8-1-2014

Design of the High-Speed Stereo Radiography System

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DESIGN OF THE HIGH-SPEED STEREO RADIOGRAPHY SYSTEM

A Thesis

Presented to

the Faculty of the Daniel Felix Ritchie School of Engineering and Computer Science

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

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August 2014

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Degree Date: August 2014

Abstract

Orthopaedic pathologies often involve disruption of the mechanical environment of a joint at/below the mm scale. The ability to measure biomechanical kinematics at the sub-mm scale is essential for obtaining valuable insight into pathologies, but small motions of the joints are difficult to quantify. Estimates of skeletal kinematics are commonly made from optical motion capture systems and markers placed on the skin. The error caused by external marker movement is largely avoided with x-ray motion capture. Dynamic radiography uses a series of x-ray images recorded at high-speed and captures *in-vivo* joint motion. Uncovering the mechanical foundation of orthopaedic pathologies requires accurate and high-speed kinematic measurement of *in-vivo* 3D, six DOF joint motion. To meet these aims, requirements were established to guide the design, construction, and validation of a high-speed stereo radiography (HSSR) system. The completed system is capable of imaging major joints from the ankle to the cervical spine.

Acknowledgements

I would like to thank all my friends and family for their support. I would like to thank those in our lab who supported me during my time of need, especially Dr. Peter Laz. I would like to thank the Lab and Engineering Department for supporting me and providing my educational opportunity. I want to thank Jon Buckley for his patents, insight and guidance throughout my DU career. I want to thank Dr. Paul Rullkoetter for being my advisor. The post-docs; Dr. Adam Cyr, Dr. Michael Harris, and fellow graduate students; Lowell Smoger, Sean Hu, Azhir Ali, and Alessandro Navacchia deserve a huge thanks for their thoughts and support of my work. I would like to acknowledge the NIH for funding the project.

Most of all I want to thank Dr. Kevin Shelburne. His contributions proved most valuable. I am most grateful to have had the opportunity to work under him. His guidance over the past two years has help define a direction for my career.

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Chapter One: Introduction

Introduction

Orthopaedic pathologies, like osteoarthritis, often involve disruption of the mechanical environment of a joint at the millimeter (mm) scale (Sharma et al., 1999; Giphart et al., 2012). In addition to gross body segment motions, normal functions of the joints include small translations and rotations. For example, during flexion of the knee, the femur and tibia translate and rotate relative to one another in all six degrees of freedom (DOF). The small motions that accompany knee flexion occur in predictable ways that are important to healthy function (Andriacchi et al., 2004). Alterations in motion can be symptomatic of pathology and/or disability, and treatment often involves precise and subtle corrections that can have dramatic effects on function. This is true for all the joints in the human body, and spans treatments from the conservative, such as physical therapy, to the invasive, such as joint replacement.

Currently, most estimates of skeletal kinematics have come from optical motion capture systems. These optical systems develop kinematic body structure positioning from 3D positions of reflective markers. These external markers are attached to the skin, or tight fitting clothing, and due to the gliding of the skin over bony structures where these markers are typically placed create error in the bone kinematic estimations (Giphart et al., 2012; You et al., 2001).

X-ray motion analysis provides a more accurate alternative for internal biomechanical motion capture. The error supplied by external marker movement are largely avoided with x-ray motion capture by providing a visual insight of internal structures and motions that would otherwise be inaccessible from an external motion capturing methods.

The small motions of the joints are difficult to quantify. Most medical imaging, like CT and plain-film radiography, as well as most applications of magnetic resonance imaging (MRI), capture static images of the body. These imaging techniques allow detailed observation of static bony and soft-tissue geometry and tissue health, but do not provide information about dynamic *in-vivo* joint motion in healthy and pathologic conditions. Furthermore, these techniques do not provide images of the joint under loading conditions and activities known to cause symptoms and deficits that accompany orthopaedic pathologies (Torry et al., 2011; Myers et al., 2011).

Dynamic radiography, including fluoroscopy, uses a series of x-ray images recorded at high-speed to capture *in-vivo* joint motion during activity. Because dynamic radiography uses x-rays, true motion between bones or implants can be captured for a given joint. Fluoroscopy, being dynamic radiography captured at low frame rates and with low radiation energy, is a common tool used in surgery to visually guide the placement of instruments and implants. Fluoroscopy systems are most often configured in a c-shaped arm that rigidly couples an x-ray generator to an imaging device. The general purpose of fluoroscopy is to provide real time visualization of dynamic anatomical/physiological processes using x-rays of a small dosage. Researchers have utilized these commercially available fluoroscopy systems to study joint motions in healthy and pathologic conditions with animals and humans (Mahfouz et al., 2003; Brainerd et al., 2010; Zhu et al., 2012). However, these systems are designed for the constrained environment of surgical operating rooms and not for high-speed image acquisition or large ranges of motion. Consequently, using dynamic radiography to record natural human movement requires modification of traditional c-arm radiography units to accommodate high-speed capture rates and an open imaging environment.

Application of Dynamic Radiography and Known Designs

Radiographic imaging is a practical method to accurately track internal bodily movement during normal motions. The movement of bony structures or implants can be tracked using a single plane radiography machine with sub-mm accuracy. The limitation of single plane capture is that the accuracy is poor in the direction normal to the imaging plane which hinders the full natural range of motion capture. The addition of another plane would be required if full range of motion capture were desired. The utilization of two single plane radiography machines is usually termed biplane or biplanar fluoroscopy (Brainerd et al., 2010; Kapron et al., 2014; Giphart et al.,2012; Li et al., 2004; Myers et al., 2011), but other names like 3D radiography or stereoradiography are also commonly used as well as other titles (You, et al, 2001).

The addition of a second single plane radiograph at an oblique angle from the original plane allows for tracking of internal structures in all 6 DOF while maintaining sub-mm accuracy. As a result, researchers have developed custom stereo radiography and dynamic radiography systems to capture a wide range of movements (Anderst et al., 2009; Tashman et al.,2009; Torry et al., 2011; Brainerd et al., 2010; You, et al., 2001; Iaquinto et al., 2012). There are a variety of systems that use dynamic radiography to capture biomechanical data. Existing systems are described below in terms of single and dual plane systems, and custom cart-based and ceiling-gantry based systems.

Single Plane Systems

A variety of single plane systems exist. One design uses just one c-arm with an x-ray source (XRS) and image intensifier (II) fixed on either ends. This type of design is commercially available. Another option is a custom robotic arm design coupling the source with the II in some fashion. Robotic arms are used to align the components. Such machines require industry grade equipment so that the components are held steady enough for capturing motions. This system has mobile capabilities as well (Banks et al., 2008). A number of radiography studies have assessed a 2D motion analysis, but the major drawback is that few movements are truly planar. Even when assuming planer motion in a biomechanical kinematic analysis, the movements of interest must be captured parallel to the camera imaging plane. Thus, this technique cannot capture a full natural range of motion for joint articulations (Brainerd et al., 2010, Komistek et al., 2003; You et al., 2001).

Dual Plane Systems

Some systems use a commercially available dual c-arm design. The space available for movement is limited and does not allow a subject to walk through. An answer to this dilemma is the addition of a treadmill. The treadmill allows an individual to walk while remaining within the viewing volume of the system. This feature is advantageous because it does not involve the construction of a custom system. A major drawback would be the inability to adjust the SID limiting the viewing capabilities as well as hindering the subject movement space.

Ceiling Mounted/Retractable Systems

Another option is the utilization of a ceiling mounted track with retractable cranes for some or all the associated x-ray components. The cranes couple two XRSs and two x-ray detectors or image intensifiers and the gantry system has a custom designed retractable crane mechanism on a mechanized pivot attached to a track system mounted to the ceiling (Tashman et al). This gives the system a great advantage for component position and orientation. Essentially, the system is capable of following a subject for a short period of time. The major limitation is the required infrastructure for such a machine. This device would require a large area and a well-structured ceiling. Another limitation is that the system's mobility prevents any type of storage or movement of the system itself. The gantry system is mounted to the ceiling and cannot be stored out of the way for other studies not involving stereo radiography. Such a design requires devoting an entire or a large portion of a room to stereo radiography.

Another option also uses the ceiling mounted tracks and retractable cranes but only for the XRSs. Custom dollies were fabricated for the IIs. The x-ray tubes are fastened to an overhead crane system and the II's are attached to a dismantled duel C-arm fluoroscope cart via custom made brackets. The configurability of the system comes mostly from the structure arrangement. The x-ray tubes, being attached to an overhead crane mounted on ceiling tracks, have a wide range of 3D movement and the II carts can be dollied to almost any part of the imaging lab. The drawback, however, exists in the system mobility. The ceiling tracks can only carry the x-ray tubes so a pre-defined distance and the intensifier carts can only serve the II's to a height limited by the custom made brackets. Studies performed using this arrangement has proven that biplanar fluoroscopy can be used for situations as complex and unique as animal kinematics for zoological studies (Brainerd et al., 2010).

Independent Cart Based Systems

Another methodology simply places the x-ray components on independent carts. The use of four standalone carts holding either an II or x-ray tube allows for greater mobility and configuration. This setup not only allows an individual to walk through a duel x-ray beam cross section but also allows for the incorporation of force plates and the typical gait lab optical motion capture system. With this configuration the free space available for movement surpasses that of any system using a c-arm design. A limitation would be the rigidity of the components and their tendency to sway with a slight bump, setting off the alignment and requiring re-calibration. Studies implemented with these systems have had a heavy focus on the knee kinematics and pathology.

Design of a Novel High-Speed Radiography System

The overall goal of orthopaedic research is to discover the mechanical foundation of orthopaedic pathologies and improve their treatment. This requires accurate and often high-speed kinematic measurement of *in-vivo* 3D, six DOF joint motion during physical activities in rehabilitation, sport, and daily living. **To meet these aims, four requirements were established to guide the design, construction, and validation of a high-speed stereo radiography (HSSR) system.** (1) The first design requirement stated that the system must be easily reconfigurable to facilitate imaging of major joints from the foot to the cervical spine. This reconfigurable nature was attributed by gantry design and its ability to orient the components in a vast number of ways. (2) The second requirement was the system must be integrated into the existing Human Dynamics Lab (HDL) space and with an existing full-body optical motion capture system. Due to the lab's high use, the system needs to function with the equipment already present and needs not to interfere with the equipment during non-radiography events. (3) The third requirement focused on the system's need to capture joint motion at high-speed and in high-definition, while maintaining low radiation dosage to human subjects. The high-speed high-definition cameras interfaced with the II's would provide such detail and the pulsed x-ray generation would drastically reduce the radiation exposure compared to the constant emission mode. (4) The fourth requirement was the system must be accurate and precise enough to capture joint motion with sub-mm accuracy. The gantry's ability to hold these devices still and rigid enough to obtain data of the necessary precision and accuracy was essential for obtaining data of the required level.

This thesis presents how the HSSR design requirements were met, detail on each of the system components, assembly instructions, and an operations manual for the structural entities. The design requirements were developed from the limitations of other systems and the needs of the DU Center for Orthopaedic Biomechanics. The assembly guide provides detailed text and pictorial representations of the steps needed to construct the HSSR system. The operations manual provides instruction on the proper gantry and component use. This newest addition to the lab is expected to provide state of the art quality data for future research.

Chapter Two: System Design

The HSSR system is a novel design approach to stereo radiography. In overview, the system is comprised of two identical and independent imaging planes; one plane is 12 feet in length and 3 feet at the widest point of the base (Figure 2-1). Like commercially available radiography/fluoroscopy systems (RF), each imaging plane of the HSSR system includes an x-ray emitter (i.e. source) and collimator that direct x-rays through a subject of interest (Figure 2-1A) where they are received by an II that converts the x-rays to visible light (Figure 2-1B). High-speed digital cameras record the resulting image. The RF components of each image plane are positioned with a custom gantry that maintains a rigid and calibrated position of the XRS relative to the image intensifier (Figure 2-1C-E). As mandated by our research goals, the HSSR system met three key design requirements.

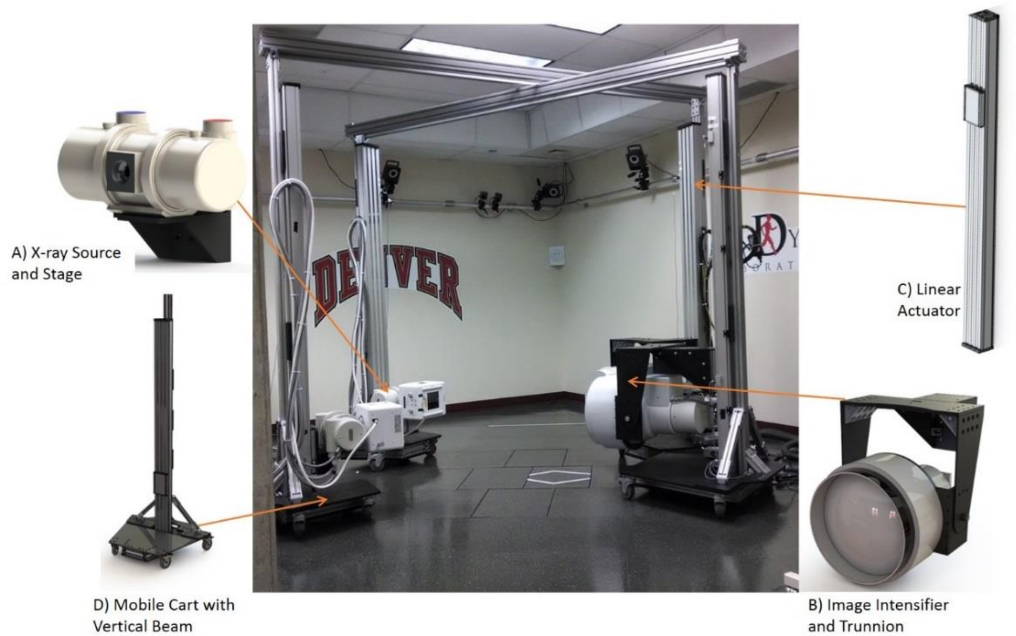


Figure 2-1: The HSSR system comprised of the following sub-systems: (A) X-ray source, (B) image intensifier, (C) linear actuators, and (D) mobile cart and vertical beam.

Requirement #1: The system must be easily reconfigurable to facilitate imaging of major joints from the foot to the cervical spine.

To achieve this goal, detailed requirements of the system were established as follows:

- Height Adjustment: 1.8m minimum based on the approximate height foot to cervical height of a 6'4" person.
- SID Adjustment: variable between 1.0 and 1.60m to enable adequate motion capture area for human movement.

- XRS and II Trunnion Pitch: ± 45° to allow the x-ray beam to be angled relative to the subject for non-sagittal viewing.
- XRS and II Trunnion Yaw: ±10° to allow flexibility in beam adjustment.
- Imaging Plane Rotation: ± 135° to allow flexibility in adjustment of the location of the viewing volume.

A framework to support the imaging components of the HSSR system was constructed with two gantries, one for each imaging plane (Figure 2-1). The gantry needed to allow a large space for subjects to perform a wide variety of activities, be reconfigurable to image joints from foot to cervical spine, and remain rigid once in position. Each gantry was constructed with vertically aligned slotted 80/20 aluminum beams (40 Series, 80/20 Inc., Columbia City, IN) connected to corresponding horizontal crossbeams mounted at a height of 1.8 meters. The horizontal crossbeams maintain the system at the chosen source-to-image distance (SID) and provide rigid and stable attachment between the XRS and II. The vertical 80/20 beams, 40-4080-VbT, were mounted to stable custom fabricated bases. Each base rides on four lockable casters to allow independent positioning of each imaging plane in the laboratory space.

Figure 2-2: The II cart with all the pieces between the overhead crossbeam structure and the base cart, labeled. The II and trunnion are hidden in this picture.

The 40-4080-VbT beams, shown in Figure 2-2, mounted to the base carts form the back and bottom brace for four linear actuators (1 per base) which facilitates vertical positioning of the HSSR imaging components (Figure 2-2). Each actuator (DLK 160, Nook Industries, Cleveland, OH) is able to support and vertically translate loads up to 400 kg. A central non-back-drivable acme screw within each actuator is turned by a computer controlled stepper motor (Applied Motion Products, Watsonville, CA) that provides vertical translations to a resolution of 0.025 mm. The overall travel of the actuators is 1.8 m for vertical positioning of the RF components from the level of the shank to the height of the cervical spine of an average adult human subject. For imaging of the ankle and foot, a short, radio-translucent platform can be provided for subjects to stand on. Each actuator motor is controlled from a PC using MINT Workbench software (ABB Motion, Bristol, UK). Actuator motion can be controlled independently or in unison (all actuators at once), and moved to preset positions based on the joint to be imaged and subject is measurements. Because the XRSs and IIs are on separate actuators and can move independently, laser sights are used to assure the II is positioned exactly in line with the XRS.

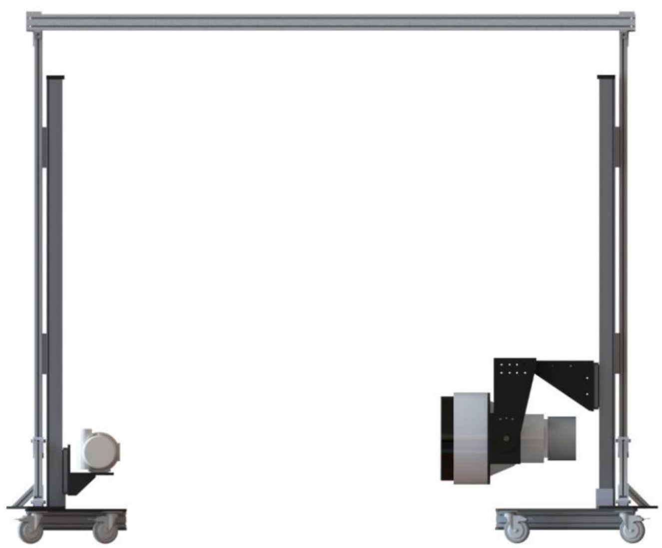


Figure 2-3: Side view of a single gantry and radiography plane.

In addition to the large vertical travel allowed by the actuators, slots in the horizontal 80/20 crossbeams or 40-4080-L3, seen in Figure 2-4, allow controlled lengthening or shortening of the SID between the XRSs and the IIs. While the standard SID of the system is 1.65m, a shorter SID may be advantageous to capture isolated activities such as wrist movement. By unlocking the casters on the gantry bases and temporarily loosening the bolts of the horizontal crossbeams, the SID can be adjusted from 1.65 m down to approximately 0.5m. Once positioned with the desired SID, crossbeam bolts are retightened to keep each source and II pair tethered and aligned.

Figure 2-4: The overhead crossbeam structure.

The IIs are mounted on an aluminum turret mechanism that allows for a pitch and yaw motion (Figure 2-5). Pitch is achieved by two steel pins located on either side of the turret. The turret rests on an aluminum structure that connects to the carriage found on the vertical linear actuator. The carriage of the linear actuator moves the entire complex vertically. At the turret connection a bolt allows rotation about the vertical yaw axis.

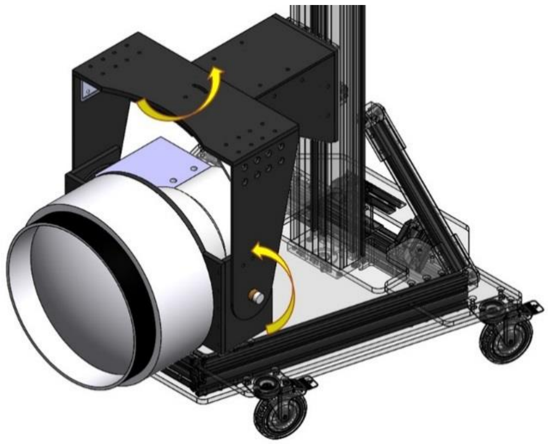
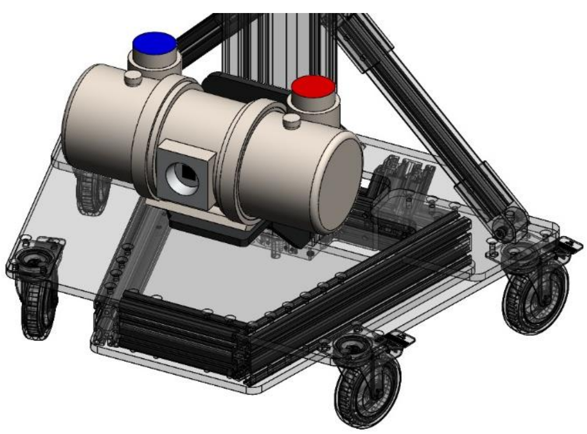
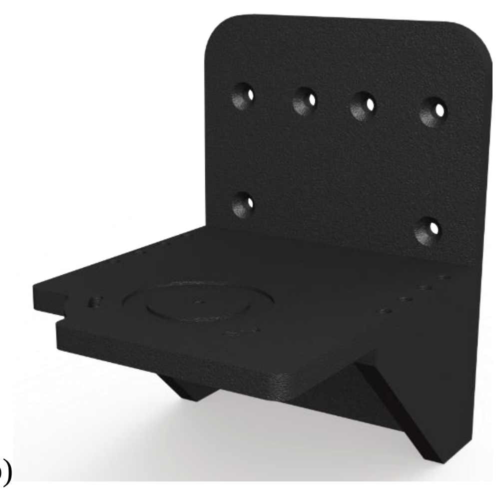


Figure 2-5: The II pitch and yaw motion allowed by the II trunnion.

Similarly, the XRSs are allowed a pitch and yaw variability (Figure 2-6). Mounting brackets supplied by the manufacturer provide the pitch through bearing rings. A rotational stage made from ½” 6061-T6 aluminum provides yaw by a thrust bearing. The stage is bolted to the linear actuator carriage which for allows vertical translation of the x-source structure.



a)



b)

Figure 2-6: The a) x-ray source and b) stage.

The HSSR's reconfigurable nature is shown through its ability to capture joint motion from the foot and ankle up to the cervical spine. The ability to arrange the components in any position necessary for the imaging of any major joint or joint system in the body relies on adjustable SID and vertical placement, pitch, and yaw of the components.

In summary, Requirement 1 was achieved with the following specifications:

- Height Adjustment: Linear Actuators enable 1.8m±0.025mm of vertical travel
- SID Adjustment: variable between 0.8 and 1.65m
- II Trunnion Pitch: + 53° to - 40°, Yaw: ±22.5°
- XRS Pitch: + 90° to - 25°, Yaw: ± 7.5°
- Imaging Plane Rotation: ± 160°

Requirement #2: The system must be integrated into an existing motion laboratory with a full-body video motion capture system.

To meet our research aims for human movement capture, the HSSR system needed to allow unimpeded walking through the capture volume with minimal visual occlusion of optical cameras mounted around the perimeter of the laboratory and force plates embedded within the laboratory floor. The optical motion capture system includes 8 Vicon MX near-infrared cameras (Vicon, Oxford, UK) designed to capture trajectories of spherical surface markers placed at bony landmarks on human subjects. Four force plates (Bertec, Columbus, OH) embedded within the floor capture ground force data simultaneously with video motion capture. At least two cameras are required to capture the instantaneous position of any given spherical marker, so the HSSR system gantries were designed with a slender profile to reduce occlusion. Power and data cables for the HSSR system were routed through the floor to further reduce occlusion of camera views. Furthermore, to maintain full functionality of the laboratory as a multi-user human dynamics testing and evaluation site that includes studies without radiography, the HSSR system was designed to easily move and compactly store outside the motion capture space.

Figure 2-7: The stored imaging planes are aligned against the wall.

Specifically, quick disconnects on all cables and casters on each gantry allow each imaging plane to be positioned independently and stored with a minimal footprint. The system can be stored and reassembled in less than 10 minutes in a limited laboratory space.

The video motion capture system can be triggered in synchrony with the HSSR system, by a synchronizing pulse from either the motion capture system or the HSSR. Co-location of the motion capture and HSSR coordinate systems are achieved by placing spherical video motion capture markers on the HSSR calibration cube (see Requirement 4 for HSSR calibration details). The result is a unique data acquisition capability of time-synchronized high-resolution radiography, full-body motion capture, and ground reaction forces for a variety of dynamic joint motions.

The systems integration into the human dynamics lab allows for normal lab motion capture function as well as radiography work and they may be ran simultaneously. The systems tall slender design minimally occludes the eight optical cameras and allows them to track the reflective markers on the subject. The space within the system allows an individual to exhibit many types of movements such as walking, running, jumping, stair stepping, squatting, and pivoting just to name a few. This space also provides ample room for the use of the four force plates.

There are a number of cords associated with the system so cord organization has also been implemented. The quick disconnect boxes located on the II carts provide a quick and easy cord disconnect for easy setup and storage capabilities. To assure the there is no disruption to foot traffic the cords have been confided to flexible plastic tubes and routed to their destination underneath the floor. This provides great cord organization and a clear floor for any type of human movement.

Requirement #3: The system must capture joint motion at high speed and in high resolution, while maintaining low radiation dosage to human subjects.

These requirements were met through selection of the maximum diameter image intensifiers, integration of high-speed high-definition cameras, and use of pulsed x-ray. Integration of the HSSR imaging chain including all x-ray equipment was accomplished by Imaging Systems and Service Incorporated (ISSI).

The detailed system requirements were as follows:

- Image Intensifier Diameter of 40cm: provides large capture volume enabling the viewing of major joints in their entirety including the foot
- High-Speed Capture of 500Hz: mimimum requirement to achieve high speed motion capture for activities such as landing from a jump (REF) and throwing.
- High-Definition of 1080x1080 pixel ratio: high definition may improve tracking of bones and implants.
- Pulsed Emissions of 60fps minimum with continuous capture mode for high speed acquisition: pulsed mode allows minimal x-ray exposure for most activities of daily living while continuous mode may be required for sporting activities.

The imaging volume is determined the x-ray beam intersection and their position and orientation relative to one another. Imaging volume was maximized by incorporating 40cm (16") diameter IIs (Thales Inc., TH 9447 QX); the largest commercially available (Figure 2-8). Maximizing the imaging volume enables recording of essential anatomy for understanding the motion of large joints such as the shoulder complex (scapula, humerus, sternum, clavicle), joint systems (e.g. the sacro-iliac joint of the lower back and the hip joint) and meaningful ranges of motion (e.g. shoulder kinematics during the wind-up of a baseball pitch) (Figure 2-8). Although digital x-ray detectors with larger image area are available, they are not currently capable of recording frame rates above 10 frames-per-second (fps) at full resolution.

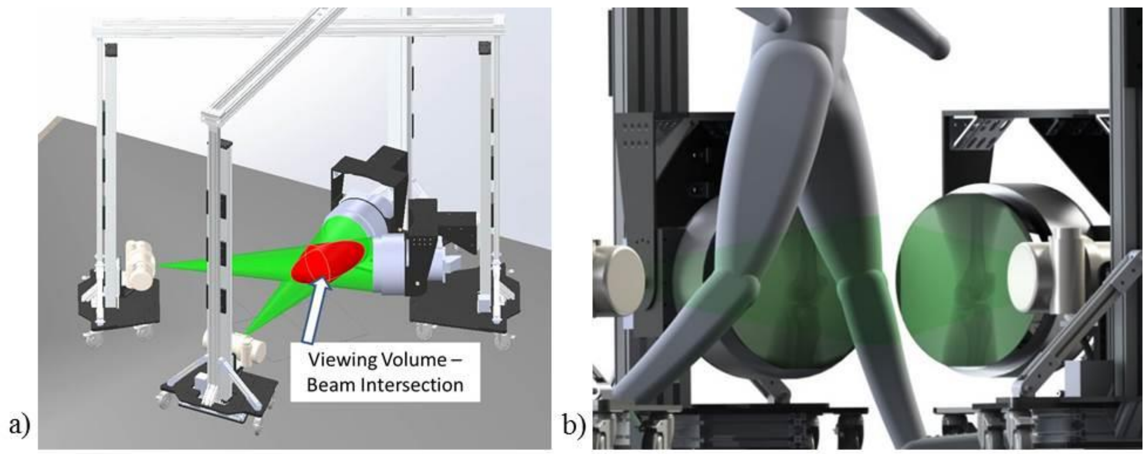


Figure 2-8: The viewing volume is determined by the intersection of the x-ray beams of the two imaging planes a), and representation of the knee imaging on the image intensifiers b).

High-speed image acquisition was achieved through integration of high-speed high-definition digital cameras onto the IIs. The IIs convert the x-ray to a visible image on a 25.4mm (1”) diameter phosphor screen. The high-speed, high-resolution digital video cameras (Miro M-120, Vision Research Inc., 1080x1080, 12 bit) were positioned to view the phosphor screen of the IIs using a custom interface designed and supplied by Imaging Systems and Service Inc. (ISSI, Painesville, OH).

The key safety consideration in the use of radiation is minimizing dosage to the patient while still capturing the needed images, also known as the As Low As Reasonably Achievable (ALARA) principle. In collaboration with ISSI, two capture modes were created to satisfy this principle. First, in pulsed acquisition mode, the system emits an x-ray pulse only during the time an image is acquired by the camera, effectively eliminating unnecessary (and unrecorded) radiation exposure to the subject. The HSSR system is capable of a wide range of pulse widths (typically 5 ms) and pulse speeds up to 120 fps. By comparison, commercially available pulsed fluoroscopy systems have a maximum frame rate of 30 fps and require continuous radiation to capture images above 30 fps, which delivers a higher radiation dose to the subject (Torry et al., 2011; Tashman et al). A frame rate of 120 fps is sufficient to capture most activities of daily living. For high-speed activities that require greater frame rates, the HSSR system is equipped with a second continuous acquisition mode with a maximum frame rate of 1,000 fps. This mode is used only for a high speed active complex motion, such as recording the shoulder when throwing a ball.

The detailed system requirements were achieved by the following parameters:

- Image Intensifier Diameter of 40cm
- High-Speed Capture of 1000Hz
- High-Definition of 1080x1080 pixel ratio
- Pulsed Emissions of 120fps

The original specifications of the system listed components were either met or exceeded. The II diameter of 40cm was achieved; the high-speed capture was exceeded by double the original value of 500Hz to 1000Hz. The Miro-120 cameras record in high definition, 1080x1080 pixel ratio. The pulsed acquisition capture speed was met with 120fps which was double the initial requirement. This pulsed acquisition was used on the human subjects because of the reduced radiation exposures. The continuous acquisition mode has been used to capture several types of fast complex movements. Two wind-up toys which exhibit quick motions were imaged during their performed actions.

Requirement #4: The system must be accurate and precise enough to capture joint motion with sub-millimeter measurements.

In order to capture such minute measurements the HSSR system must be robust to disturbances. System Rigidity is of great importance because stiffness enables reliable repeatability. The gantry system was required to remain rigid while supporting the weight of the structure, vertical actuators (Nook Industries, Cleveland, Ohio), and the x-ray components. Specifically, to maintain precise positioning of the imaging components, the system was designed to maintain a maximum deflection of less than 1 mm in the loaded structure. Deflection of the gantry system under varying loads was investigated using a series of finite element analyses of select portions of the gantry using the SolidWorks' (Dassault Systemes Solidworks Corp, Waltham, MA) simulation package. Analyses of II trunnion, cart, and source stages were completed separately and evaluated with the requirement of sub-mm maximum deflection. Detailed engineering analysis and FEA information can be found in Appendix B. The maximum deflections are as follows:

- Element error – 8%

- II side of the viewing plane – 0.329mm
- II Trunnion – 0.326mm
- XRSS – 0.035mm

The ability to capture skeletal motion with sub-mm accuracy and resolution follows several calibration steps. These steps are performed prior to data acquisition. The first step aligns each source to its respected II, and is assured through adjustment of the elevation, pitch, and yaw of the x-ray components. After the initial relative alignment of the two image planes, the casters are locked to prevent any movement of the base carts. The IIs are moved to the correct elevation to establish the capture volume for the desired region. To match the elevation of the sources with their respected II, each source is equipped with a laser that spans the width of the II's. The sources are then adjusted such that the lasers cross the midpoint of the IIs, marked with a horizontal line. Then, the yaw is adjusted to ensure the sources emit perpendicular to the input face of the IIs. The yaw of the sources can be adjusted such that the vertical crosshair line is aligned over the center of the II, marked with a small icon. Last, pitch is set by placing mirrors over each II. The mirror reflects the laser from the source back to its origin, which allows for adjustment of the source to maintain a relative source-II angle less than 1°.

There are a variety of image distortions that are created through the use of the IIs and must be corrected prior to data processing, i.e. bone and implant tracking. The distortions are corrected by imaging a radio-opaque mesh (9255T641, McMaster-Carr, Robinson, NJ) with known hole locations and application of a custom MATLAB (The Mathworks, Natick, MA) script to determine a transform to un-distort the captured images. The position and orientation of the bones are found by matching the pose of the 3D bone/implant model to images captured from the subject. The 3D viewing space or viewing volume is calibrated using images of a calibration object, or calibration cube, of precisely known size and orientation. The calibration cube is a custom design made of radio-translucent plastic and 52 radio-opaque steel beads. The cube is centered in the viewing volume, and simultaneous radiographs are captured from each plane. The relative bead locations from each 2D planar image are then identified, and direct linear transform (DLT) coefficients for each source-II plane are calculated based on the known actual coordinates of the beads on the calibration cube.

To prove the system's ability to capture accurate and precise measurements the calibration cube as well as an implant were tracked using the tracking software and calibration script. The absolute translations and rotations were measured with translational (tolerance: ±0.001") and rotational (tolerance: ±0.01°) stages. Radiographs were taken at an oblique angle of 60° between the viewing planes. The calibration cube was set atop the translational stages and imaged in four different positions 1" apart. The translational stage was exchanged for the rotational stage and three different rotational positions were measured and captured. The rotation was horizontal to the lab floor. These captured data were processed using the tracking software and the output compared to the absolute measurements. The same procedure was performed on the femoral implant. The calibration cube bead tracking had translational error of 0.2mm (0.008") and a rotational error of 0.11°. The implant tracking exhibited an error of 0.15mm (0.006") and a rotational error of 0.40°.

These results prove the HSSR’s ability to capture minute measurements. The femoral implant’s translational error was smaller than the calibration cube tracking. This can be attributed to the implants size and relative edge length compared to the steel beads tracked in the cube. This provides more information for the tracking software ergo more accurate data obtained.

Chapter Three: Assembly Instructions

This chapter discusses the assembly instructions for the HSSR system. These instructions assume the user has already machined the parts and cut the 80/20 extrusions needed for the assembly. The system should be assembled in sections. The sections consist of two II carts, XRS carts, II trunnions, x-ray source stages (XRSSs), and Overhead Beam Structures, and are described below with step-by-step assembly instructions.

Note: See Appendix C for Engineering Drawings.

Warning: Assembly of the HSSR system is a two or more person job. The assemblers should be comfortable handling overhead loads of up to 50lbs.

Tools Required: Common size metric socket set and wrenches, metric Allen key wrenches, and rubber mallet.

II Cart Assembly

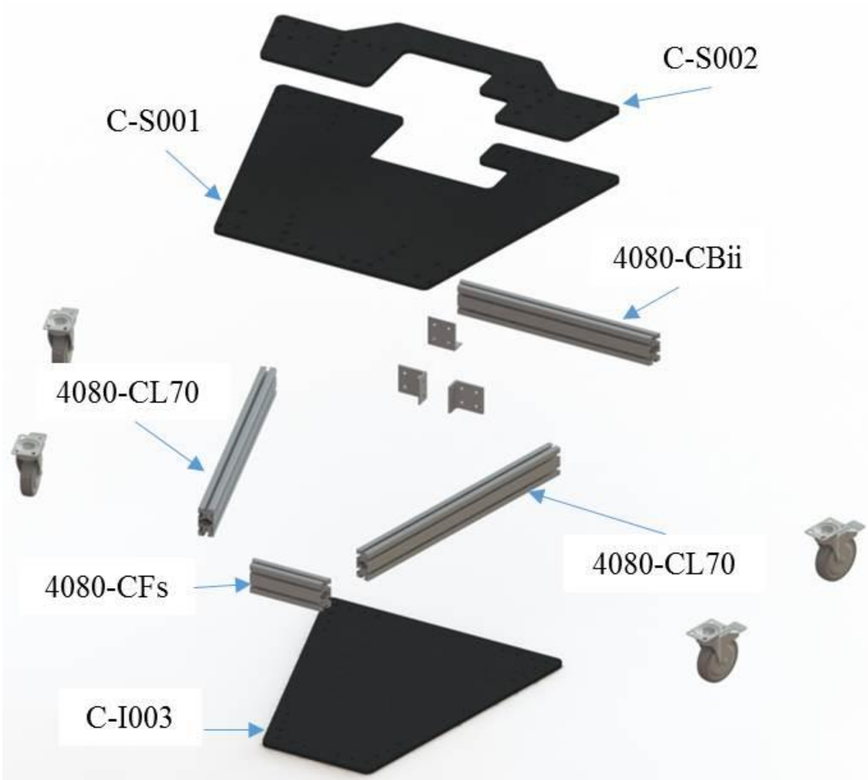


Figure 3-1: Exploded view of the II Cart Assembly.

Step 1: Four total 80/20 extrusions are required for one II cart. Gather all the correct sized fasteners, the aluminum plating and casters.

Step 2: Start by fixing one 80/20 extrusion, 4080-CL70, to the C-S001 plate on the left side (Figure 3-2). The easiest way to accomplish this is to insert the correct countersink bolts into the appropriate holes and place the T-nuts on to the bolts using only two threads. This allows the 80/20 extrusion to slide into place.

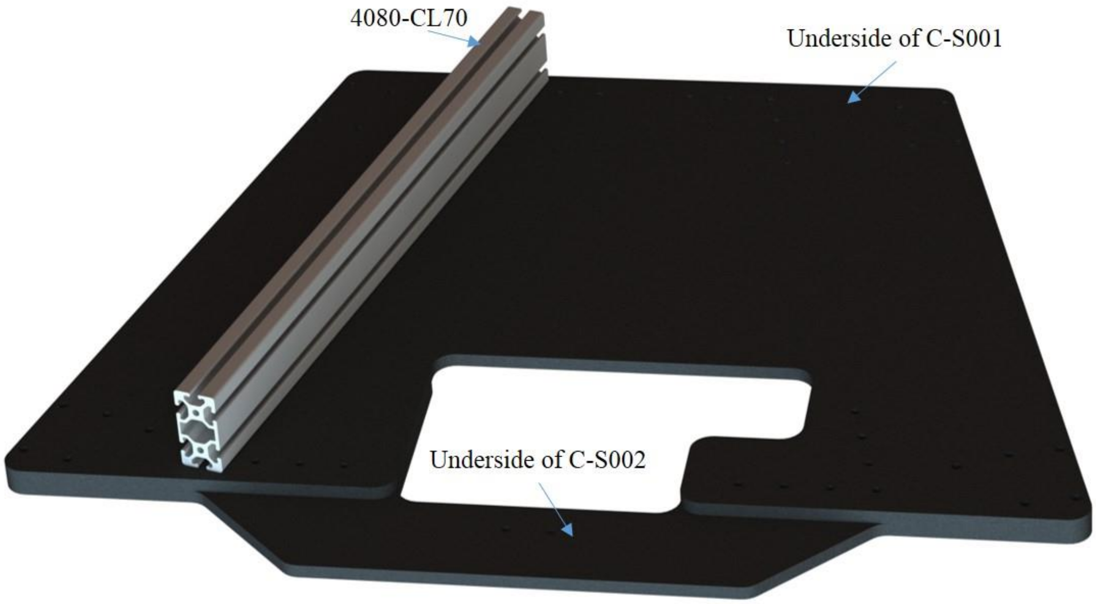


Figure 3-2: Attaching the left 4080-CB70 to the C-S001.

Note: Do not tighten the bolts into place and make sure the flange side of the T-nuts are facing away from C-S001 plate. The T-nut flanges can become lodged with in the 80/20 extrusion grooves.

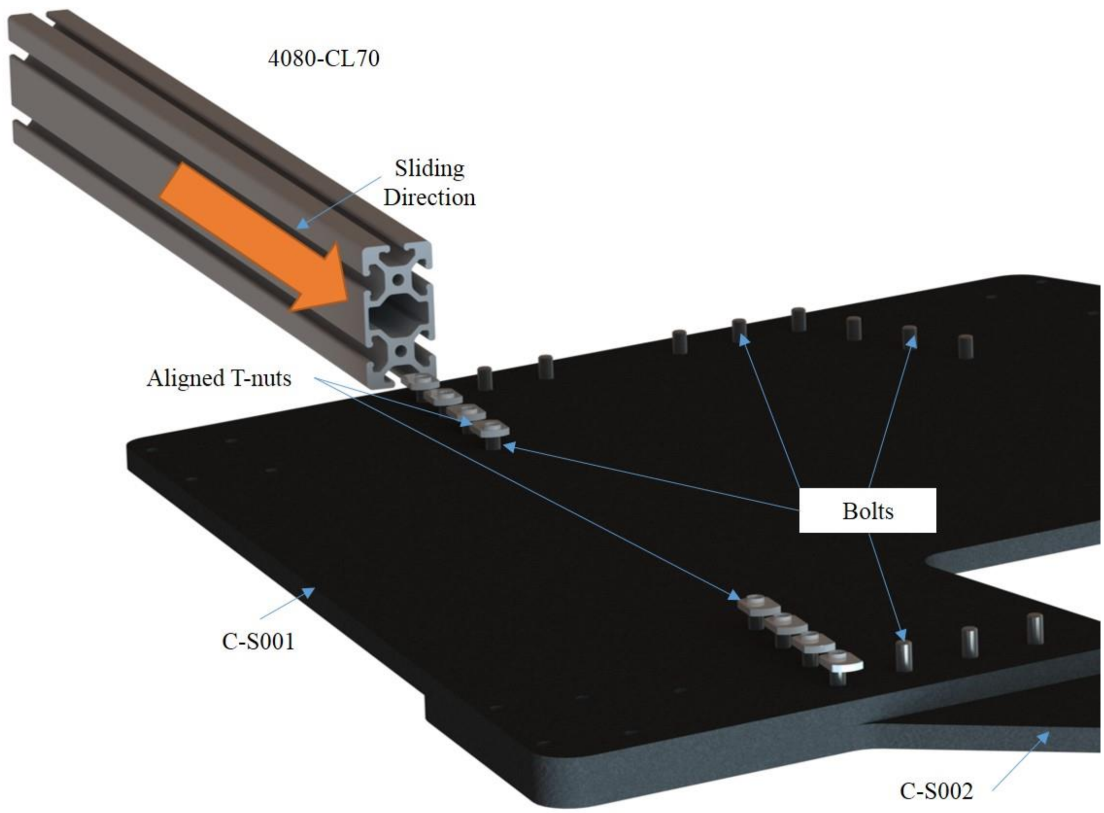


Figure 3-3: Aligned T-nuts and sliding action used when placing the 4080-CL70 extrusion.

Step 3: Attach the 4080-CFs extrusion to the front side of the cart. Again, load the required countersink bolts and T-nuts into the appropriate holes and slide the extrusion into place (Figure 3-3).

Note: Accurately aligning the T-nuts will make sliding the extrusion into place easier.

Step 4: Attach the 4080-CBii extrusion by sliding the required T-nuts into the appropriate positions to match the holes on the C-S001 and C-S002 plates. Make sure there are two extra T-nuts placed between the two sets of T-nuts that attach the plates to the extrusions (Figure 3-4).

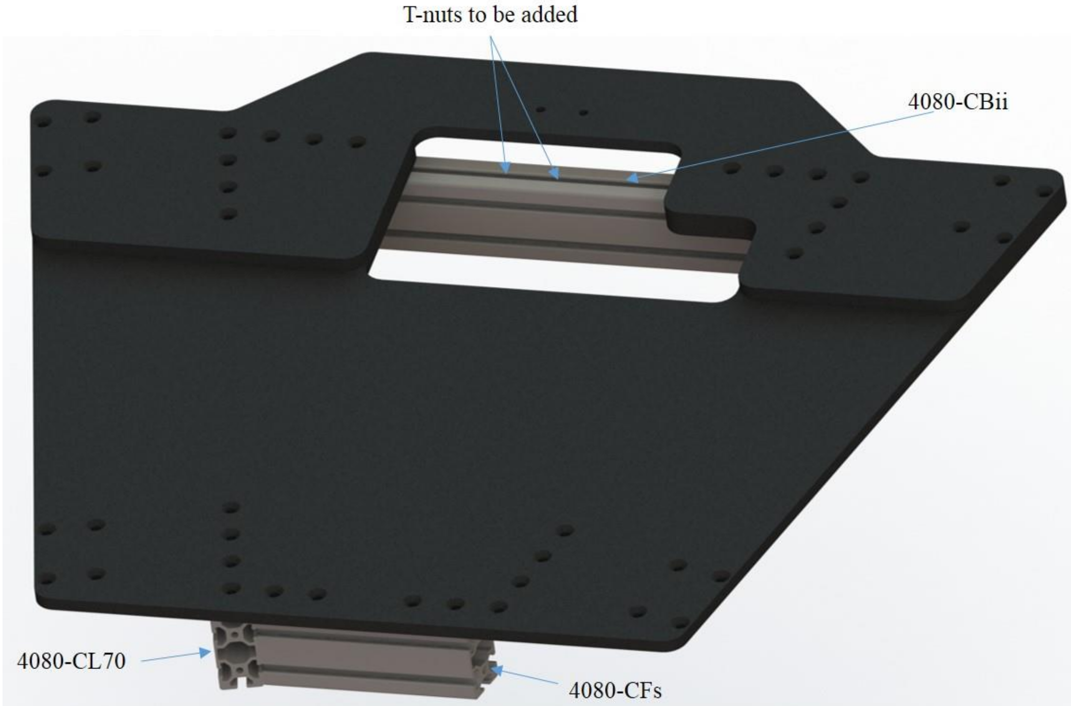


Figure 3-4: The cart with the 4080-CL70, 4080-CFs, and 4080-CBii extrusions with the extra two T-nut locations labeled.

Step 5: Insert the required number of T-nuts on the bottom grooves (Figure 3-5) of the 4080-CFs, four T-nuts, and the bottom grooves, four T-nuts, and interior grooves, eight T-nuts, of the 4080-CBii extrusions, because when attaching the bottom plate, C-I003, these grooves will be inaccessible to the T-nuts that were not pre-placed.

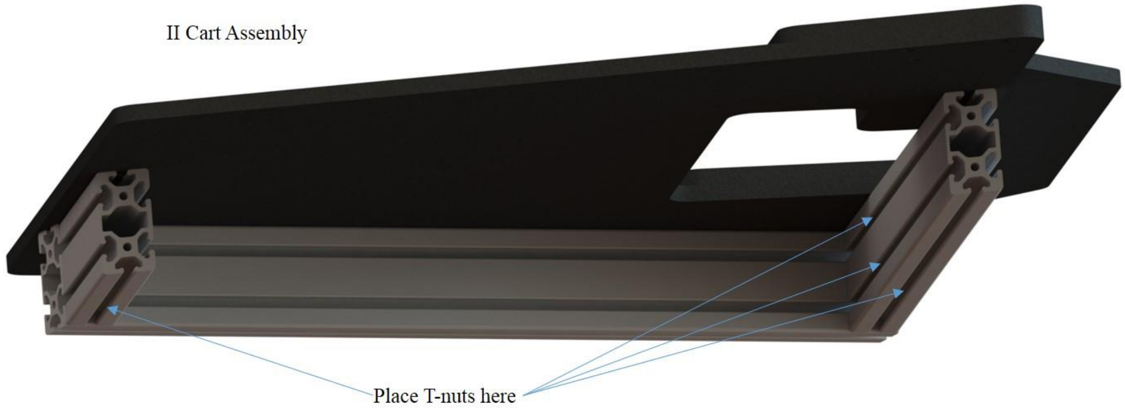


Figure 3-5: The II cart with the extra T-nut locations labeled.

Step 6: Attach the other 4080-CL70 on the right side in the same fashion as stated in step 2.

Step 7: Flip the cart over and slide the required T-nuts into the 4080-CL70 extrusions and place all the T-nuts to match the holes on the C-L003 plate.

Step 8: Attach the C-L003 plate to the extrusions and tighten all the fasteners (Figure 3-6).

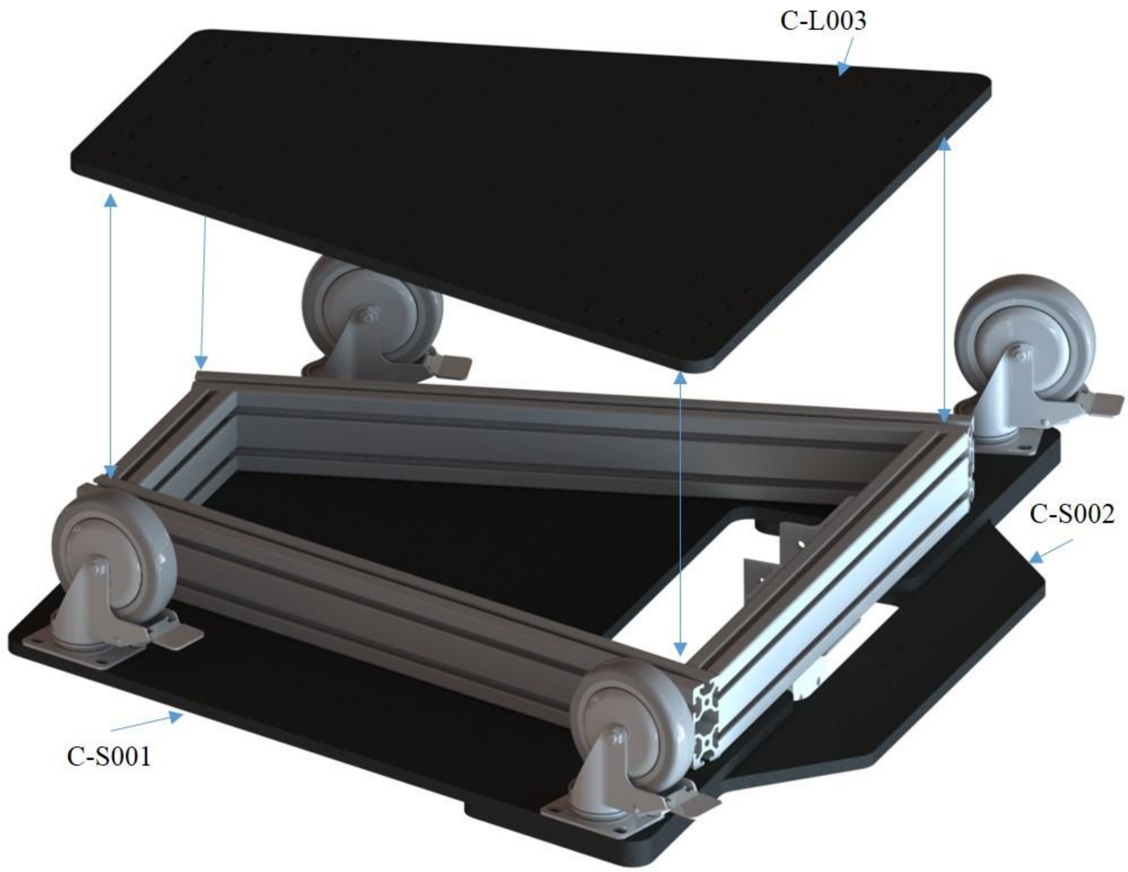


Figure 3-6: Attaching the C-L003 plate.

