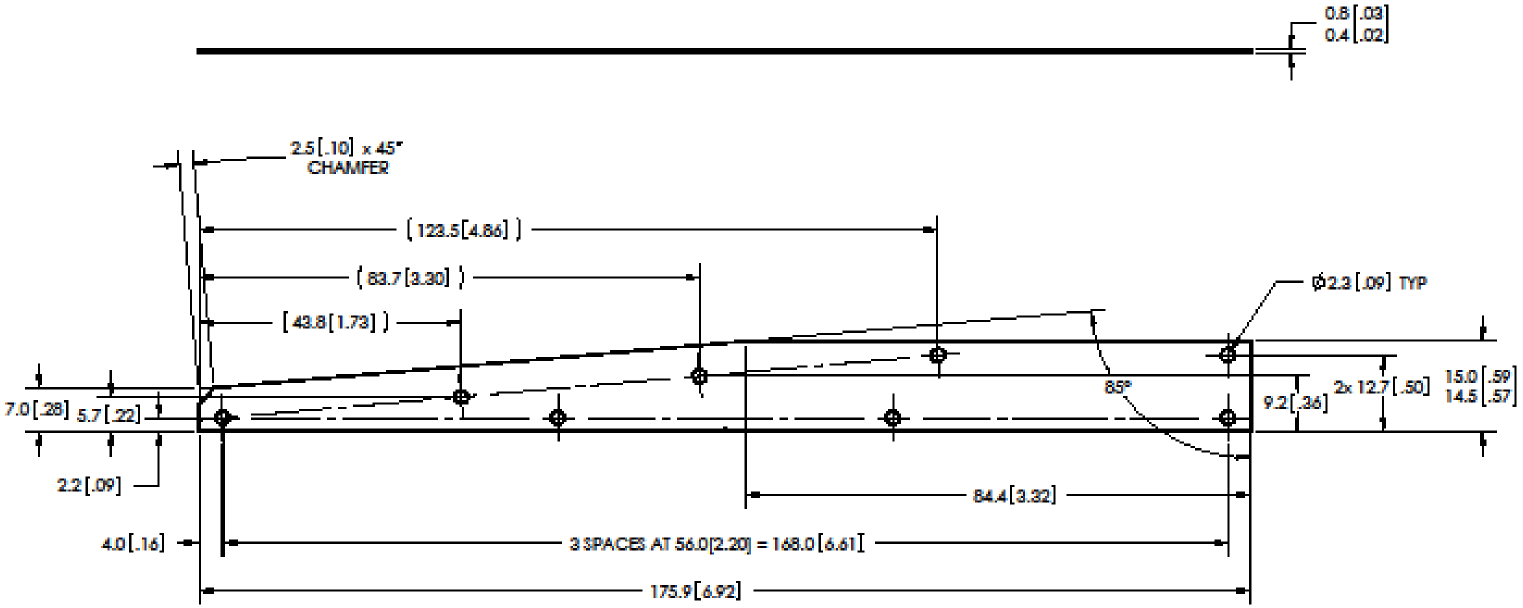

MAT'L 1018 OR LESS
ERIK OBERSTAR
WEDGE ASSEMBLY
EDGE
USED ON XXXXC005

UNLESS NOTED
UNIT: INCH

DATE 2-26-10
DRAWN GMG
CHK'D -
APP'D -
SCALE 1:1

PHYSICAL SCIENCES LABORATORY
UNIVERSITY OF WISCONSIN
(608-877-2200)

