Digital Beam Attenuator

Mid-Semester Report

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Client:

Professor Charles Mistretta

Advisor:

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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. Our group first addressed system design and examined the use of electrical controls to actuate the wedges. We determined that linear servomotors are the most feasible option to control the system electrically. Throughout the remainder of the semester we will examine the benefits of hydraulic controls and make a final decision about the control system, whether electric or hydraulic, design. We will then design and implement a control mechanism that actuates a single wedge of the prototype.

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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 [6]. 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 [7]. 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 [6]. Dr. Mistretta has published work in numerous peer-reviewed journals and has generated 33 US patents as a result [7].

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 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 a 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 [2]. The variation in density and composition of the patient would correspond to the black and white contrast in the final X-Ray image [1].

In 1979, the Nobel Prize in Physiology or Medicine was awarded to Allan M. Cormack and Godfrey N. Hounsfield for their "development of the computer assisted tomography."[1] 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. Retrieved from 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 [2]. 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 [2]. 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” [2]. 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 [2]. 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 [3]. The method, however, also carries the disadvantage of increased lifetime cancer risk for the patient due to exposure to high intensity X-Ray beams [3]. 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.

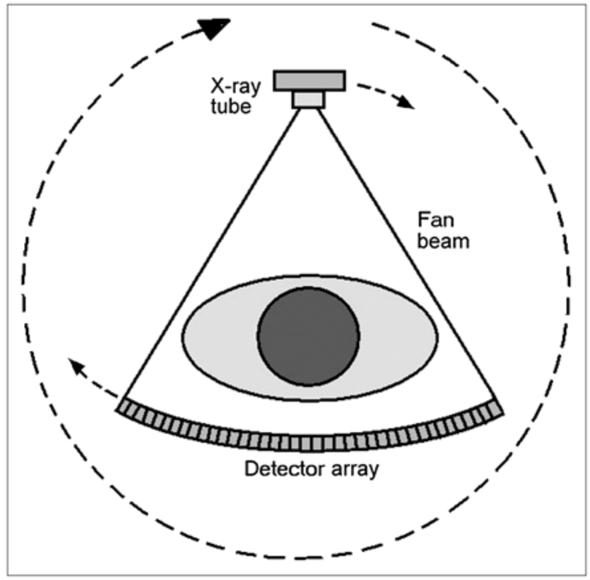

Figure 2: Schematic of a point-source-generated fan shaped X-Ray beam with a patient positioned between the beam source and the detector. No beam attenuation exists in this model. Retrieved from http://tech.snmjournals.org/content/35/3/115.full

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 [4]. 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 be scatter, consequently resulting in a clearer final image [4]. Finally, there are significantly higher doses than necessary being administered to some regions and insufficient doses 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 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 [5]. 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

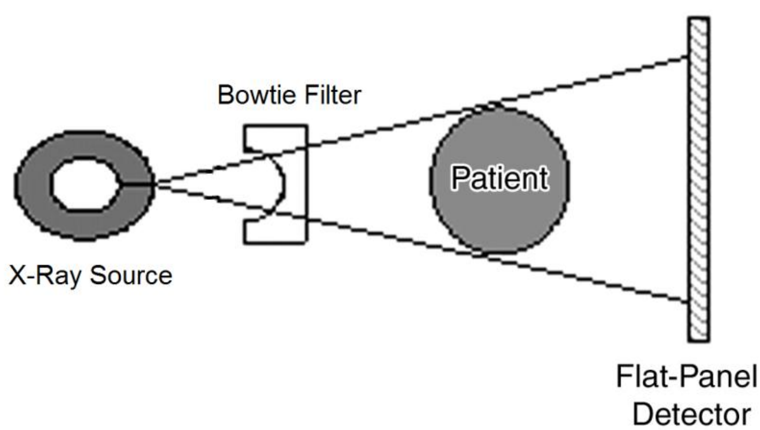

Figure 3: Schematic of a point-source-generated fan shaped X-Ray beam with a bowtie filter positioned between the beam source and the patient. Passive beam attenuation exists in this model.

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 [5]. 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 [5]. 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 [5]. 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 [2]. These high X-Ray dosages are also thought to increase the long-term risk of developing cancer or other radiation-induced complications [3].

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

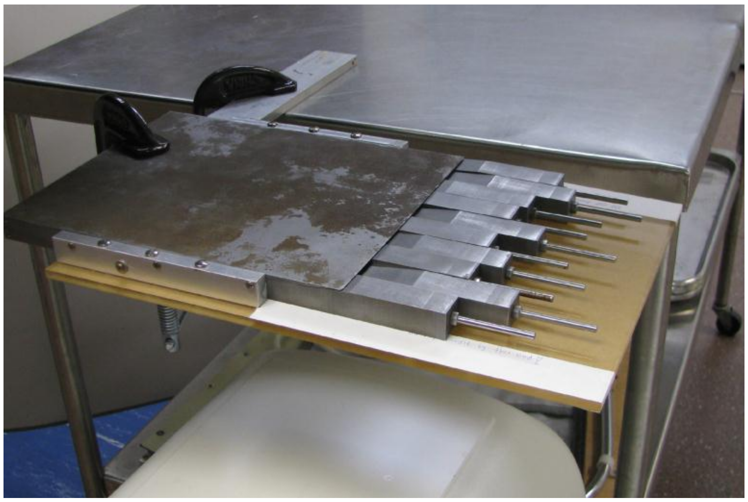

Figure 4: The current DBA prototype, pictured here mounted to a table. Photo Credit: Timothy Szczykutowicz

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.