Step 9: Attach the six holed corner brackets and then attach the casters (Figure 3-7).

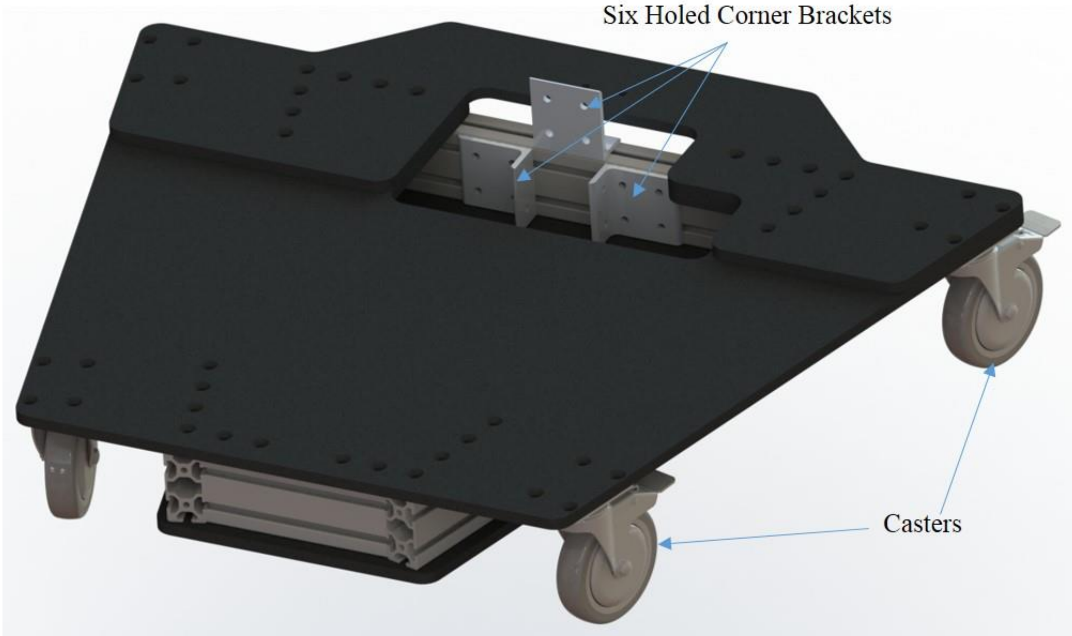


Figure 3-7: The six holed corner brackets and casters are labeled above.

Step 10: Place the 4080-Vb(T or S). Start by loading the T-nuts and bolts into the six holed corner brackets. Then, slide the 4080-Vb extrusion into place and tighten the bolts. Slide the required T-nuts down the now vertically standing extrusion to attach the 90° extrusion, 40-2530, and the 0° living hinge, 40-4383(Figure 3-8).

Note: Due to the overall height of the 4080-Vb extrusion, it may be necessary to assemble the rest of the system in the room/space intended for its use.

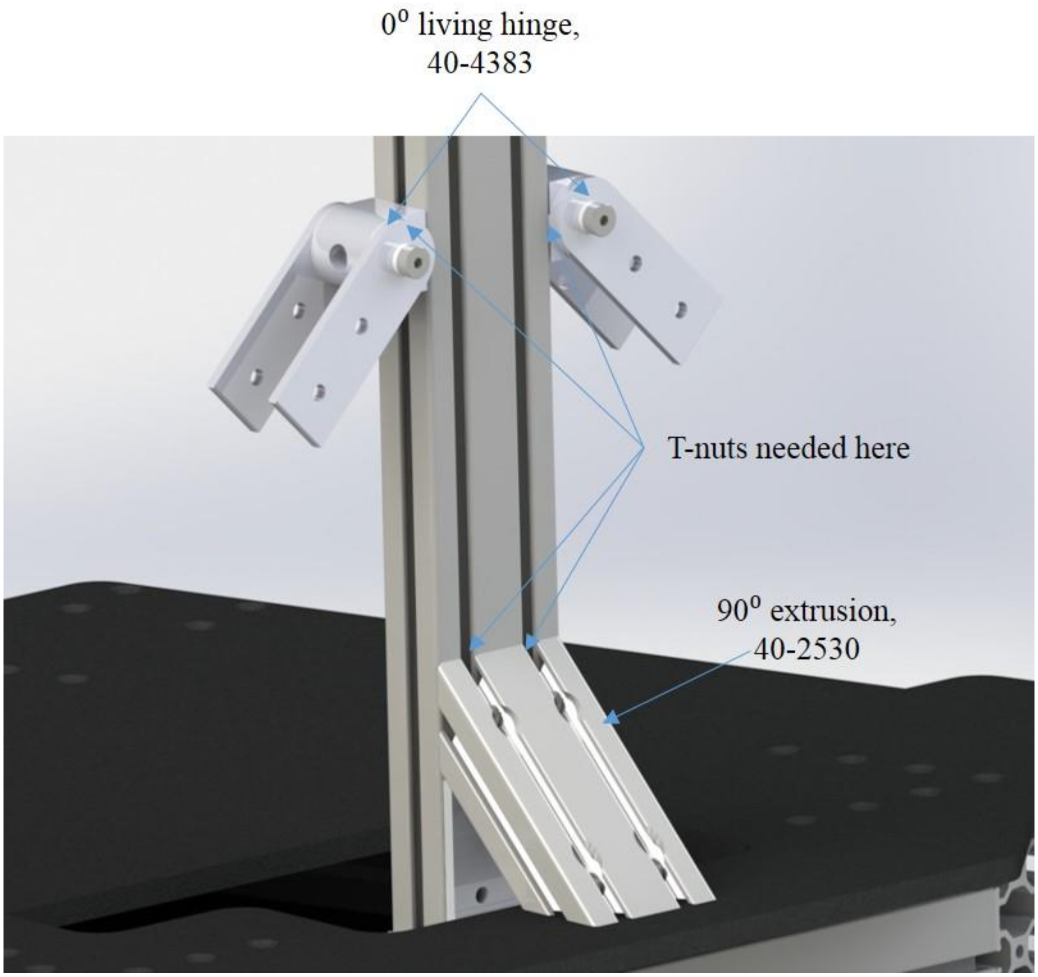


Figure 3-8: The T-nuts needed to attach the 40-2530 and 40-4383 are labeled above.

Step 11: Fasten the 40-4040 extrusion to the 40-4383. It is easiest to pre-load the fasteners and slide the extrusion into place. Then attach another 40-4383 to the opposite end of the extrusion.

Step 12: Attach the 40-4383, found on the end of the 40-4040 extrusion, and 40-2530, if not done already, to the cart. There is a pair of holes on the back section of the C-S002 plate for the 40-2530 fasteners and one hole on either side of the C-S002 plate between the extrusion holes and the caster holes for the 40-4383 fasteners (Figure 3-9).

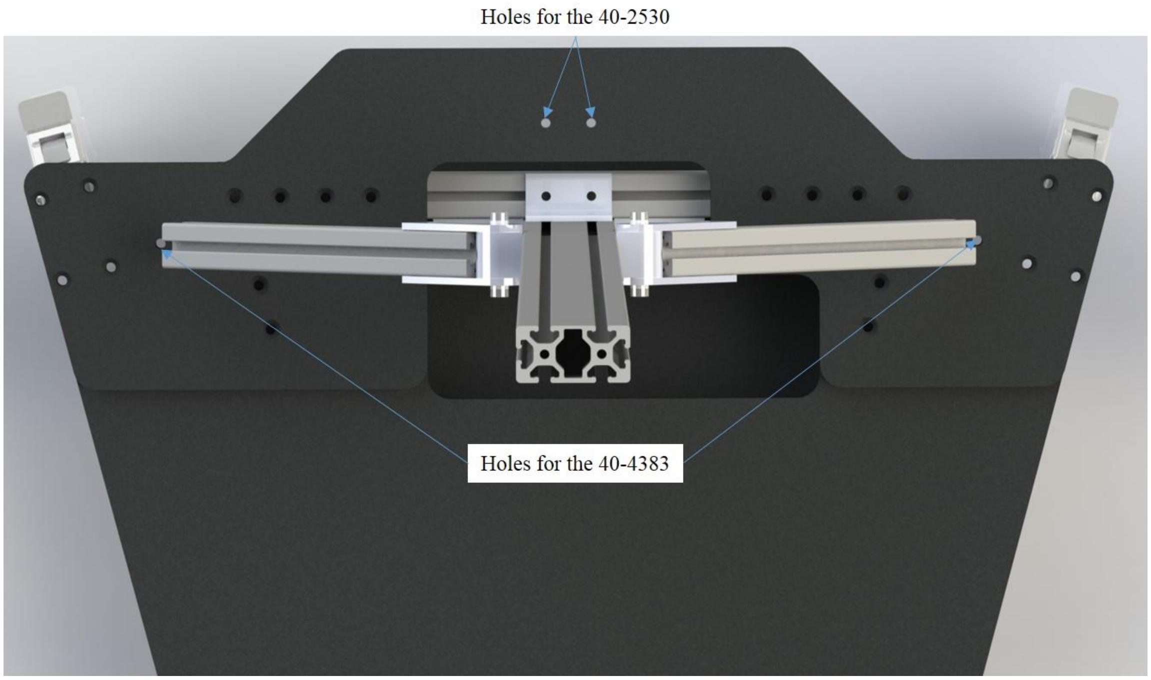


Figure 3-9: The holes for the 40-2530 and 40-4383.

Step 13: Attach two sets of the Act-8020 plates to the 4080-Vb extrusion (Figure 3-10). Make sure the lower sets of plates are 32in above the C-L003 plate and 32in between the two sets of Act-8020 plates. One set of Act-8020 plates are the combination of two black 6061-T6 aluminum plates. The images portray these sets in their combined form.

<u>Note</u>: The bolts to attach the linear actuator should be pre-loaded into the plates before attaching the plates to the extrusion.

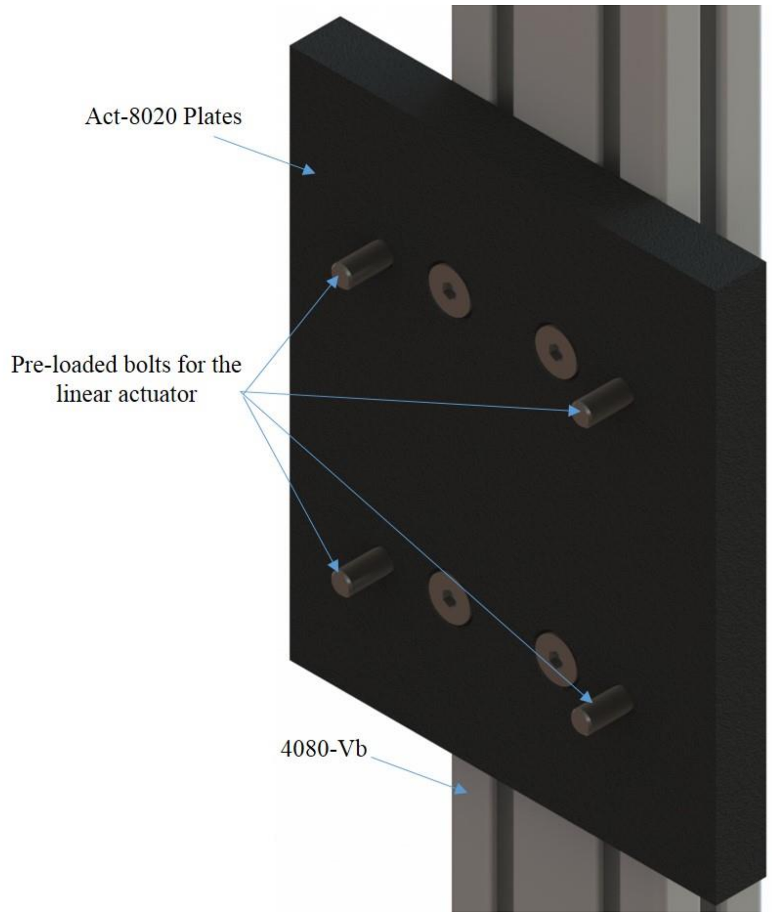


Figure 3-10: The pre-loaded bolts for the actuator.

Step 14: Attach the gear boxes to the shaft end of the linear actuator. Then, attach the servo motor to the gear box.

Note: Make sure the motor attachment is on the correct side; see cart images.

Step 15: Attach the linear actuator. Flip the cart assembly on the backside (Figure 3-11). Place the T-nuts, specific to the actuator, in the grooves on the back face of the actuator and align them to the Act-8020 plates. Due to the geometrical constrains of this interface between the actuator and the Act-8020 plates, the bolts cannot be fully screwed into place and must be tightened one full rotation, one bolt at a time.

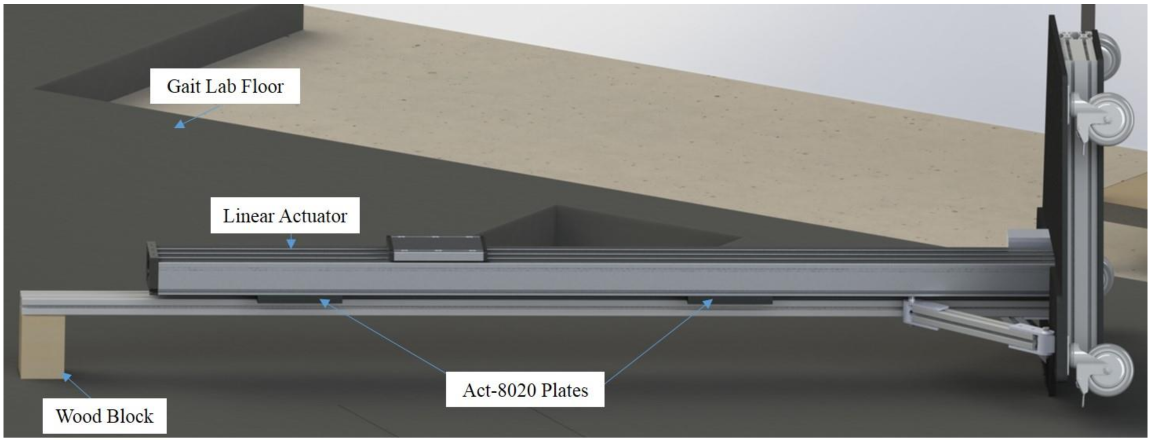


Figure 3-11: The orientation of the cart for the actuator installation.

XRS Cart Assembly

The differences between the II cart and the XRS cart are the plate and extrusion sizes and the number of extrusions. For the XRS cart the C-S0L1, C-S0L2, and C-I0L3 plates are smaller versions of the C-S001, C-S002, and C-L003 respectively. The extrusions, 4080-CL5L and 4080-CL5S, found on the right side of the actuators need to be cut into two pieces to accommodate the size of the servo motor (Figure 3-12).

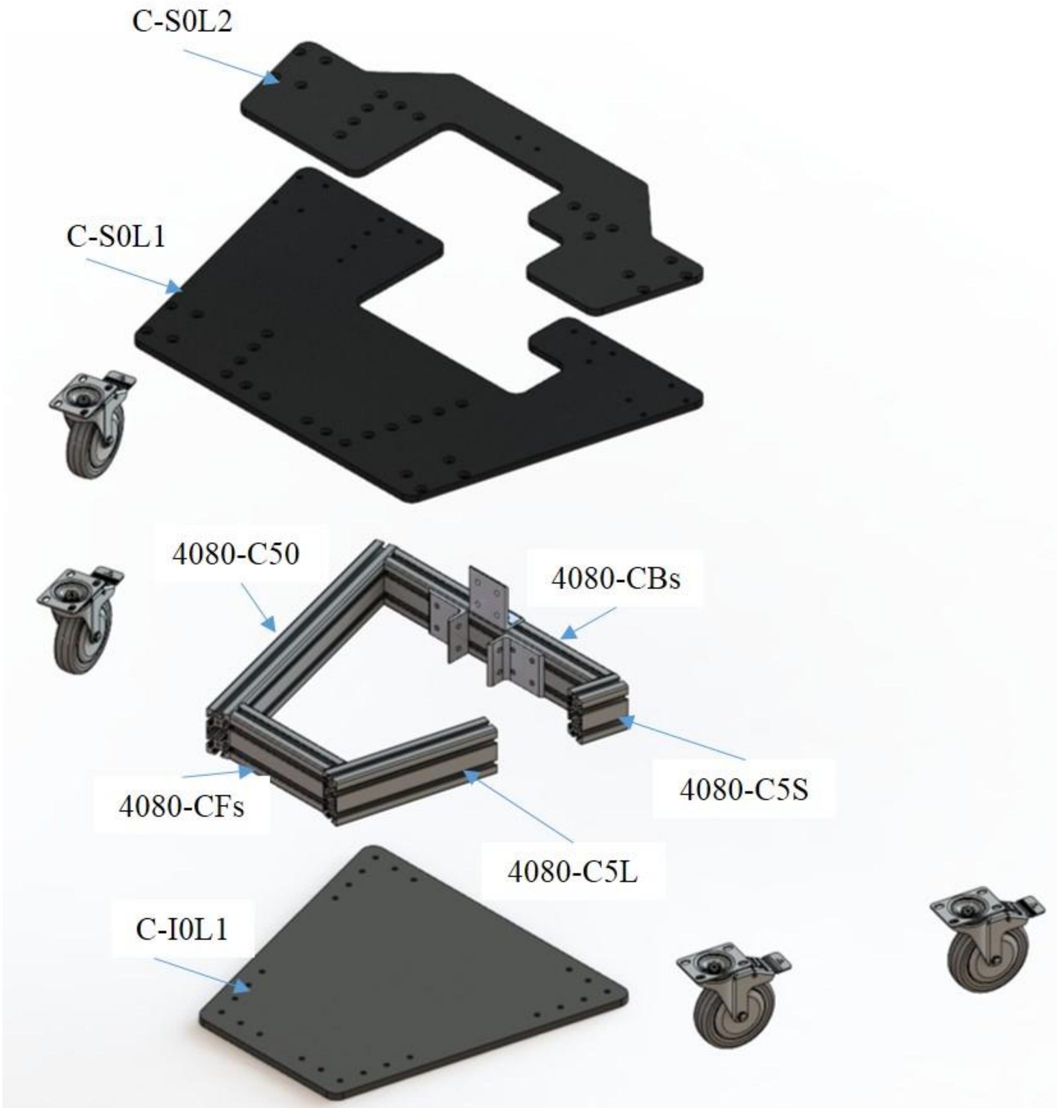


Figure 3-12: The XRS cart is smaller than the II cart and has two extrusions, 4080-C5L and 4080-C5S, to accommodate the size of the servo motor.

Assembly of the Yoke Stage

Step 1: Start by attaching the two-hole corner gussets, 40-4332, to the AII-000 plate using the five countersink holes on the back face and the AII-002 plate using the five countersink holes found on the back face (Figure 3-13).

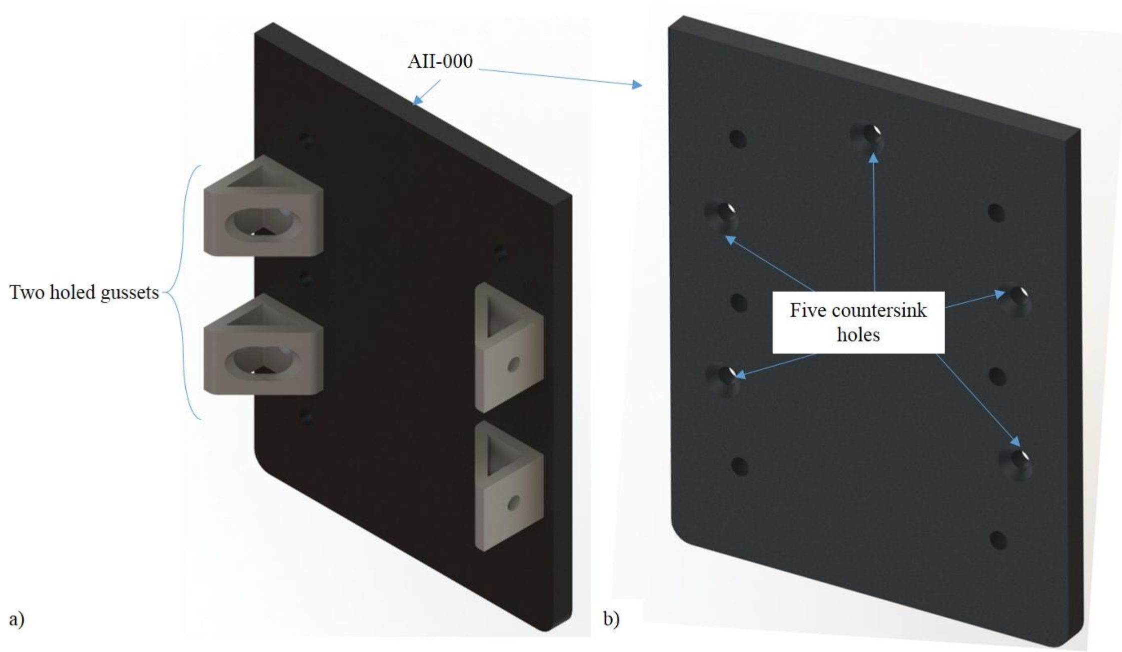


Figure 3-13: The a) two holed gussets and the b) four countersink holes on the back of the AII-000.

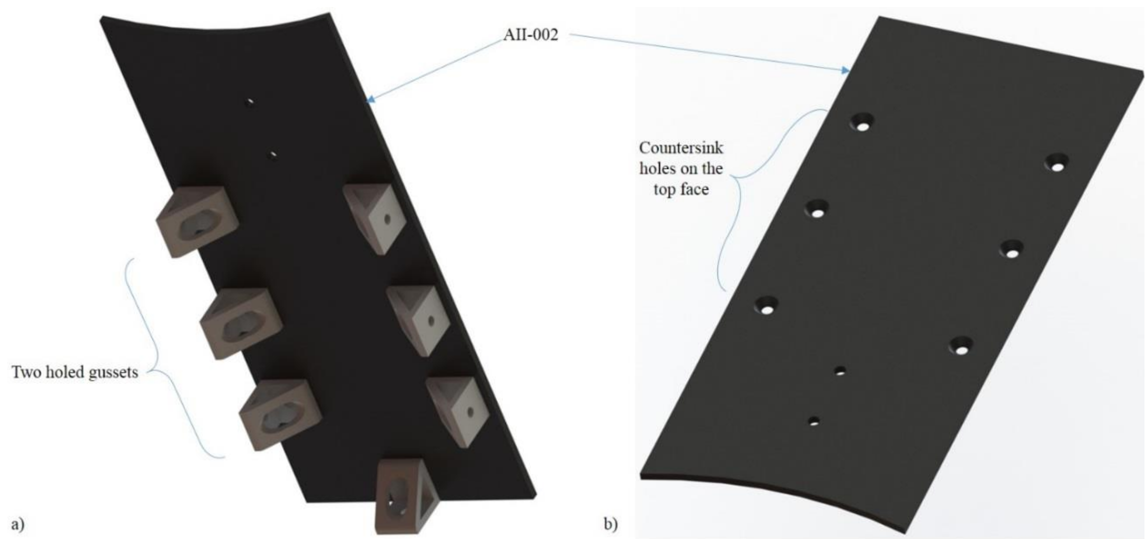


Figure 3-14: The a) two holed gussets and the b) countersink holes.

Step 2: Attach one AII-001 plate on either side of the yoke stage using the vacant holes on the 40-4332, button head bolts and locking nuts. Make sure the locking nuts are placed on the exterior side of the yoke stage. The limited space within the gussets does not allow more than one locking nut.

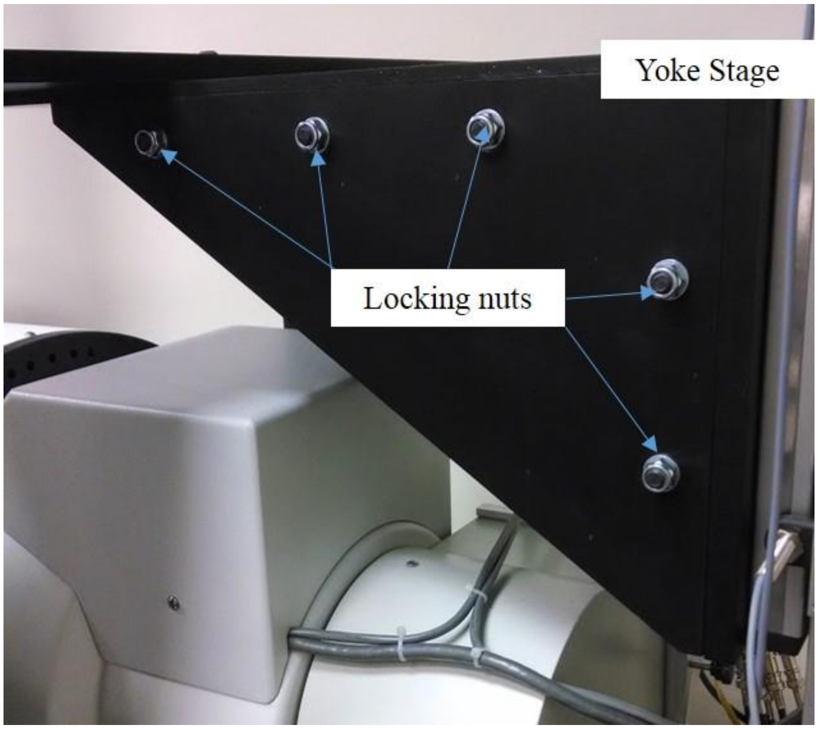


Figure 3-15: The locking nuts need to be on the exterior face of the yoke stage.

Assembly of the Yoke

Step 3: Attach the eight holed gussets, 40-4338, to the AII-003 via the sixteen countersink holes on the top face (Figure 3-16).

Step 4: Attach the AII-004L and AII-004R arms to their respective sides using the remaining holes on the 40-4338 gusset (Figure 3-16).

Step 5: Press fit the brass bushings into the 1-1/8" hole found on the AII-004 (Figure 3-16).

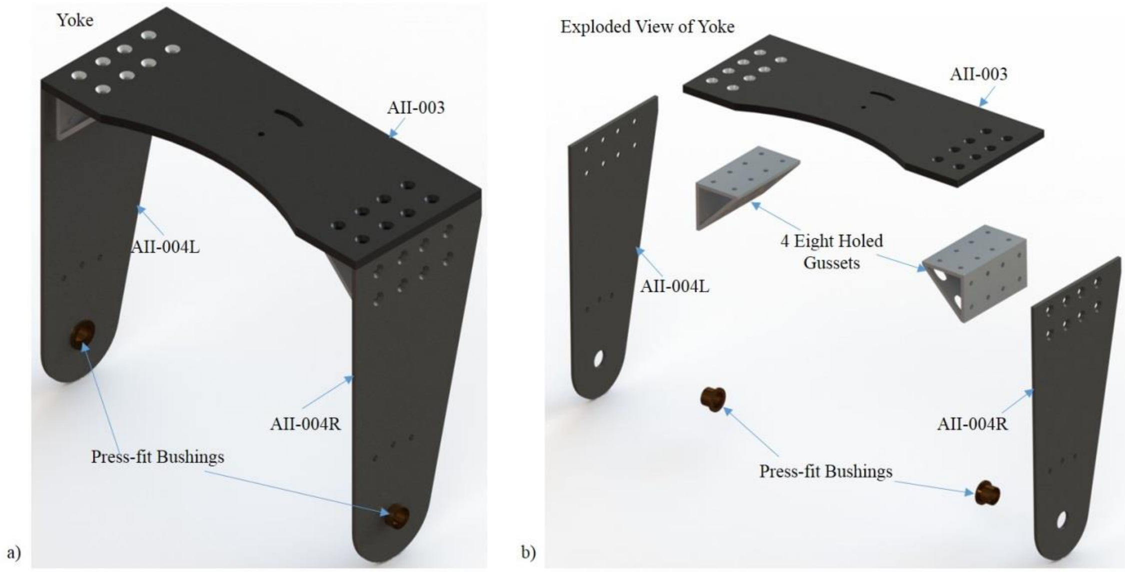


Figure 3-16: The yoke components in assembled (a) and exploded (b) views.

Assembly of the Hoop

Step 6: Attach a set of AII-005 plates to the AII-006 using the threaded holes and the through holes found on the right and left sides respectively (Figure 3-17).

Step 7: Press fit the brass bushings into the 1-1/8" hole found on the AII-005 plates (Figure 3-16).

Step 8: Attach the II to the AII-006 plate.

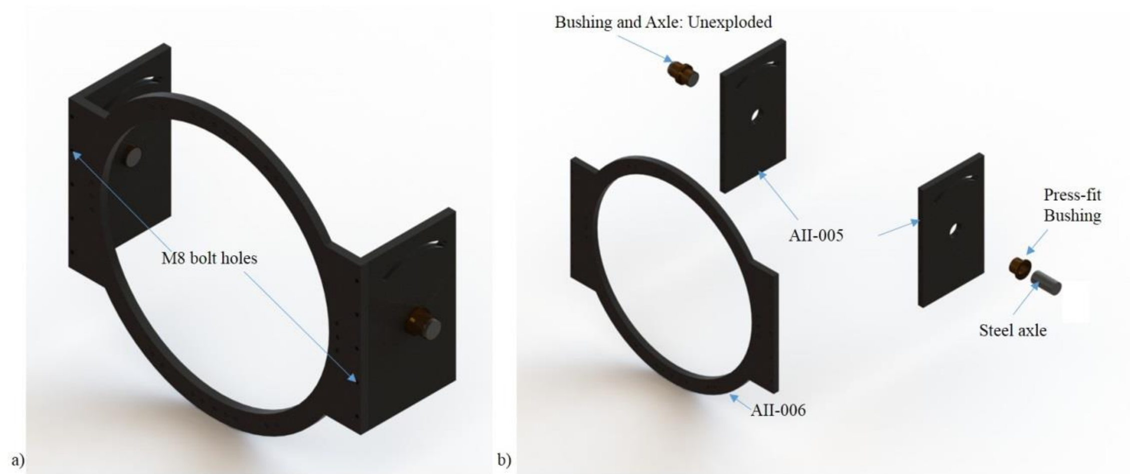


Figure 3-17: The Hoop assembly components assembled a) and exploded b).

Assemble the Trunnion

Step 9: Attach the yoke stage to the linear actuator carriage (Figure 3-18).

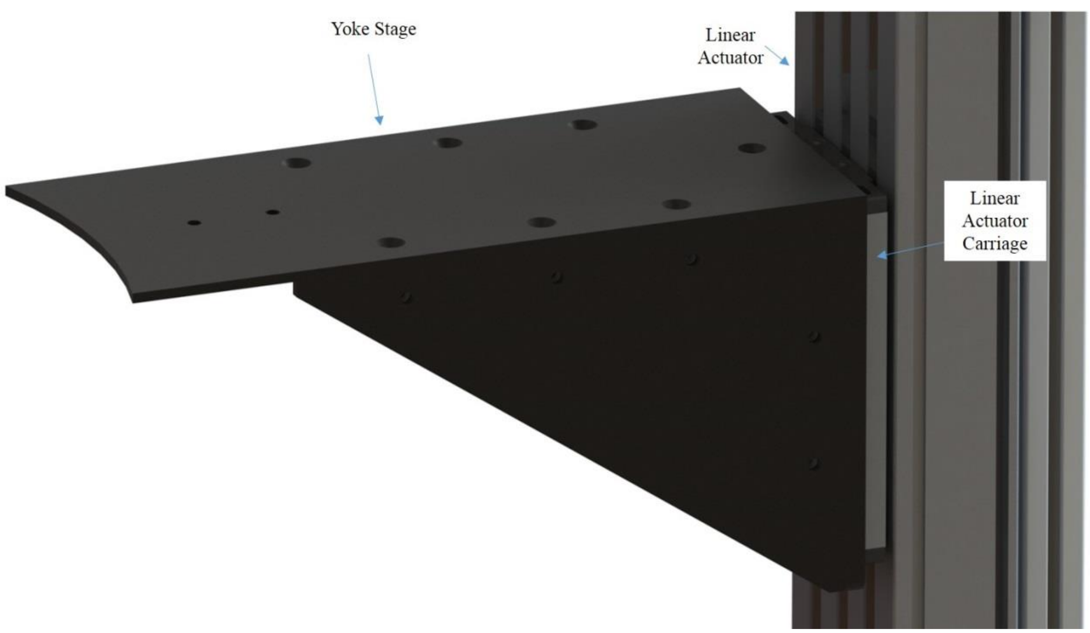


Figure 3-18: The yoke stage attached to the linear actuator carriage.

Step 10: Attach the yoke to the yoke stage using the two vacant holes on AII-002 and the hole and slot on the AII-003 (Figure 3-19).

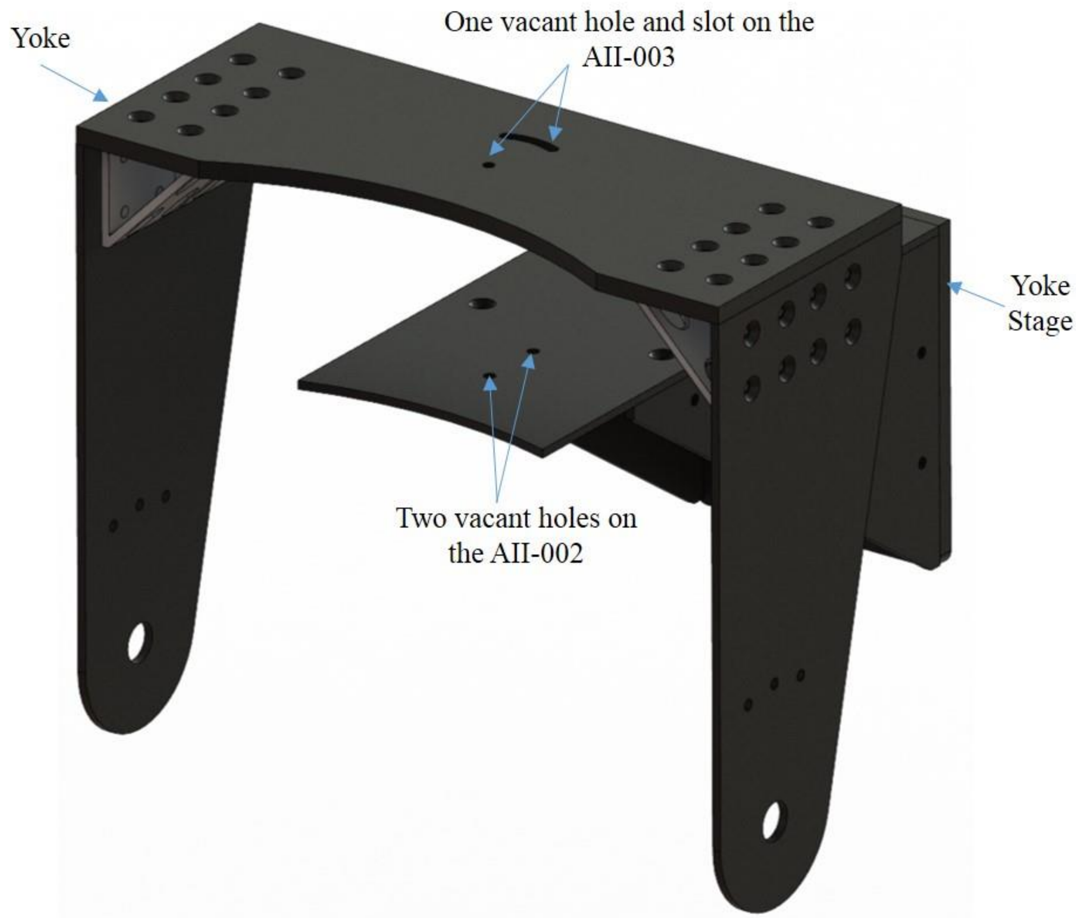


Figure 3-19: The two vacant holes on AII-002 and one vacant hole and slot on the AII-003.

Step 11: Align the bushings and insert the Steel Rod locking it in place with E-locking rings (Figure 3-20).

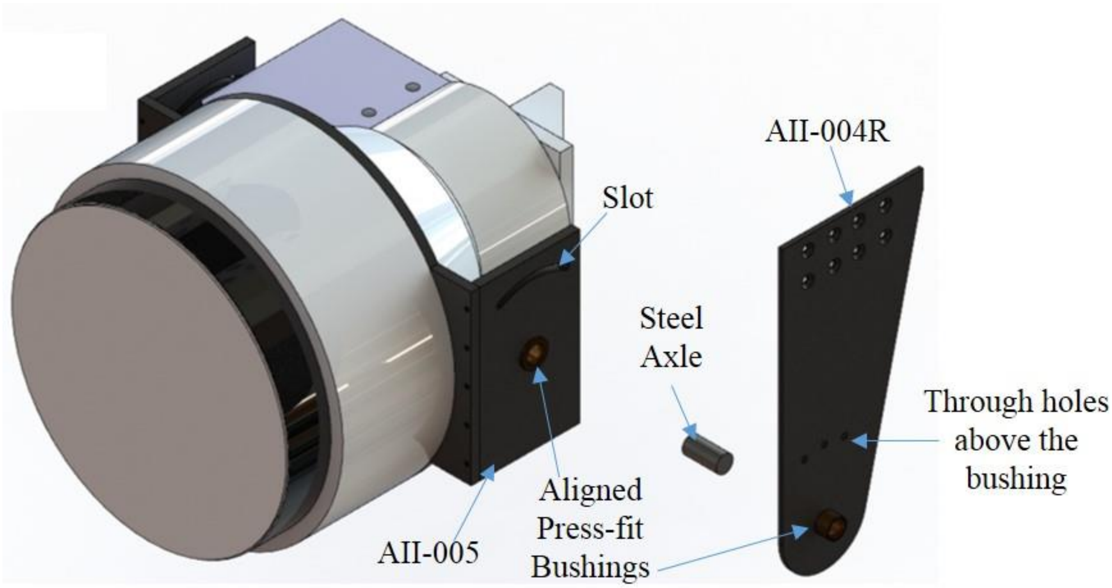


Figure 3-20: The right aligned bushings and steel axle alignment.

Step 12: Make sure to hold the II in place while placing the fasteners in the AII-004 and AII-005 using the holes and slot, respectively, just above the bushings. These fasteners use a button head bolt and locking nut with a nylon washer between the two plates (Figure 3-21).

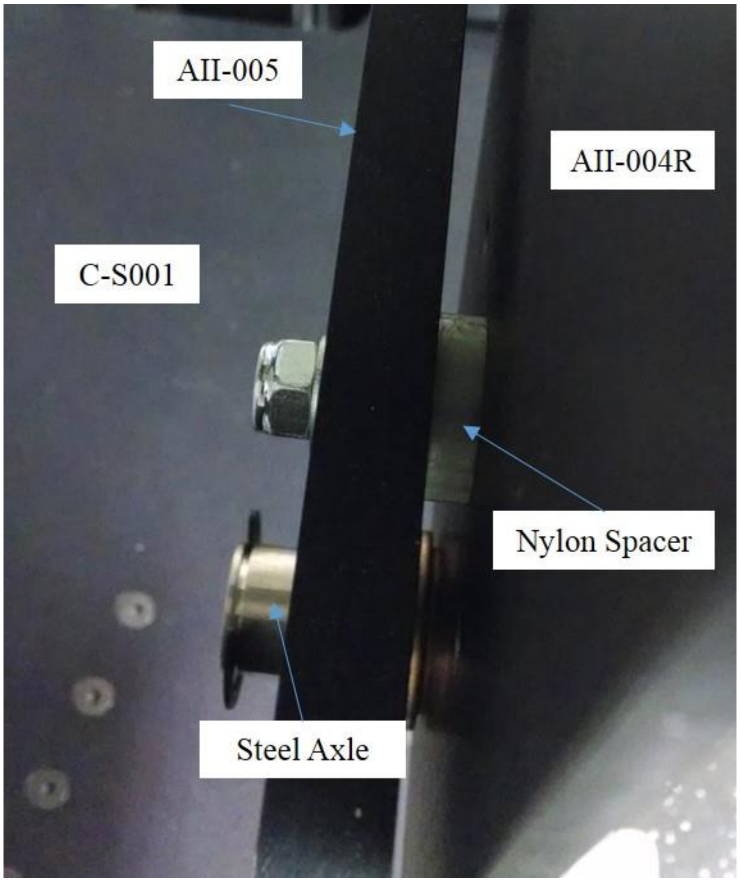


Figure 3-21: The nylon spacer is shown above.

X-Ray Source Stage Assembly

Step 1: Attach one XS-GUS on either side of the XS-0EV1 plate using the M8 threaded holes and through holes respectively (Figure 3-22).

Note: Make sure the countersink holes remain on the same face as the XS-GUS plates. This allows the attachment to the actuator carriage.

Step 2: Attach the XS-0EB3 plate to the vacant XS-GUS M8 holes (Figure 3-22).

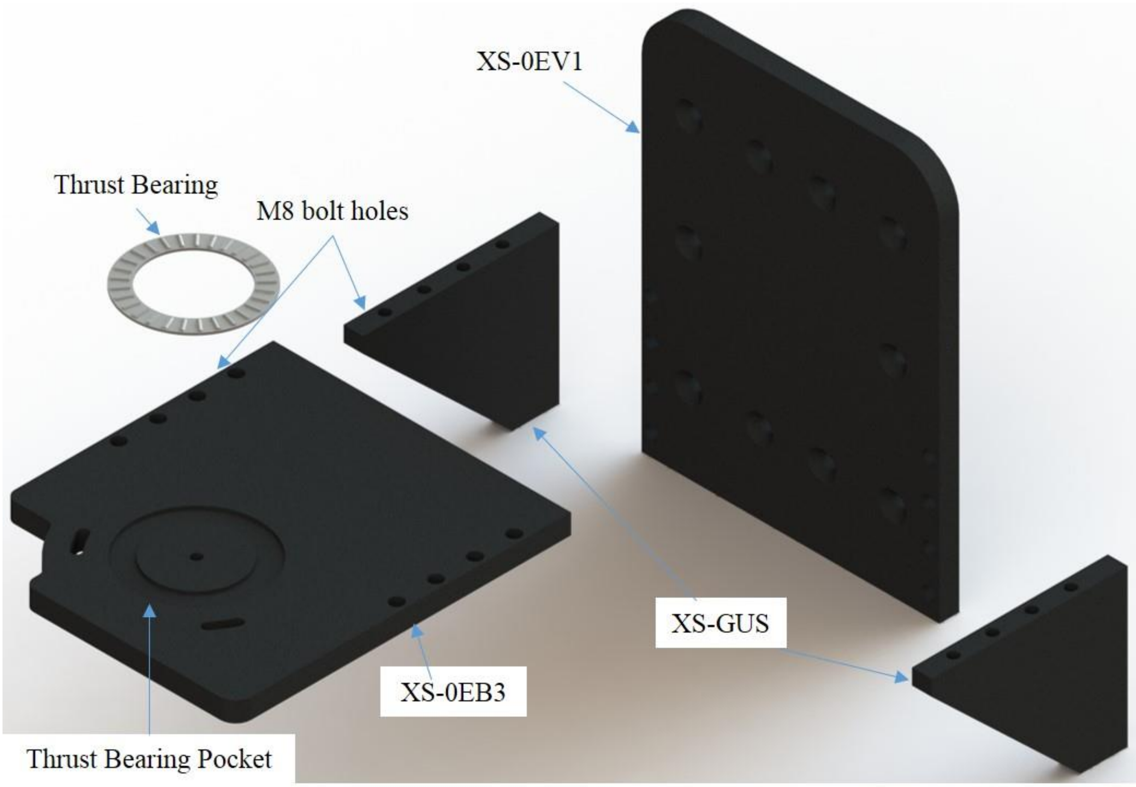


Figure 3-22: The XRSS components.

Step 3: Fasten the assembled XRSS to the actuator carriage.

Step 4: Place the thrust bearing in the thrust bearing pocket on the XS-0EB3 plate (Figure 3-22).

Step 5: Secure the XRS trunnion using the one vacant hole and two slots. Make sure the locking bolt on the side of the source trunnion is near the geometric feature on the left side of the XRSS (Figure 3-23).

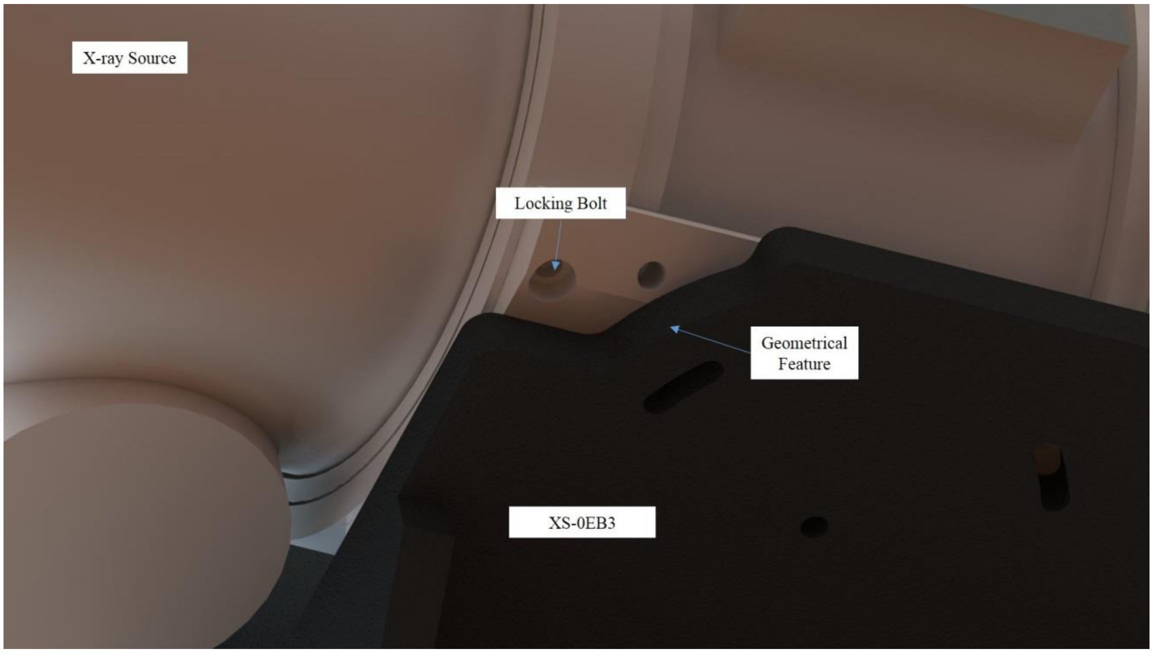


Figure 3-23: The geometrical feature on the left side of XS-0EB3 plate allowing access to the locking bolt found on the XRS trunnion.

Overhead Crossbeam Assembly

Step 1: Fasten the six holed bracket to the 4080-S12 extrusion as shown in Figure 3-24.

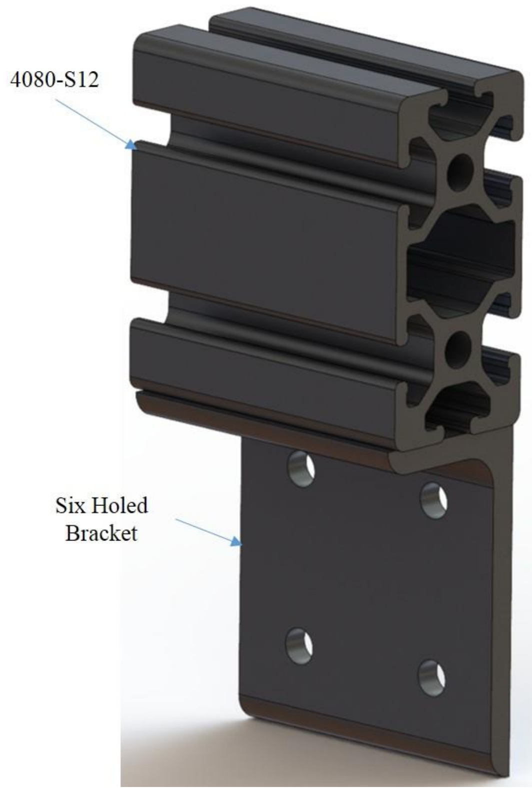


Figure 3-24: The 4080-S12 and six holed bracket attachment.

Step 2: Attach the eight holed plate to the top face of the 4080-S12 extrusion as shown in Figure 3-25.

Figure 3-25: The eight holed plate attachment.

Note: Be sure to construct two of these assemblies shown in Figure 3-25.

Step 3: Attach the 4080-L3 extrusions as seen in Figure 3-26.

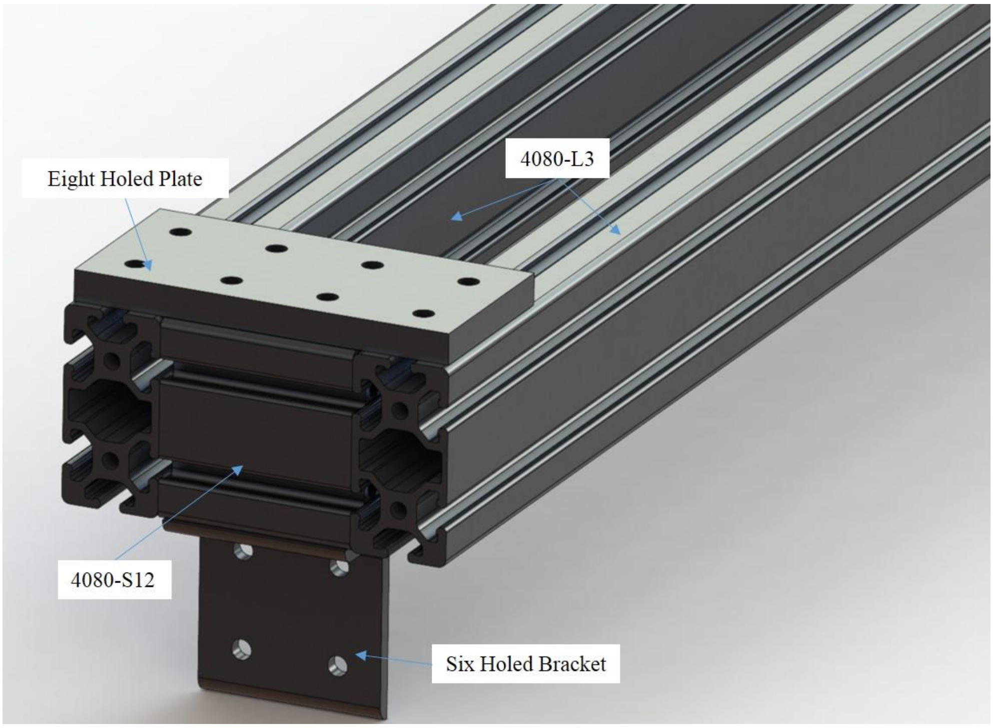


Figure 3-26: Detailed view of Overhead Crossbeam.