NO REQ'D 2
SHEET 1 OF 1
DWG NO XXXX B 004
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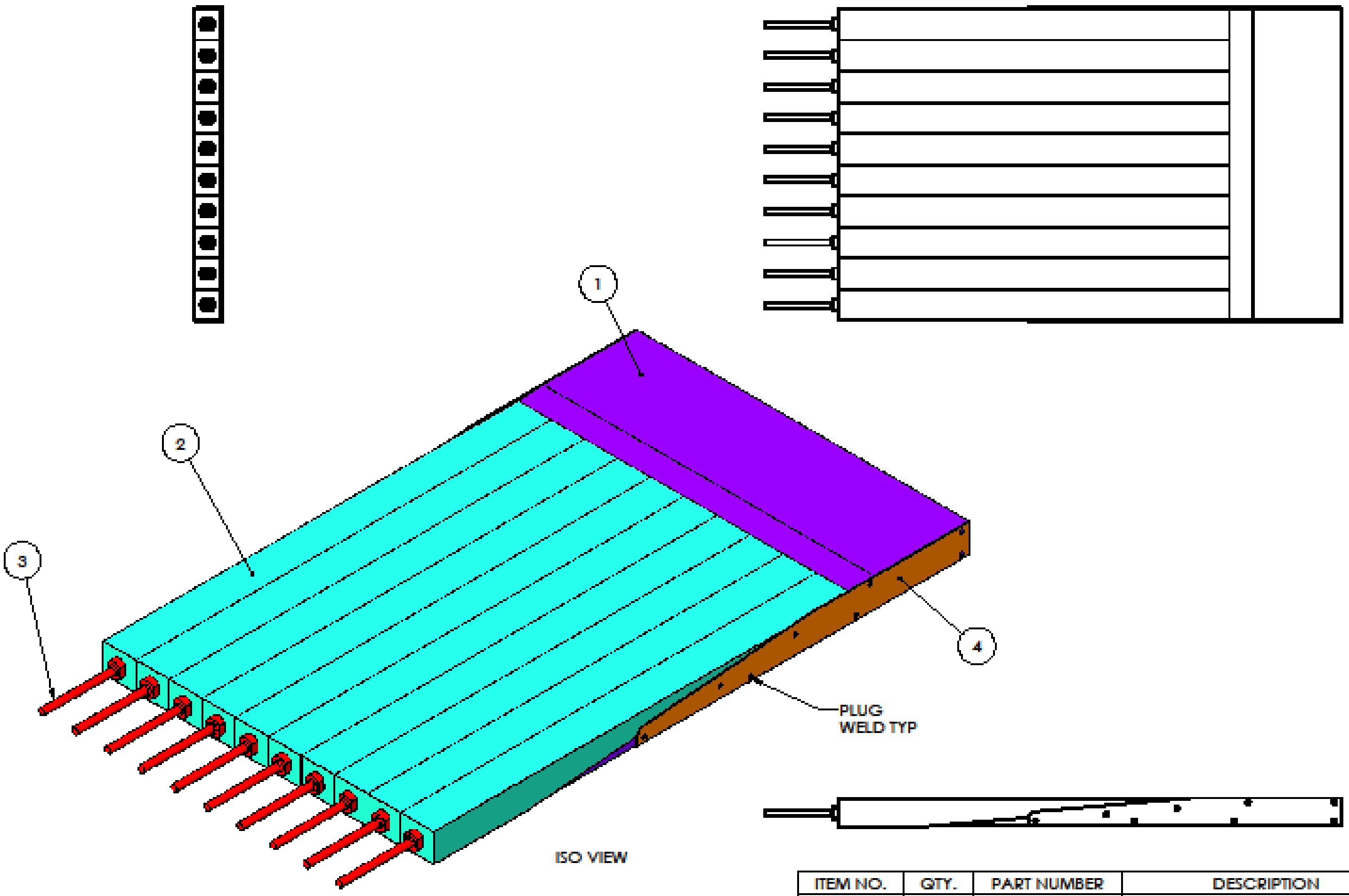

ITEM NO.	QTY.	PART NUMBER	DESCRIPTION
1	1	XXXXB001	BASE WEDGE
2	10	XXXXB002	FINGER WEDGE
3	10	XXXXB003	WEDGE HANDLE
4	2	XXXXB004	EDGE

SEE BOM

ERIK OBERSTAR

-

WEDGE ASSEMBLY

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2-26-10

GMG

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PHYSICAL SCIENCES LABORATORY