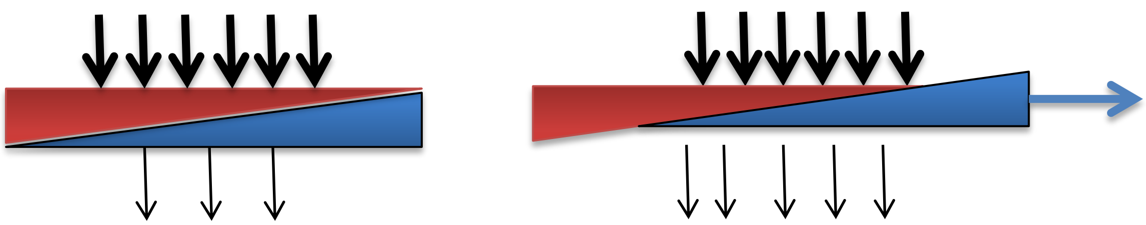

Figure 5: Beam attenuation using wedge prototypes. Credit: Katherine Lake

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 1mm of accuracy. 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 [8]. 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 [9].

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 [12]. The built-in feedback system provides precise details about the position of the linear actuating arm [12]. 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 [9]. An example of a Firgelli Linear Servomotor can be seen in Figure 6. The motor can be controlled by its specific commercial

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. Retrieved from www.firgelli.com

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.

Step Motors

Step motors are brushless, electric motors that rotate based on the activation of electromagnetic teeth in the motor [11]. Electromagnetic teeth are arranged around a central gear-shaped core [11]. The rotation of the gear-shaped core is produced by the attraction of an electromagnetic tooth at a programed position [11]. The activation of the electromagnetic teeth are controlled by an electric pulse; one pulse activates one tooth at the appropriate position [11]. The speed of the motor is regulated by the frequency of the electric pulses [11]. The size of a step motor can vary from 6 millimeters to several centimeters in diameter [9]. Two examples of step motors can be seen in Figure 7.

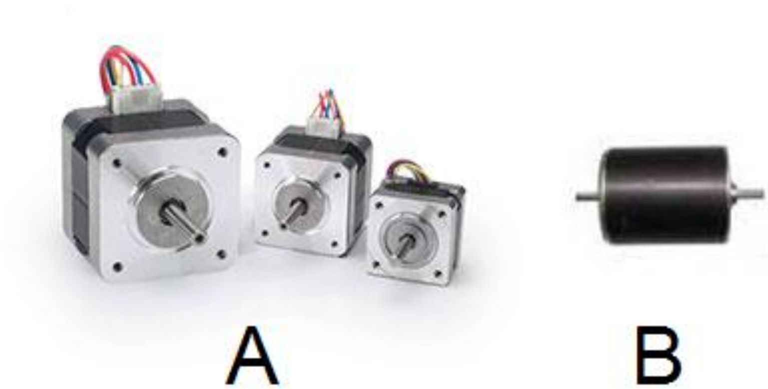

Figure 7: A and B show step motors from different manufactures. Step motor housing design is highly variable. (A) step size of these motors is 7 degrees. Retrieved from http://wintechprecision.com/StepMotors.aspx (B). step size of this motor is 180 degrees, Retrieved from http://www.micromo.com

The design of a step motor is such that it produces rotational motion, so 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) [11]. Another method is using more precise gears or threads to translate the rotational motion into linear motion [11]. 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 [10]. As the polarities of the electromagnets change based on the input current, the permanent magnet rotates due to the effect of the magnetic force [10]. The major difference between brushless DC motors and other types of DC motors is that brushless DC motors have lower wear cost because there is no physical contact of the moving parts in the motor [10]. Compared to step motors, brushless DC motors are controlled by a continuous DC current [10]. 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 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 if we control the prototype electrically, we will use linear servomotors to actuate the wedges. This semester's prototype using a linear servomotor would consist of a single wedge actuated by a linear actuator that drives the wedge to a pre-programmed position based on a time in the scan. As we have not decided yet decided the control mechanism, more specific details of the final design are currently unknown.

Future Work

As the digital beam attenuator project is still primarily conceptual at this point, and a considerable amount of research and development remains before the device can be integrated into CT machines. For the remainder of this semester, our team will focus on extensively researching and testing hydraulic and electrical systems and methods of actuating the wedges. We intend to purchase required components to build an initial wedge actuation prototype and work with the CT lab at the Wisconsin Institute for Medical Research to iterate the design. The lab has agreed to provide us with several different motors and control boards to begin prototyping.

To better understand hydraulic systems, we will continue researching hydraulic actuation and meet with Erick Oberstar, the head of the Mechatronics lab at UW-Madison, to discuss hydraulic systems.

Ideally, by the end of the semester, we will have selected a wedge actuation mechanism and have fabricated a functioning prototype that moves a single wedge. The scope of the DBA project goes far beyond a single semester. In subsequent semesters, we hope to continue developing and testing numerous design iterations. Future prototypes will be smaller and contain greater numbers of wedges. Eventually, Siemens hopes to integrate the digital beam attenuator device into an Artis zeego C-Arm CT scanner.

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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.