Step 4: Attach the other assembly shown in Figure 3-25 on the opposite end of the 4080-L3 extrusions. The overhead beam structure should resemble Figure 3-27.

Figure 3-27: The assembled overhead beam structure.

Step 5: Attach the overhead beam structure to the 4080-Vb on the XRS and II cart. Place the eight holed plate on the top face of the 4080-Vb extrusion and fasten the six holed bracket and the two holed gusset to the 4080-Vb as seen in Figure 3-28.

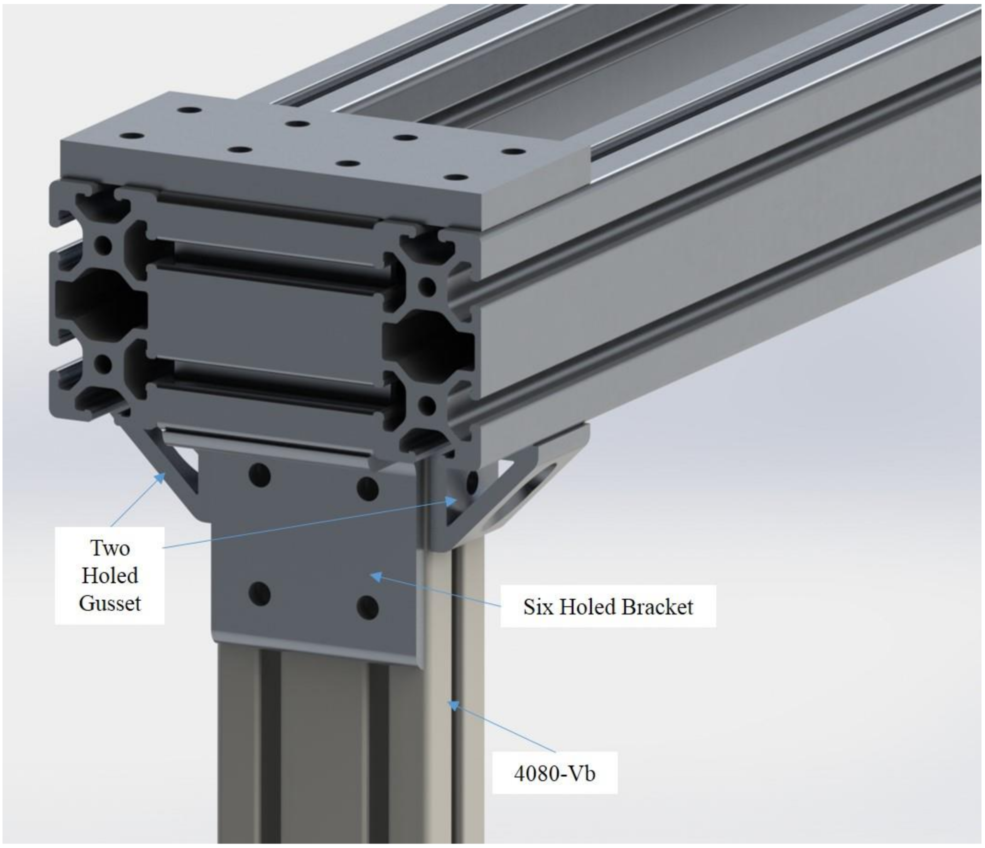


Figure 3-28: Attaching the overhead beam structure to the 4080-Vb extrusion.

Final Step: The end product should resemble Figure 3-29.

Figure 3-29: The completed plane consisting of an II trunnion, an XRSS, their respected carts and an overhead crossbeam to tie them together.

Chapter Four: HSSR Gantry Operations Manual

This chapter provides the standard operating procedure (SOP) for the HSSR Gantry system. The manual gives a step by step guide for general operation. This manual does not provide instructions for any type of x-ray capture. Only qualified professionals should operate the x-ray generators. This manual starts with the system in storage against the wall. Plane A is in the storage position in Figure 4-1.

Warning: The positioning and operation of the HSSR is a two or more person task.

Positioning the A and B Planes

Step 1: Assuming the HSSR system is in storage, pull B-plane (note: B-plane has a lower overhead beam than A-plane) out from the wall and position it as shown in Figure 4-1.

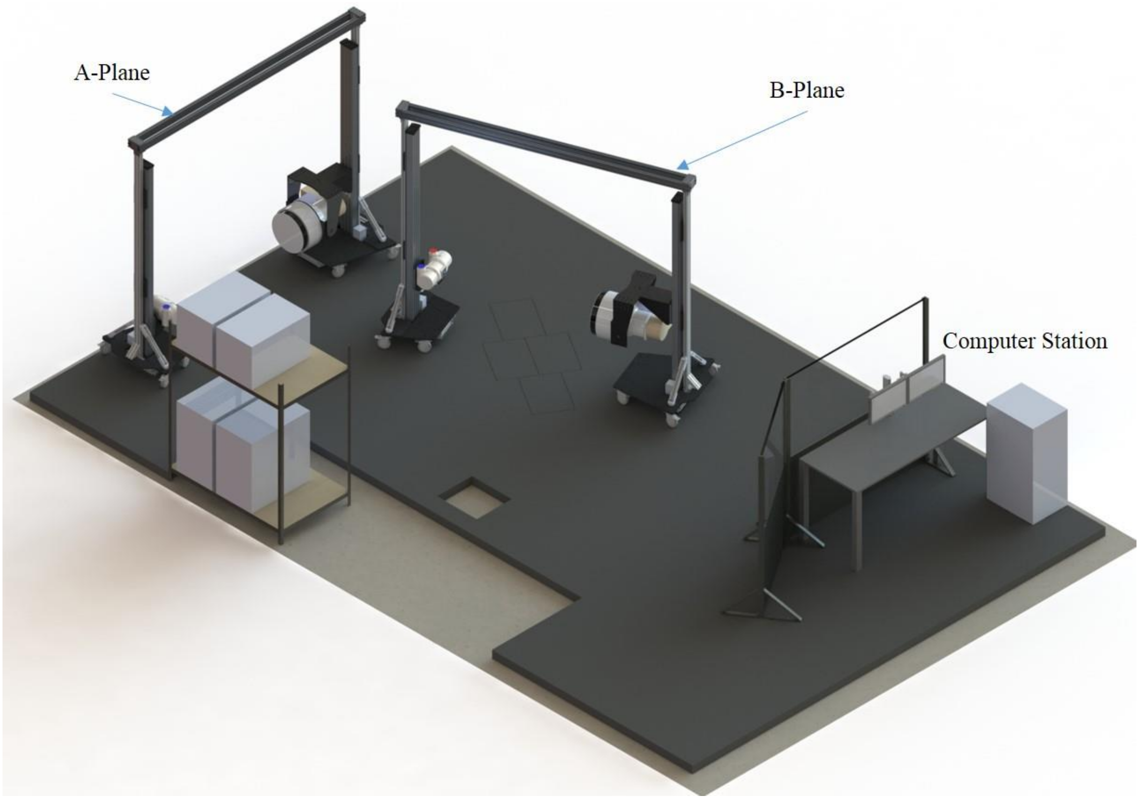


Figure 4-1: B-Plane positioned and the A-Plane stored against the wall.

Step 2: Position the A-Plane as shown in Figure 4-2. When the planes are positioned lock the wheels in place.

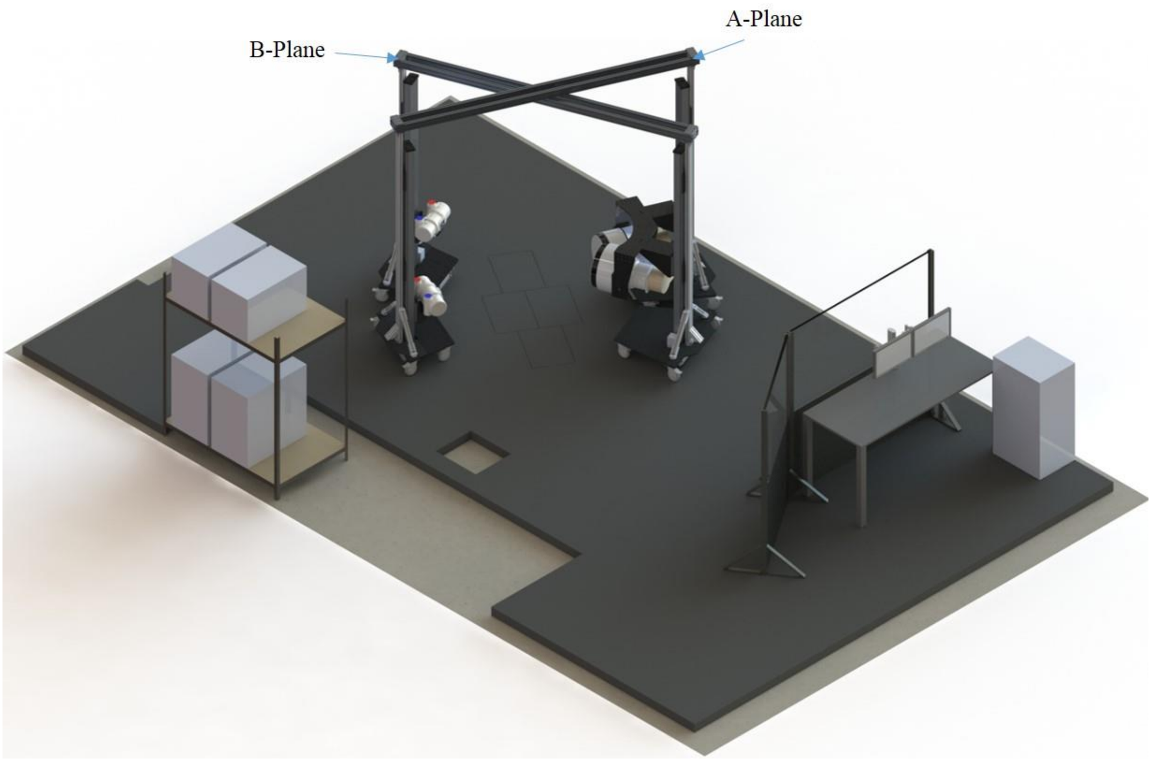


Figure 4-2: The two planes positioned in the gait lab.

Step 3: After positioning the two planes the vertical position of the x-ray components need to be set using the four linear actuators. The linear actuators are computer operated and can move independently or simultaneously (Figure 4-3). Operation instructions for the linear actuators can be found in Appendix A.

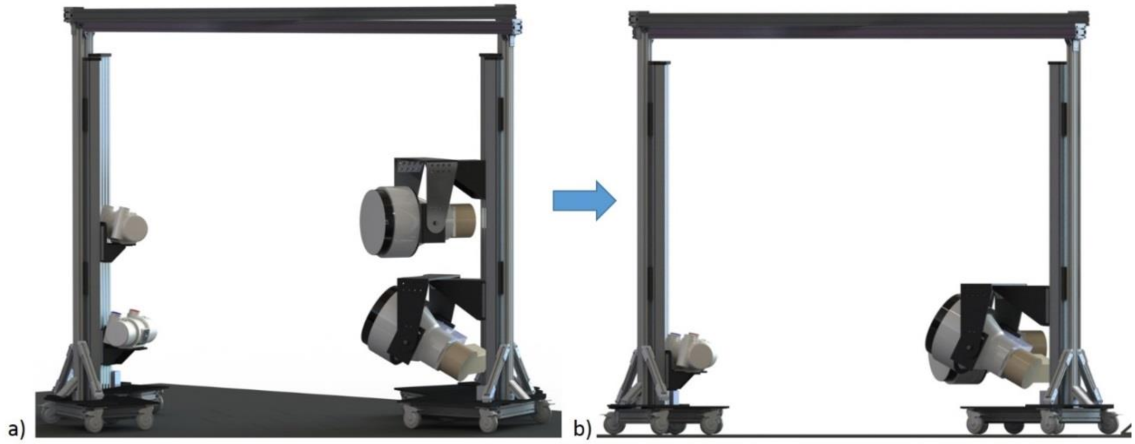


Figure 4-3: The image above shows the components a) not vertically aligned and b) vertically aligned.

Adjusting the XRS Pitch and Yaw

Step 1: Now that the components have been vertically positioned, the pitch and yaw must be adjusted to align the x-ray beam directly to the II's.

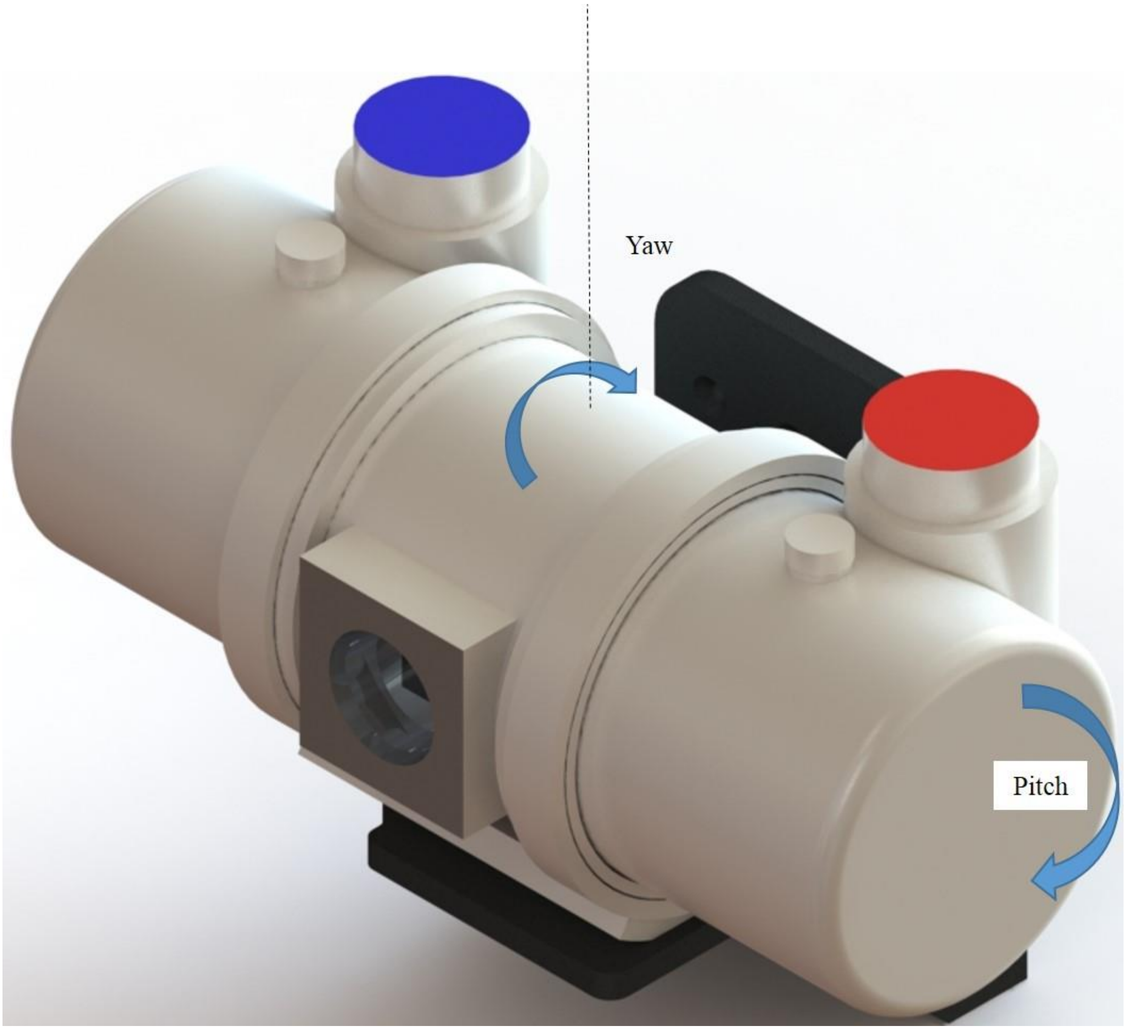


Figure 4-4: The pitch and yaw of the XRS is shown above.

The XRS yaw can be adjusted by loosening the bolts on the bottom of the stage (Figure 4-5). Roughly position the yaw for now; in a later step laser sights will be used to fine tune the adjustment.

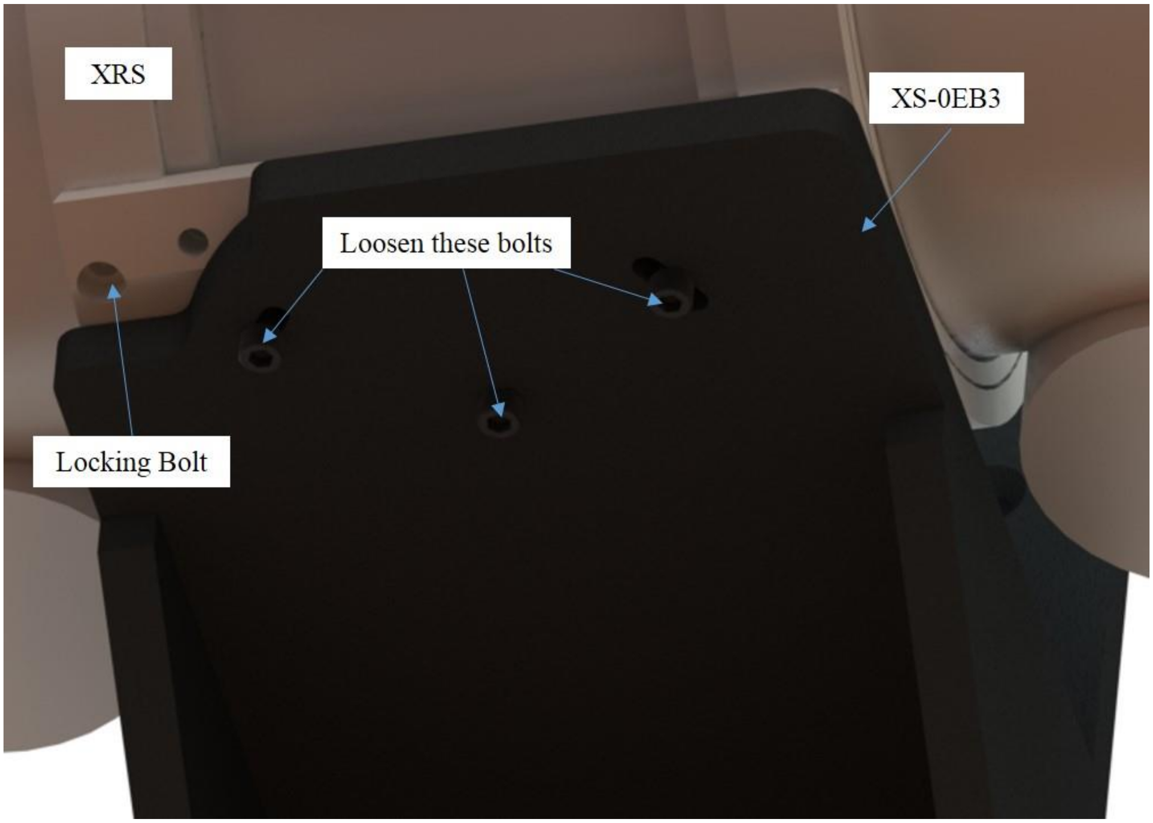


Figure 4-5: The bolts underneath the XS-0EB3 plate.

Step 2: With the yaw roughly positioned the pitch should now be adjusted by loosening the locking bolt (Figure 4-5). Rotate the XRS to a level position (Figure 4-6) and check using a spirit level.

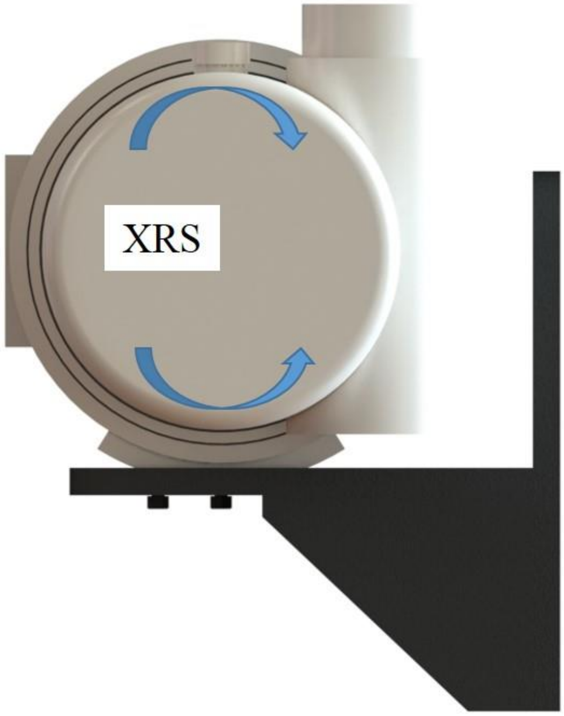


Figure 4-6: The XRS adjustable pitch.

Adjusting the II Trunnion Pitch and Yaw

Step 1: The II trunnion yaw and pitch needs to be modified to line-up with the XRS. The yaw can be altered by loosening the bolts found on the yoke stage and yoke (Figure 4-7).

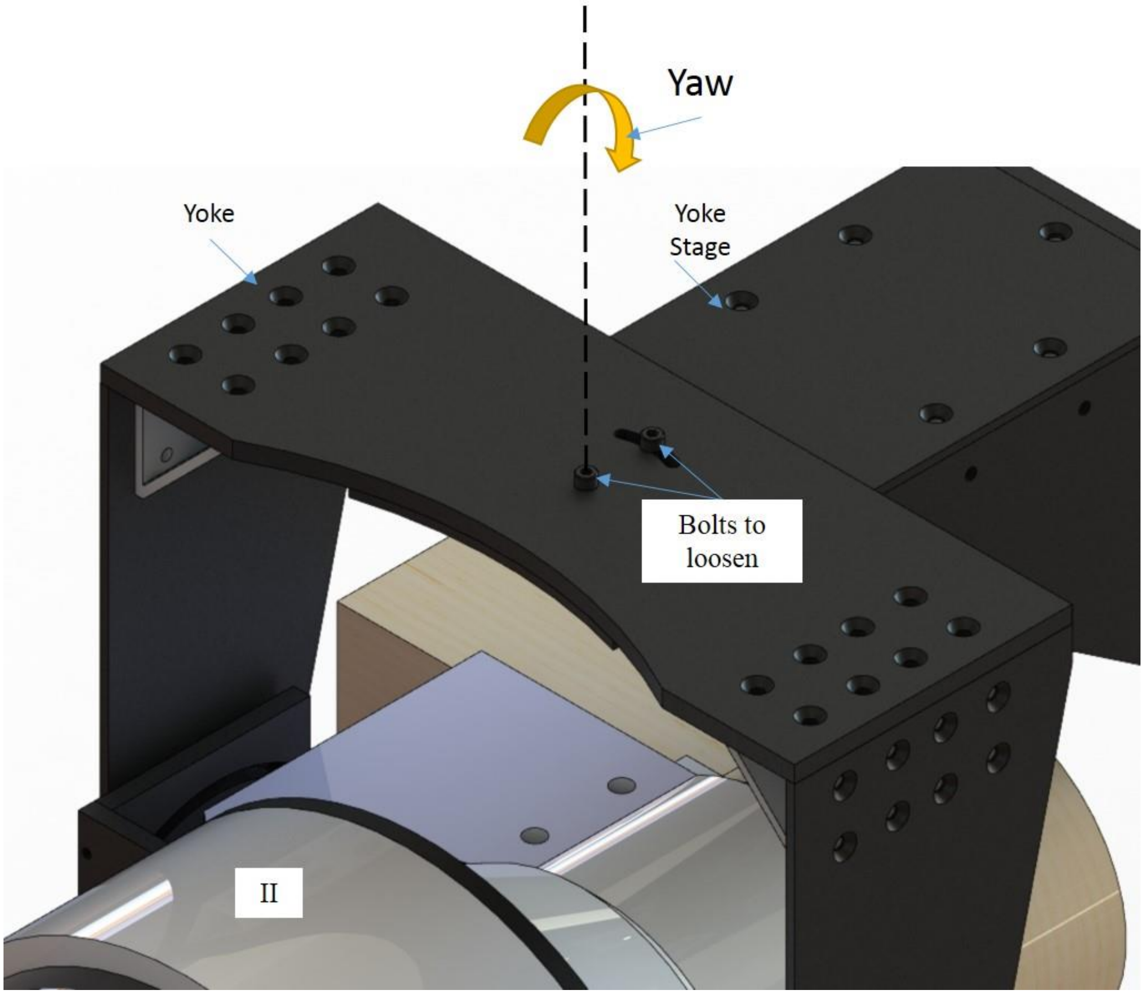


Figure 4-7: The bolts need to be loosened to modify the yaw position.

Step 2: The pitch needs to me modified by loosening the bolts found on the AII-004(R and L) and AII-005 (Figure 4-8). The II will pivot about the steel axle.

Note: Hold the II in position because its center of gravity is near the front and it will roll forward potentially damaging any components. Check the pitch of the II using a spirit level placed on the outer housing of the intensifier.

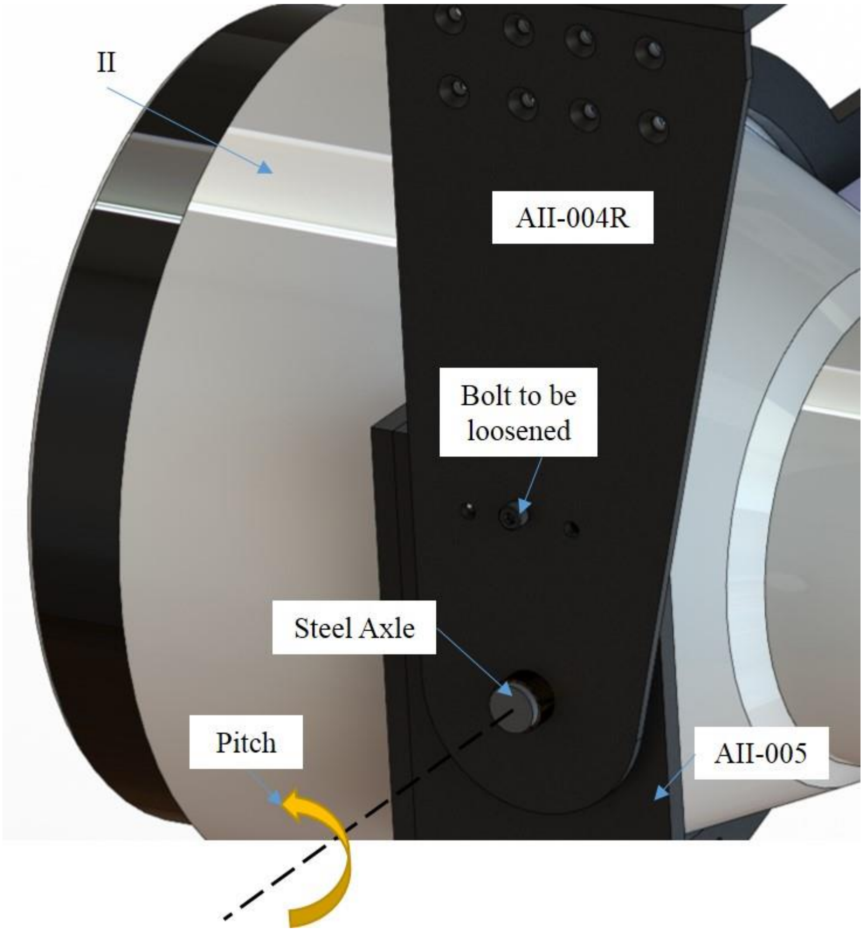


Figure 4-8: The bolt on the AII-004(R and L) must be loosened to adjust the II pitch.

Changing the SID

Step 1: Unlock the casters.

Step 2: The bolts directly attached to the 4080-L3 need to be loosened. The bolts are also attached to the eight holed plate and the two holed gussets (Figure 4-10). The four bolts a) on the eight holed plate and the two bolts b) in the gussets are directly attached to the 4080-L3 extrusions.

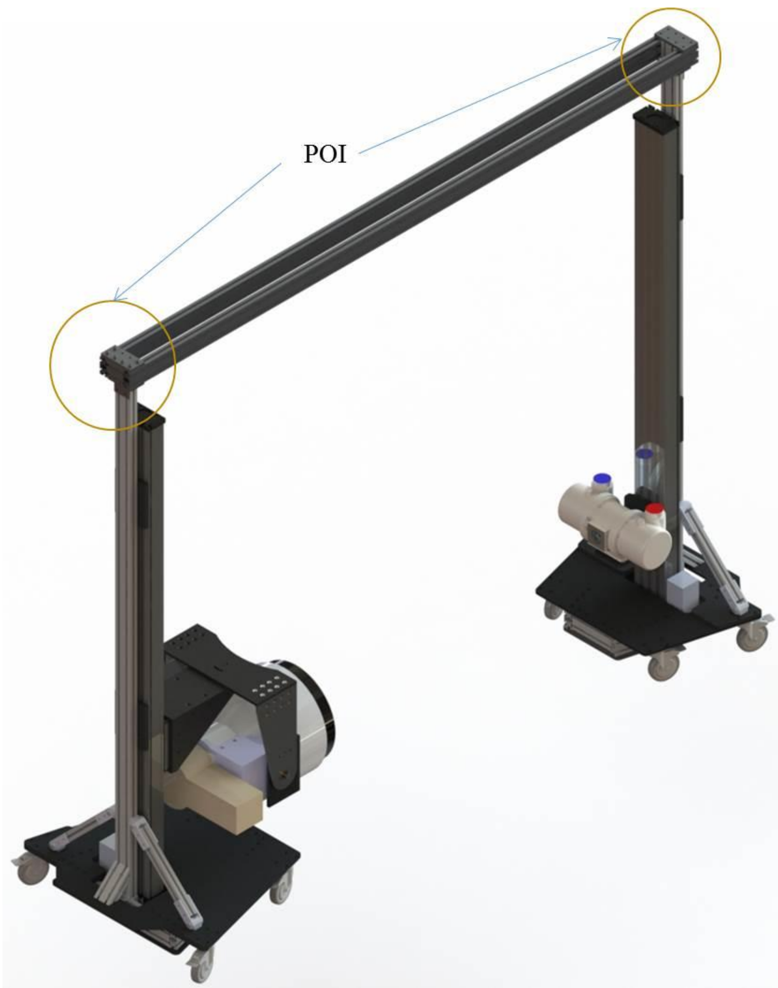


Figure 4-9: The bolts of interest are found on both ends of the overhead beam.

<u>Note</u>: Having a rubber hammer to bump the 4080-S12 extrusion will help initiate the sliding action.

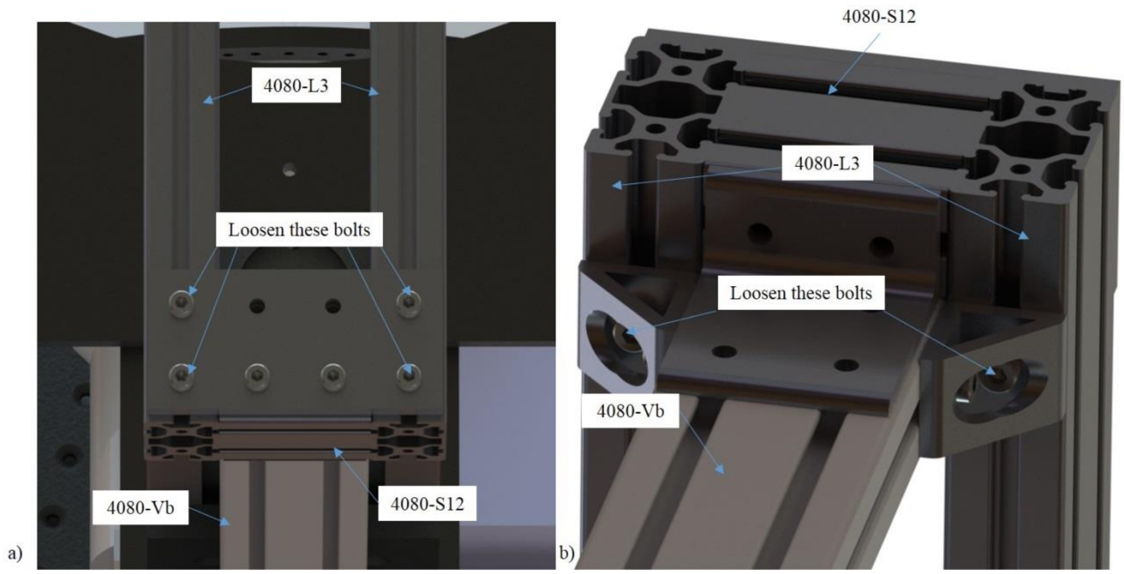


Figure 4-10: The bolts directly attached to the 4080-L3 extrusions

.

Fine Tuning the Vertical Placement, Pitch and Yaw

Step 1: Start fine tuning the vertical placement by pressing the light and laser emitter button located on the XRS collimator's control panel (Figure 4-11). These sights are used to judge the II height with respect to the source height. The light shadow and laser sights should align with the center line geometry found on the II's front face (Figure 4-12). Check the cross-hairs for lateral alignment (yaw). The cross-hair shadow coming from the source should be aligned with the keyhole outline in the center of the center line.

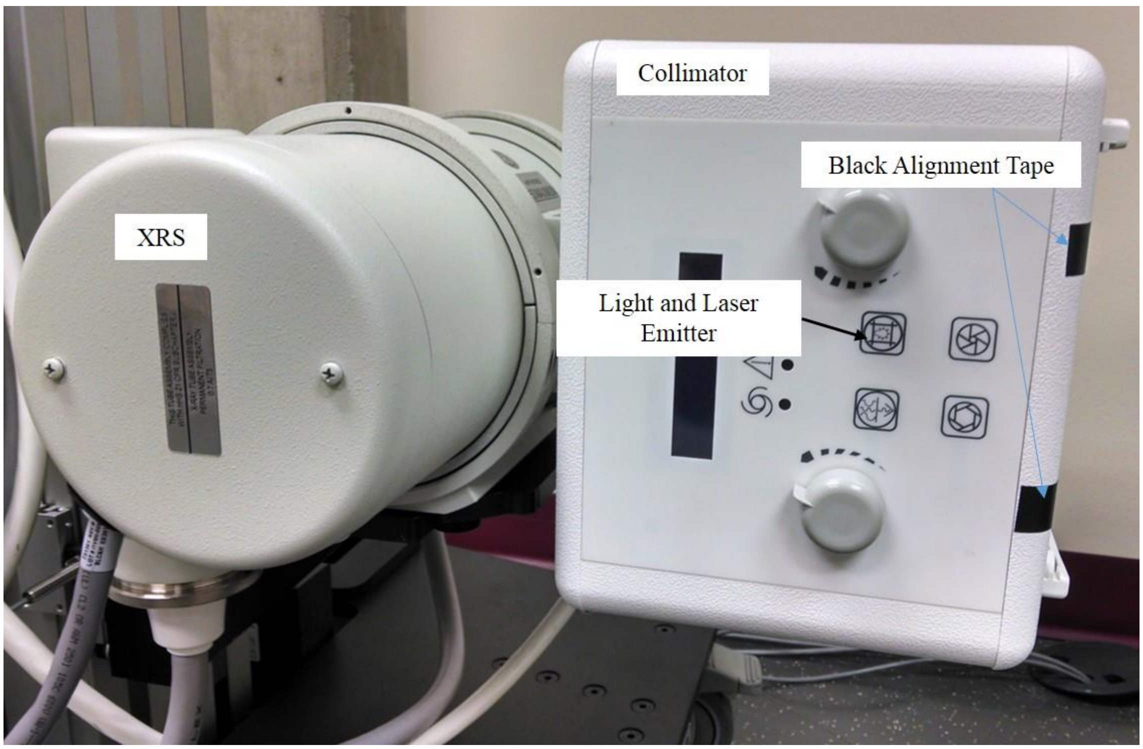


Figure 4-11: The collimator with the light and laser emitter button labeled.

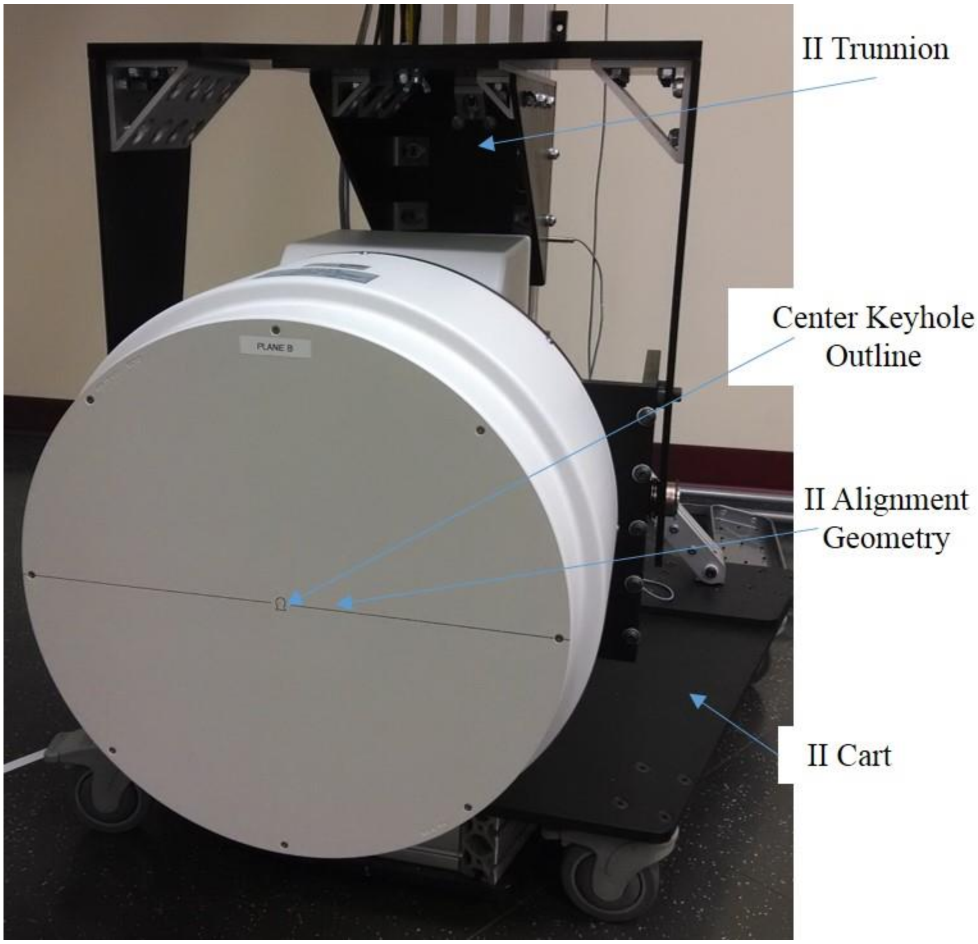


Figure 4-12: The II alignment geometry labeled.

Step 2: Carefully place the mirror on the II so that it is flush with the front face (Figure 4-13). Activate the light and laser once again. The mirror reflects the light and laser back onto the collimator and should strike between the two strips of tape located on the collimators (Figure 4-11). This determines the pitch of the components. If the light/laser is between the strips of tape the pitch of the components are aligned and are ±1° of being parallel.

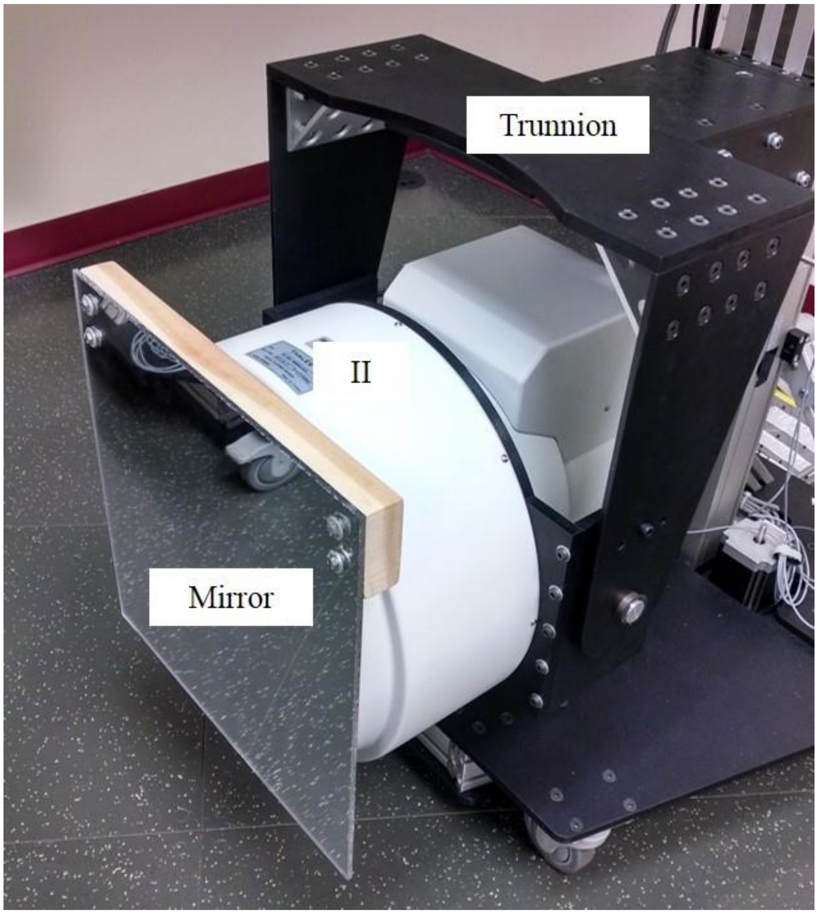


Figure 4-13: The mirror used for pitch adjustment.

Storage Procedure:

When the HSSR session is over the system needs to be stored away. To ready the system for storage the x-ray components need to be lowered, and powered off. Next, unplug the II cables from the quick disconnect box and unlock the wheels. Then, roll the Plane A back to the storage area or along the wall. Roll Plane B alongside Plane A making sure the XRS cables are moved to the edges of the room and out of the way of high traffic areas.

Chapter Five: Discussion

The goal of this work was to design and build a stereo radiography machine for quantifying the biomechanical movement of natural internal anatomy to better understand orthopaedic pathologies and, ultimately, to improve clinical treatment and outcome. In order to accomplish this, the design of the HSSR system was initiated and driven by four design requirements. The four design requirements involved the design, fabrication, and validation of the HSSR system. The first requirement assured the system's reconfigurable nature so that body segments from the cervical spine to the foot could be captured. The linear actuators attached to the gantry structure allow for 2.13 m of vertical travel, and the SID is adjustable through the overhead crossbeam structure. The rotational aspect, or pitch and yaw, of the x-ray components is controlled through the II trunnion and the source stage providing additional imaging perspectives. The second design requirement focused on the integration of the HSSR system with the human dynamics lab. The system was designed to be large enough for a subject to perform functional tasks like walking, running, and jumping, and allowing simultaneous data collection with marker-based motion capture. The third design requirement addressed the system's need to capture joint motion at high-speeds and in high-resolution with a low radiation dosage. The IIs used, the largest commercially available with a diameter of 40 cm, and the 20 µm pixel size and 12 bit-depth high-speed cameras allow for a large viewing volume to be captured at high frame rates and high resolution. Also, the x-ray generators allow for a pulsed mode of operation which dramatically reduces radiation dosage to the subject. The last requirement stated the system must be accurate and precise enough to capture joint motion with sub-millimeter measurements. It was essential that the gantry be able to hold the devices still and rigid enough to obtain data of the necessary precision and accuracy for obtaining data of the required level. The validation of this last requirement involved a series of calibration steps followed by image distortion correction procedures. The precision of the system for capturing bead, bone, and implant motion was verified to be sub-mm in translation and sub-degree in rotation.

The sub-assemblies of the overall structure provided most of the functionality for the system. The base carts allowed the system to be mobile for ease of use and storage. The linear actuators allowed precise placement of the x-ray components and provided stiffness to the gantry structure. The overhead crossbeam structure tied the corresponding XRS and II together and provided a variable SID. The II trunnion gave the pitch and yaw provided two degrees of freedom. The roll of the components was unnecessary. The source stage allowed for a yaw motion and the trunnion rings, provided by the original equipment manufacturer, were responsible for the pitch. Also, one imaging plane was 80mm taller than the other, allowing the other imaging plane to slide under, allowing the x-ray beams to intersect, creating the capture volume.

The HSSR system has a variety of limitations. The system's large space for subject movement provides sufficient room for a variety of movements, but when an angle greater than 60^{o} between the x-ray beams is required movement can become impeded by the components. The pulsed mode of 120 frames per second drastically reduces the radiation dosage. However, continuous exposure mode is still required to capture high-speed activities like throwing a ball. The system's reconfigurable nature, one of its most important qualities, requires additional calibration procedures post any orientation change. The system's height could potentially impede human movement but this can be compensated for by removing the crossbeams. Capturing usable data of the foot will be challenging for the HSSR's current design but modifications/procedures are in the works for this issue.

Future work to the HSSR gantry structure should involve a more controlled and mechanized adjustment of the components. This could be solved with the addition of two extra linear actuators with dual carriages attaching where the overhead crossbeam structure currently resides. Worm gear driven pitch and yaw would provide a more controllable and accurate placement of the XRS and II. In order to capture foot images a walking stage, radio translucent in key areas, and fitting over the force platforms would need to be constructed. A separate structure allowing the II to be placed in a low position would also need to be fabricated. For subject following mobilization of the HSSR system rails could be used for short displacements. This could be screw or belt driven. When the system is on placed on the rails there would be enough clearance to remove and/or attach the casters. This arrangement would be easily stored by attaching the casters and removing the rail end blocks and sliding the HSSR off and into a storage area.

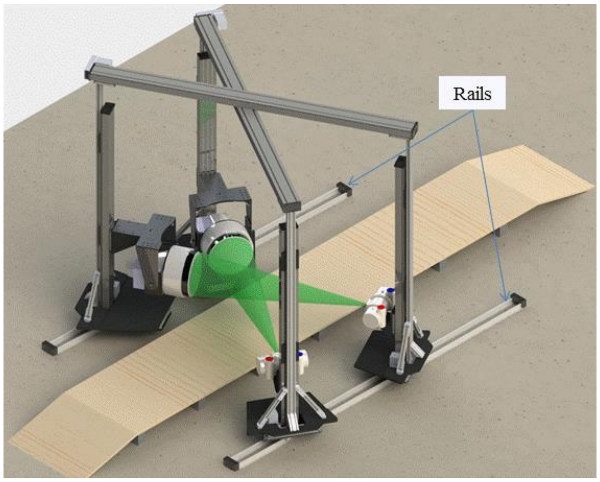


Figure 5-1: The rail system suggested for future additions to the HSSR system.

In conclusion, all the design requirements were met and/or exceeded. The HSSR system has the capability of imaging major joints from the ankle to the cervical spine. This machine will provide quality data for years to come.

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Appendix A: Issuing DLT-160 Linear Actuator Commands

Issuing commands outside the script should be performed carefully, considering the commands are being issued on the fly. The commands are entered in the black "Command" window.

An example has been stated showing a STOP command. This command stops the motion of the carriage. The structure of the language is to write the command, followed by parentheses containing the axis number.

For example,

STOP(0)

will stop the motion of the 1st actuator (axis 0).

Note: The axis number scheme begins with zero (0) and ends on three (3).

To issue multiple commands simultaneously issue the following,

STOP(0) : STOP(1).

This command line will stop the motion of axes zero (0) and one (1). Only one type of command may be issued in parallel. For example, avoid using,

STOP(0) : MOVEA(0)

A common command may be written as(*R* meaning hit the enter key),

MOVEA(0) = 4000 *R*

GO(0) *R*

Any command issued prior to the GO command will be executed in series.

To execute commands in parallel use the following,

MOVER(0) = 4000 : MOVER(1) = 4000 *R*

GO(0) : GO(1) *R*

STOP(0) : STOP(1) *R*

The MOVEA AND MOVER commands will move the carriages a variable distance. The STOP command only needs to be issued to stop the motion early.

Common Commands:

STOP(#) – stops motion on # axis

MOVEA(#) = ## - move the actuator in absolute distances. (i.e. MOVEA(2) = 30, moves actuator 2 to 30, regardless of the carriage's current position)

MOVER(#) = ## - move the actuator in relative distances. (i.e. MOVER(2) = 30, moves the actuator 2 to 30 from the current location)

Note: For the MOVEA and MOVER commands negative numbers move the actuator carriage up and positive numbers move the actuator carriage down.

SPEED(#) = ## - sets the speed of the actuator. Generally 200 is a reasonable speed.

GO(#) = ## - executes the previously entered command.

Axes are ordered as follows

- Axis 0 = Source on Plane-A
- Axis 0 = Source on Plane-A
- Axis 1 = II on Plane-A
- Axis 2 = Source on Plane-B
- Axis 3 = II on Plane-B

Appendix B: Engineering Analysis.

The Solidworks simulation package was used for the simulation of the HSSR system components. The simulation package automesh default was a higher order linear tetrahedron element. All FE models were assembled through a bonding technique that treats the models as a single solid linear continuum. Considering the stiffness tetrahedron elements can exhibit a simple beam bending analysis was ran on a length of 80/20 extrusion and compared to a theoretical calculation of the beams displacement under a load. This provided a value of error for this model and the theoretical displacement. This extrusion was meshed and solved in the Solidworks simulation package.

The equation used to calculate deflection of the 80/20 extrusion was:

Equation B- 1: $\frac{L^3 * W}{3 * E * I} = D \rightarrow \frac{0.7m^3 * 10kN}{3 * 7.03 * 10^{10} \frac{N}{m^2} * 9.77 * 10^{-7} m^4}$ **= 0.0166m or 16.6mm**

The equation B-1 was used to calculate a theoretical deflection in the y-direction where L was the length, W was the load, E was the elastic modulus, and I was the moment of inertia.