UNIVERSITY OF WISCONSIN

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1 OF 1

XXXX C 005

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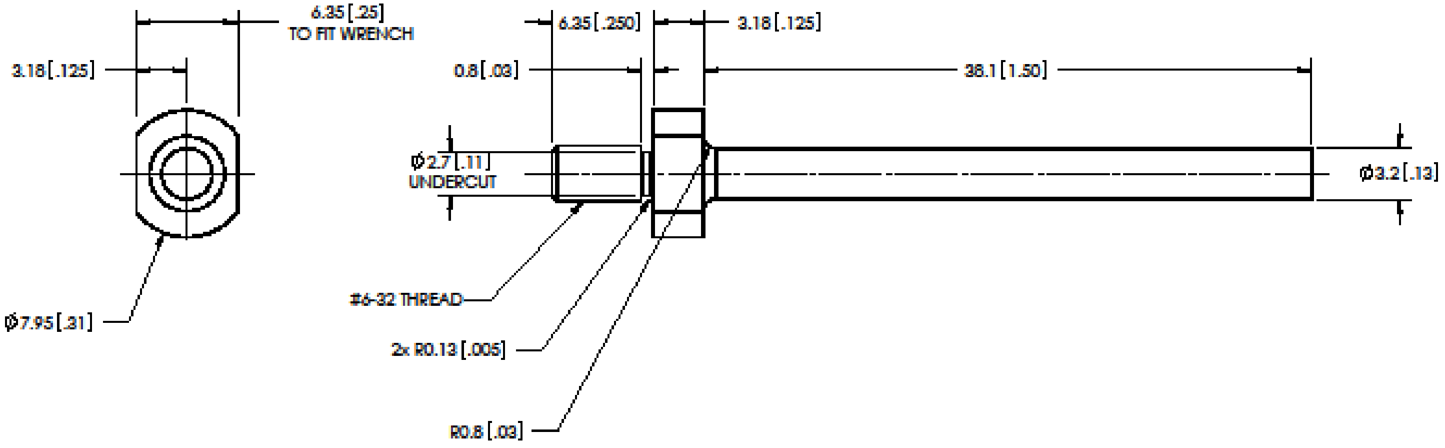

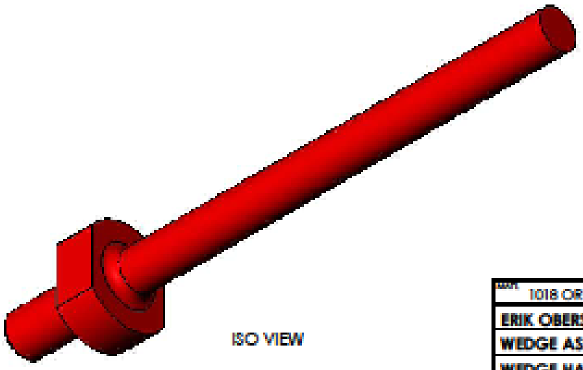

ISO VIEW

1018 OR LESS		2-25-10	**PHYSICAL SCIENCES LABORATORY** UNIVERSITY OF WISCONSIN (608-877-2200)
ERIK OBERSTAR		GMG	
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WEDGE HANDLE		-	10
XXXC005		4:1	1 OF 1

XXXX B 003

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Appendix B

Project Design Specifications

12/14/2011

Group Members: Katherine Lake, Henry Hu, Sarvesh Periyasamy, Alexander Eaton

Advisor: Professor Chris Brace

Function:

Since the advent of X-Ray Computed Tomography, a relatively uniform X-Ray incident beam has been used in spite of the fact that the transmission though the patient varies significantly from point to point. The use of a uniform X-Ray incident beam results in a non-uniform signal-to-noise ratio, a sub-optimal distribution of X-Ray scatter, and significantly higher or lower dose than necessary to some regions of the body. We propose to actuate a series of wedge pairs placed in the X-Ray beam between the X-Ray source and the patient and use the changing thickness of the wedge pairs to locally attenuate the incident beam, improve image quality, and reduce X-Ray dosages.

Client Requirements:

- The system shall automate the movement of the current prototype.
- The wedges of the prototype shall move in response to pre-programmed positions.
- The wedges of the prototype shall move independently.
- The software shall generate a feedback report of wedge position versus time.
- The device shall be mountable on a table for testing.

1. Physical and Operational Characteristics

A. **Performance requirements**: The device shall attenuate the strength of the X-Ray beam as a function of position for the duration of the Computed Tomography (CT) scan. The device must move at a minimum speed of 15 mm/s. The prototype must actuate the wedge a minimum of 4 cm and a maximum of 10 cm. The wedges of the prototype must be able to move flush with the housing in order to minimize the gap between wedges. The force applied by the actuation method must be strong enough to overcome all internal and external forces experience by the wedge during motion.

B. **Safety**: The product must not be harmful to the researcher. The maximum amount of inertia generated by a moving wedge shall be sufficiently small so to minimize the risk of a wedge falling off during actuation.

C. **Accuracy and Reliability**: The device shall provide the user with an accurate and precise measurement of its position in the prototype. The accuracy must be within 1 mm.
D. **Life in Service**: The device will be a prototype and thus has a limited life in service. The device shall have a life in service of one year of frequent use.
E. **Operating Environment**: The product is to be used by graduate students and professors in a CT research lab. During testing the product will be exposed to X-Ray radiation, and so design components shall be resistant to X-Ray damage.
F. **Ergonomics**: The product will be frequently tested and so shall be as compact and easy to move as possible.
G. **Size**: The product shall fit within the dimensions of a C-arm CT scan device to facilitate testing. The product must also be scalable for eventual implementation.
H. **Weight**: The product shall be as lightweight as possible to ensure ease of eventually mounting it within a CT scanner.
I. **Materials**: All the materials shall be resistant to damage by X-Ray radiation. The wedge material shall uniformly transmit X-Rays to correctly attenuate the X-Ray beams. The wedge material shall slide with a low coefficient of friction.
J. **Aesthetics, Appearance, and Finish**: The device is a prototype and therefore functionality is the dominant consideration over aesthetics and appearance. The device shall be unobtrusive to the researcher or test subject during the CT scan.

2. Production Characteristics

A. **Quantity**: One prototype shall be produced.
B. **Target Product Cost**: Siemens has provided a budget of $10,000 for the entire year, so the semester cost of the project shall be under $5,000.

3. Miscellaneous

A. **Standards and Specifications**: The final product will require the approval of the Food and Drug Administration. The prototype will not require the approval of the Food and Drug Administration.
B. **Customer**: The intended user is a medical professional or researcher who will utilize Digital Beam Attenuation to improve CT image quality during a medical procedure or for diagnostic purposes. The customer prefers a small design over a large one, so the device shall be as compact as possible.

C. **Patient-related Concerns**: As our design may eventually be commercially available for medical professional use, it must follow all restrictions enforced by the Food and Drug Administration. It must not cause any harm to its user.
D. **Competition**: No other forms of Digital Beam Attenuation exist at this time. Statistical CT Image Reconstruction is also being used to create better quality CT images, but that technology is currently in development. X-Ray tube modulation is also used to control the X-Ray beam intensity. A bowtie filter is another passive method of X-Ray beam attenuation.

Appendix C:

Appendix C contains the Test Plan document.

1. Introduction

This test approach document describes the appropriate strategies and processes used to plan, organize, and execute testing of the digital beam attenuator project actuated wedges.

1.1 Quality Objective

1.1.1 Primary Objective

The primary objective of testing this system is to ensure it meets the full requirements, including the quality requirements, provided by the client. The system shall satisfy the use case scenarios and maintain the quality of the project. At the end of the design project, the client should find that the project has met or exceeded all of their expectations as detailed in the requirements.

1.2.1 Secondary Objective

The secondary objective of testing the digital beam attenuator actuation system is to identify and expose all issues and associated risks, communicate discovered issues to the design team, and ensure that all issues are addressed prior to the completion of the design project. All areas of the system must be examined and all issues found must be documented and dealt with appropriately.