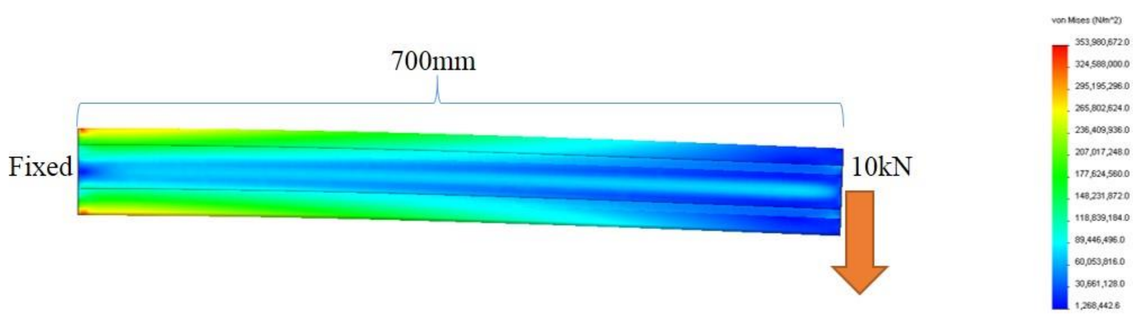


Figure B- 1: Stress plot of 80/20 extrusion.

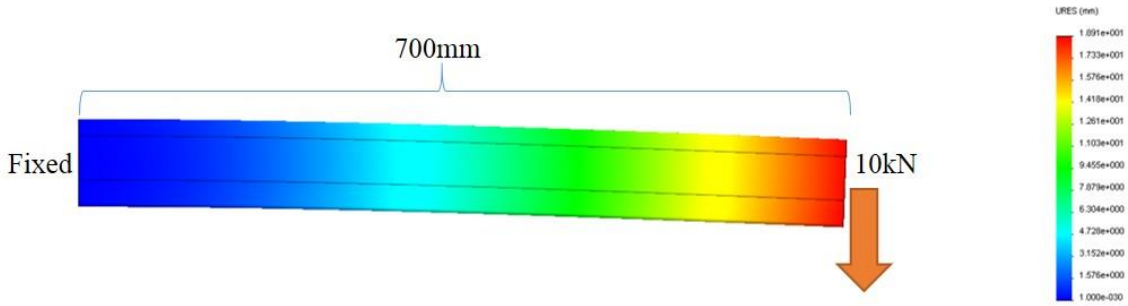


Figure B- 2: Displacement plot of 80/20 extrusion.

The maximum y-deflection is 0.0188m or 18.8mm. Considering the theoretical deflection calculation yielded a 16.6mm deflection, the following equation provides an error for the simulation.

Equation B- 2: $\frac{(Theory - Observation)}{Theory} = err \rightarrow \frac{(16.6mm - 18.8mm)}{16.6mm} = 8.1\%\ err$

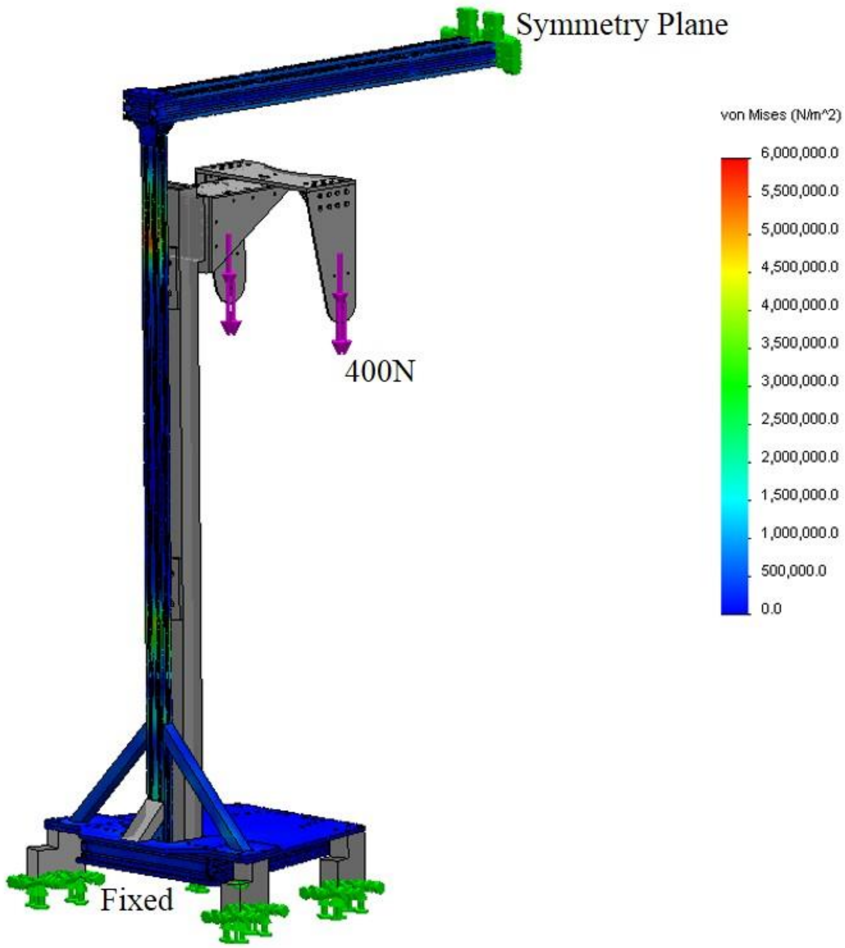


Figure B- 3: Stress plot of the II Cart supporting the linear actuator and the II.

The II side of the imaging plane was setup to simulate the cart plates, rear CBii extrusion, VbT extrusion, and overhead crossbeam. The load was applied to the AII-004 bushing holes and calculated by multiplying the mass, 36kg, by gravity, 9.81 m/s^2, and round to the nearest single significant figure. The result is 400N. This value provides an overestimate of the forces this structure will experience. The casters were fixed in their positions. The II trunnion was simplified by removing the Hoop sub-assembly and making the structure rigid. The linear actuator and casters were also simplified and made rigid. The overhead crossbeam component was cut in half as shown in Figure B- 3 and set as symmetric about that cut. The rigid simplified geometry reduces the computation time and makes the model easier to solve and the symmetrical setup allows for a performance assessment of the overhead crossbeams without having to run the entire view plane model.

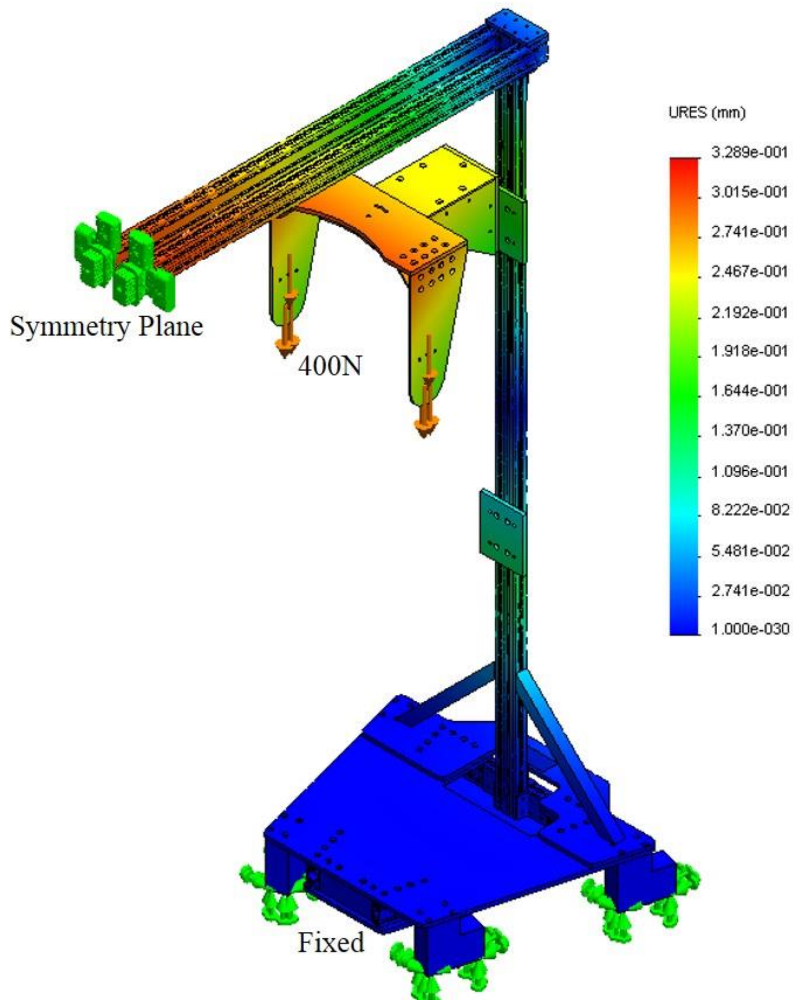


Figure B- 4: Displacement plot of the II cart supporting the II.

The deflection model of the II cart supporting the 36kg image intensifier shows a maximum deflection of 0.329mm. This value was well within the <1mm maximum deflection goal.

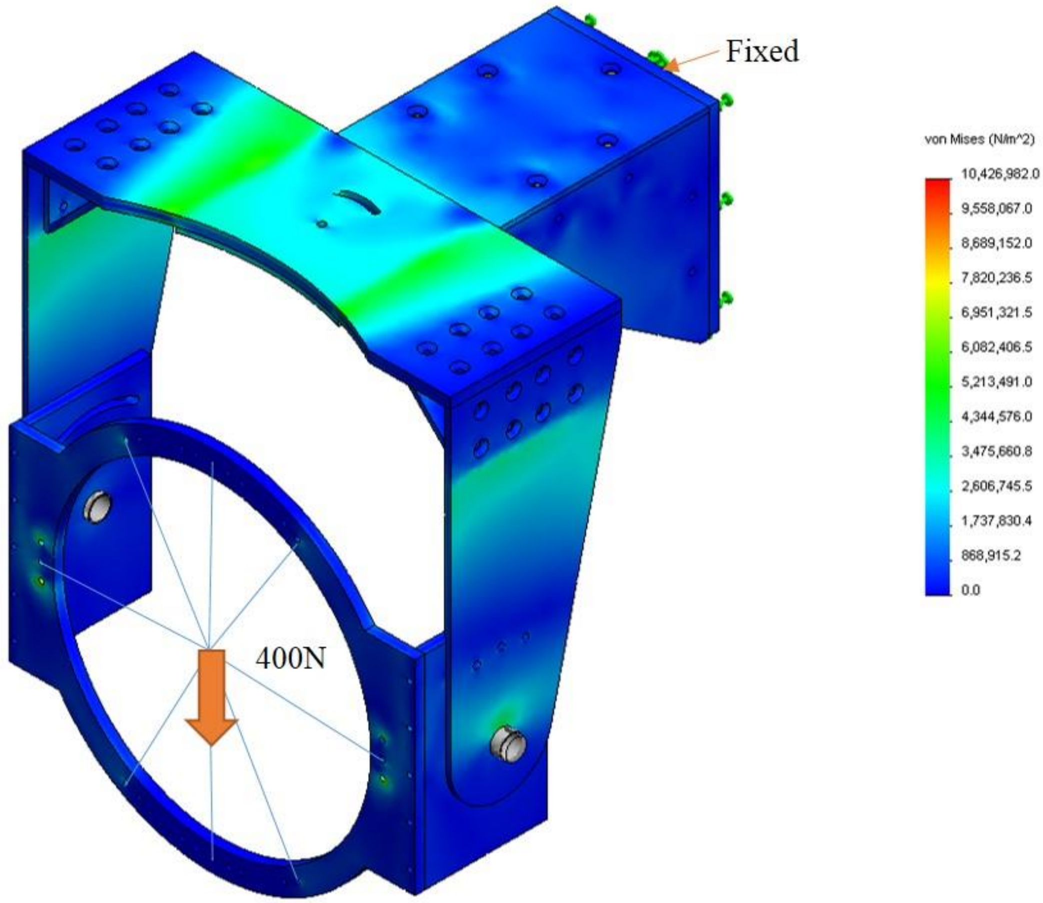


Figure B- 5: Stress plot of II Trunnion while holding II in place.

The II trunnion had little simplification needs. The press fit bushings, axel, and the 2 holed brackets were made rigid. The back plate that attaches to the actuator carriage, AII-000, was held fixed. The II was used as a remote load which provided a central load that was connect to the through holes associated with the II. These holes are found on the AII-006 plate. The load was calculated by multiplying the mass, 36kg, by gravity, 9.81 m/s^2, and round to the nearest single significant figure. The result is 400N. This value provides an overestimate of the forces this structure will experience.

According to Figure B- 5 the largest amount stress can be seen on the middle portion of the yoke assembly's top plate, AII-003. These stress outline the yoke stage. Large amounts of stresses can be seen on the yoke arms, AII-004(L and R), just under the 8 holed 80/20 brackets and near the pivot point of the Hoop.

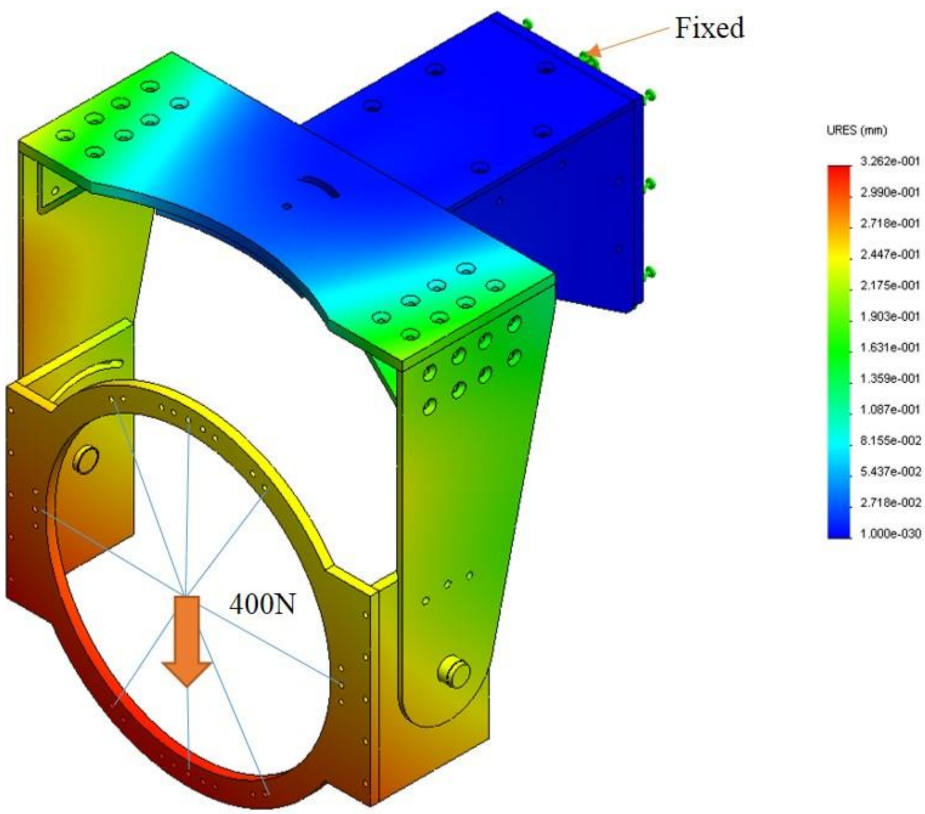


Figure B- 6: Displacement of the II Trunnion while holding the II in place.

Most deflection of the trunnion can be seen near the bottom of the Hoop sub-assembly. The maximum deflection was 0.326 mm, which was well within the stated goal of <1mm maximum deflection.

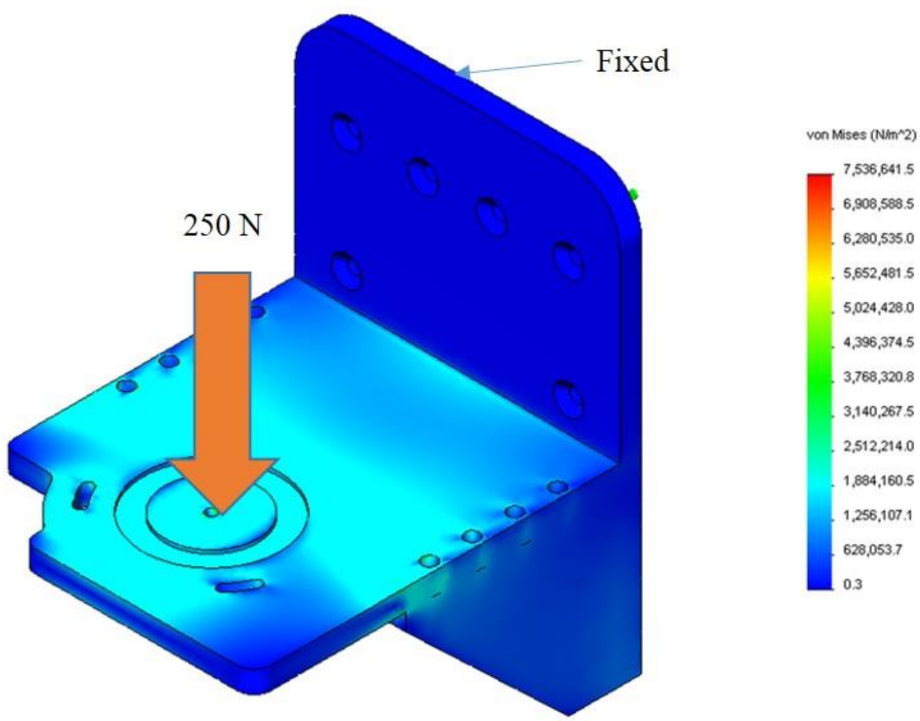


Figure B- 7: Stress plot of the XRSS supporting the x-ray source.

The x-ray source stage was simulated such that the back face of the XS-0EV1 was held rigid and a force of 250N were placed on the circulate feature where the XRS resides.

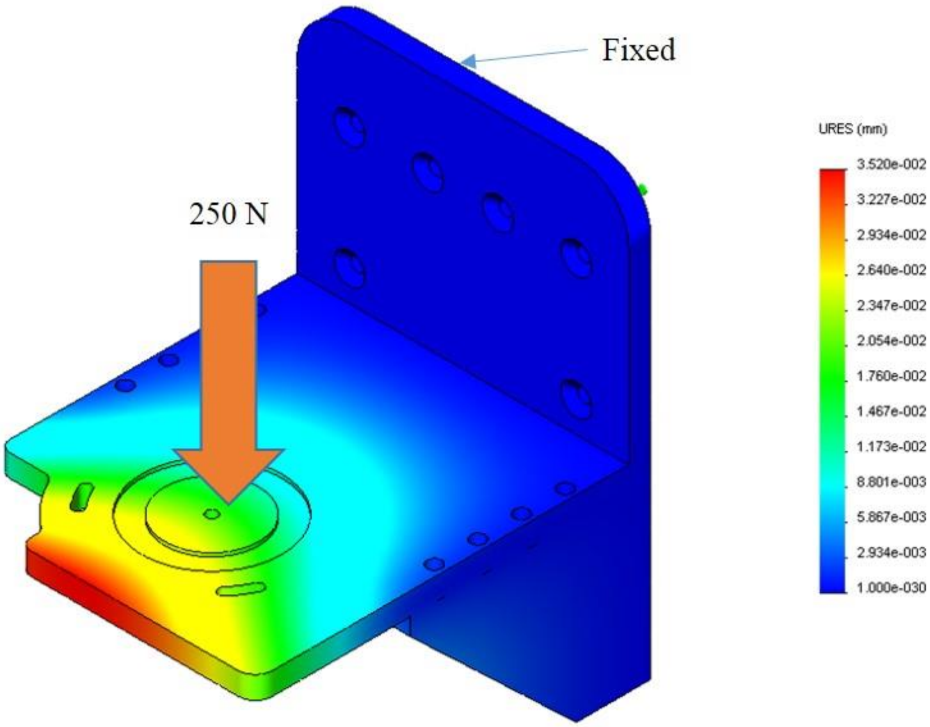


Figure B- 8: Displacement of the XRSS supporting the x-ray source.

The displacement observed from the simulation was 0.035mm, which was well within the sub-mm maximum displacement goal.

Appendix C: Parts List and Engineering Drawings.

Parts List

Bolt and Nut Count

Countersink (CS)

- M8X1.25X20 – Quantity 50
- M8X1.25X22 – Quantity 120
- M8X1.25X30 – Quantity 100
- M8X1.25X35 – Quantity 50
- M8X1.25X40 – Quantity 20

Button Head Bolts

- M6X1.25X20 – Quantity 50
- M8X1.25X16 – Quantity 210
- M8X1.25X25 – Quantity 65
- M8X1.25X30 – Quantity 5
- M8X1.25X35 – Quantity 5
- M8X1.25X25 – Quantity 25

Socket Head Bolt

- M8X1.25X30 – Quantity 10
- M8X1.25X70 – Quantity 10

80/20 T-Nuts

- M8X1.25 – Quantity 450

Nook Industries T-Nut

- M8x1.25 – Quantity 25

Nylon Locking Nuts

- M8x1.25 – Quantity 85

6061-T6 Aluminum Plating

Thickness – 12.7mm (0.5”)

- C-S001 – Quantity 2
- C-S002 – Quantity 2
- C-I003 – Quantity 2
- C-S0L1 – Quantity 2
- C-S0L2 – Quantity 2
- C-I0L3 – Quantity 2
- XS-0EV1 – Quantity 2
- XS-GUS – Quantity 4
- XS-0EB3 – Quantity 2
- AII-000 – Quantity 2
- AII-003 – Quantity 2
- AII-005 – Quantity 4
- AII-006 – Quantity 2
- Act-8020 – Quantity 8

Thickness - 6.35mm (0.5”)

- AII-001 – Quantity 4
- AII-002 – Quantity 2
- AII-004L – Quantity 2
- AII-004R – Quantity 2

Linear Actuator

- DLT-160 Nook Industries Linear Actuator – Quantity 4
- Stepper Motor and Gear Box – Quantity 4

80/20 Components

Extrusions

- 40-4080-L3 – Quantity 4
- 40-4080-S8 – Quantity 4
- 40-4080-VbT – Quantity 2
- 40-4080-VbS – Quantity 2
- 40-4080-CBii – Quantity 2
- 40-4080-CL70 – Quantity 4
- 40-4080-CFs – Quantity 4
- 40-4080-CBs – Quantity 2
- 40-4080-C5 – Quantity 2
- 40-4080-C5L – Quantity 2
- 40-4080-C5S – Quantity 2
- 40-4040 – Quantity 16

Accessories

- 40-4365 – Quantity 4
- 40-4375 – Quantity 16
- 40-2530 – Quantity 4
- 40-4332 – Quantity 30
- 40-4338 – Quantity 8
- 40-4383 – Quantity 16

Thrust Bearings

- Part No. 5909K22 – Quantity 2

Bushings

- Oil impregnated Brass Bushing – Quantity 16

Steel Axle

- Steel Axle – Quantity 8

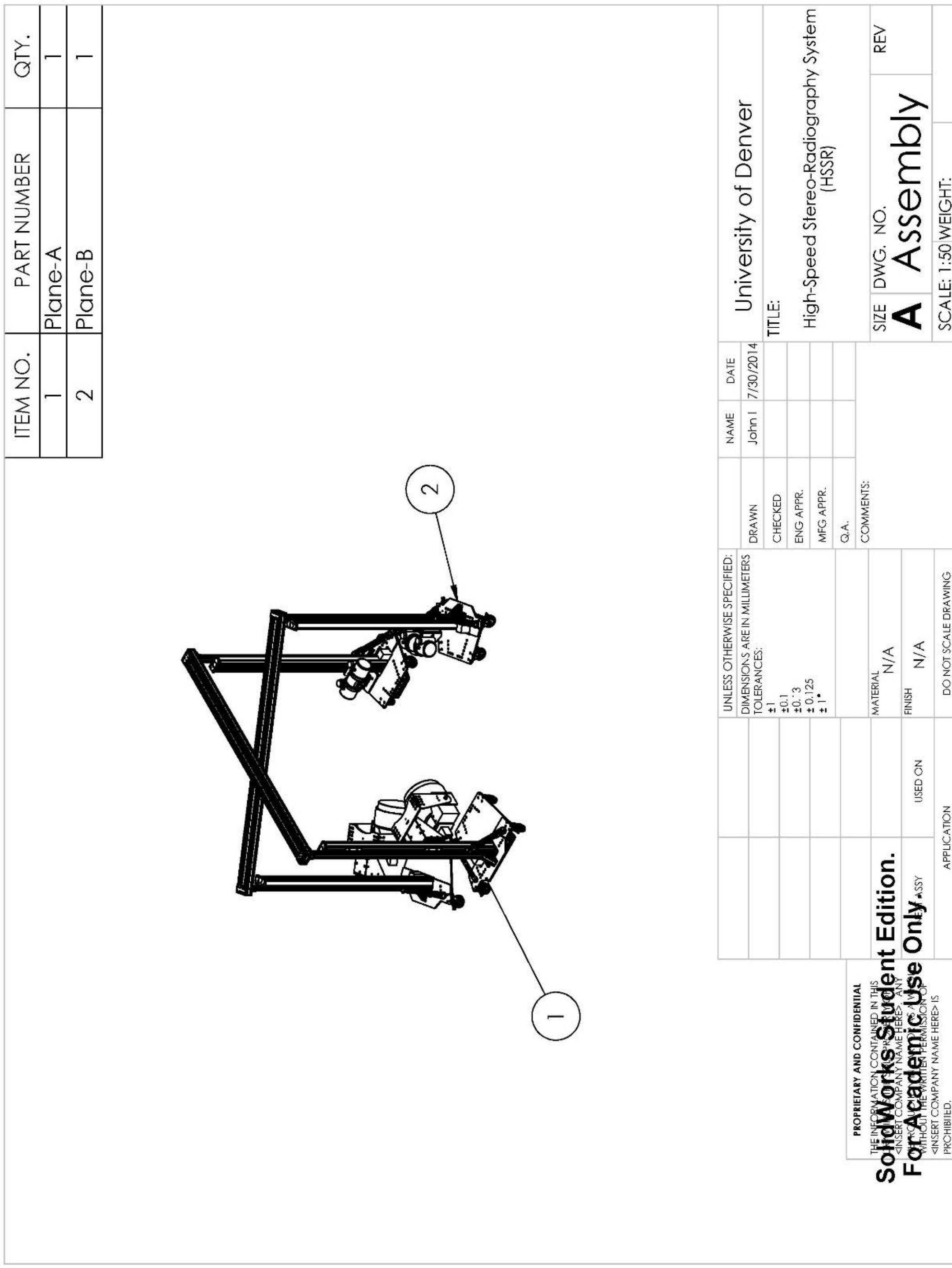
Casters

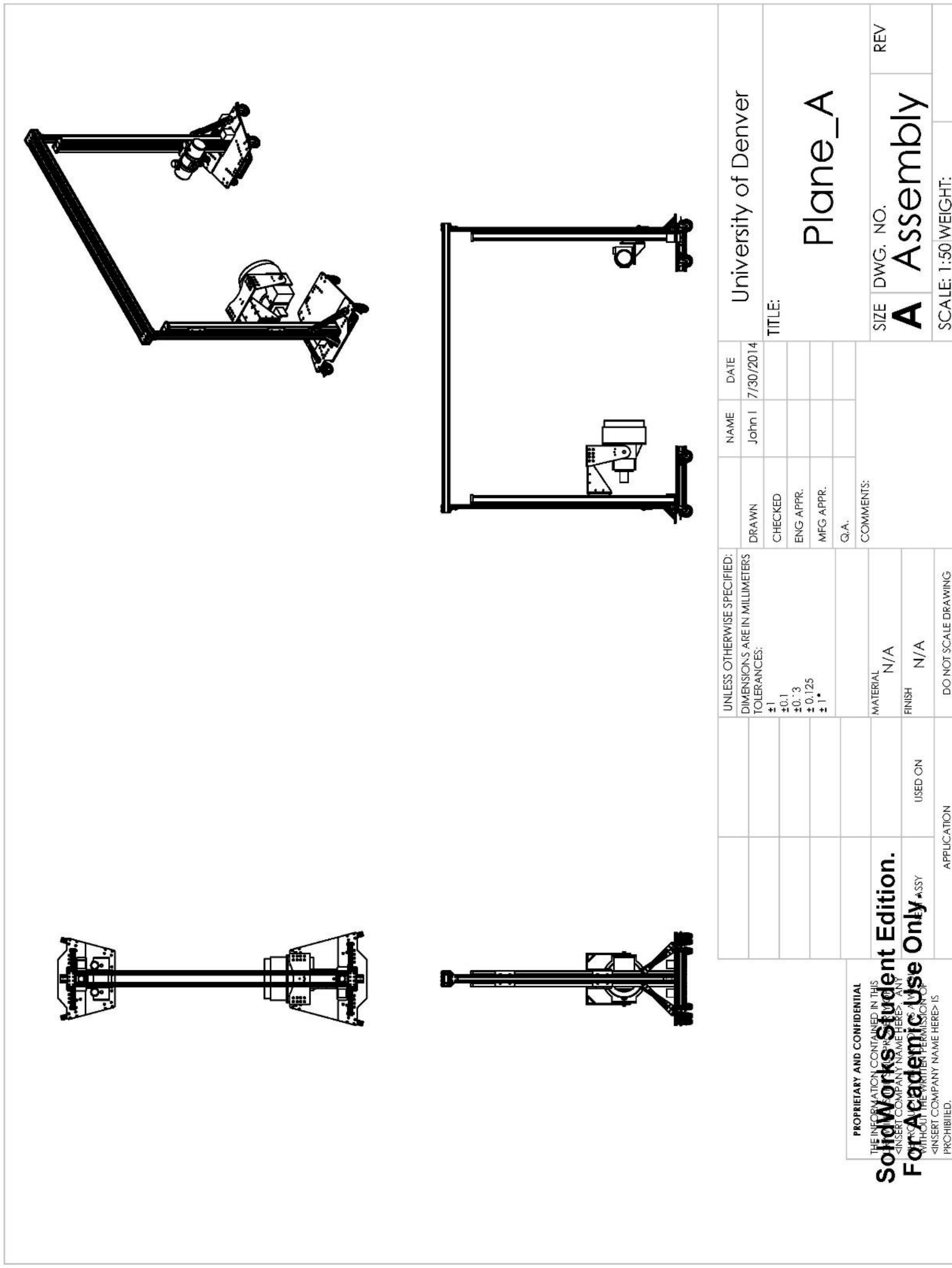
- Shepherd Caster Corporation – Quantity 16

X-ray Components

- X-ray tubes Varian 400KHU with mounting hardware – Quantity 2
- 16” Thales Image Intensifier with camera mounting hardware and video objective lens – Quantity 2

Mechanical Drawings

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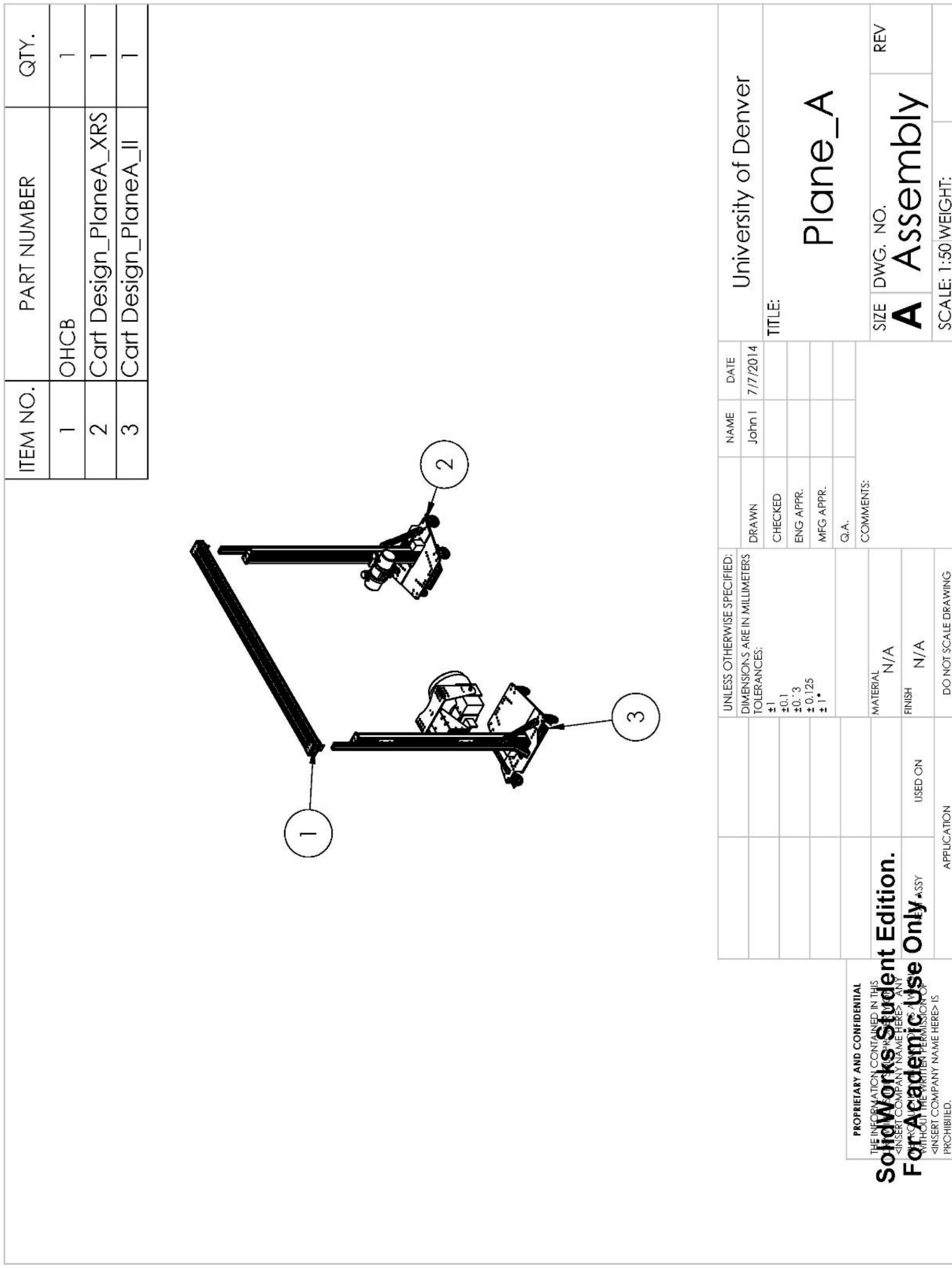
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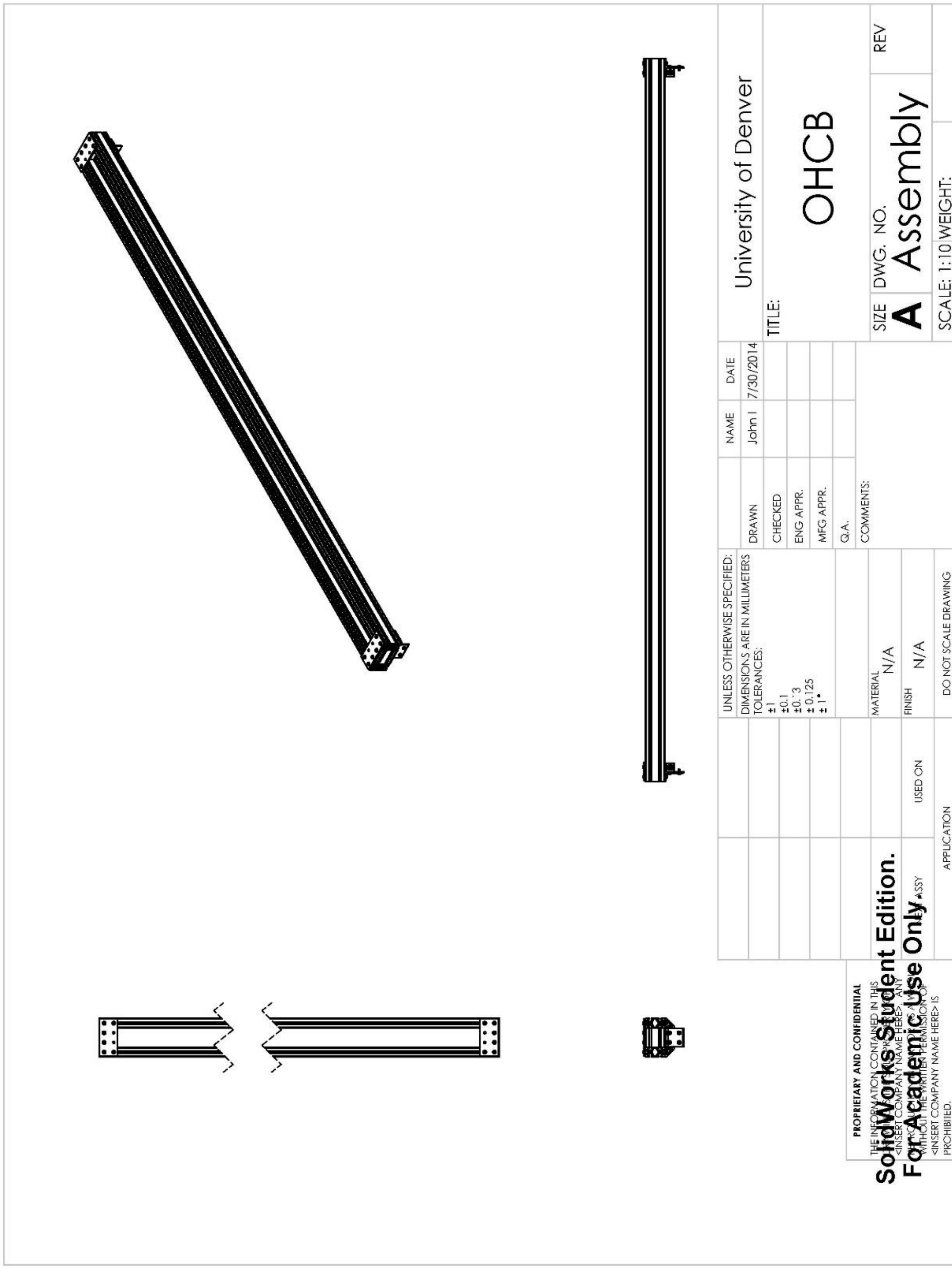
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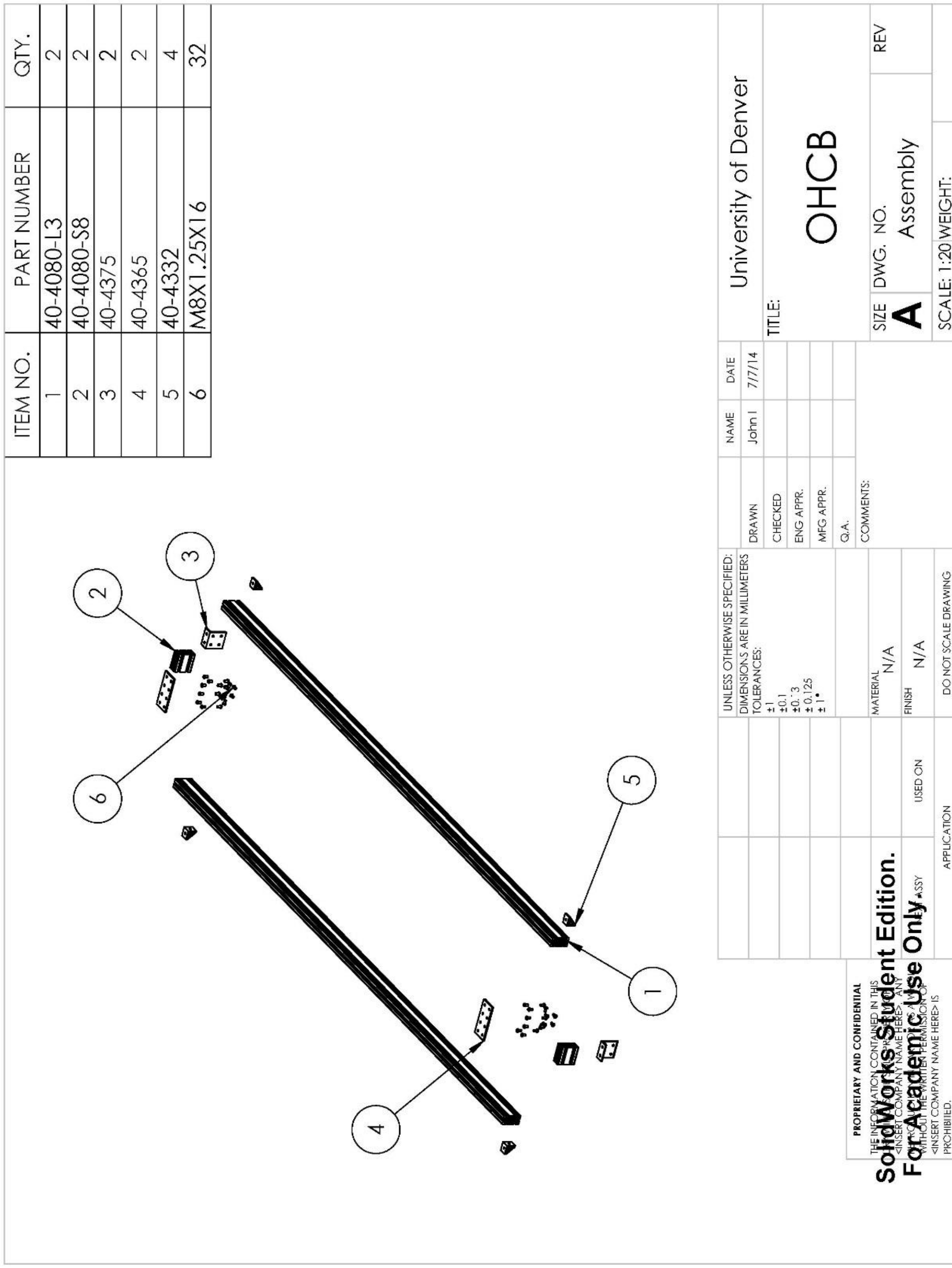

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4 | 40-4365 | 2
5 | 40-4332 | 4
6 | M8X1.25X16 | 32
University of Denver
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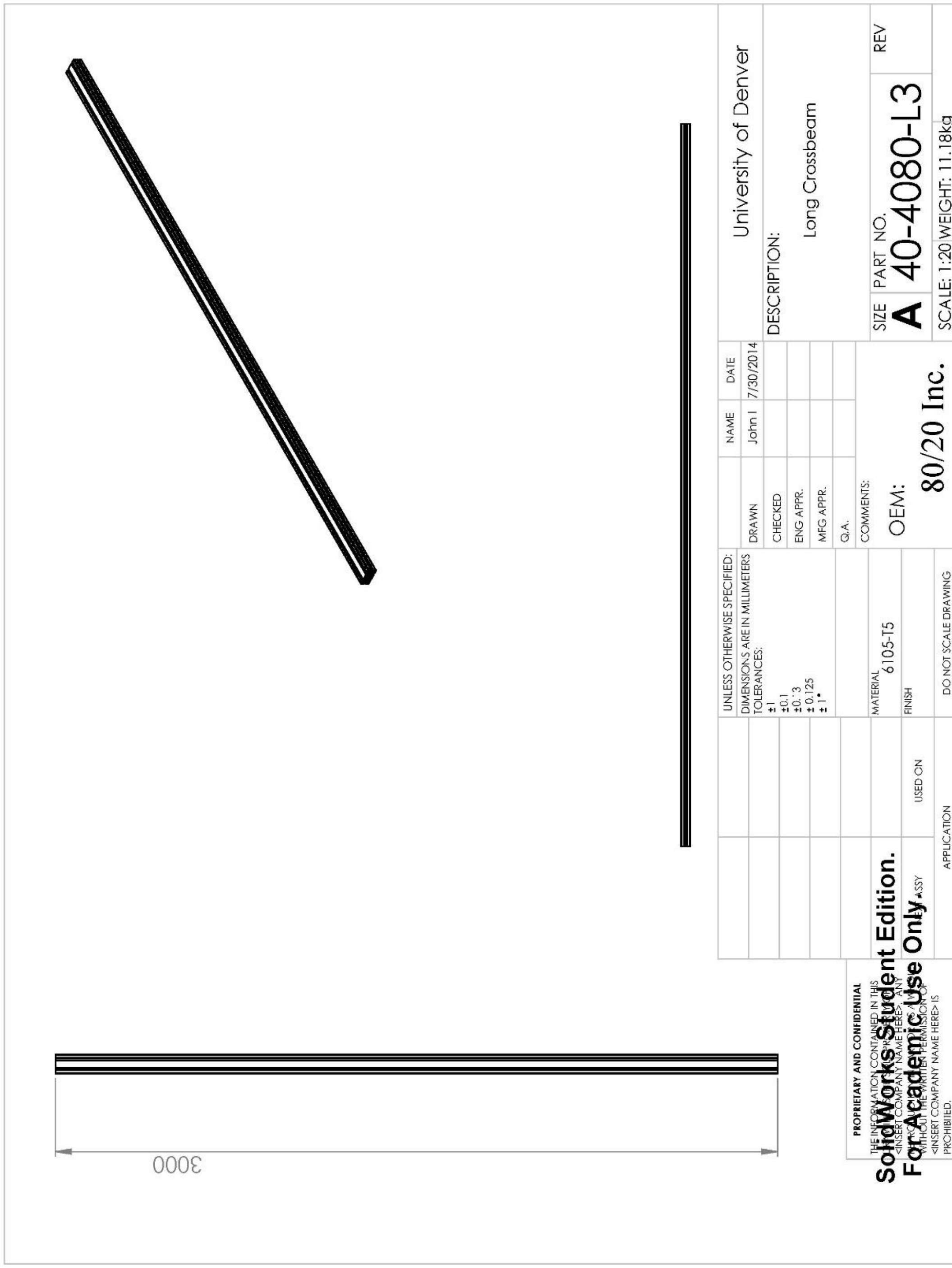
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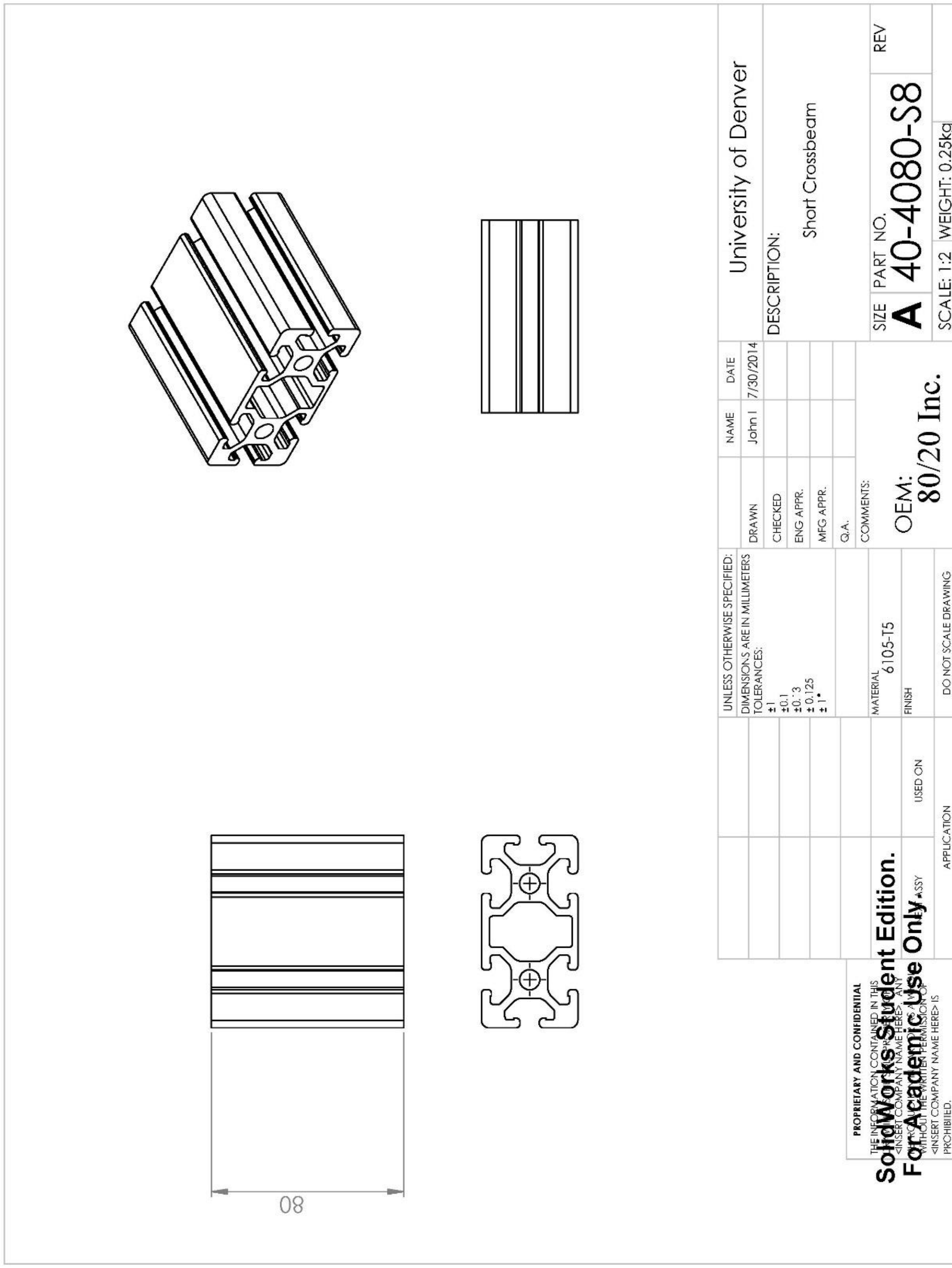
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
University of Denver
DESCRIPTION:
Long Crossbeam
SIZE
A
PART NO.
40-4080-L3
REV
SCALE: 1:20
WEIGHT: 11.18kg