2. Test Methodology

2.1 Purpose

The purpose of the Test Plan is to achieve the following:

- Define strategies to test all the functional and quality requirements.
- Identify required resources and related information.

2.2 Test Strategies

2.2.1 Velocity Test

The purpose of this test is to determine the average linear velocity the motor is capable of pushing the wedge at.

The test shall be conducted as follows:

- The motor shall be connected to the wedge it will actuate.
- Determine the number of steps required to travel a pre-specified distance.
    - Distances shall be n = 20, 30, 40, 50, 70 mm.

    - Distances lower than 20 mm shall not be tested due to potential inaccuracies caused by the use of stopwatches.
- Run a program that causes the motor to move the pre-specified distance.
- Determine the amount of time required to transverse the distance using two stopwatches.
    - Two different people will be used to run two stopwatches.

The values obtained from test shall be recorded in a Microsoft Excel spreadsheet.
The speed shall be calculated by:

- Determine the average velocity required for the wedge to travel the given distance by dividing the distance by the time required.
    - This will be performed for each trial at each distance.
- Take the average of all the calculated velocities for each trial to find an estimated velocity for each distance.

2.2.2 Acceleration Test

The purpose of this test is to determine the average acceleration of the wedge.
The test shall be conducted as follows:

- The average velocity values calculated in 2.2.1 Velocity Test will be plotted. The value on the X axis shall be the average time, taken as an average of all the times recorded, that corresponds to that particular velocity value.
- A linear trendline shall be added using Microsoft Excel.
- The slope of the linear trendline will be taken as the average linear acceleration.

2.2.3 Position Test

The purpose of this test is to determine the accuracy and precision of the motor.
The test shall be conducted as follows:

- Connect the motor to the wedge via the adapter.
- Send the motor a command that causes it to move to its absolute zero point.
- Run a program that causes the motor 500,000 µsteps using the Move Absolute command.
- Measure the distance the wedge travelled by measuring the distance between the body of the motor and the back of the adapter. This will remove any inaccuracies caused by the motor moving the test and misplacing the wedge from its initial position.
- Divide the number of steps by the distance travelled to determine the number of µsteps travelled per millimeter.
- Use n = 9 trials total and run the motor 500,000 µsteps each trial, moving the motor to absolute zero position each time.

- Average the number of µsteps per millimeter over each of the nine trials.
    - Find the standard deviation to determine the precision of the motor.
    - Find the percent error, comparing the actual µsteps travelled to the number of µsteps travelled per millimeter given in the M Drive 23 Plus Linear Actuator datasheet. The given number is based on the leadscrew pitch, which should be determined before comparison to the estimated value. The percent error is a measure of the accuracy of the motor.

All values shall be recorded in a Microsoft Excel spreadsheet.

2.2.4 Scalability Analysis

The purpose of this test is to determine if the chosen actuation method can made smaller and used to control more than one wedge or to control smaller wedges.

The test shall be conducted as follows:

- The width of the chosen actuation method at an area close to the attachment point shall be compared to the width of a single current prototype wedge.
- If the width of the chosen actuation method is less than the width of the current wedge, the chosen actuation method is considered sufficiently small to be used to actuate more than one wedge and the scalability requirement is satisfied.
    - No further actuation methods shall be investigated.
- If the width of the chosen actuation method is greater than the width of the current wedge, the chosen actuation is considered not sufficiently small to be used to actuate more than one wedge and the scalability requirement is not satisfied.
    - Further investigation shall be performed to determine if a similar actuation method can be used to actuate the wedges.
    - A similar actuation method is defined as a smaller diameter or width motor-controlled or hydraulically-controlled system; the smaller system shall be the same kind of system (motor-based or hydraulics-based) as the original larger system.
    - If similar actuators can be found with diameters or widths less than the width of the current wedge, the chosen actuation method is therefore considered scalable and therefore satisfies scalability requirements.
    - If similar actuators cannot be found with diameters or widths less than the width of the current wedge, the chosen actuation method is considered not scalable and therefore does not satisfy scalability requirements.