University of Denver
DESCRIPTION:
Short Crossbeam
SIZE
A
PART NO.
40-4080-S8
REV
SCALE: 1:2
WEIGHT: 0.25kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
APPLICATION
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1
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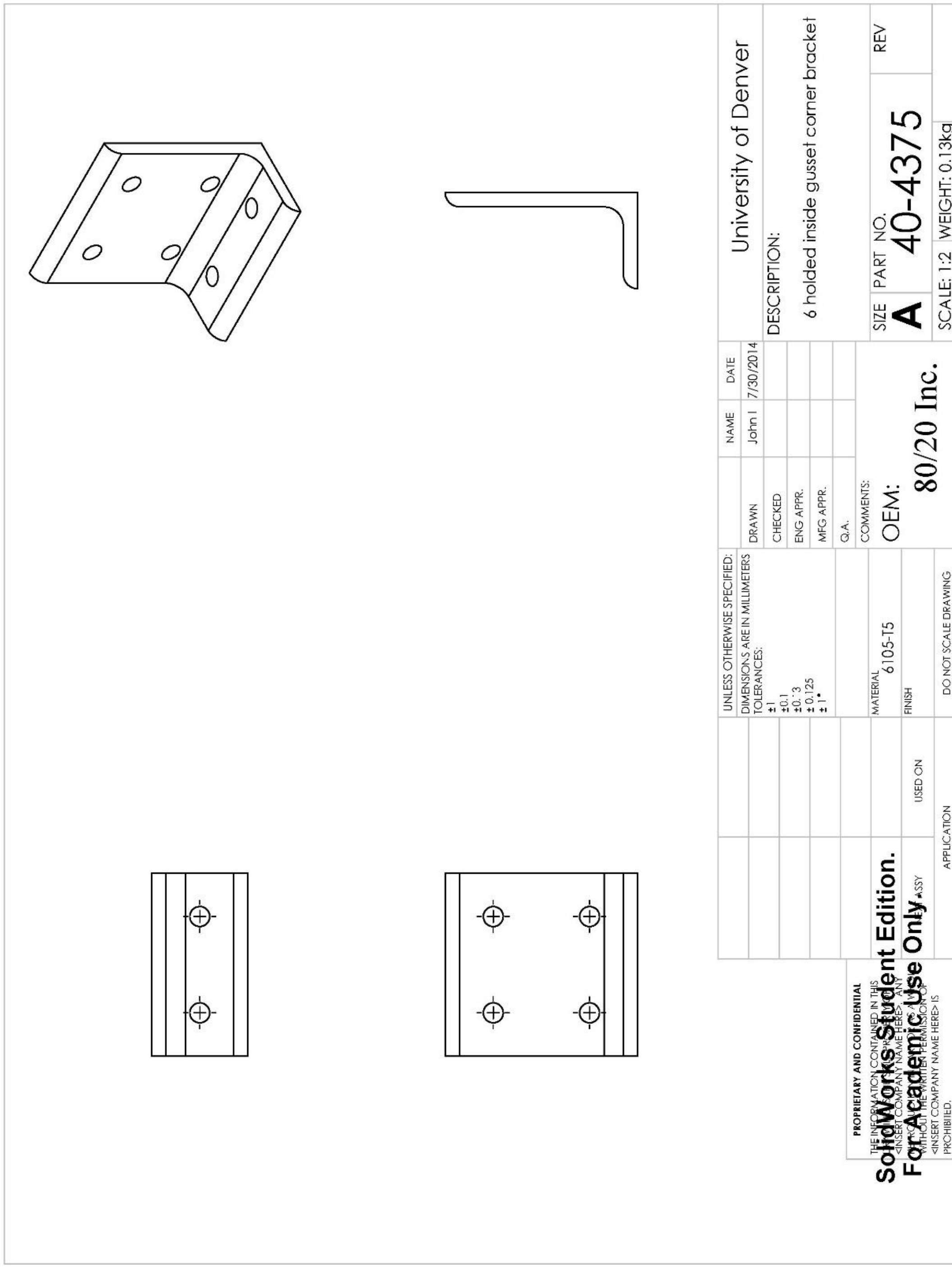
80


University of Denver
DESCRIPTION:
6 holded inside gusset corner bracket
SIZE
A
PART NO.
40-4375
REV
SCALE: 1:2
WEIGHT: 0.13kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
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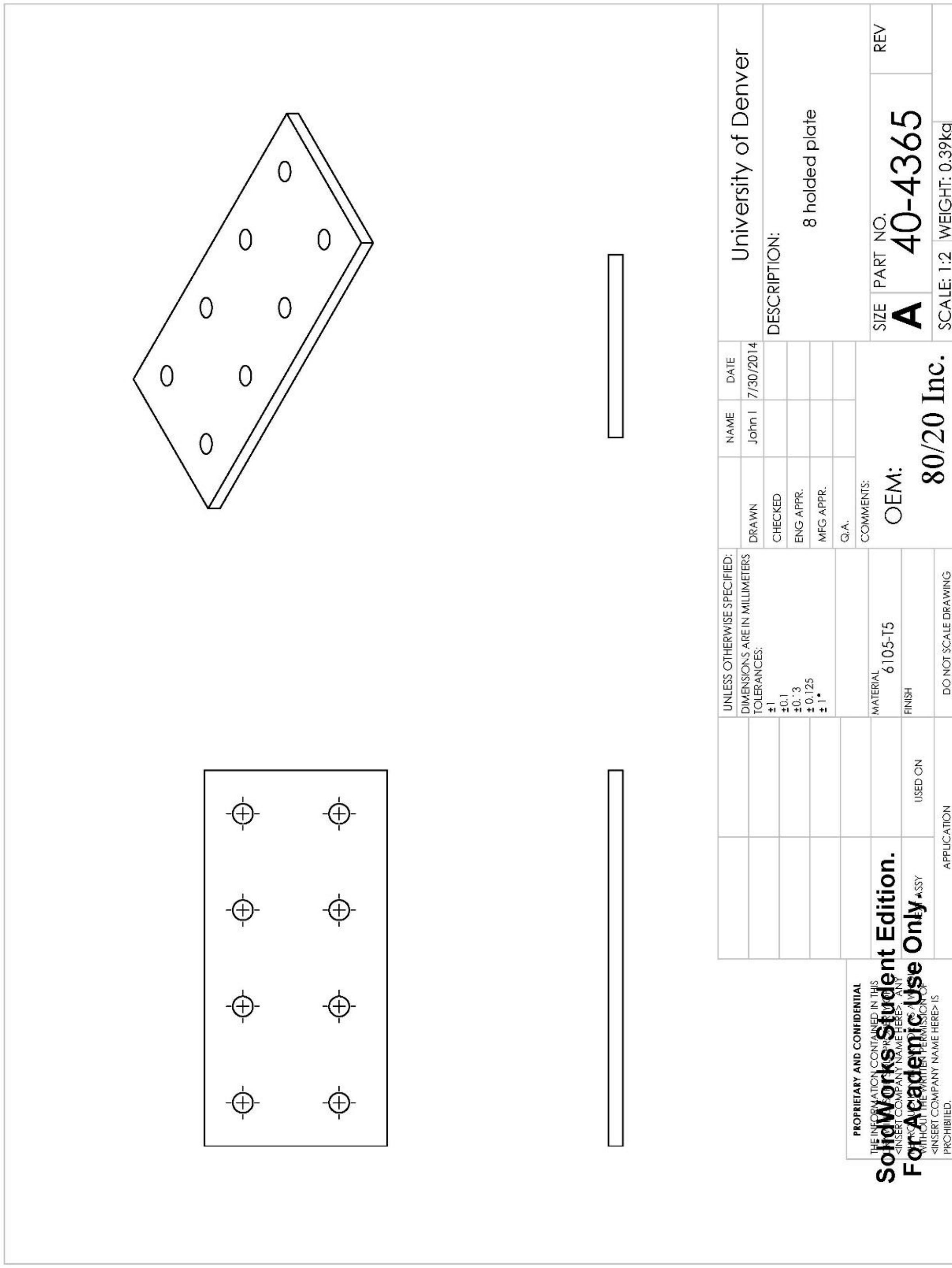
University of Denver
DESCRIPTION:
8 holded plate
SIZE
A
PART NO.
40-4365
REV
SCALE: 1:2
WEIGHT: 0.39kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
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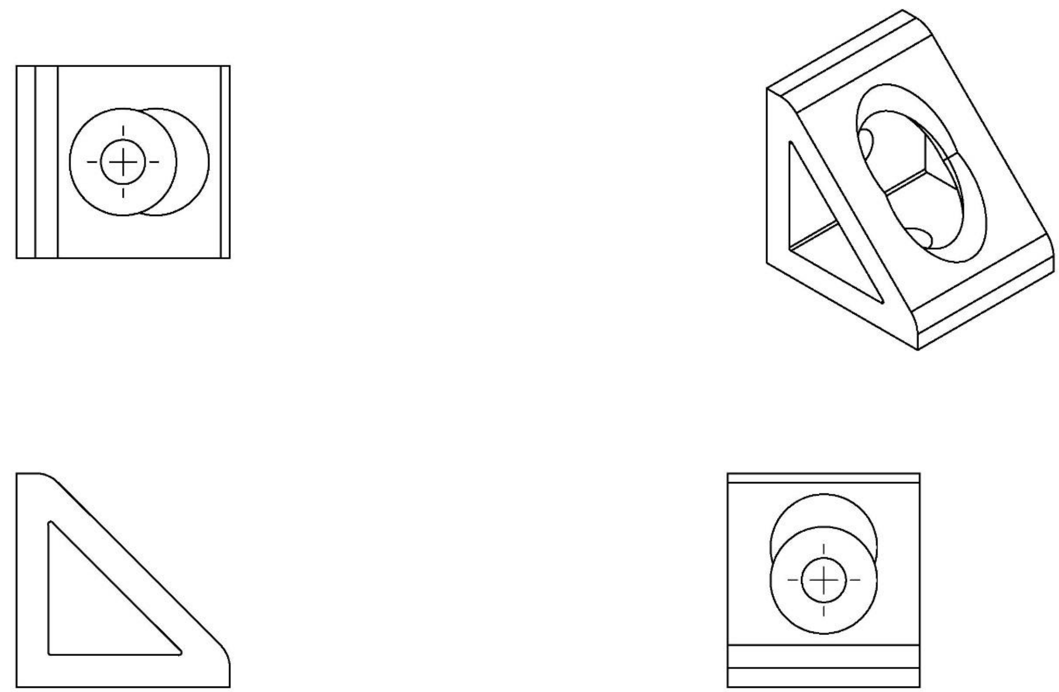

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	University of Denver
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ±1 ±0.1 ±0.`3 ± 0.125 ± 1°	DRAWN	John I	7/30/2014	DESCRIPTION: 2 holded inside gusset corner bracket
			CHECKED			
			ENG APPR.			
			MFG APPR.			
			Q.A.			
		MATERIAL 6105-T5	COMMENTS: OEM: 80/20 Inc.			SIZE A PART NO. 40-4332 REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: 0.58kg

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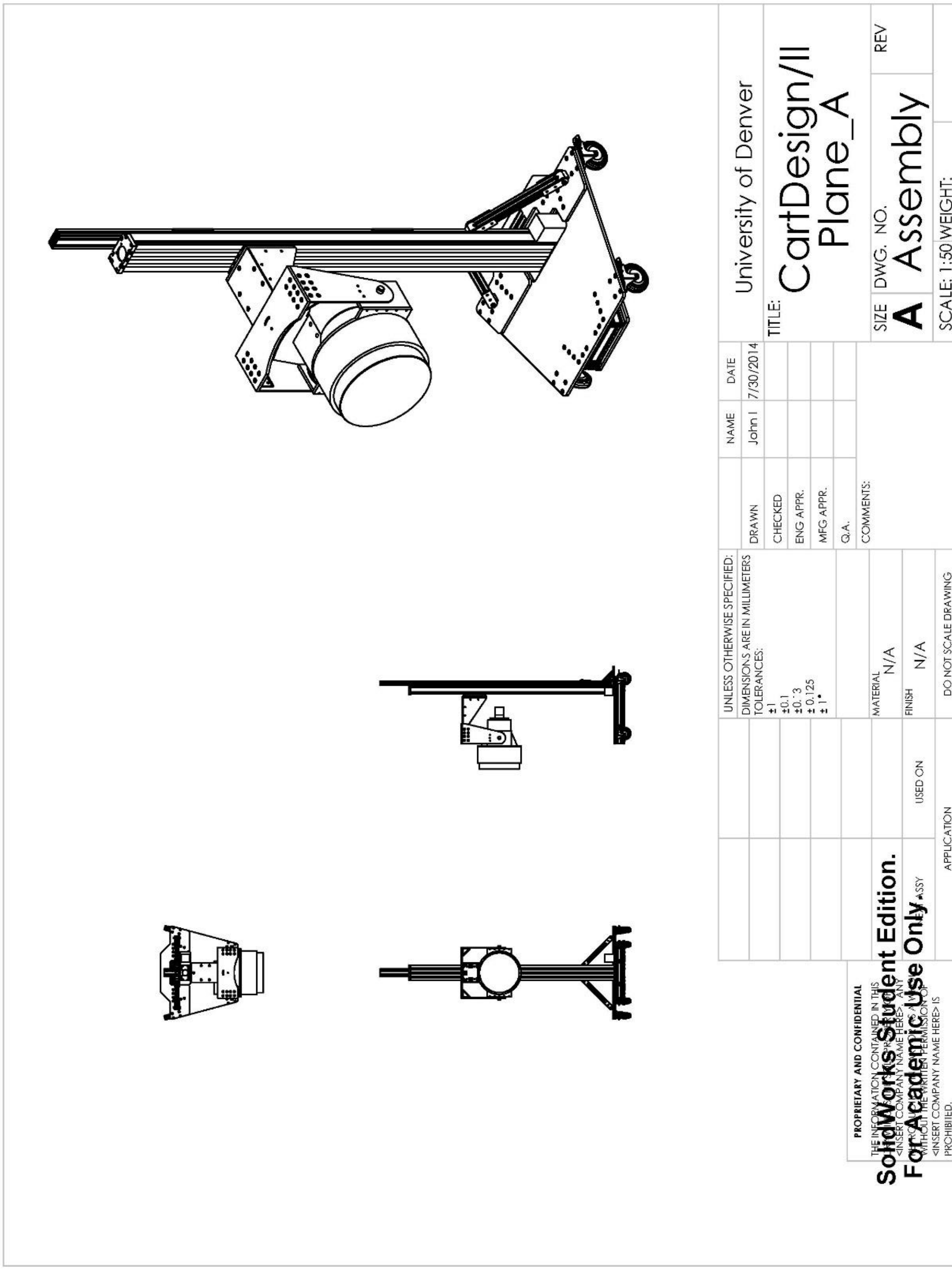
5 4 3 2 1


University of Denver
TITLE:
CartDesign/II Plane_A
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:50
WEIGHT:
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
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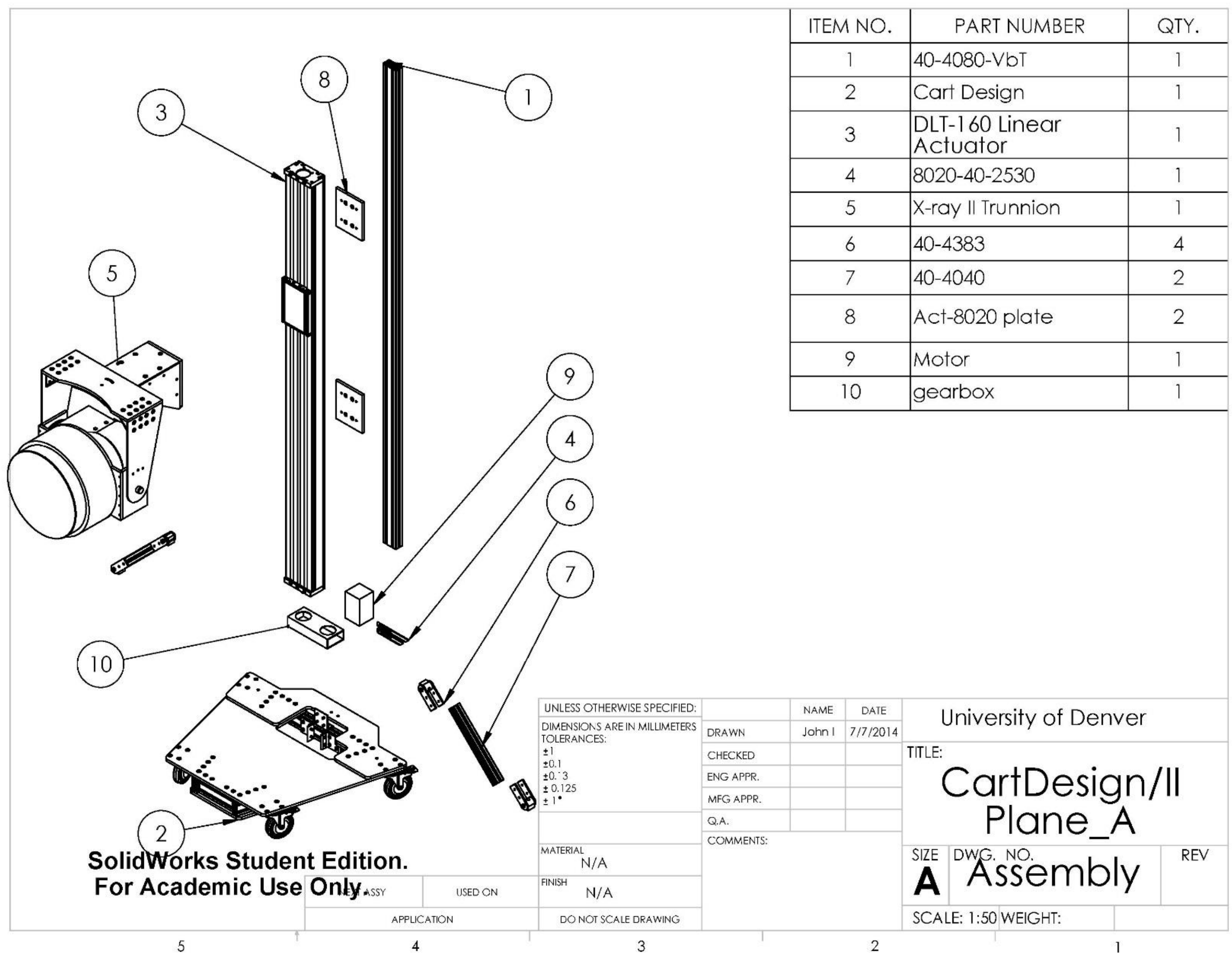
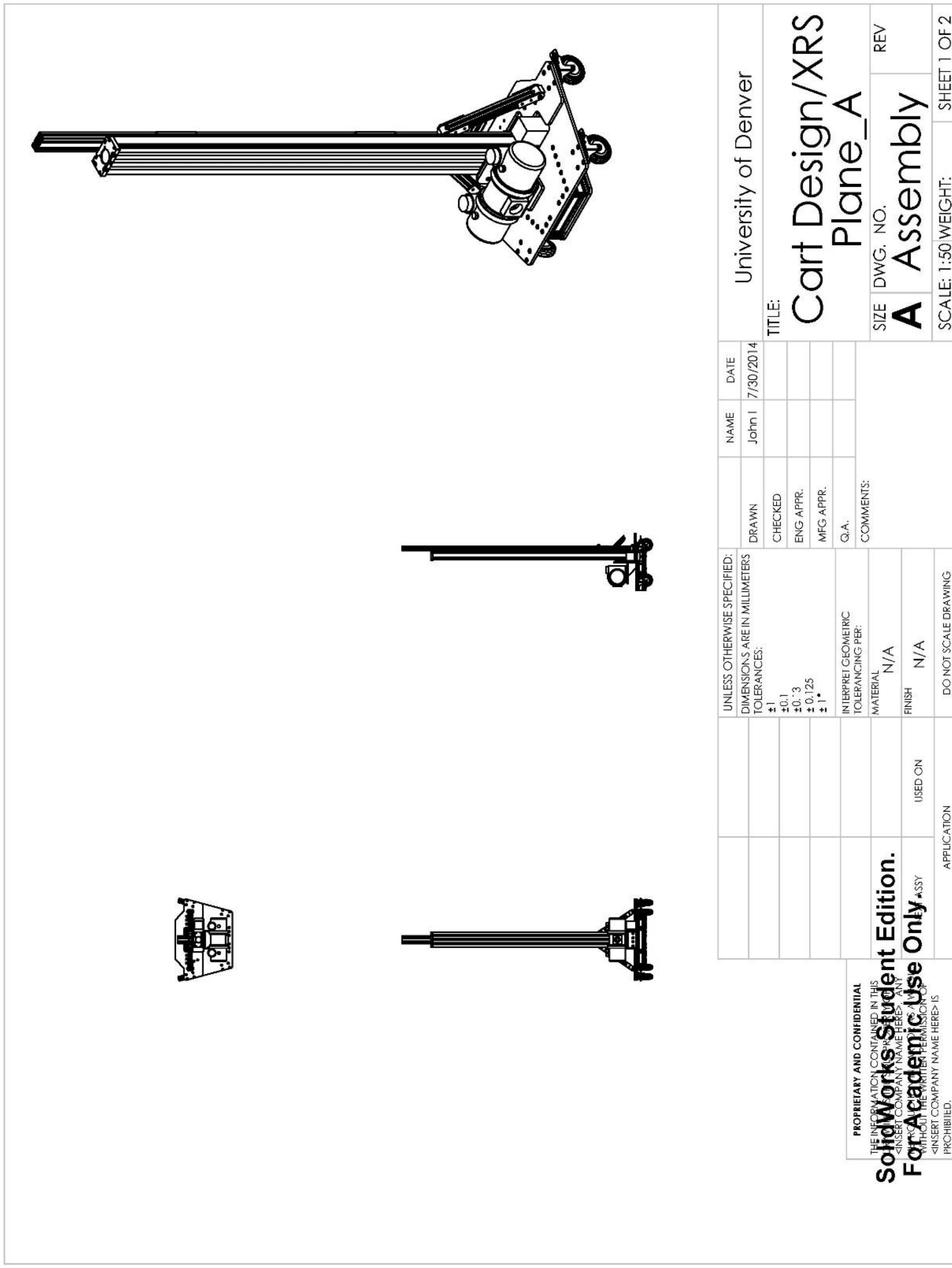


ITEM NO.	PART NUMBER	QTY.
1	40-4080-VbT	1
2	Cart Design	1
3	DLT-160 Linear Actuator	1
4	8020-40-2530	1
5	X-ray II Trunnion	1
6	40-4383	4
7	40-4040	2
8	Act-8020 plate	2
9	Motor	1
10	gearbox	1



University of Denver
TITLE:
Cart Design/XRS Plane_A
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:50
WEIGHT:
SHEET 1 OF 2
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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2
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4
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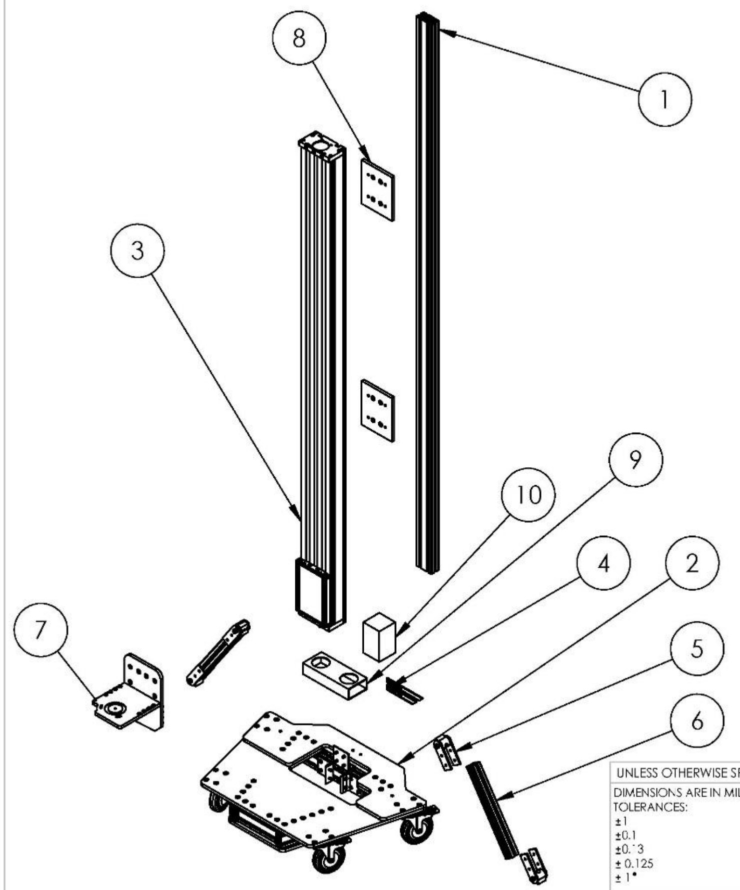

ITEM NO.	PART NUMBER	QTY.
1	40-4080-VbT	1
2	Cart Design_XRS	1
3	DLT-160 Linear Actuator	1
4	40-2530	1
5	40-4383	4
6	40-4040	2
7	XRSS	1
8	Act-8020 plate	2
9	gearbox	1
10	Motor	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.ʹ3
± 0.125
± 1°

MATERIAL N/A
FINISH N/A

	NAME	DATE
DRAWN	John I	7/7/2014
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

University of Denver

TITLE:

Cart Design/XRS Plane_A

SIZE A | DWG. NO. Assembly | REV

SCALE: 1:50 WEIGHT:

NEXT ASSY | USED ON

APPLICATION | DO NOT SCALE DRAWING

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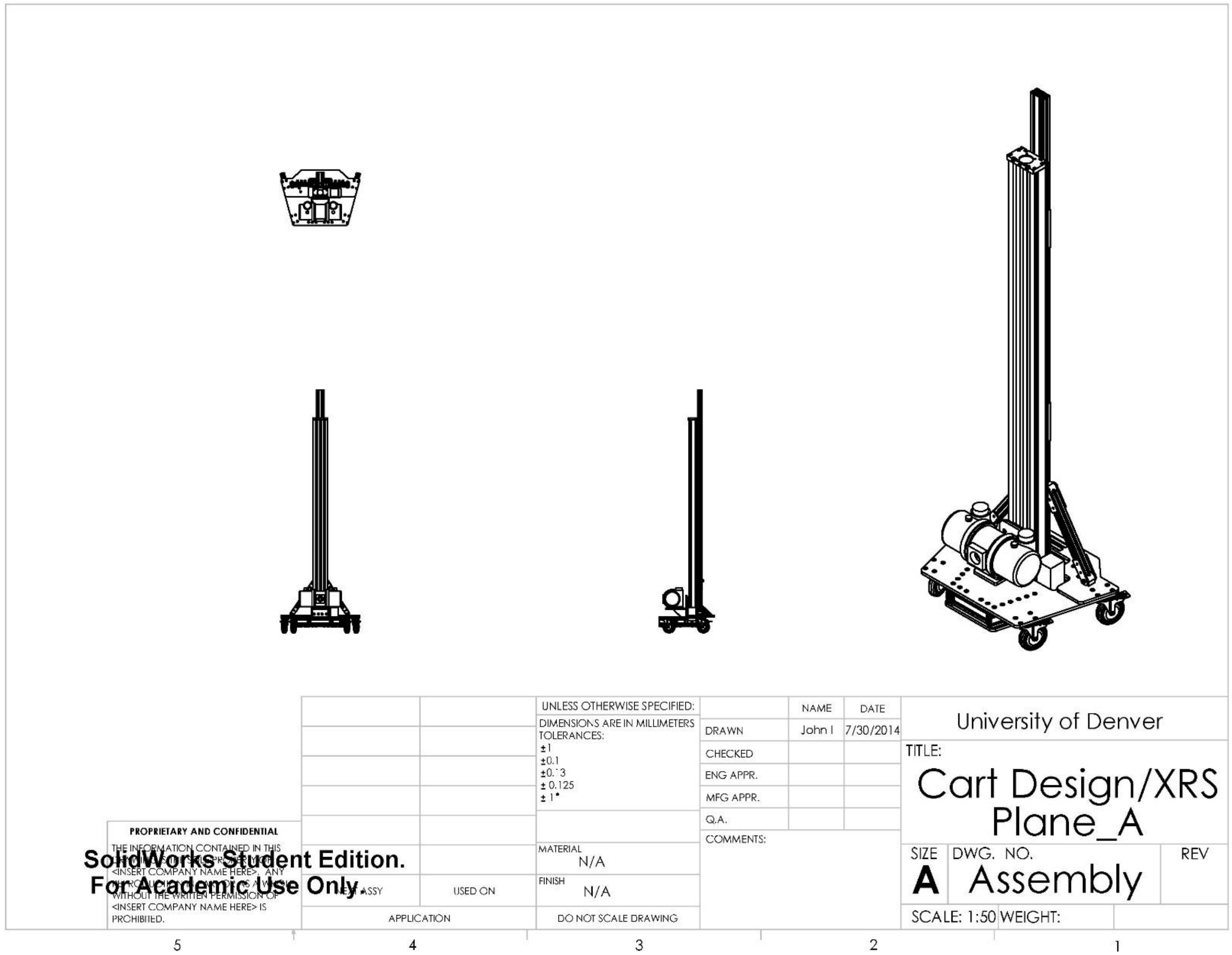
5 4 3 2 1


University of Denver
TITLE:
Cart Design/XRS Plane_A
SIZE A
DWG. NO. Assembly
REV
SCALE: 1:50 WEIGHT:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°
NAME DATE
DRAWN John I 7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL N/A
FINISH N/A
DO NOT SCALE DRAWING
USED ON
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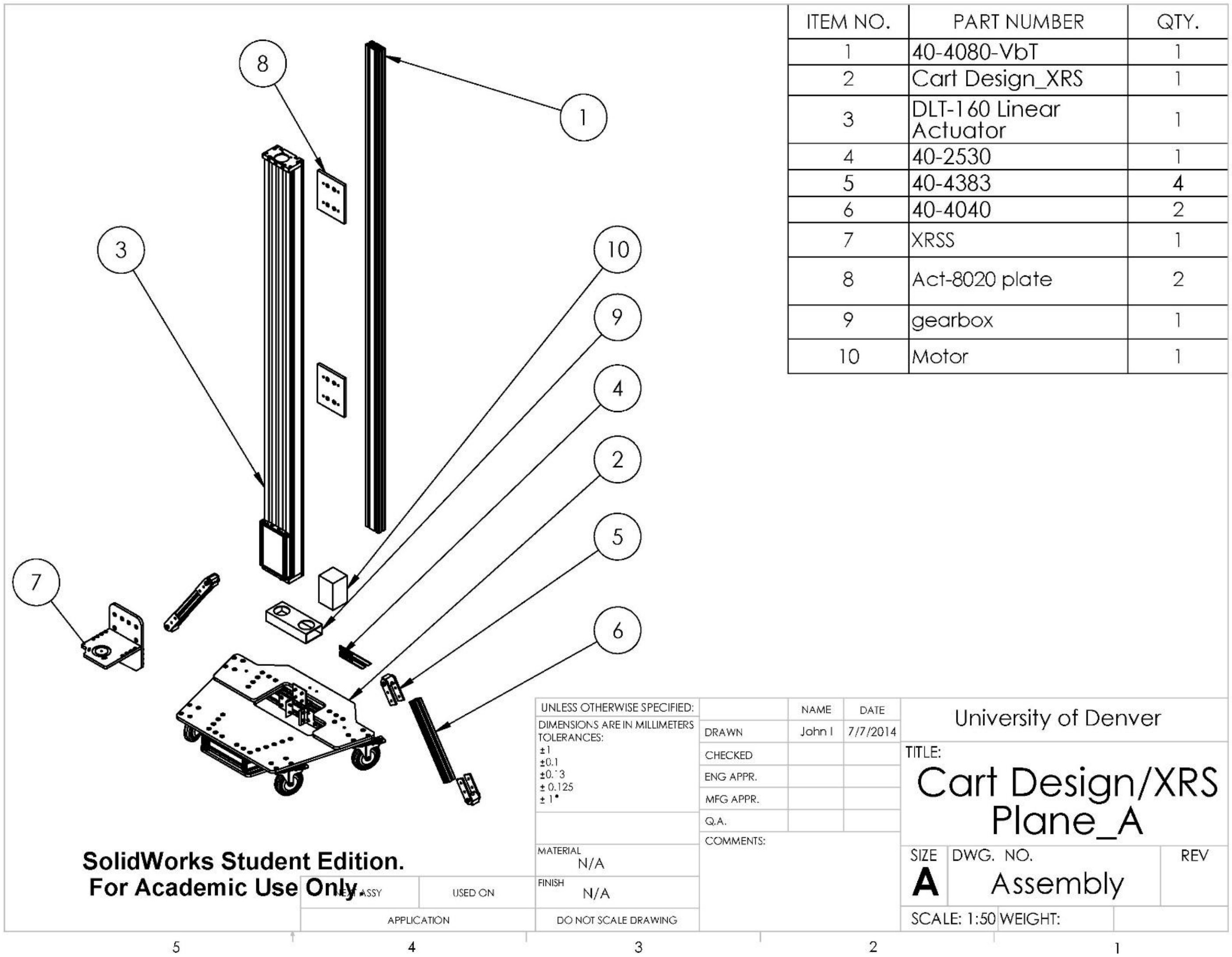
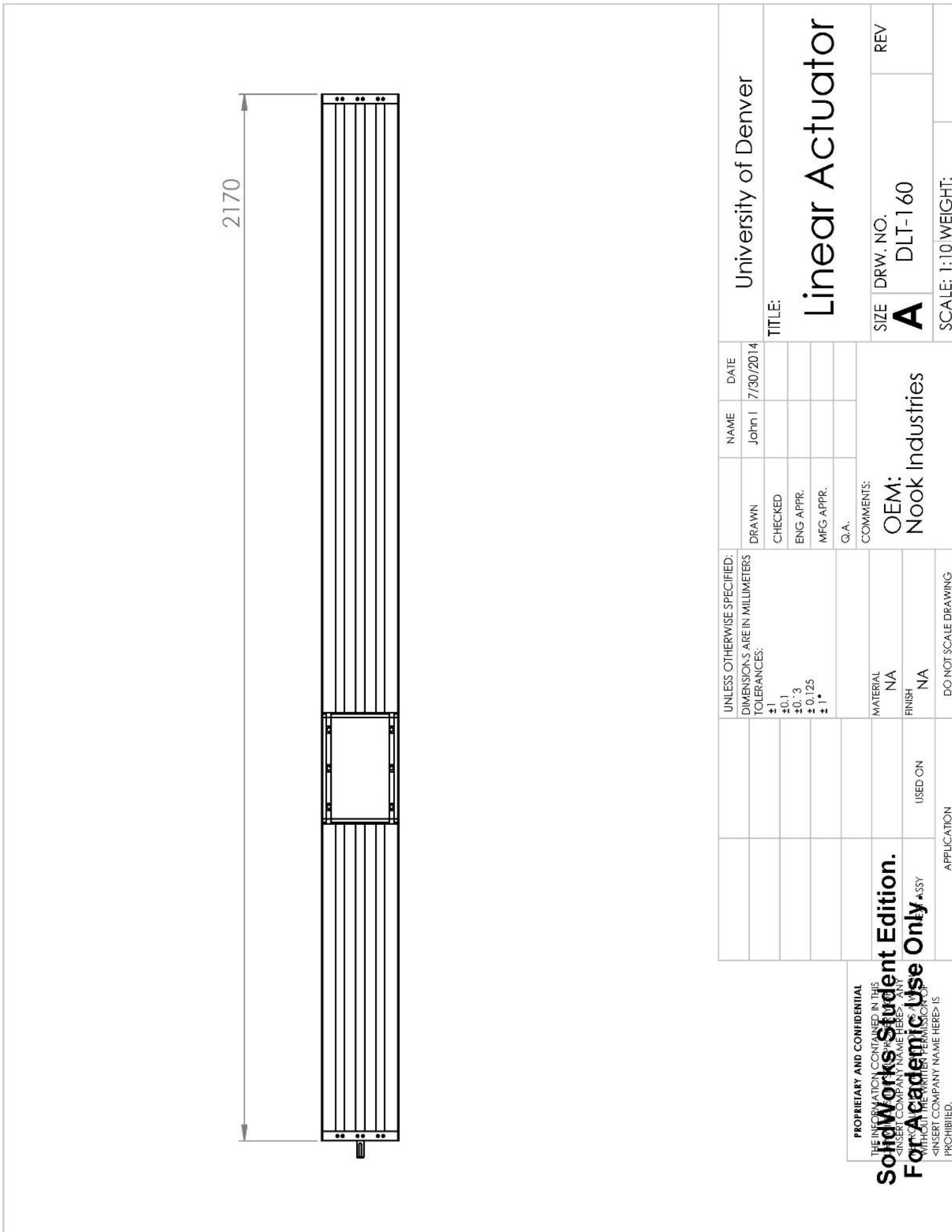
PROHIBITED.
5
4
3
2
1



ITEM NO.	PART NUMBER	QTY.
1	40-4080-VbT	1
2	Cart Design_XRS	1
3	DLT-160 Linear Actuator	1
4	40-2530	1
5	40-4383	4
6	40-4040	2
7	XRSS	1
8	Act-8020 plate	2
9	gearbox	1
10	Motor	1



2170
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
Nook Industries
University of Denver
TITLE:
Linear Actuator
MATERIAL
NA
FINISH
NA
USED ON
APPLICATION
DO NOT SCALE DRAWING
SIZE
A
DRW. NO.
DLT-160
REV
SCALE: 1:10
WEIGHT:
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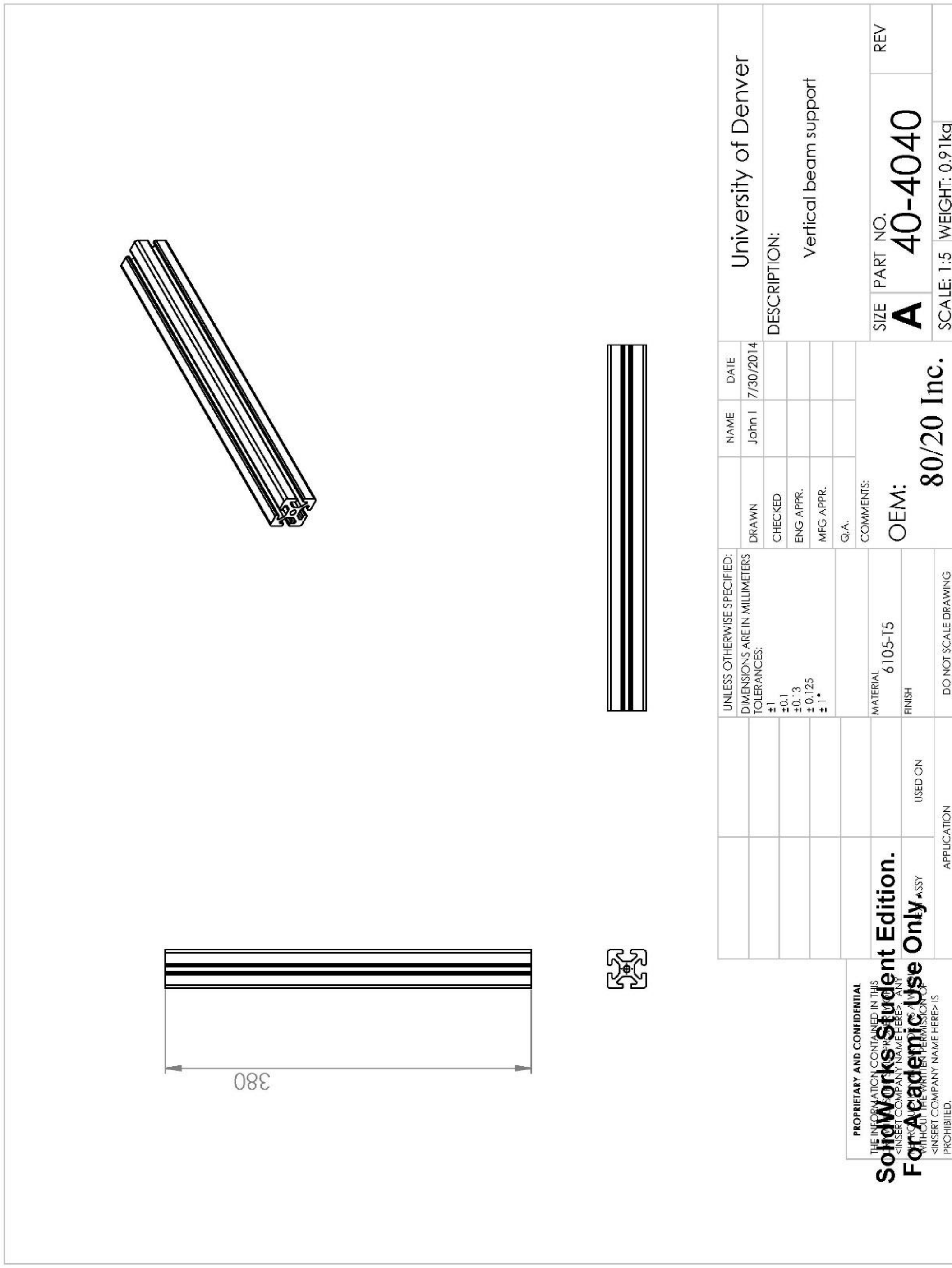
University of Denver
DESCRIPTION:
Vertical beam support
SIZE
A
PART NO.
40-4040
REV
SCALE: 1:5
WEIGHT: 0.91kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
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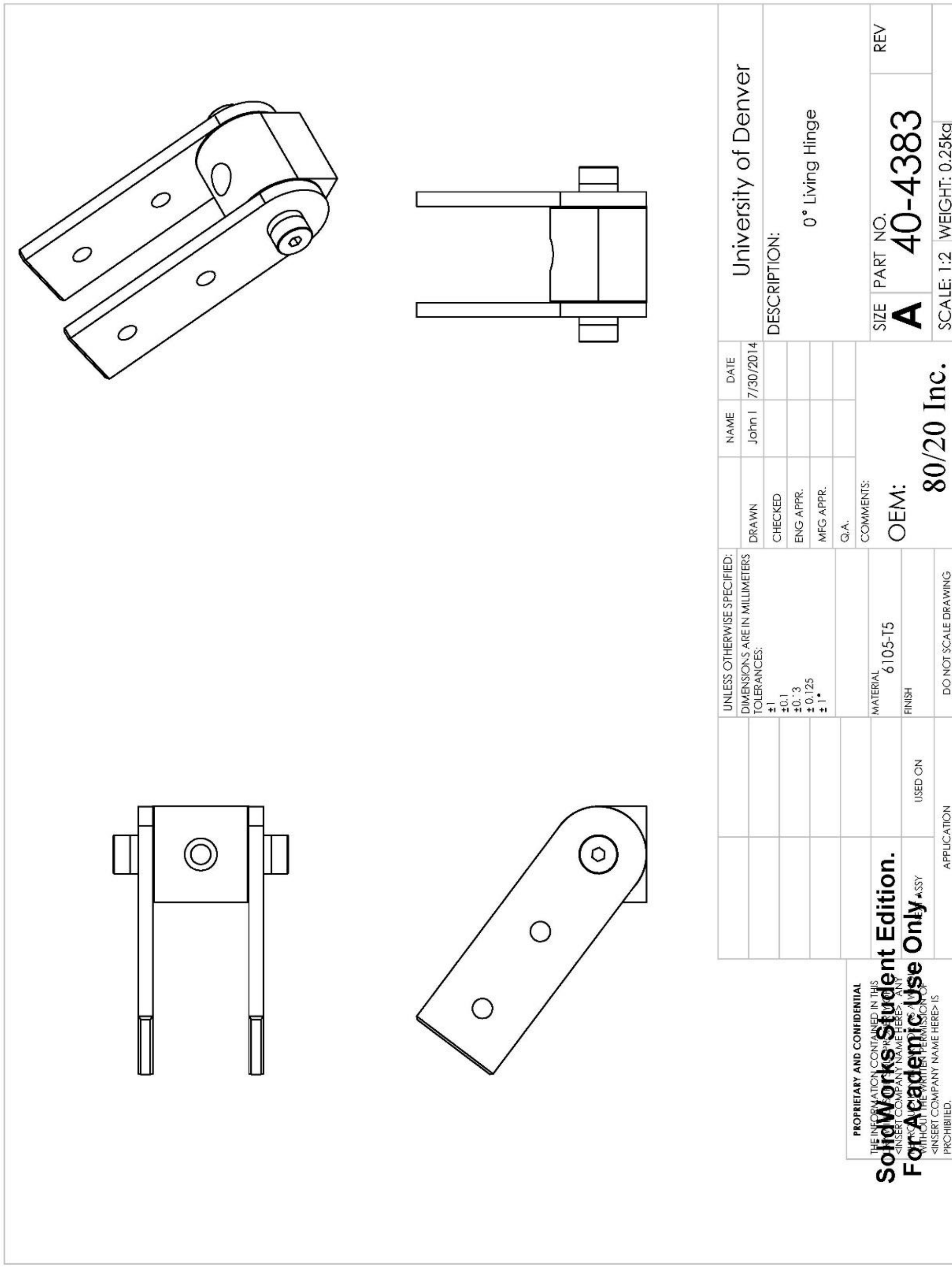
380
1
2
3
4
5


University of Denver
DESCRIPTION:
0° Living Hinge
SIZE
A
PART NO.
40-4383
REV
SCALE: 1:2
WEIGHT: 0.25kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
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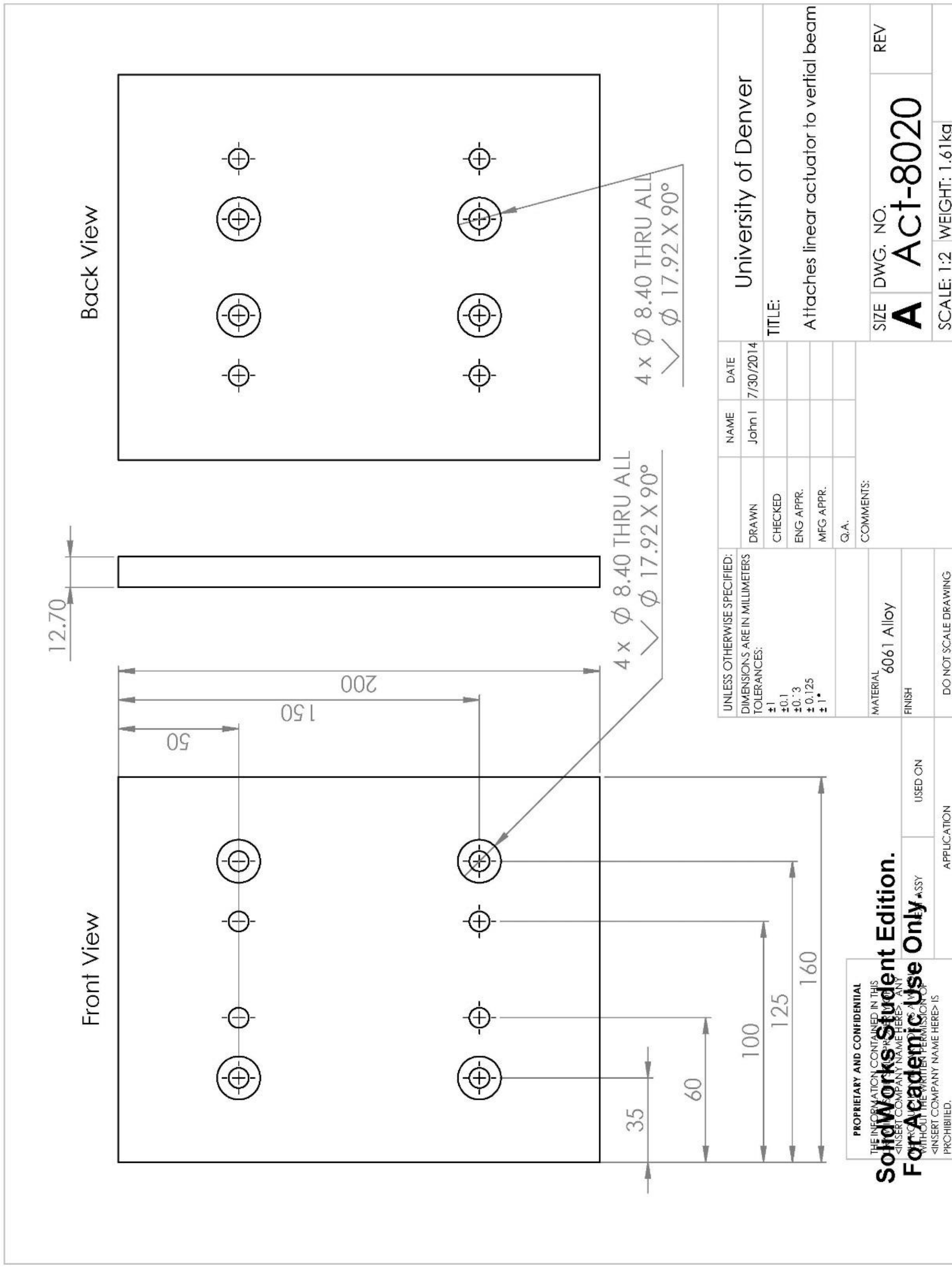
Front View
Back View
4 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
4 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
12.70
50
150
200
35
60
100
125
160
University of Denver
TITLE:
Attaches linear actuator to vertial beam
SIZE A
DWG. NO.
Act-8020
REV
SCALE: 1:2
WEIGHT: 1.61kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061 Alloy
FINISH
DO NOT SCALE DRAWING
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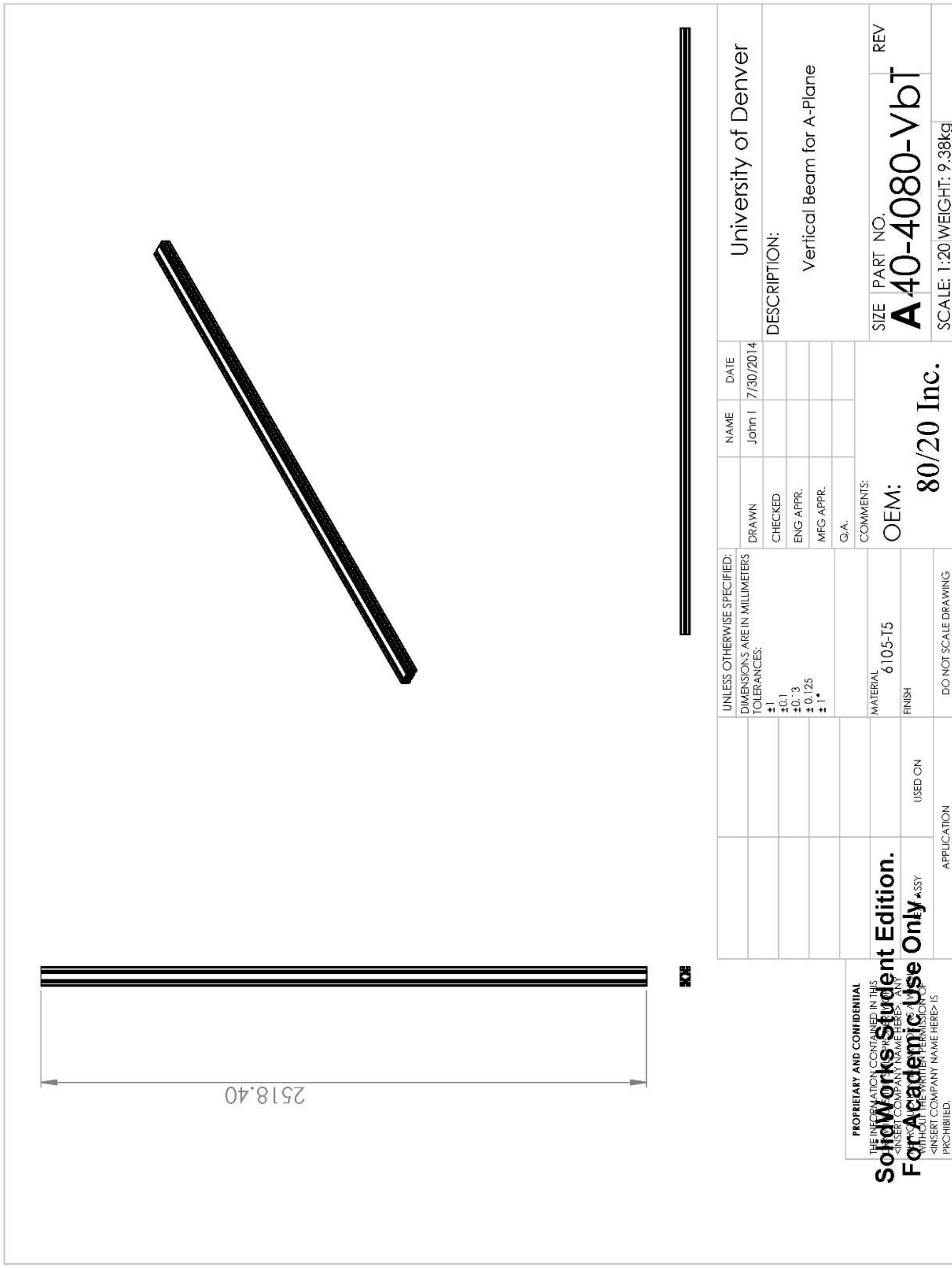

2518.40
University of Denver
DESCRIPTION:
Vertical Beam for A-Plane
SIZE
A
PART NO.
40-4080-VbT
REV
SCALE: 1:20
WEIGHT: 9.38kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
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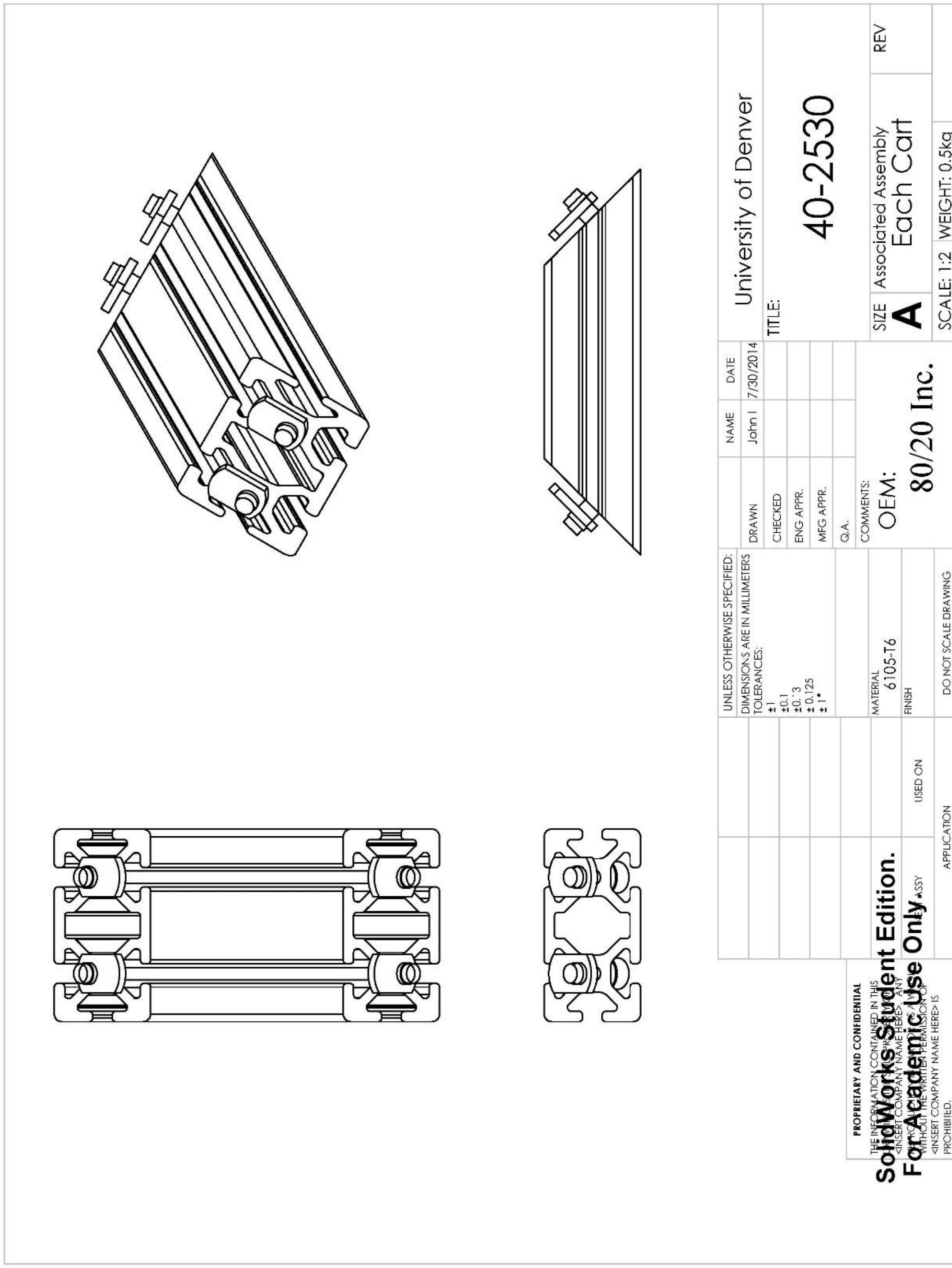
University of Denver
TITLE:
40-2530
Associated Assembly
Each Cart
SIZE
A
REV
SCALE: 1:2
WEIGHT: 0.5kg
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T6
FINISH
DO NOT SCALE DRAWING
USED ON
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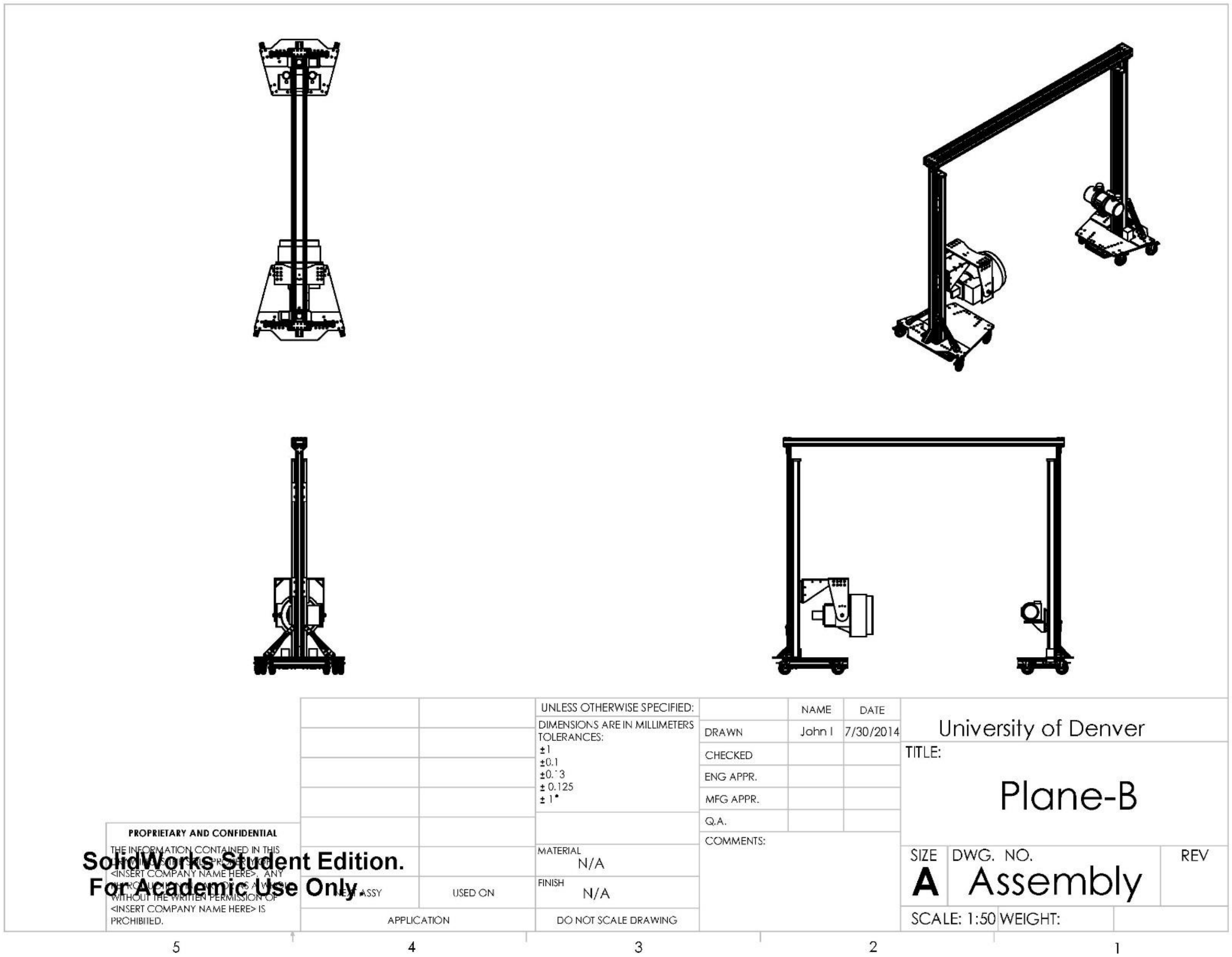

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.`3
± 0.125
± 1°
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
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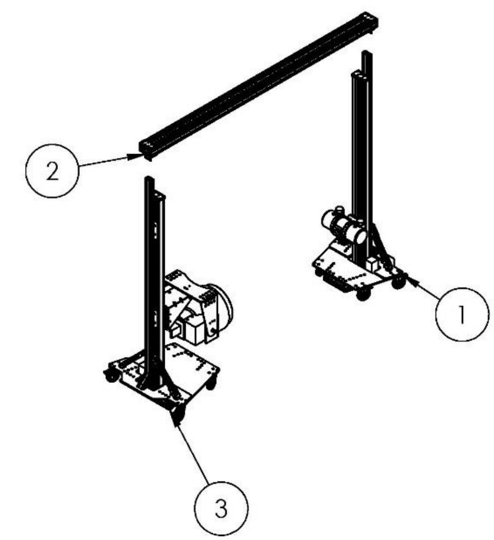
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
University of Denver
TITLE:
Plane-B
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:50
WEIGHT:
5
4
3
2
1

ITEM NO.	PART NUMBER	QTY.
1	Cart Design-PlaneB-XRS	1
2	OHCB	1
3	Cart Design-PlaneB- II	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°

MATERIAL NA
FINISH NA
DO NOT SCALE DRAWING

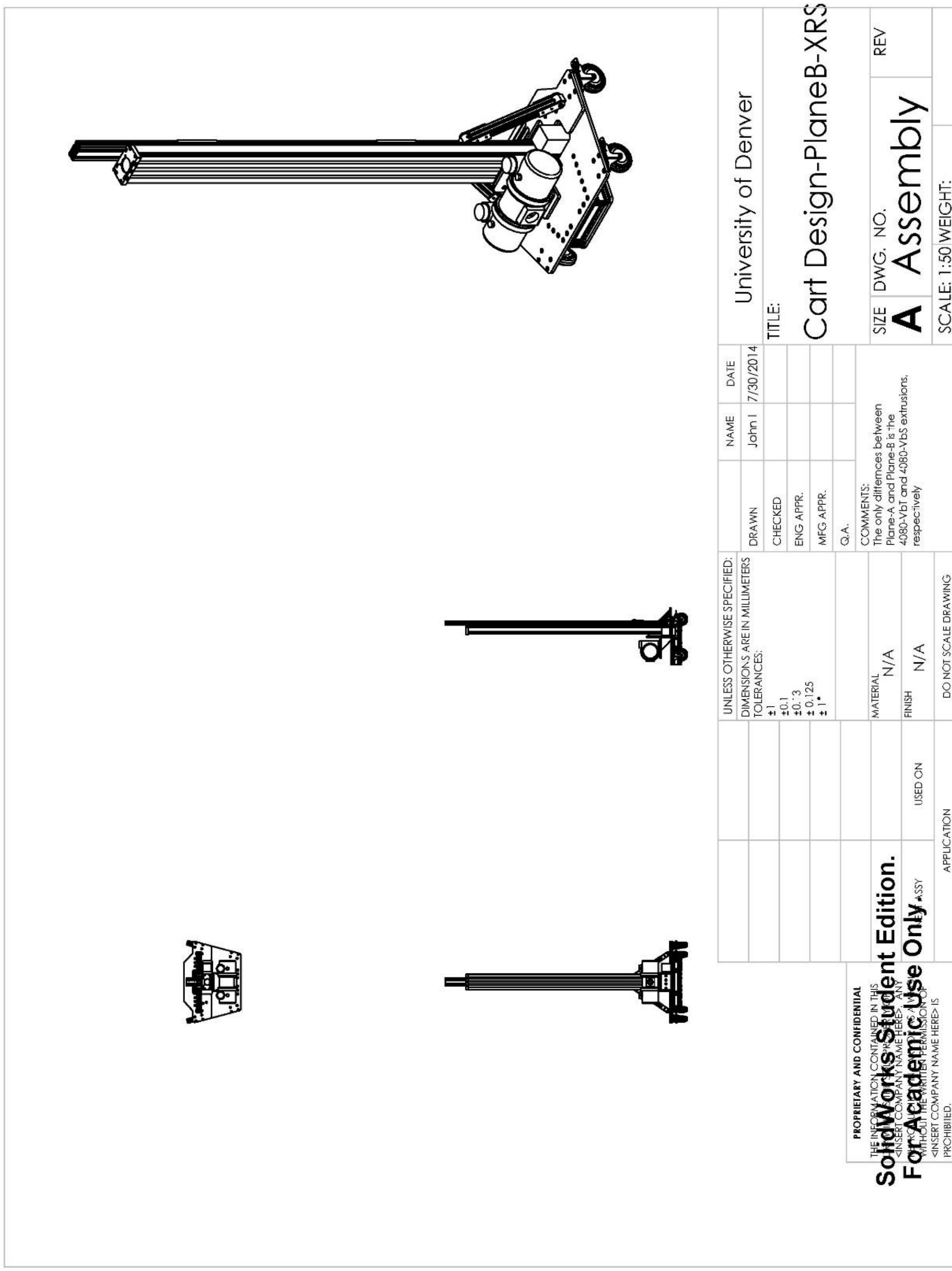
	NAME	DATE
DRAWN	John I	7/7/2014
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

University of Denver
TITLE:
Plane-B
SIZE A DWG. NO. Assembly REV
SCALE: 1:50 WEIGHT:

NEXT ASSY USED ON
APPLICATION

5 4 3 2 1



University of Denver
TITLE:
Cart Design-PlaneB-XRS
SIZE A
DWG. NO.
Assembly
REV
SCALE: 1:50 WEIGHT:
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The only differnces between Plane-A and Plane-B is the 4080-VbT and 4080-VbS extrusions, respectively
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
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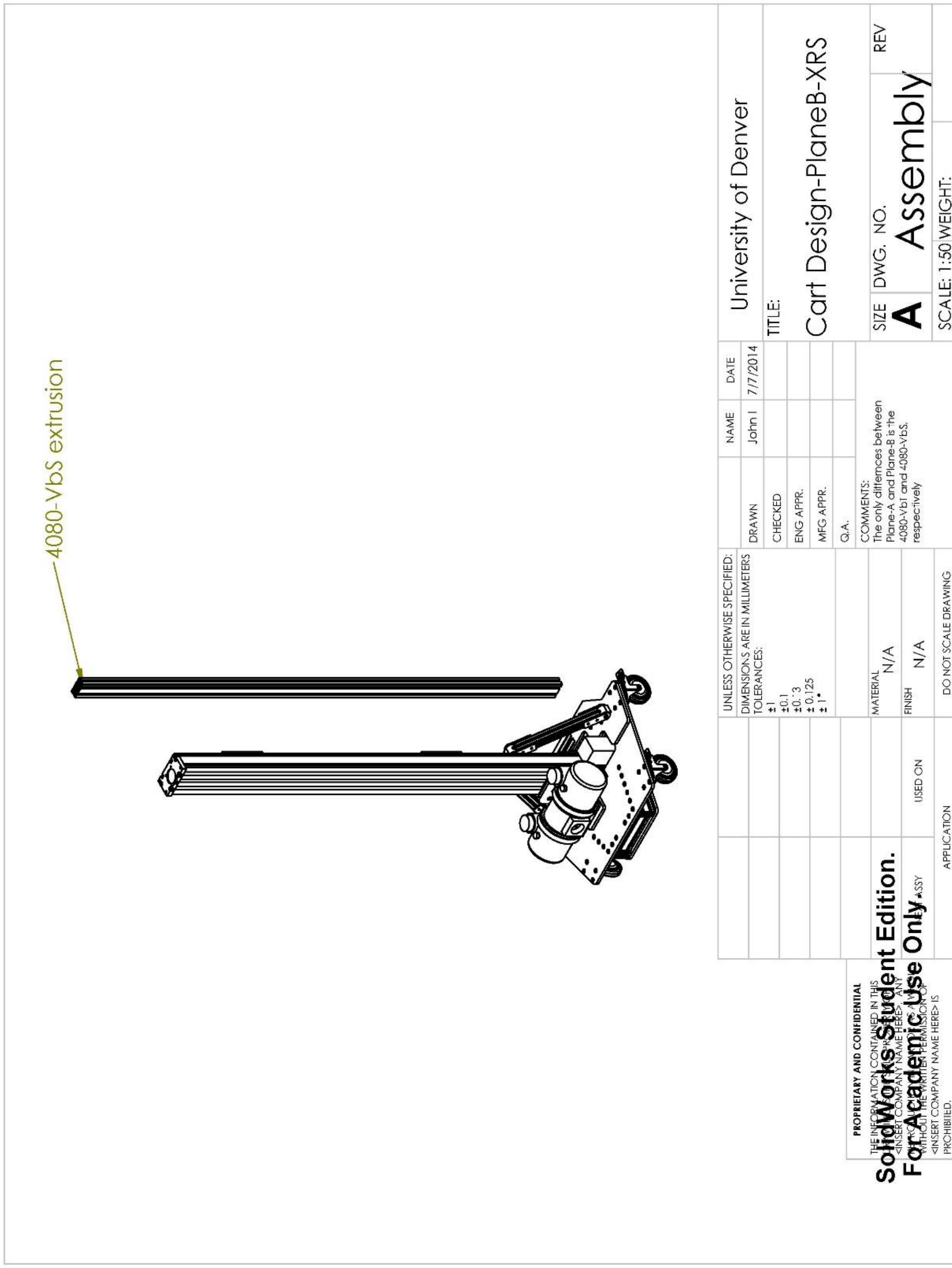
4080-VbS extrusion
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.03
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The only differnces between Plane-A and Plane-B is the 4080-VbT and 4080-VbS, respectively
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
University of Denver
TITLE:
Cart Design-PlaneB-XRS
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:50
WEIGHT:
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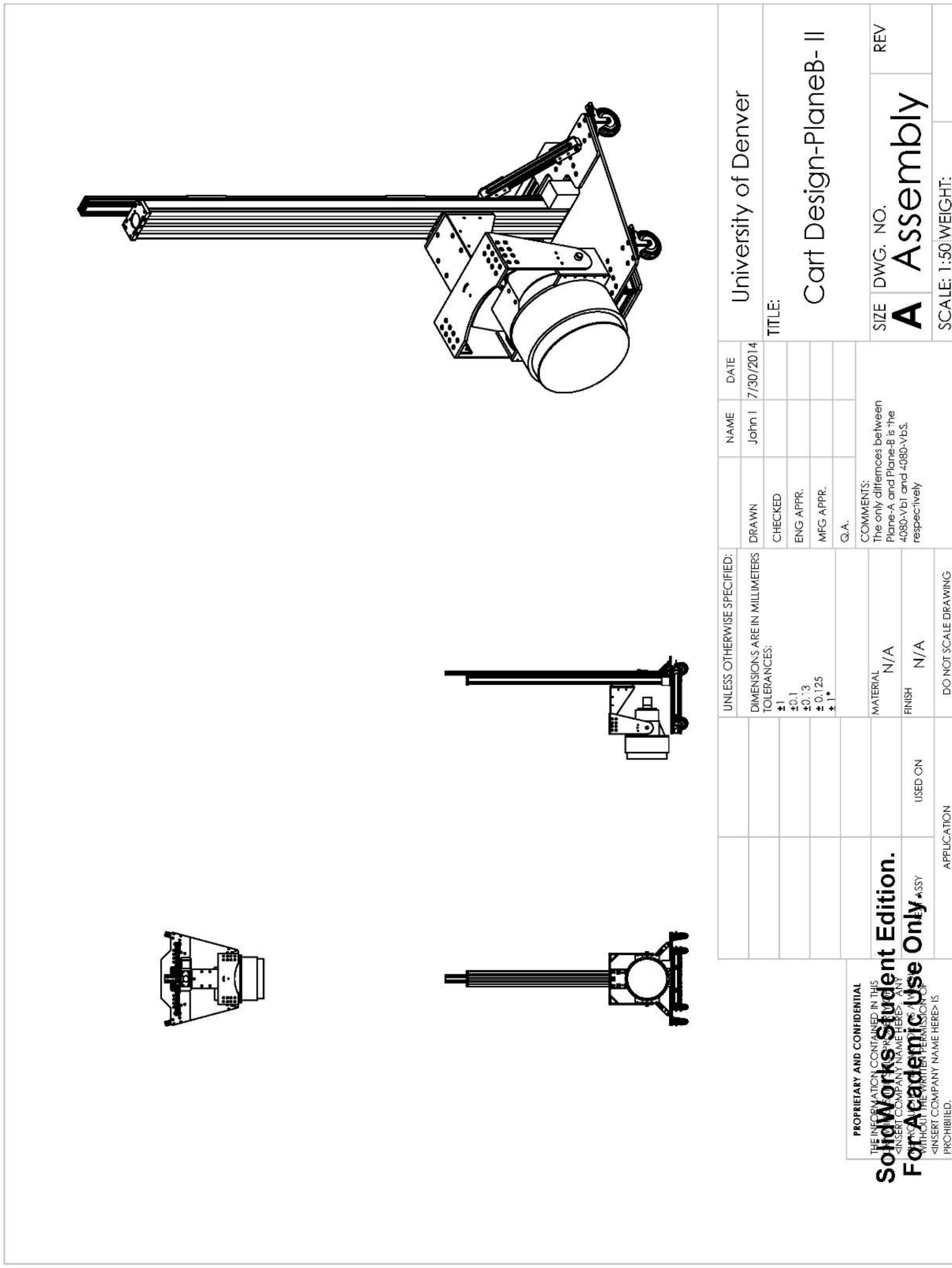

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/30/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The only differnces between Plane-A and Plane-B is the 4080-VbT and 4080-VbS, respectively
University of Denver
TITLE:
Cart Design-PlaneB- II
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:50
WEIGHT:
MATERIAL
N/A
FINISH
N/A
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USED ON
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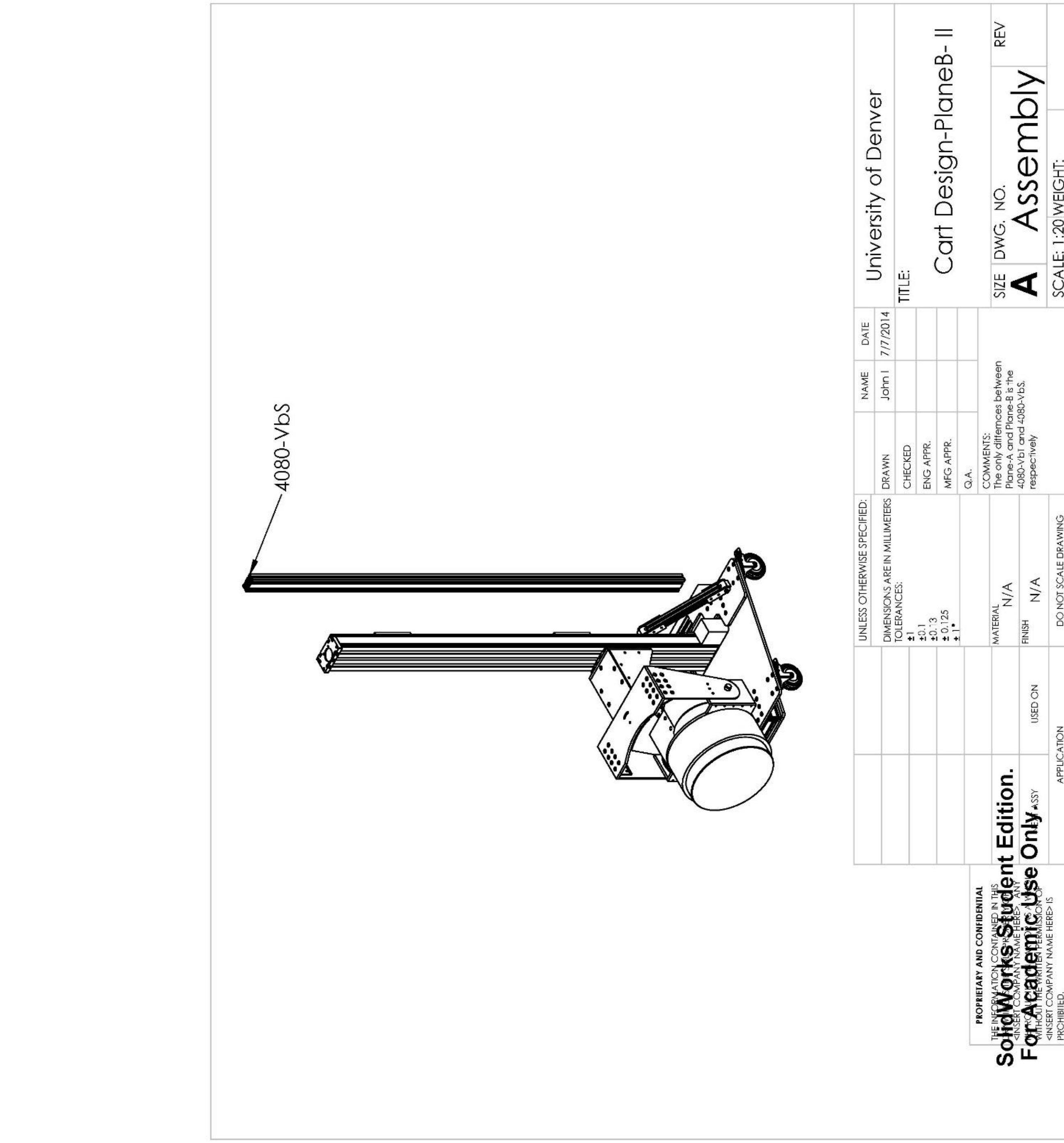

4080-VbS
University of Denver
TITLE:
Cart Design-PlaneB- II
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:20
WEIGHT:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
The only differnces between Plane-A and Plane-B is the 4080-Vb1 and 4080-VbS. respectively
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
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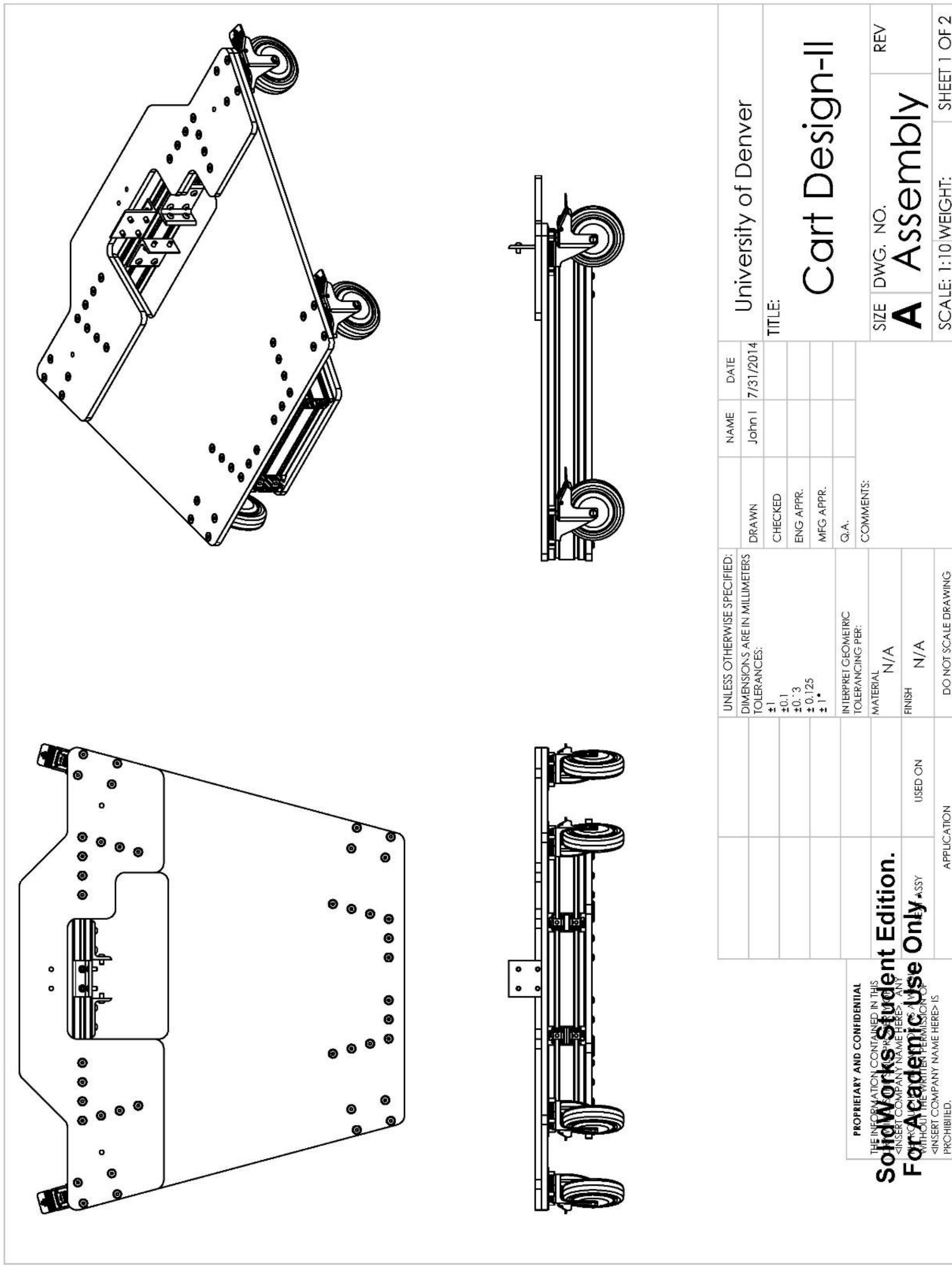

University of Denver
TITLE:
Cart Design-II
SIZE A
DWG. NO.
Assembly
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 2
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.3
± 0.125
± 1°
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
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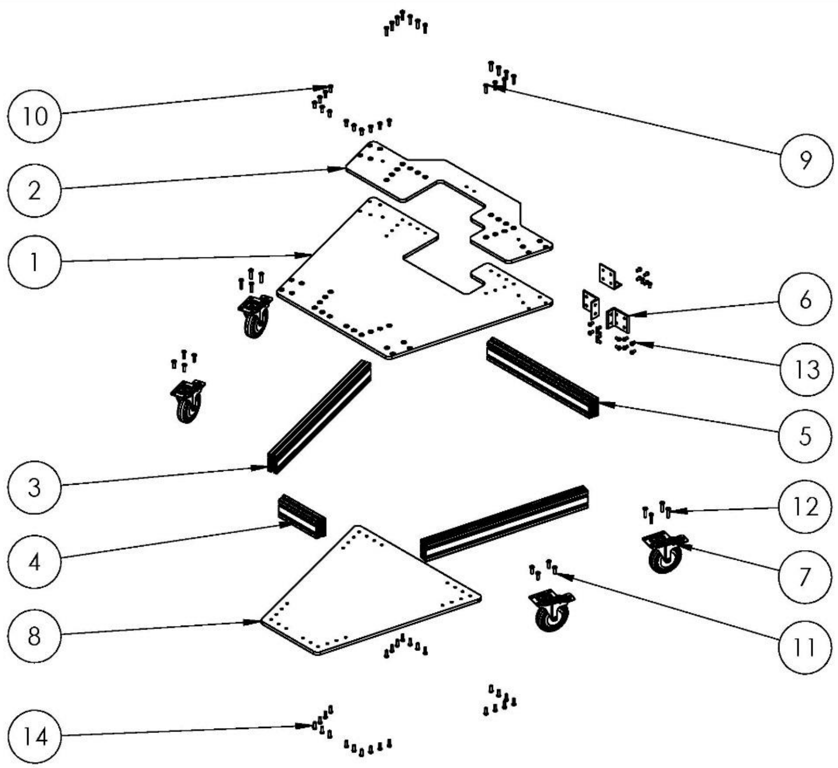
1
2
3
4
5



ITEM NO.	PART NUMBER	QTY.
1	C-S001	1
2	C-S002	1
3	40-4080-CL70	2
4	40-4080-CFs	1
5	40-4080-CBii	1
6	40-4375	3
7	ShepherdCasterCorp-PAT50161TZ-TPR33(GG)	4
8	C-I003_Future	1
9	M8X1.25X35	14
10	M8X1.25X25	12
11	M8X1.25X30	8
12	M8X1.25X40	8
13	M8X1.25X16	18
14	M8X1.25X25	26

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°

	NAME	DATE
DRAWN	John I	7/7/2014
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

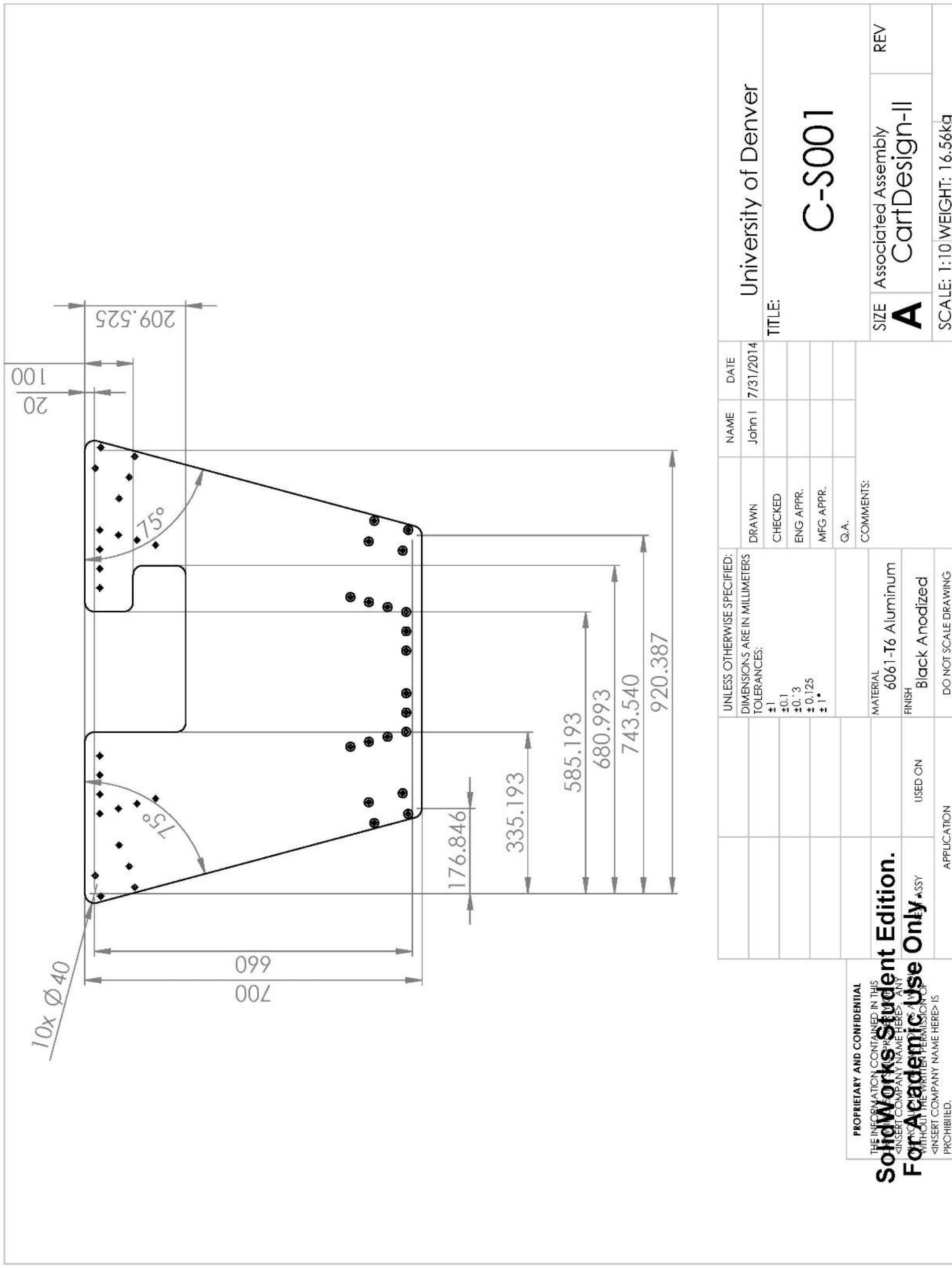
COMMENTS:
All bolts are black oxide coated.

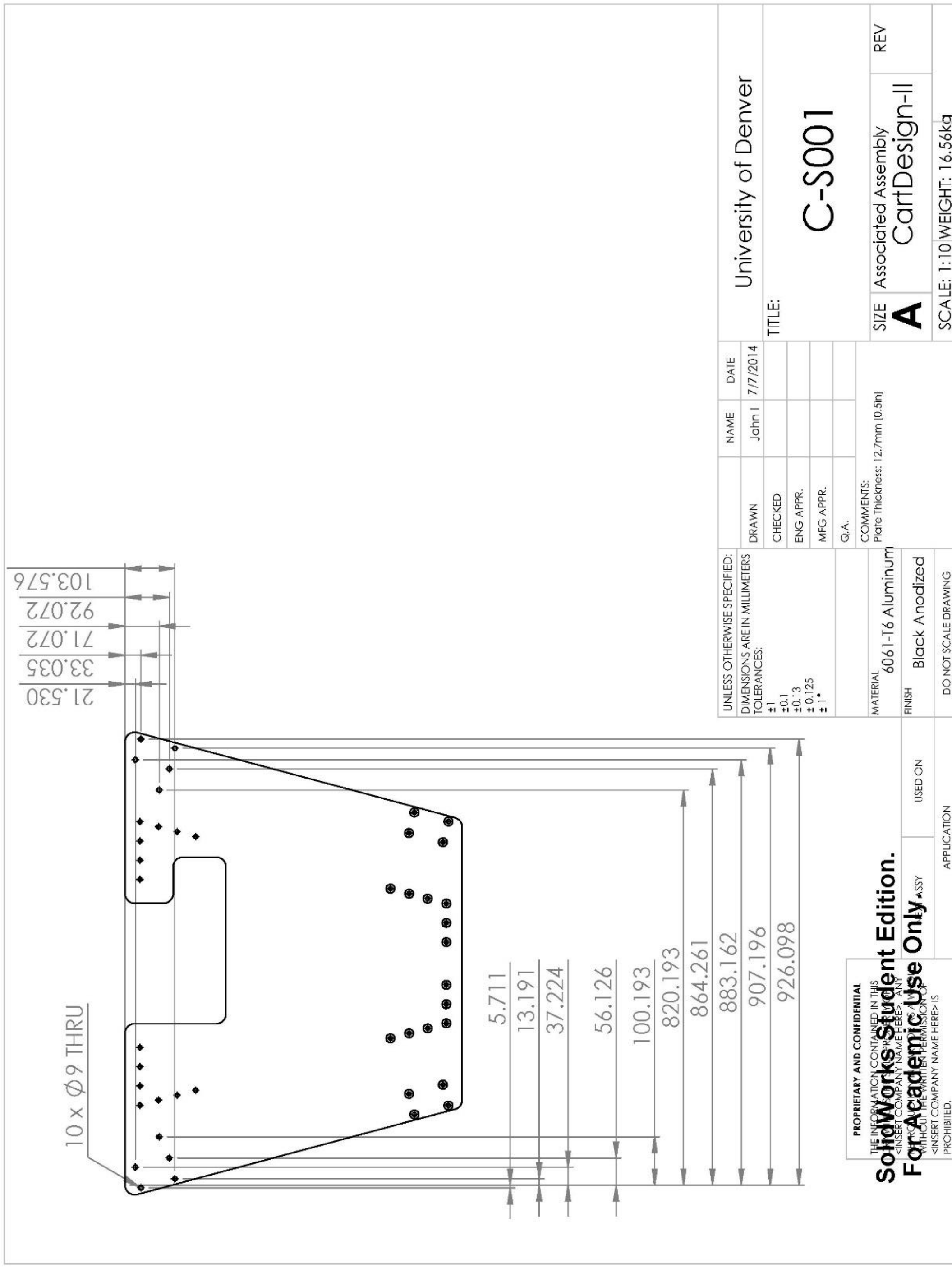
MATERIAL N/A
FINISH N/A
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

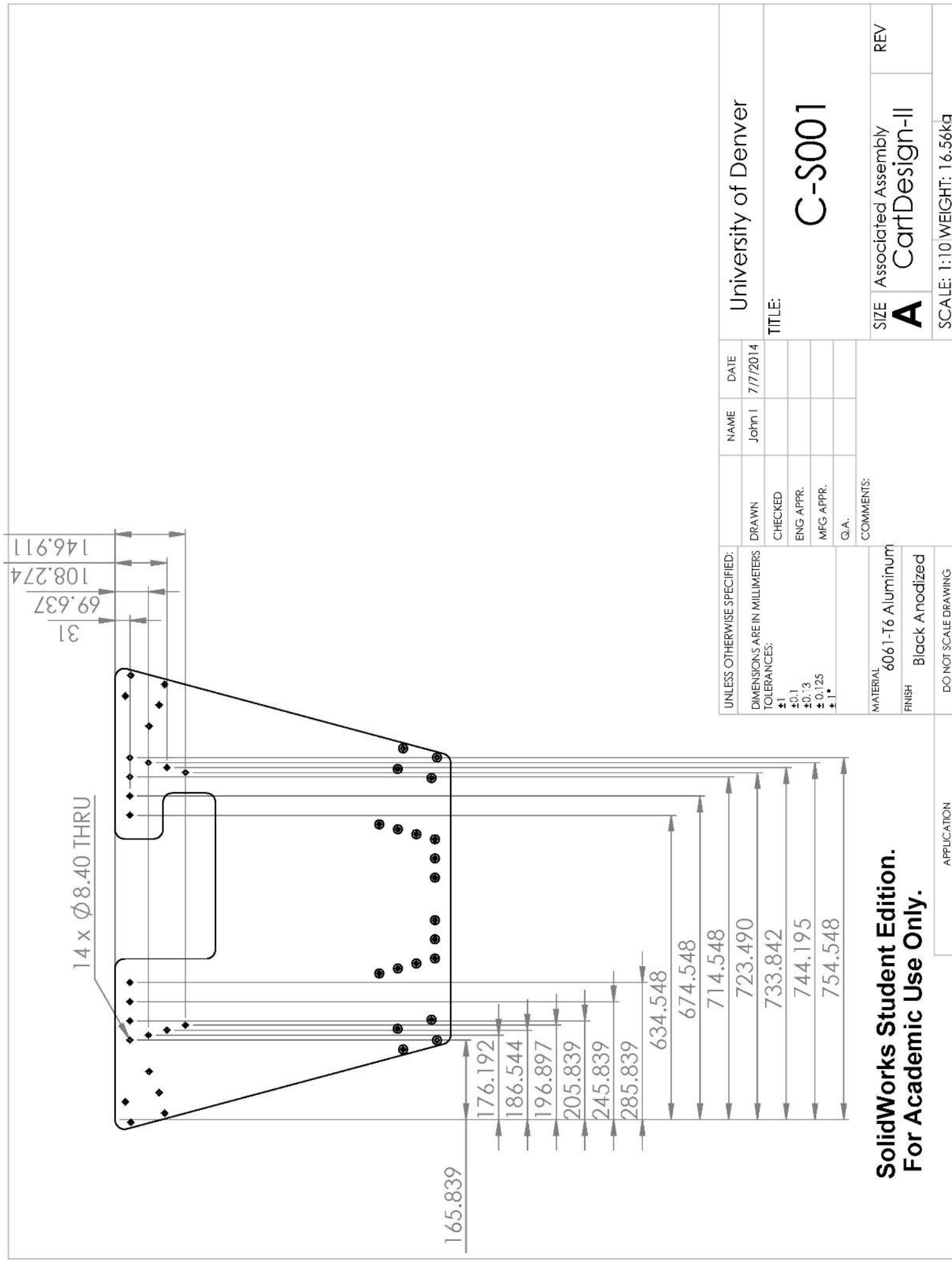
University of Denver
TITLE:
Cart Design-II-II
SIZE A DWG. NO. Assembly REV
SCALE: 1:10 WEIGHT:

5 4 3 2 1

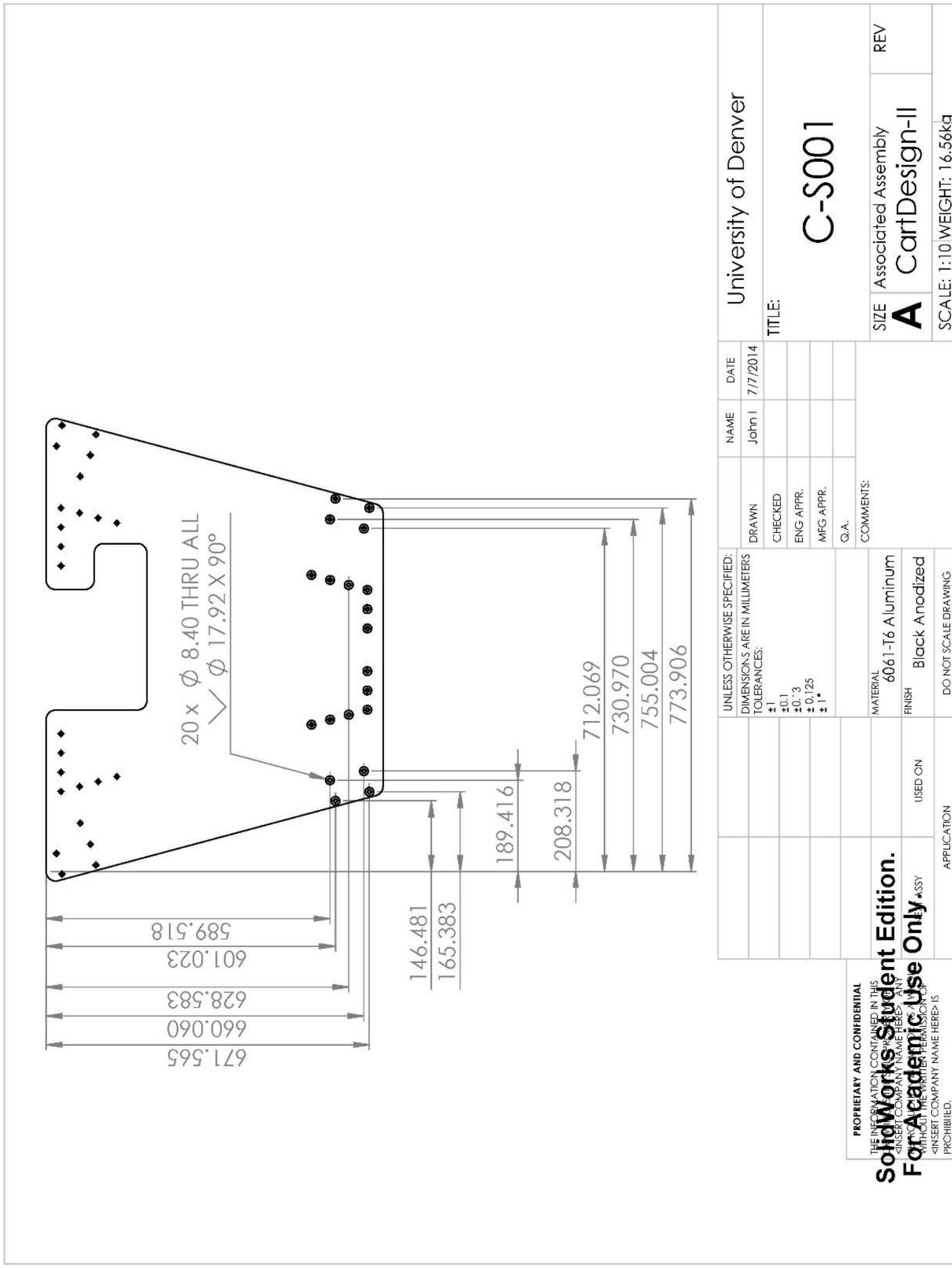

University of Denver
TITLE:
C-S001
SIZE A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10 WEIGHT: 16.56kg
NAME DATE
DRAWN John I 7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
SolidWorks Student Edition.
For Academic Use Only.
PROPRIETARY AND CONFIDENTIAL
10x Ø40
700
660
209.525
100
20
75°
75°
176.846
335.193
585.193
680.993
743.540
920.387

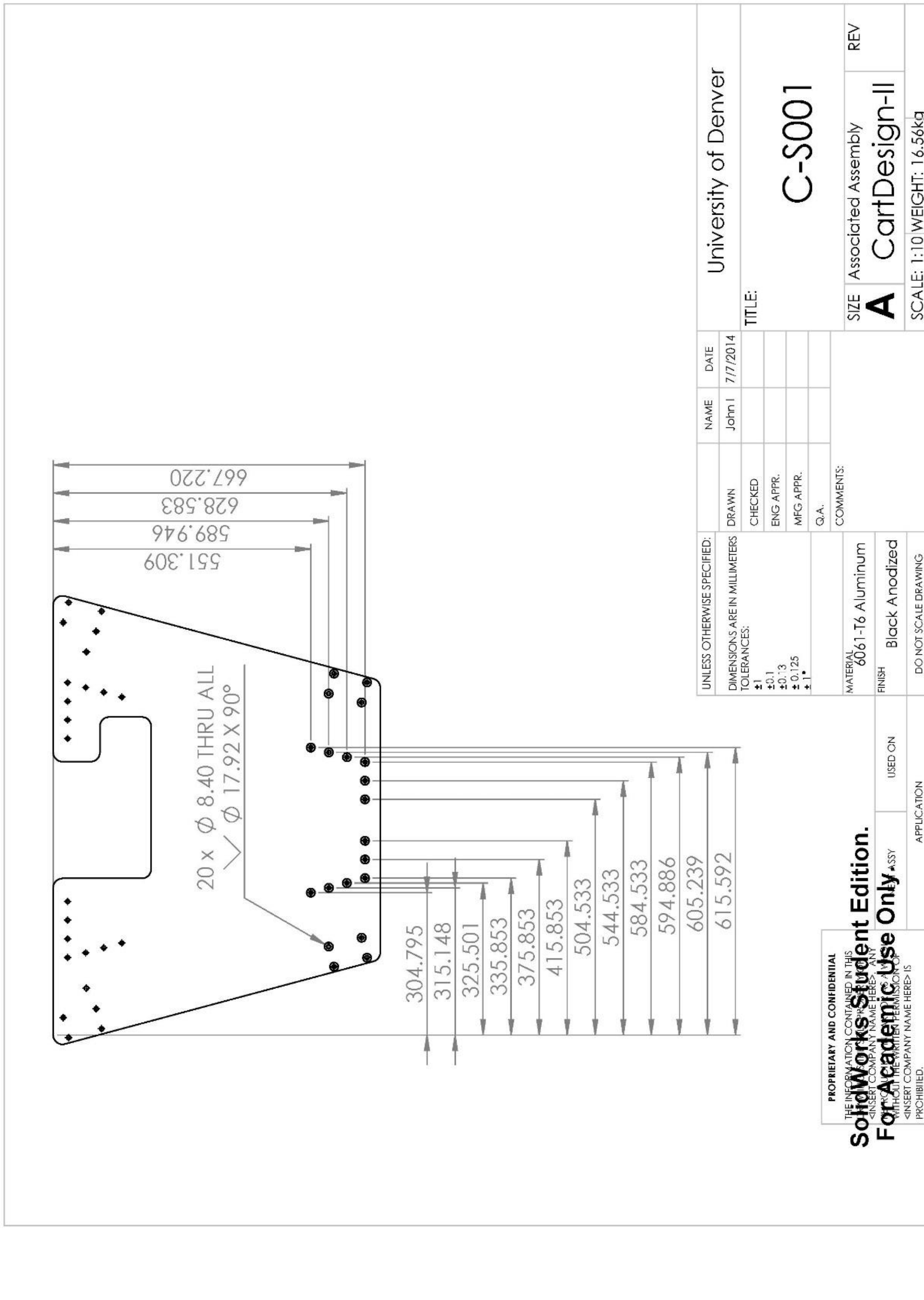


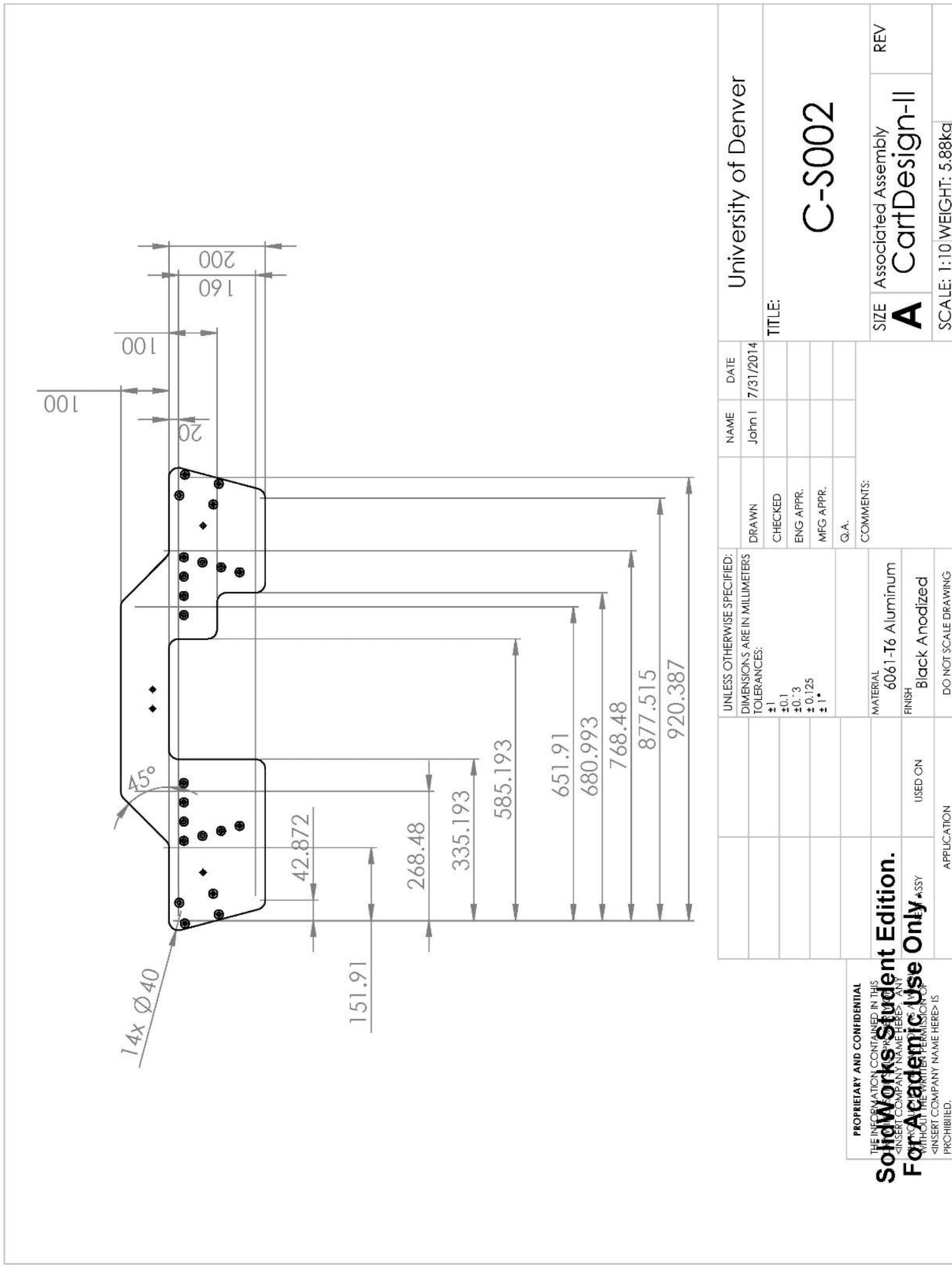
10 x Ø9 THRU
21.530
33.035
71.072
92.072
103.576
5.711
13.191
37.224
56.126
100.193
820.193
864.261
883.162
907.196
926.098
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
University of Denver
TITLE:
C-S001
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
SIZE
A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 16.56kg
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.



14 x Ø8.40 THRU
31
69.637
108.274
146.911
165.839
176.192
186.544
196.897
205.839
245.839
285.839
634.548
674.548
714.548
723.490
733.842
744.195
754.548
SolidWorks Student Edition.
For Academic Use Only.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
APPLICATION
University of Denver
TITLE:
C-S001
SIZE
A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 16.56kg


20 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
712.069
730.970
755.004
773.906
189.416
208.318
146.481
165.383
589.518
601.023
628.583
660.060
671.565
University of Denver
TITLE:
C-S001
SIZE
A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 16.56kg
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5


20 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
551.309
589.946
628.583
667.220
304.795
315.148
325.501
335.853
375.853
415.853
504.533
544.533
584.533
594.886
605.239
615.592
University of Denver
TITLE:
C-S001
SIZE
A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 16.56kg
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5



200
160
100
100
20
45°
14x Ø40
42.872
151.91
268.48
335.193
585.193
651.91
680.993
768.48
877.515
920.387
University of Denver
TITLE:
C-S002
SIZE
A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10 WEIGHT: 5.88kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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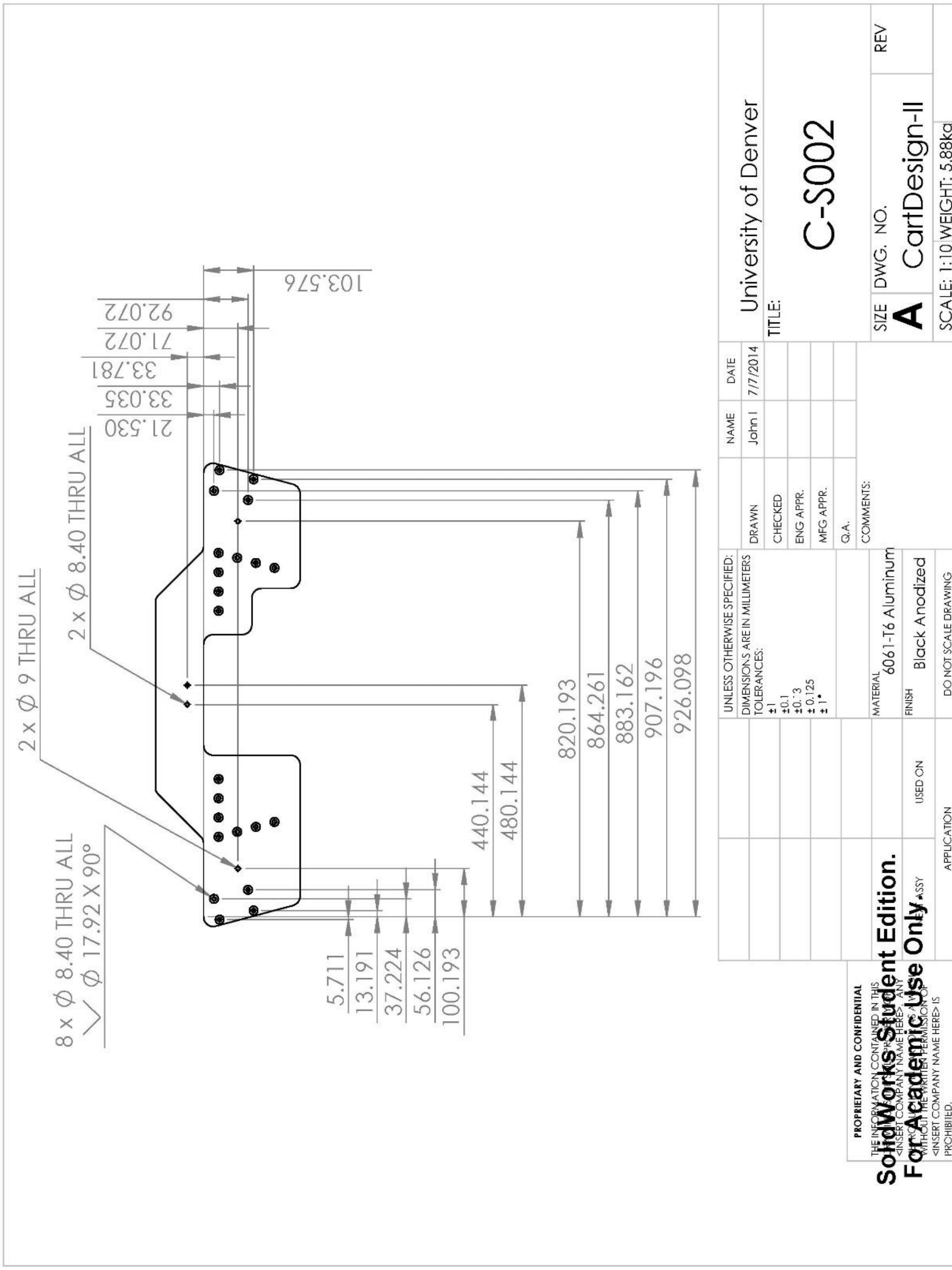
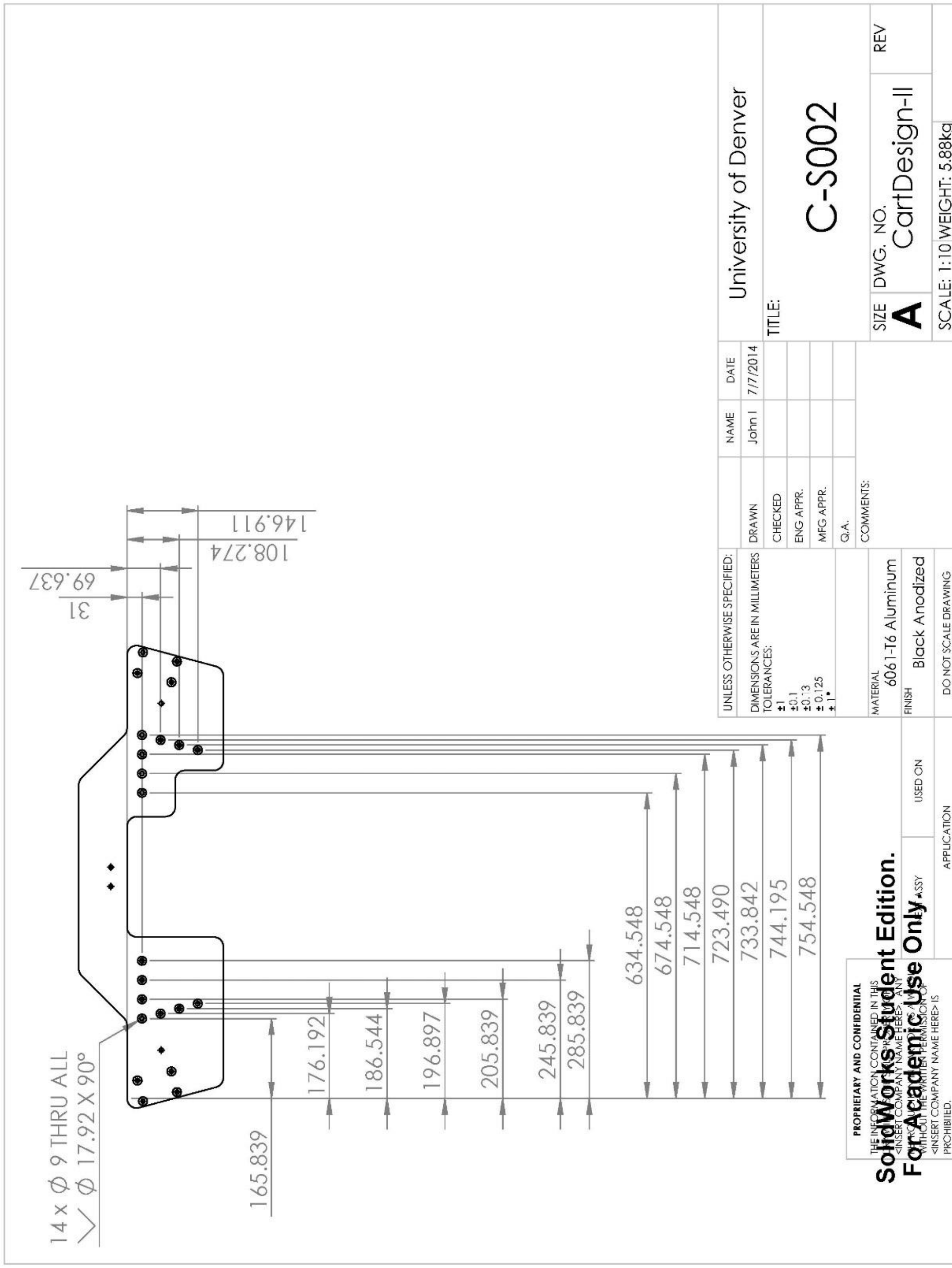
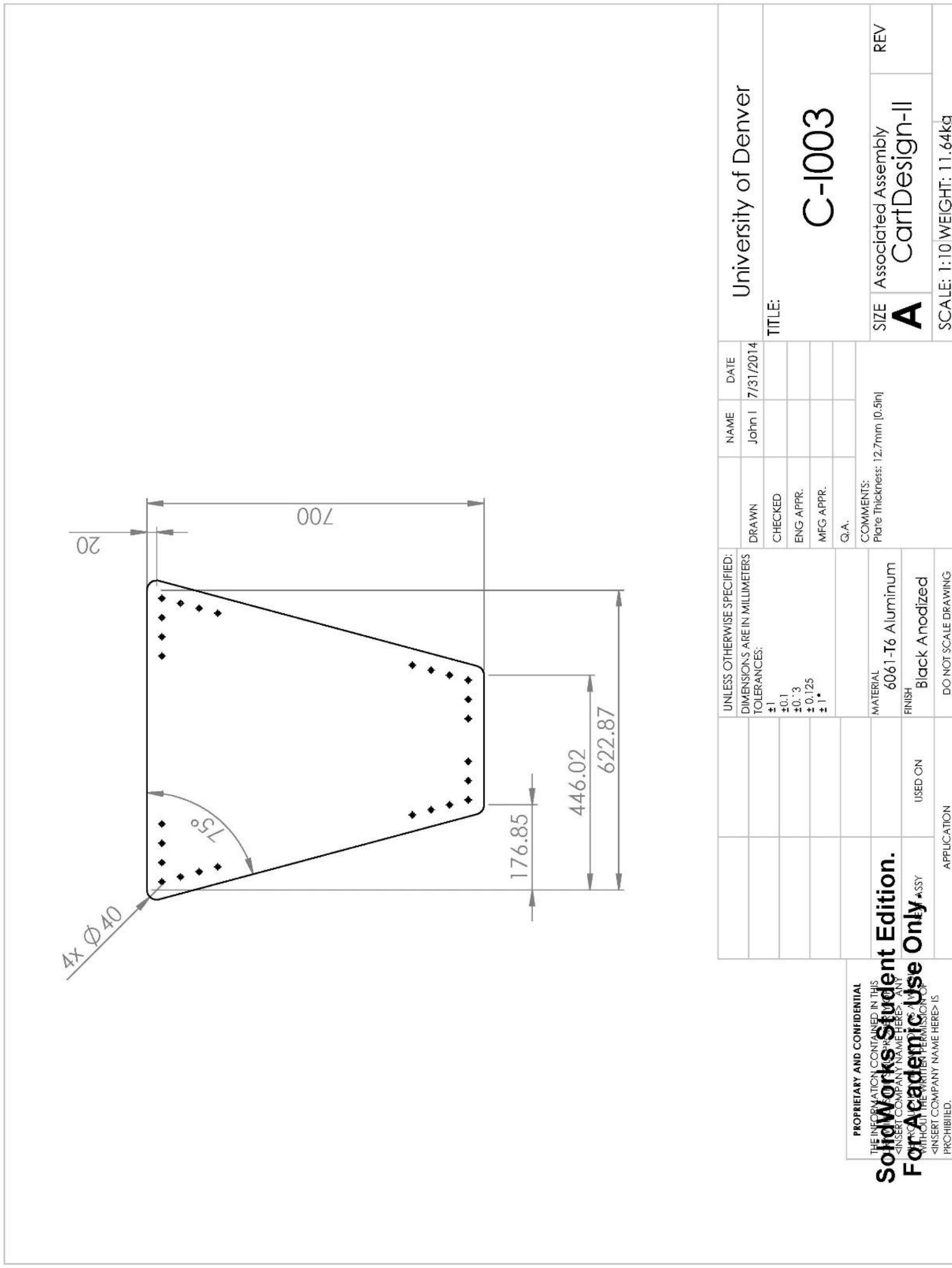
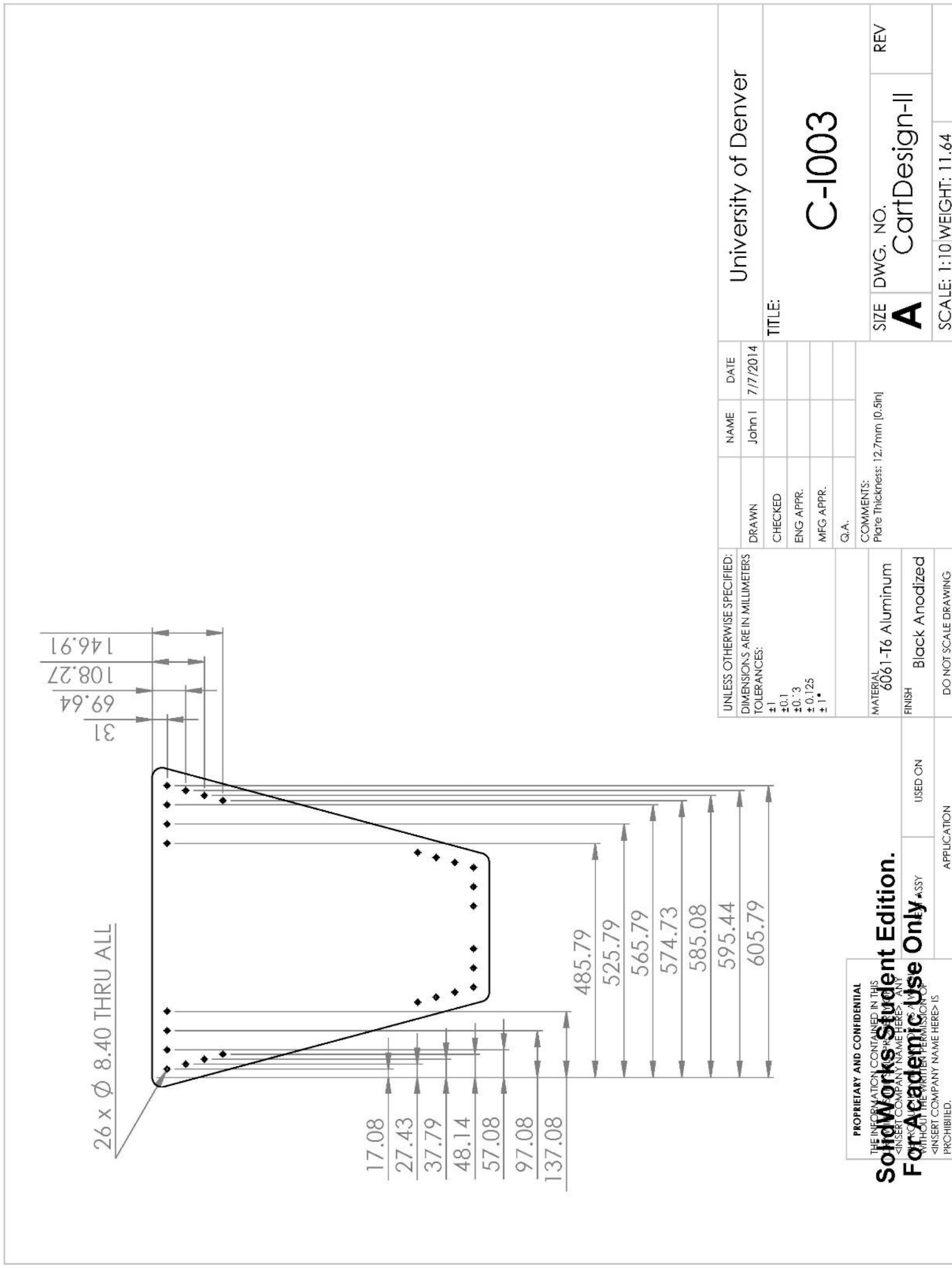

8 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
2 x Ø 9 THRU ALL
2 x Ø 8.40 THRU ALL
5.711
13.191
37.224
56.126
100.193
440.144
480.144
820.193
864.261
883.162
907.196
926.098
21.530
33.035
33.781
71.072
92.072
103.576
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
APPLICATION
USED ON
University of Denver
TITLE:
C-S002
SIZE
A
DWG. NO.
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 5.88kg
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.


14 x Ø 9 THRU ALL
Ø 17.92 X 90°
165.839
176.192
186.544
196.897
205.839
245.839
285.839
634.548
674.548
714.548
723.490
733.842
744.195
754.548
31
69.637
108.274
146.911
University of Denver
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
C-S002
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
SIZE
A
DWG. NO.
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 5.88kg
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.


4X Ø40
20
700
75°
176.85
446.02
622.87
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm [0.5in]
University of Denver
TITLE:
C-I003
SIZE
A
Associated Assembly
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 11.64kg
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5


26 x Ø 8.40 THRU ALL
17.08
27.43
37.79
48.14
57.08
97.08
137.08
485.79
525.79
565.79
574.73
585.08
595.44
605.79
31
69.64
108.27
146.91
University of Denver
TITLE:
C-I003
SIZE A
DWG. NO.
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 11.64
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm [0.5in]
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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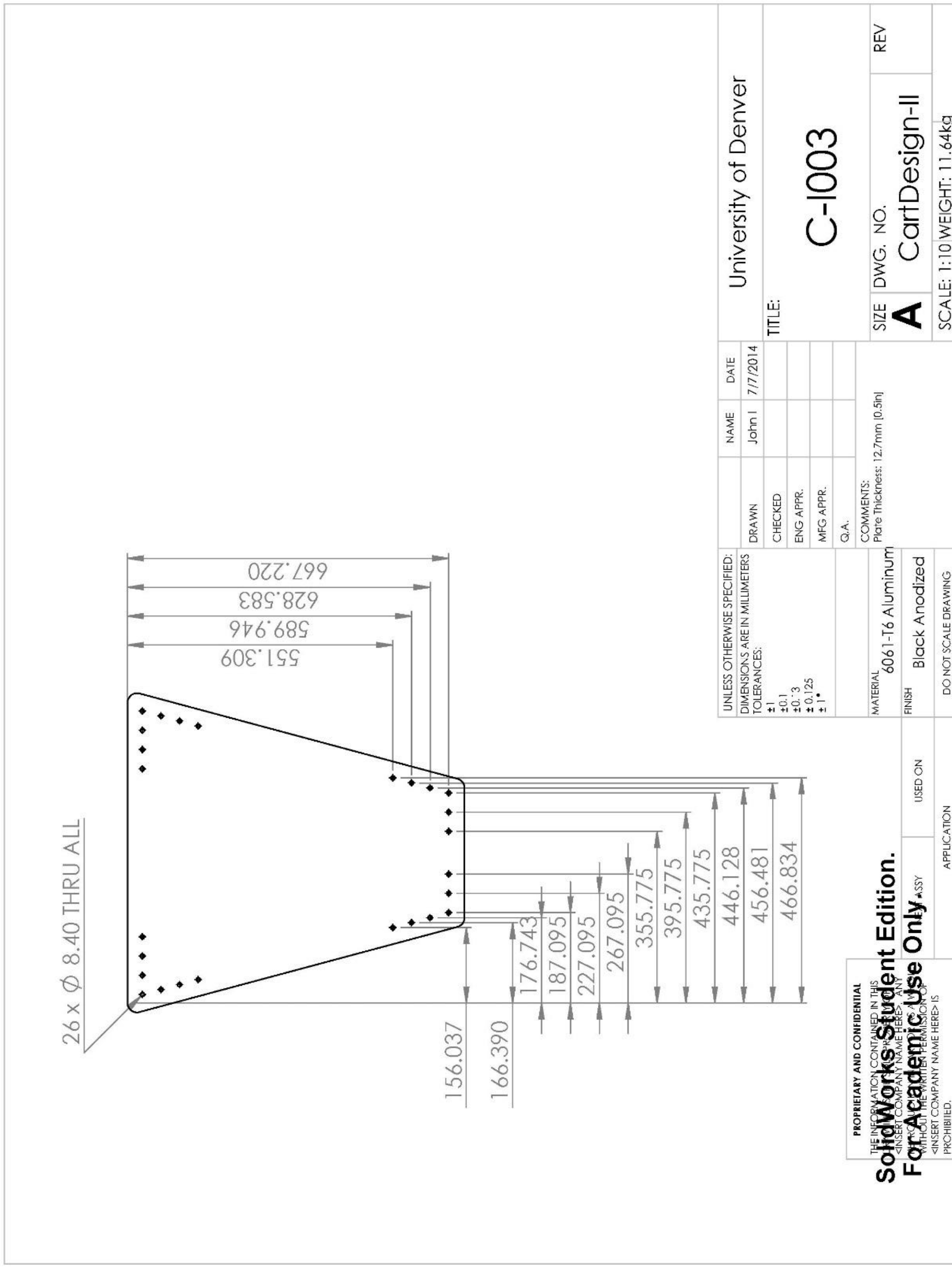
26 x Ø 8.40 THRU ALL
551.309
589.946
628.583
667.220
156.037
166.390
176.743
187.095
227.095
267.095
355.775
395.775
435.775
446.128
456.481
466.834
University of Denver
TITLE:
C-I003
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
SIZE
A
DWG. NO.
CartDesign-II
REV
SCALE: 1:10
WEIGHT: 11.64kg
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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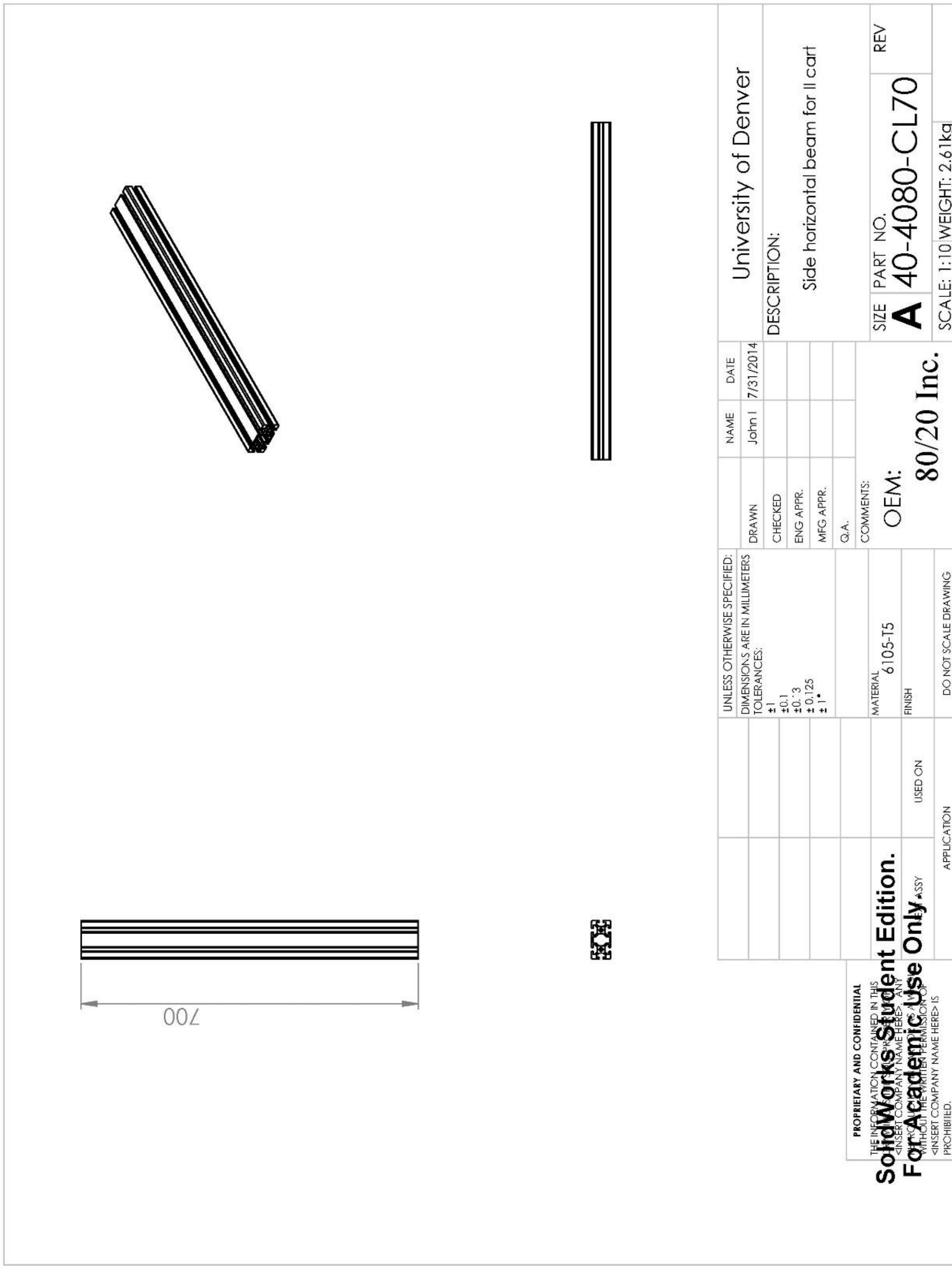
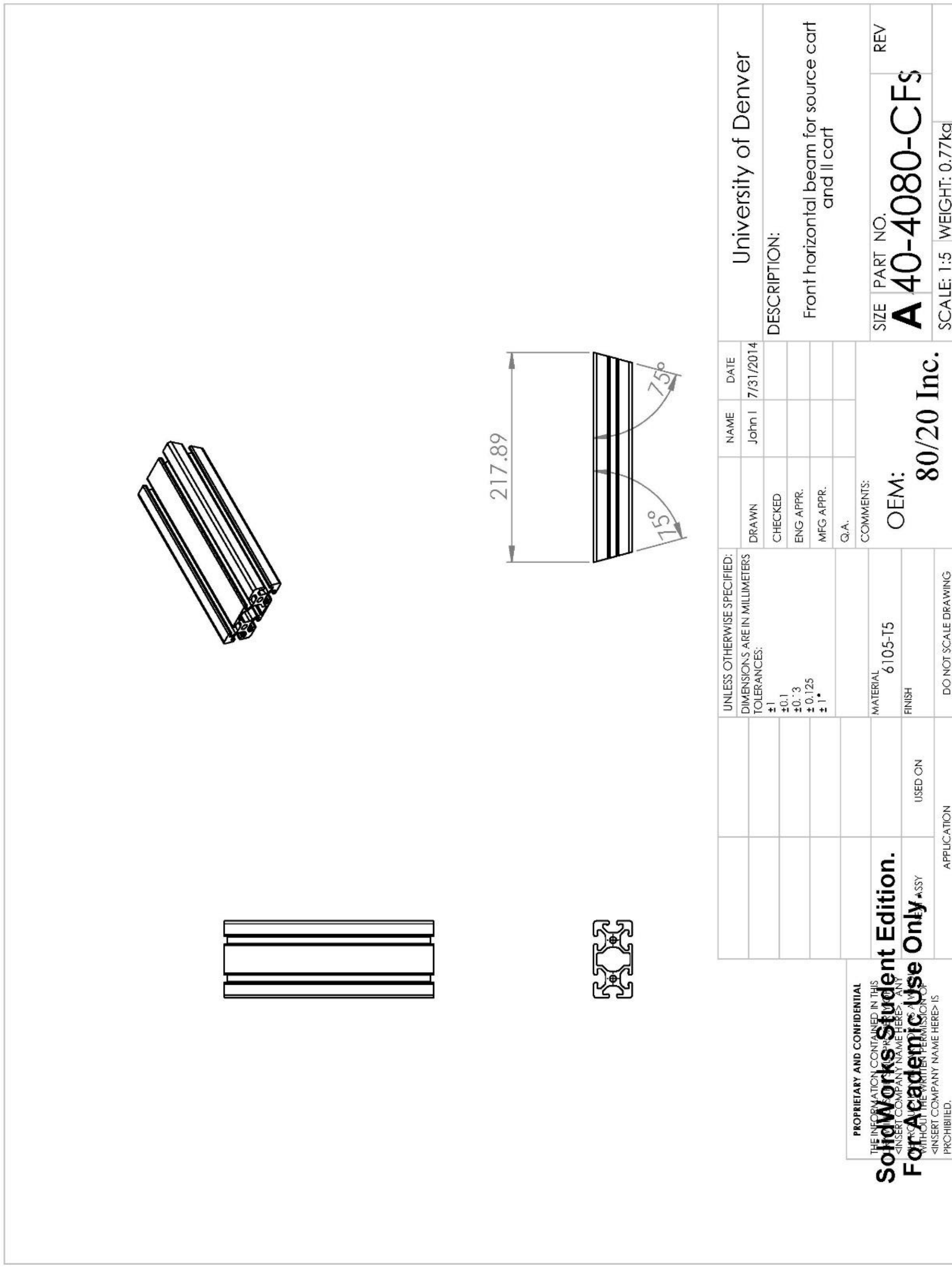
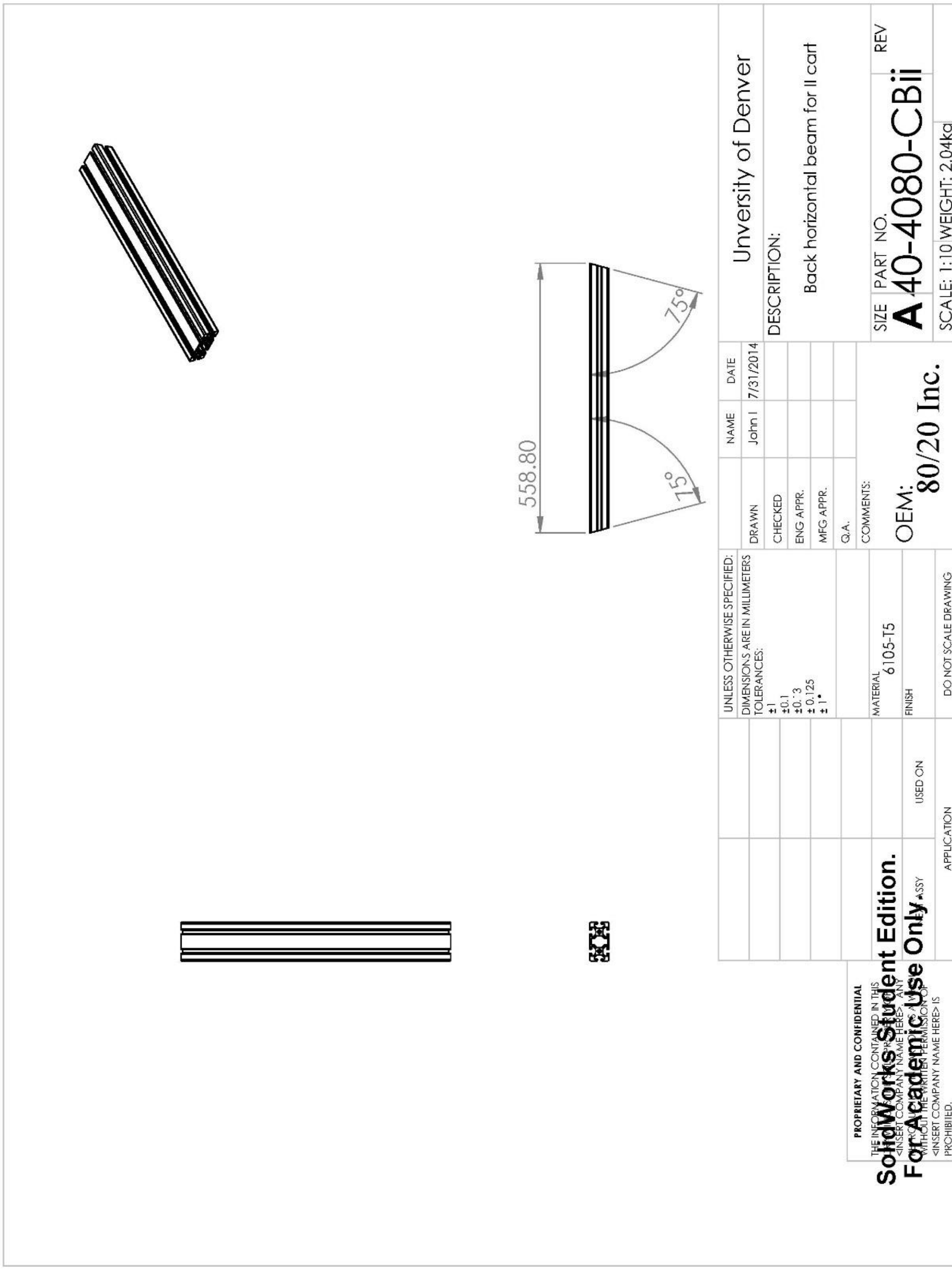

700
University of Denver
DESCRIPTION:
Side horizontal beam for II cart
SIZE
A
PART NO.
40-4080-CL70
REV
SCALE: 1:10
WEIGHT: 2.61kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5


217.89
75°
75°
University of Denver
DESCRIPTION:
Front horizontal beam for source cart and II cart
SIZE
A
PART NO.
40-4080-CFs
REV
SCALE: 1:5
WEIGHT: 0.77kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.


Unversity of Denver
DESCRIPTION:
Back horizontal beam for II cart
SIZE
A
PART NO.
40-4080-CBii
REV
SCALE: 1:10
WEIGHT: 2.04kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.3
± 0.125
± 1°
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
558.80
75°
75°
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
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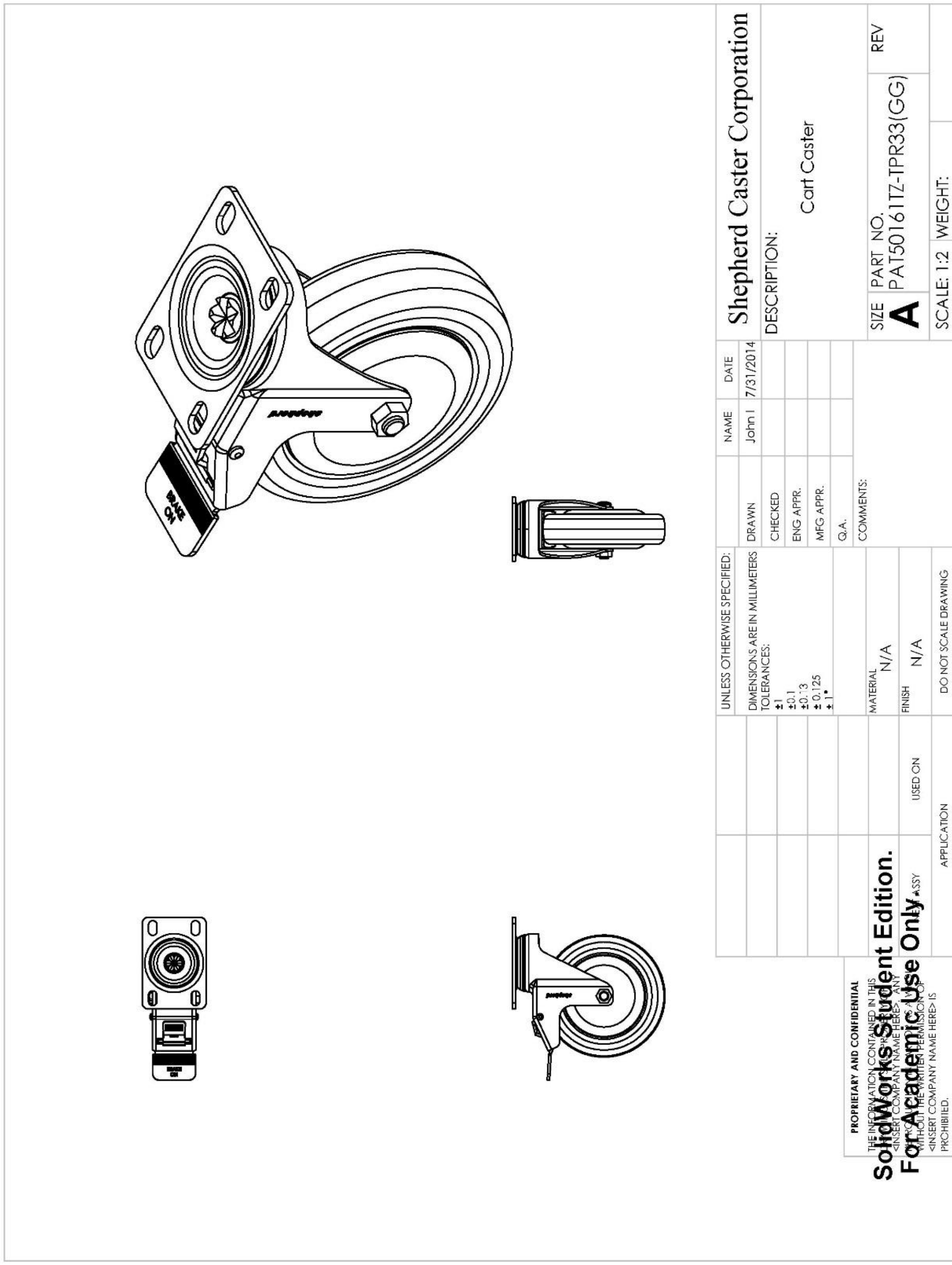
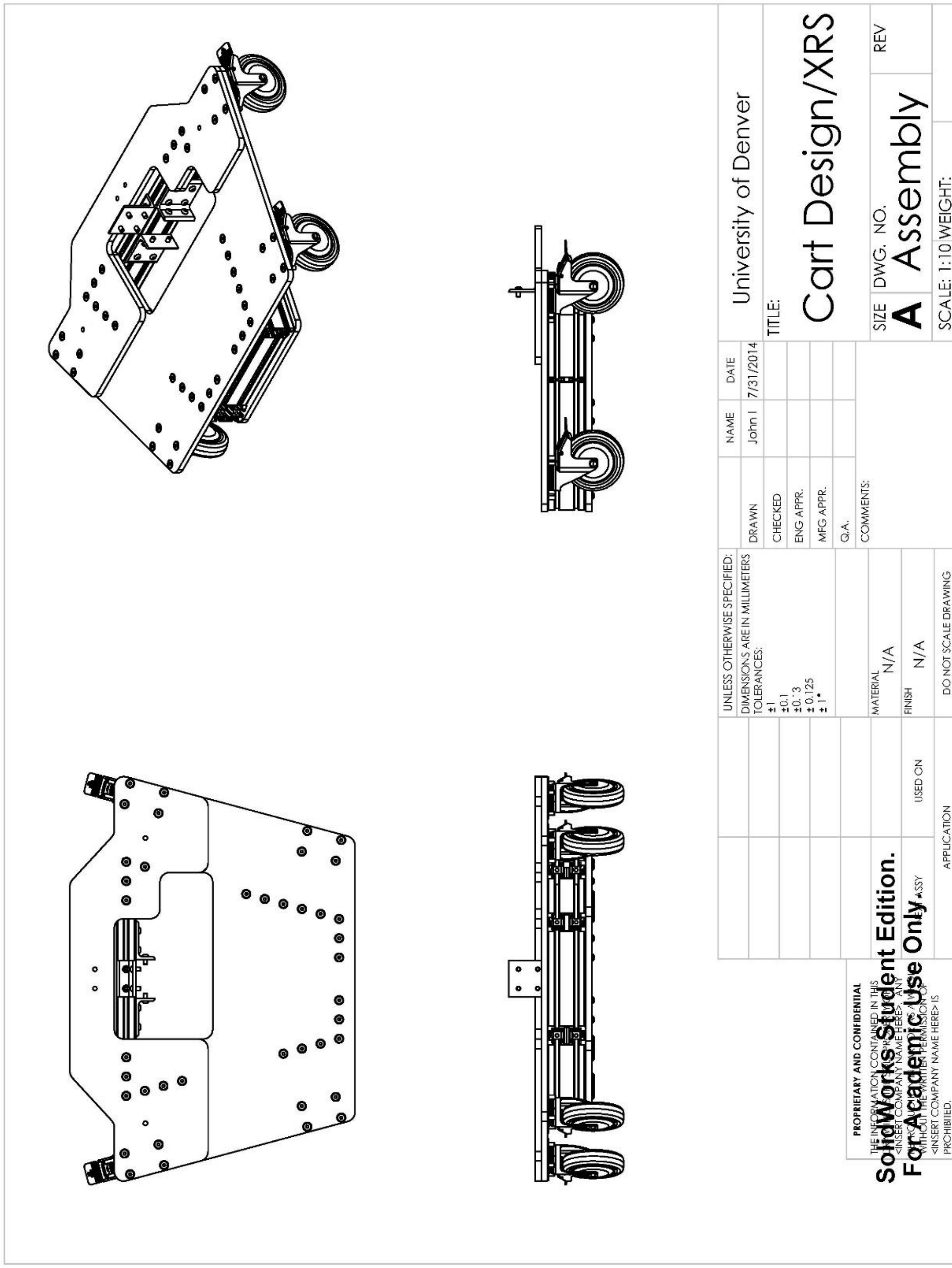


BRAKE ON
Shepherd Caster Corporation
DESCRIPTION:
Cart Caster
SIZE
A
PART NO.
PAT50161TZ-TPR33(GG)
REV
SCALE: 1:2
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
<INSERT COMPANY NAME HERE> IS PROHIBITED.
SolidWorks Student Edition.
For Academic Use Only.


University of Denver
TITLE:
Cart Design/XRS
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:10
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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1
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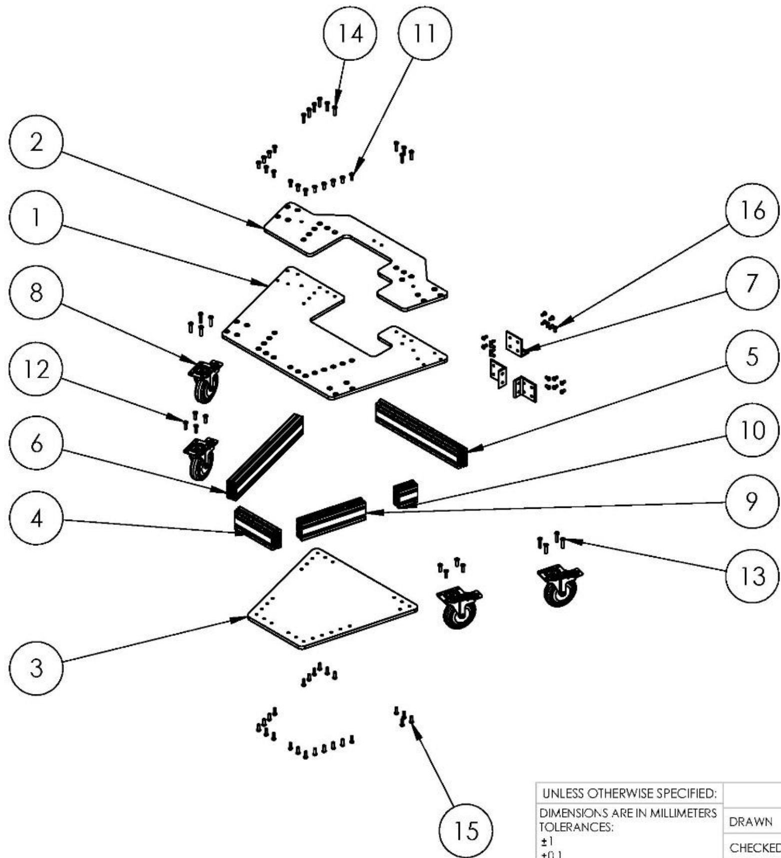


ITEM NO.	PART NUMBER	QTY.
1	C-SOL1	1
2	C-SOL2	1
3	C-IOL3	1
4	40-4080-CFs	1
5	40-4080-CBs	1
6	40-4080-C5	1
7	40-4375	3
8	ShepherdCasterCorp-PAT50161TZ-TPR33(GG)	4
9	40-4080-C5L	1
10	40-4080-C5S	1
11	M8X1.25X25	14
12	M8X1.25X30	8
13	M8X1.25X40	8
14	M8X1.25X35	10
15	M8X1.25X25	24
16	M8X1.25X16	18

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°

	NAME	DATE
DRAWN	John I	7/7/2014
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL N/A

FINISH N/A

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

University of Denver

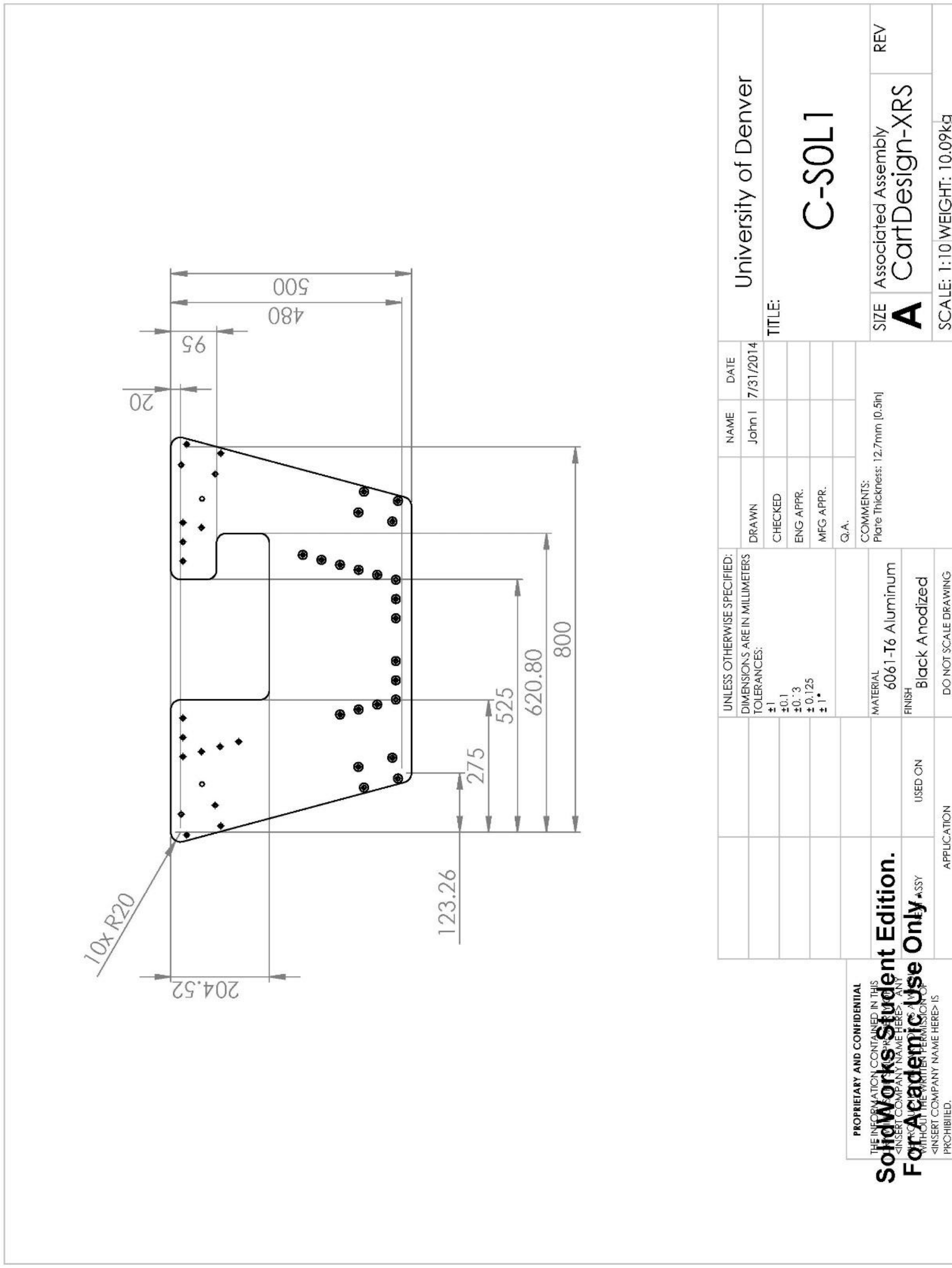
TITLE:

Cart Design/XRS

SIZE A | DWG. NO. Assembly | REV

SCALE: 1:10 WEIGHT:

5 4 3 2 1



500
480
95
20
10x R20
204.52
123.26
275
525
620.80
800
University of Denver
TITLE:
C-SOL1
Associated Assembly
CartDesign-XRS
SIZE A
REV
SCALE: 1:10 WEIGHT: 10.09kg
NAME DATE
DRAWN John I 7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.`3
± 0.125
± 1°
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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1
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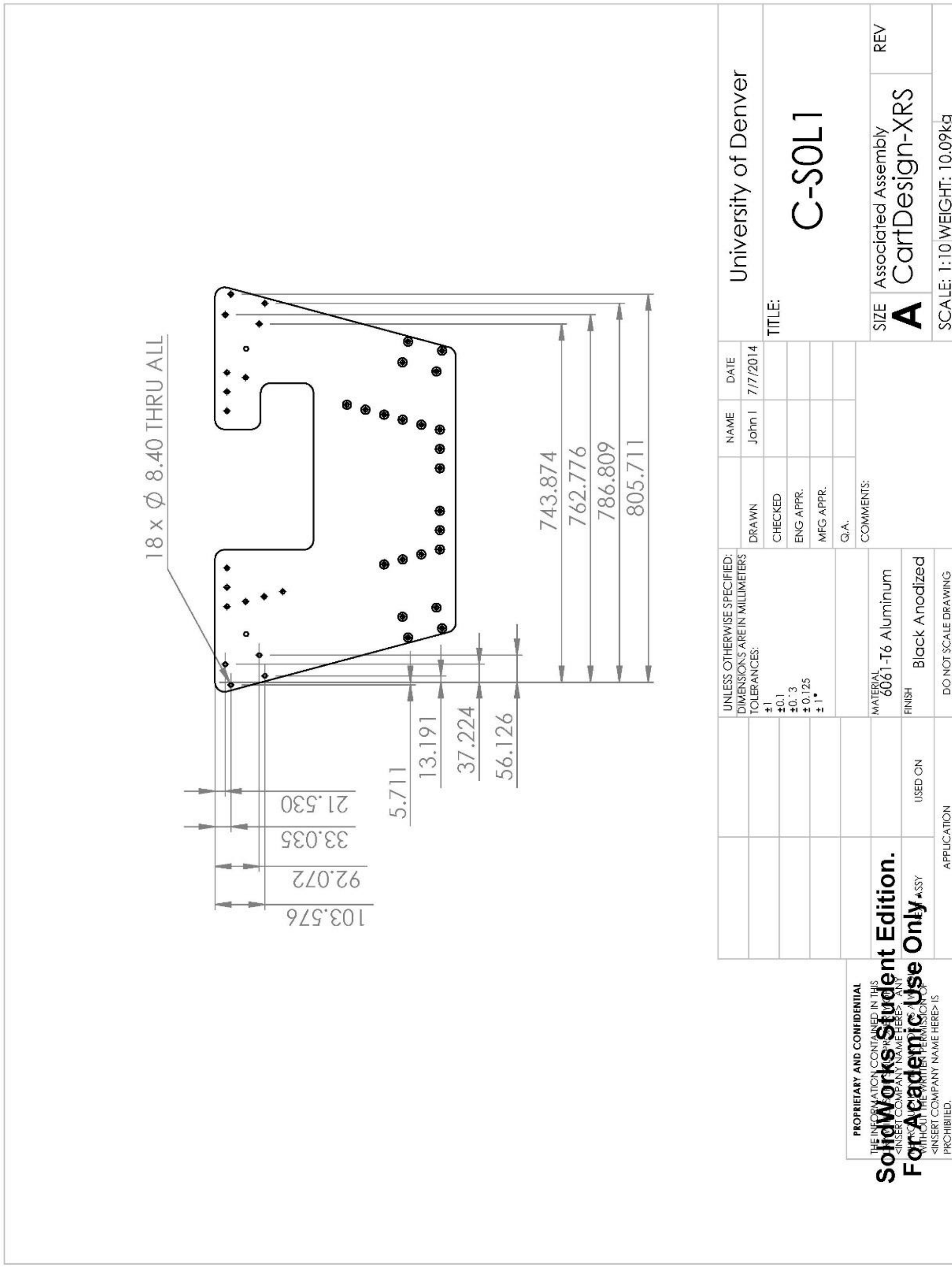
18 x Ø 8.40 THRU ALL
743.874
762.776
786.809
805.711
5.711
13.191
37.224
56.126
21.530
33.035
92.072
103.576
University of Denver
TITLE:
C-SOL1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
SIZE
A
Associated Assembly
CartDesign-XRS
REV
SCALE: 1:10
WEIGHT: 10.09kg
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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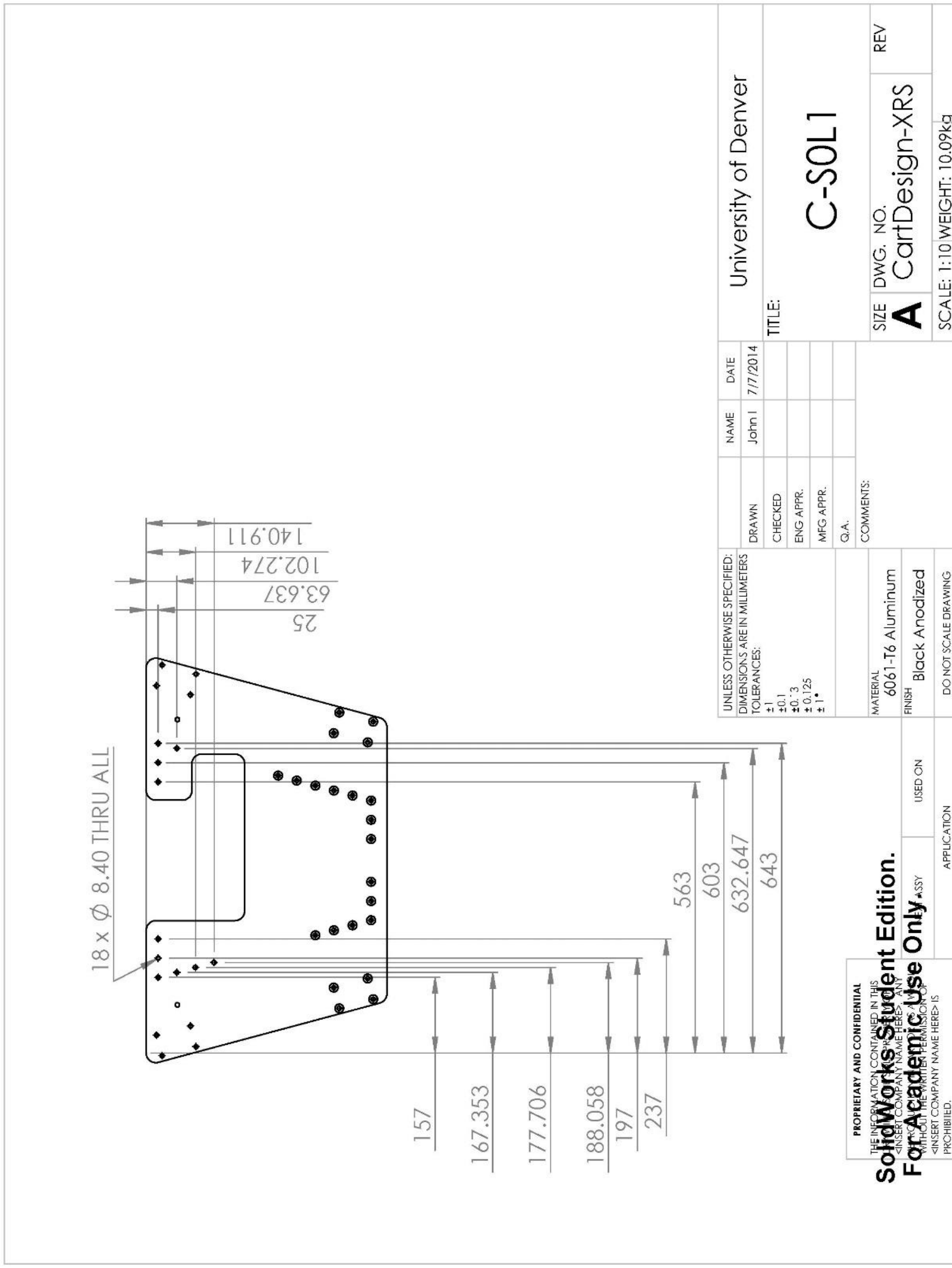
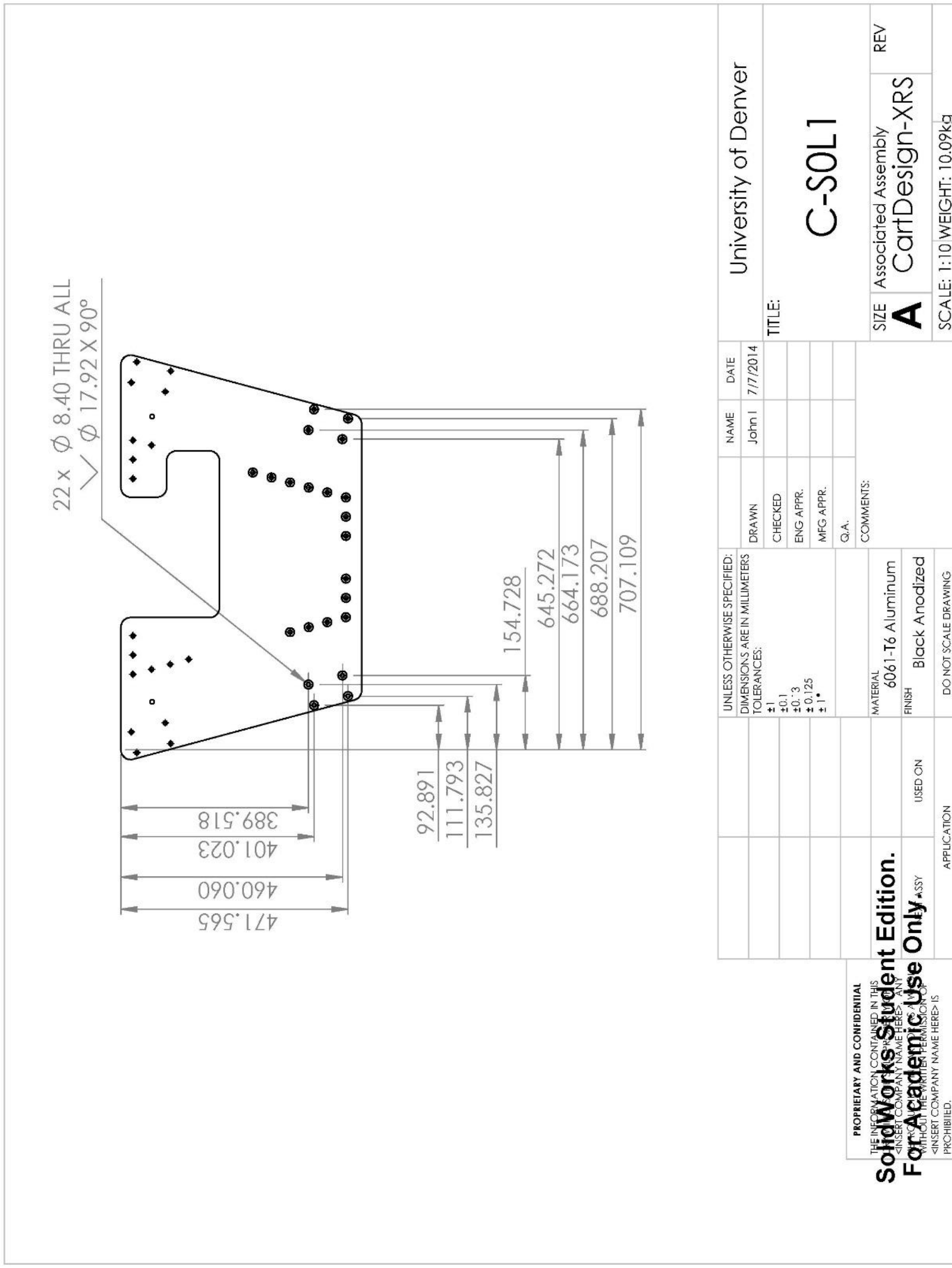

18 x Ø 8.40 THRU ALL
25
63.637
102.274
140.911
157
167.353
177.706
188.058
197
237
563
603
632.647
643
University of Denver
TITLE:
C-SOL1
SIZE
A
DWG. NO.
CartDesign-XRS
REV
SCALE: 1:10
WEIGHT: 10.09kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5



22 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
389.518
401.023
460.060
471.565
92.891
111.793
135.827
154.728
645.272
664.173
688.207
707.109
University of Denver
TITLE:
C-SOL1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
SIZE
A
Associated Assembly
CartDesign-XRS
REV
SCALE: 1:10
WEIGHT: 10.09kg
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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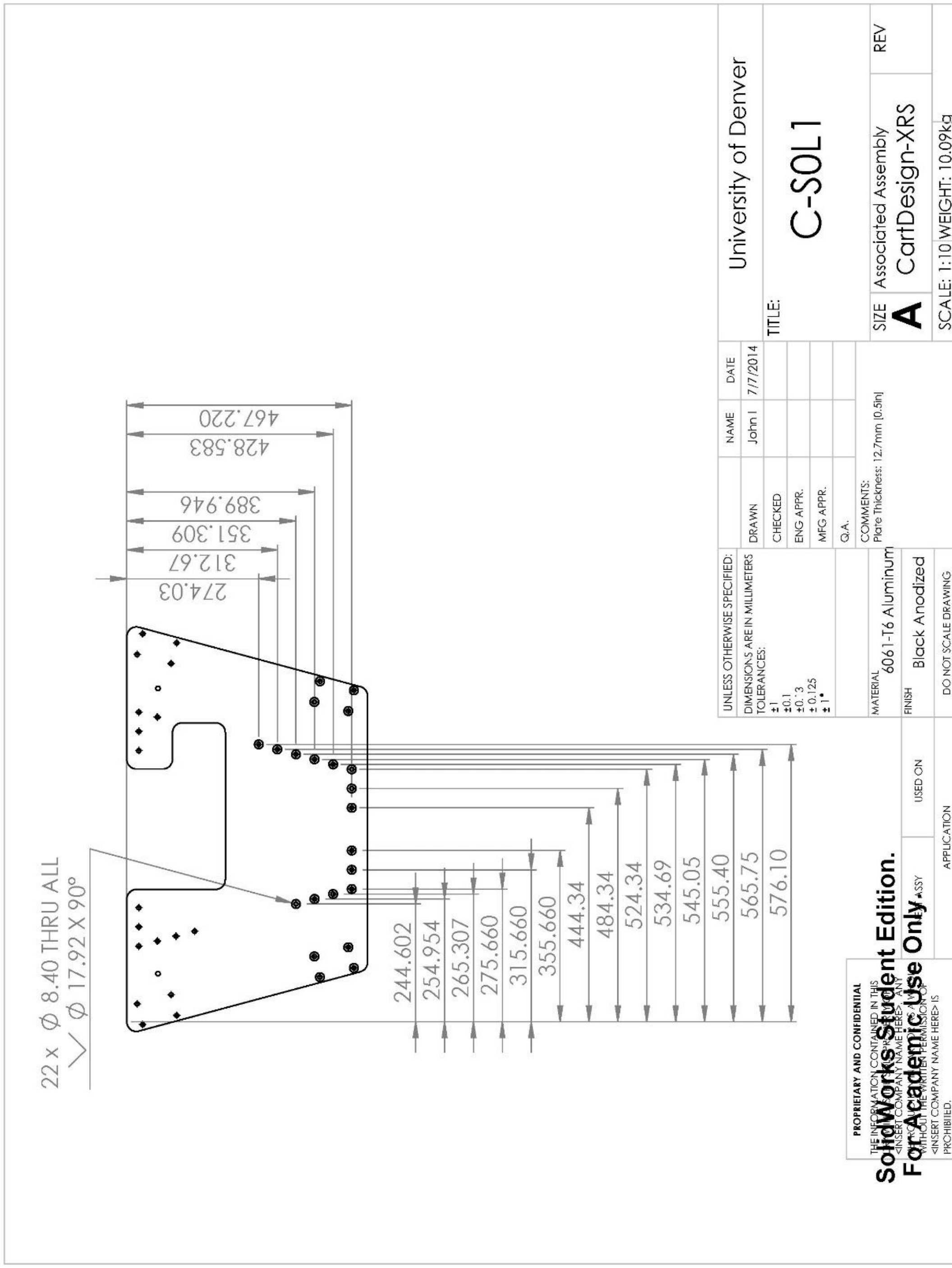
22 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
467.220
428.583
389.946
351.309
312.67
274.03
244.602
254.954
265.307
275.660
315.660
355.660
444.34
484.34
524.34
534.69
545.05
555.40
565.75
576.10
University of Denver
TITLE:
C-SOL1
SIZE
A
Associated Assembly
CartDesign-XRS
REV
SCALE: 1:10
WEIGHT: 10.09kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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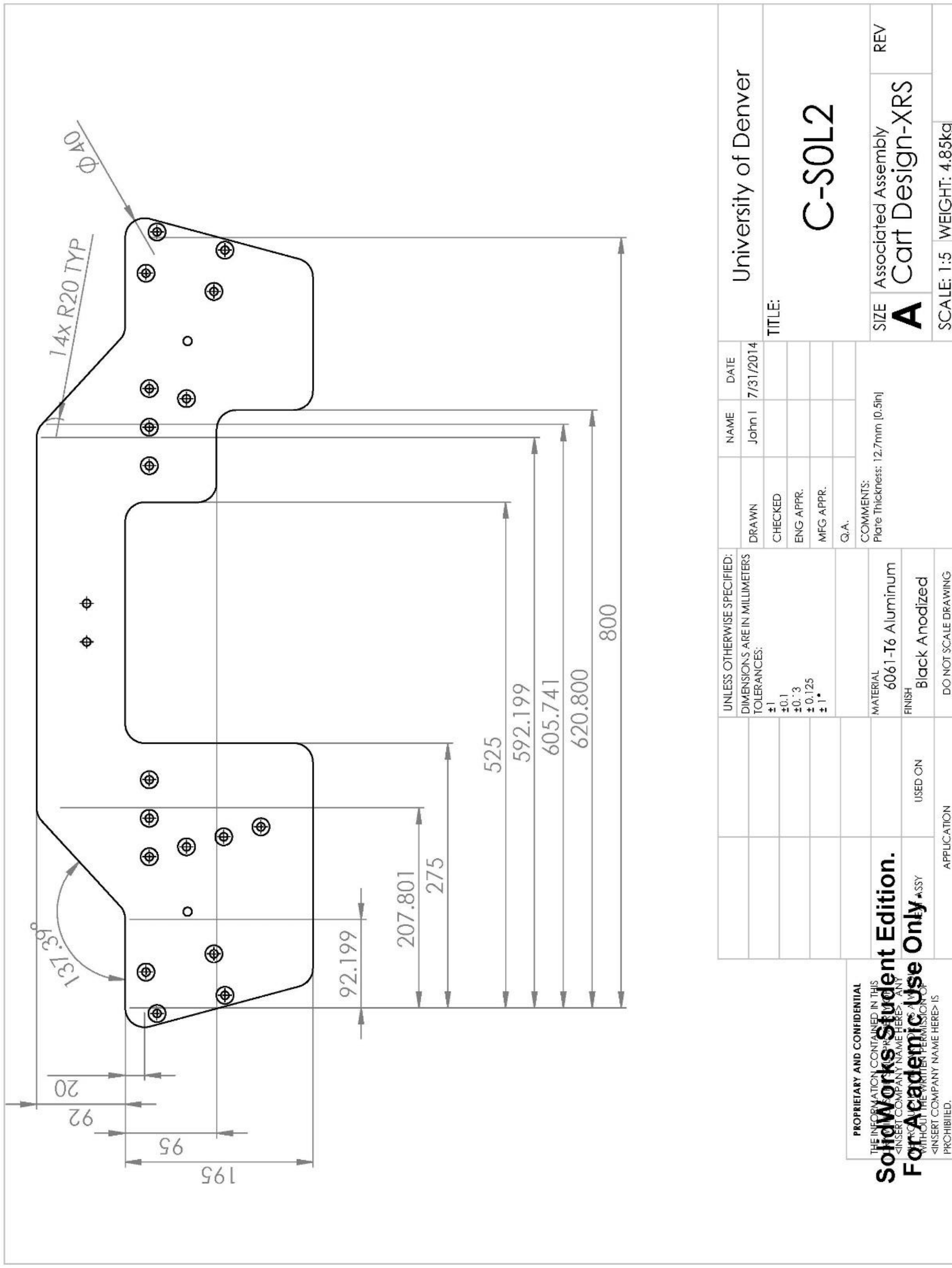

Φ40
14x R20 TYP
137.39°
20
92
95
195
92.199
207.801
275
525
592.199
605.741
620.800
800
University of Denver
TITLE:
C-S0L2
SIZE A
Associated Assembly
Cart Design-XRS
REV
SCALE: 1:5
WEIGHT: 4.85kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm [0.5in]
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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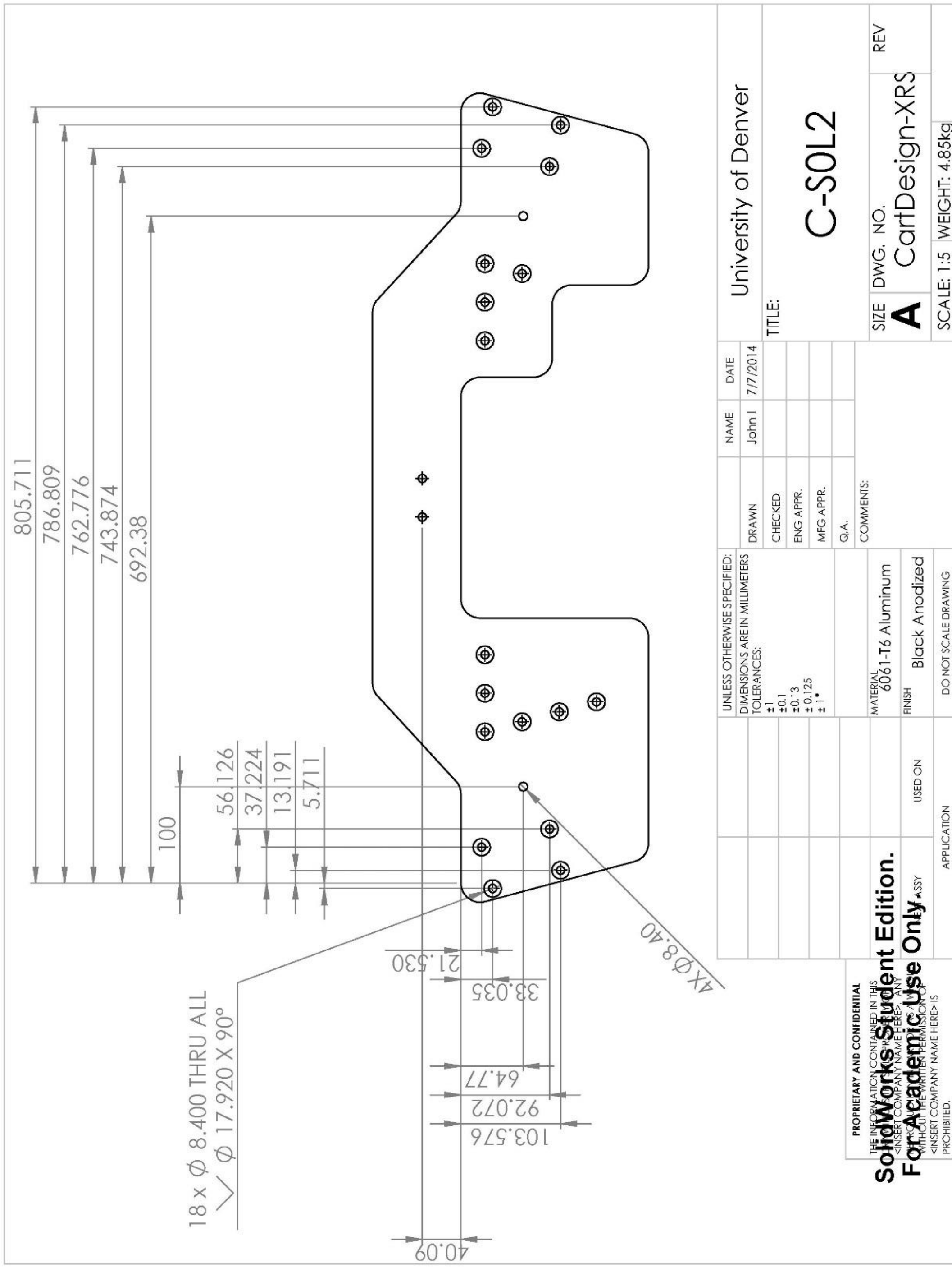
1
2
3
4
5


805.711
786.809
762.776
743.874
692.38
100
56.126
37.224
13.191
5.711
21.530
33.035
64.77
92.072
103.576
40.09
18 x Ø 8.400 THRU ALL
⌵ Ø 17.920 X 90°
4X Ø8.40
University of Denver
TITLE:
C-SOL2
SIZE
A
DWG. NO.
CartDesign-XRS
REV
SCALE: 1:5
WEIGHT: 4.85kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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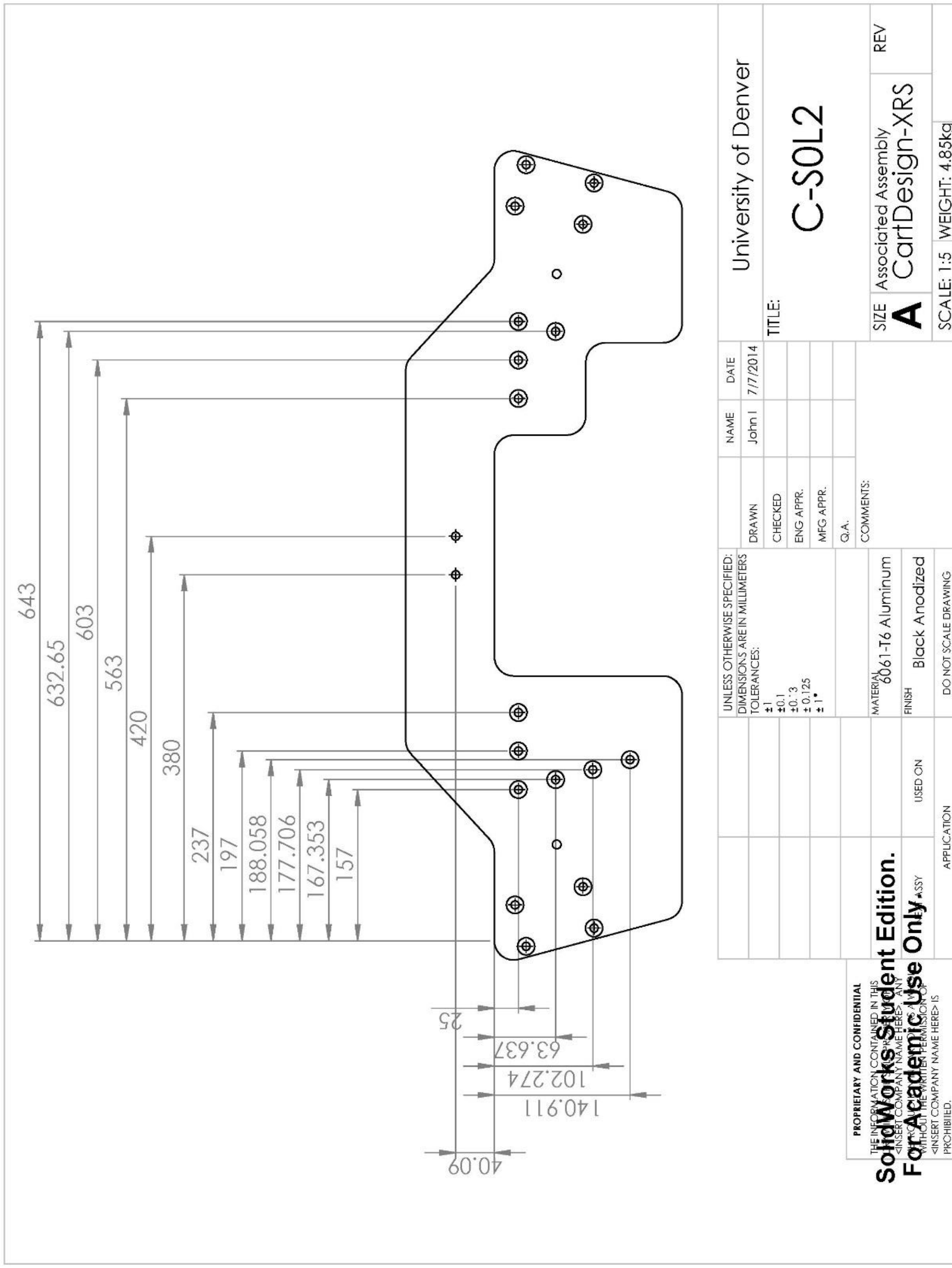
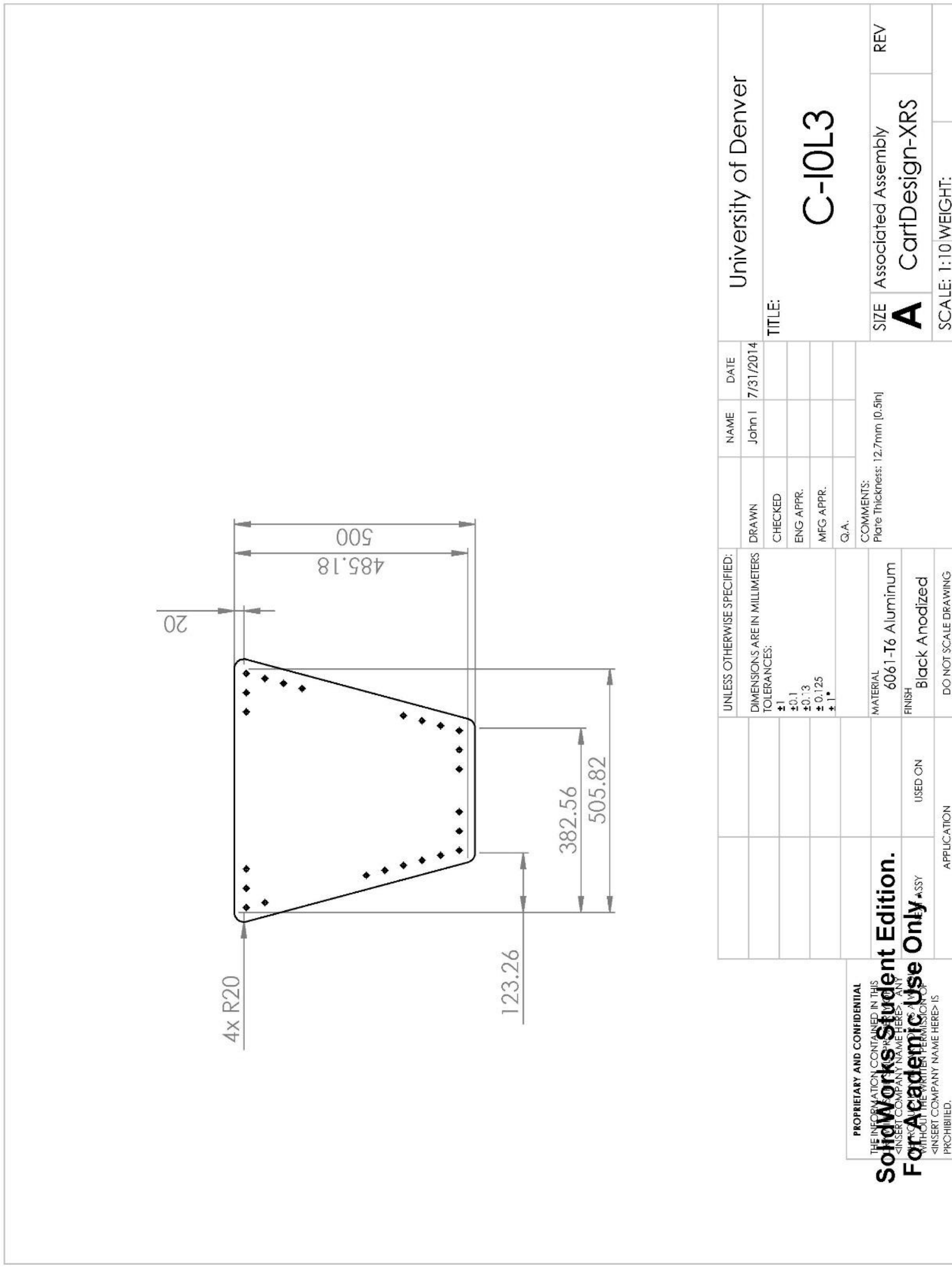


643
632.65
603
563
420
380
237
197
188.058
177.706
167.353
157
25
63.637
102.274
140.911
40.09
University of Denver
TITLE:
C-SOL2
SIZE
A
Associated Assembly
CartDesign-XRS
REV
SCALE: 1:5
WEIGHT: 4.85kg
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5



500
485.18
20
4x R20
123.26
382.56
505.82
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm [0.5in]
University of Denver
TITLE:
C-I0L3
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
SIZE
A
Associated Assembly
CartDesign-XRS
REV
SCALE: 1:10
WEIGHT:
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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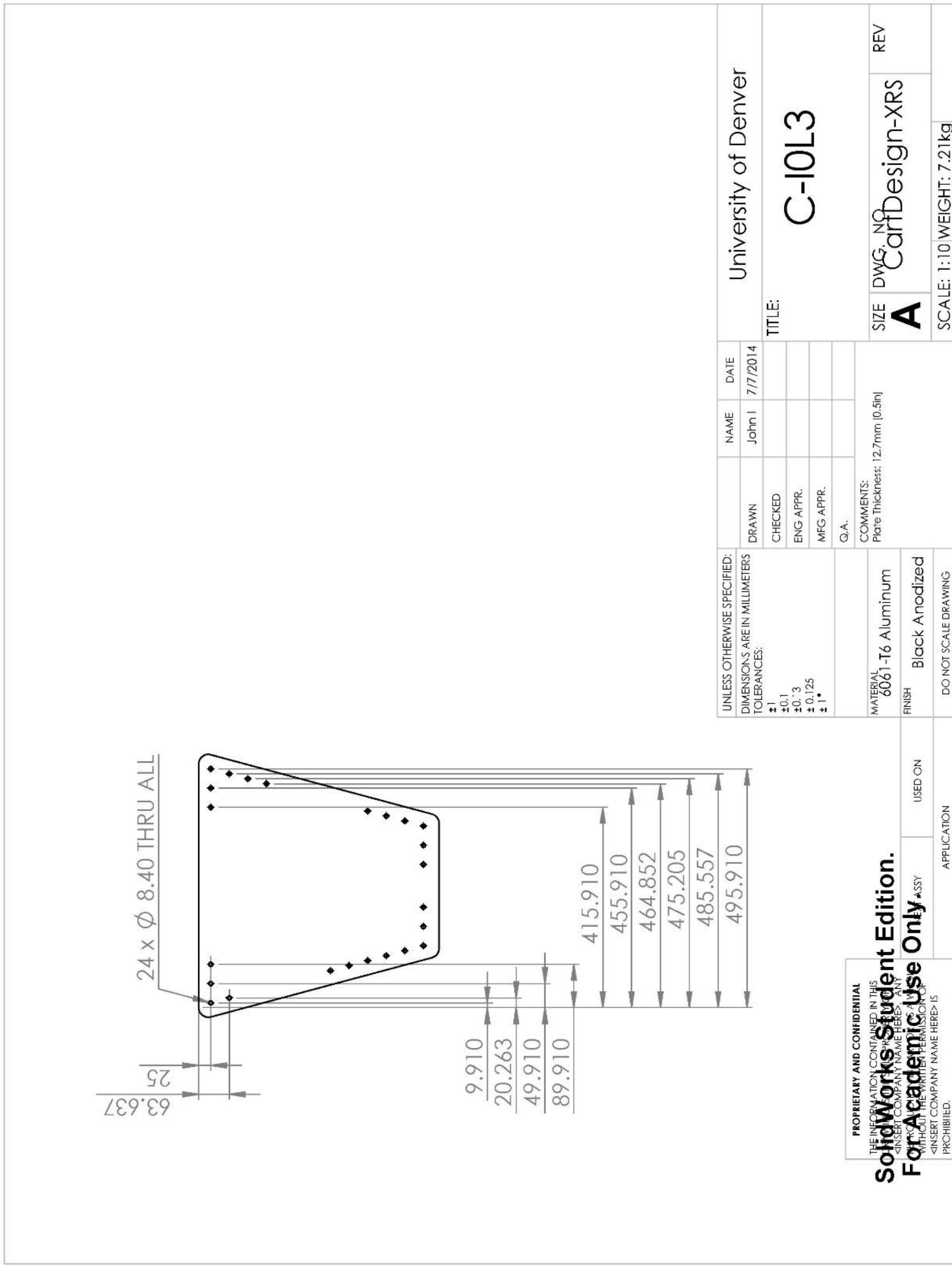
24 x Ø 8.40 THRU ALL
415.910
455.910
464.852
475.205
485.557
495.910
9.910
20.263
49.910
89.910
25
63.637
University of Denver
TITLE:
C-I0L3
SIZE
A
DWG. NO.
CartDesign-XRS
REV
SCALE: 1:10 WEIGHT: 7.21kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm [0.5in]
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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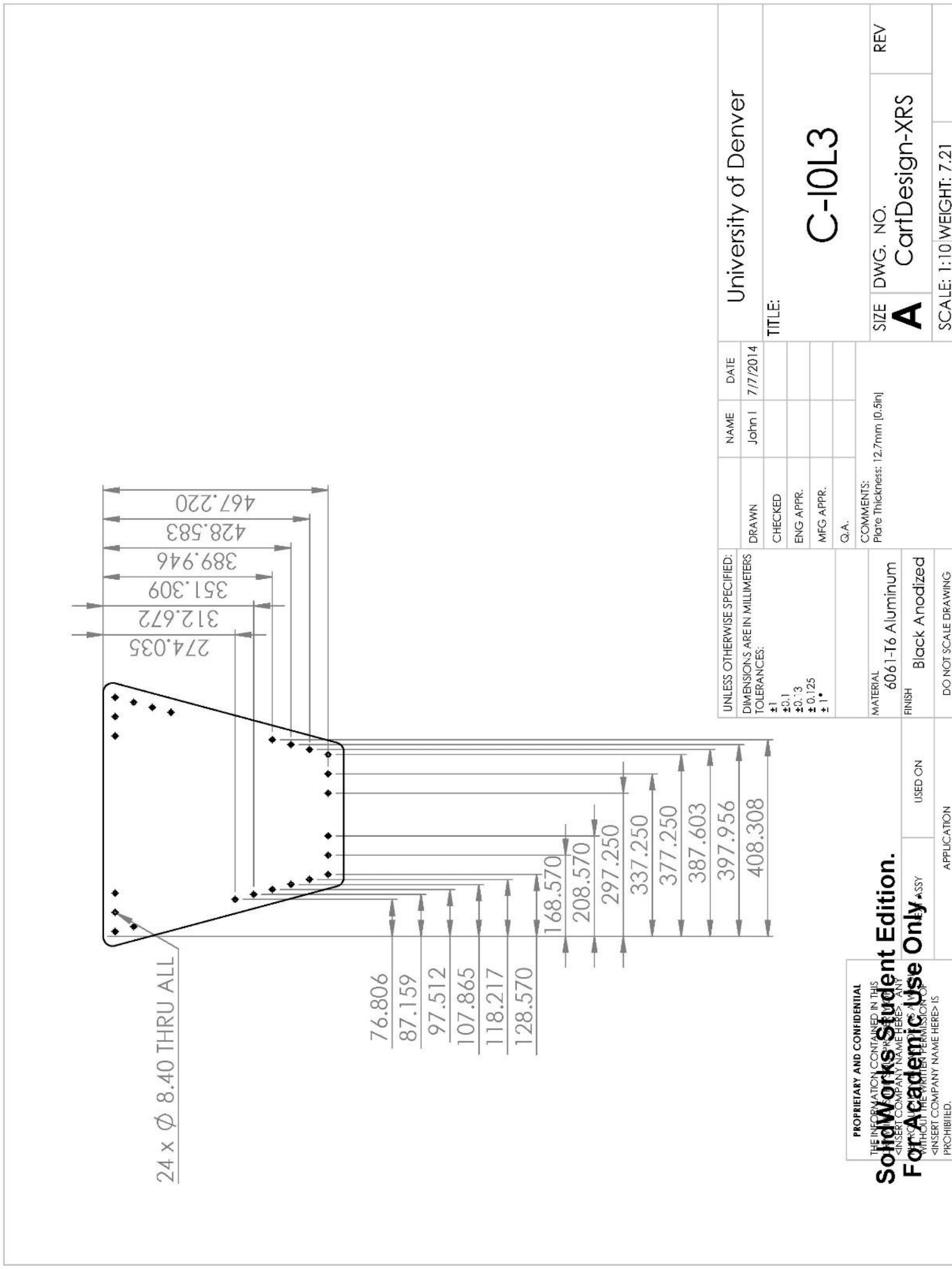

University of Denver
TITLE:
C-I0L3
SIZE A
DWG. NO.
CartDesign-XRS
REV
SCALE: 1:10
WEIGHT: 7.21
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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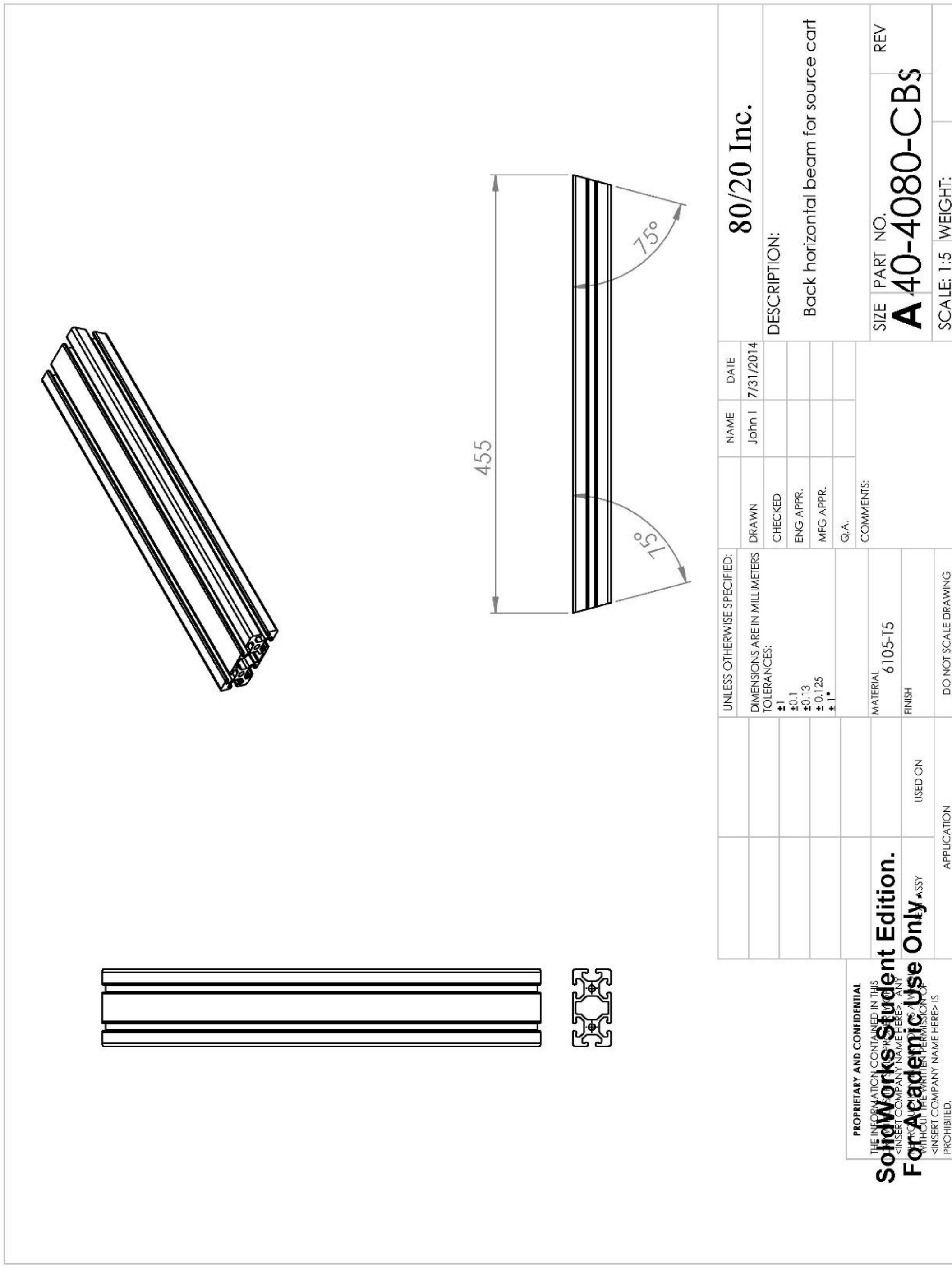
24 x Ø 8.40 THRU ALL
274.035
312.672
351.309
389.946
428.583
467.220
76.806
87.159
97.512
107.865
118.217
128.570
168.570
208.570
297.250
337.250
377.250
387.603
397.956
408.308


80/20 Inc.
DESCRIPTION:
Back horizontal beam for source cart
SIZE
A
PART NO.
40-4080-CBs
REV
SCALE: 1:5
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
455
75°
75°
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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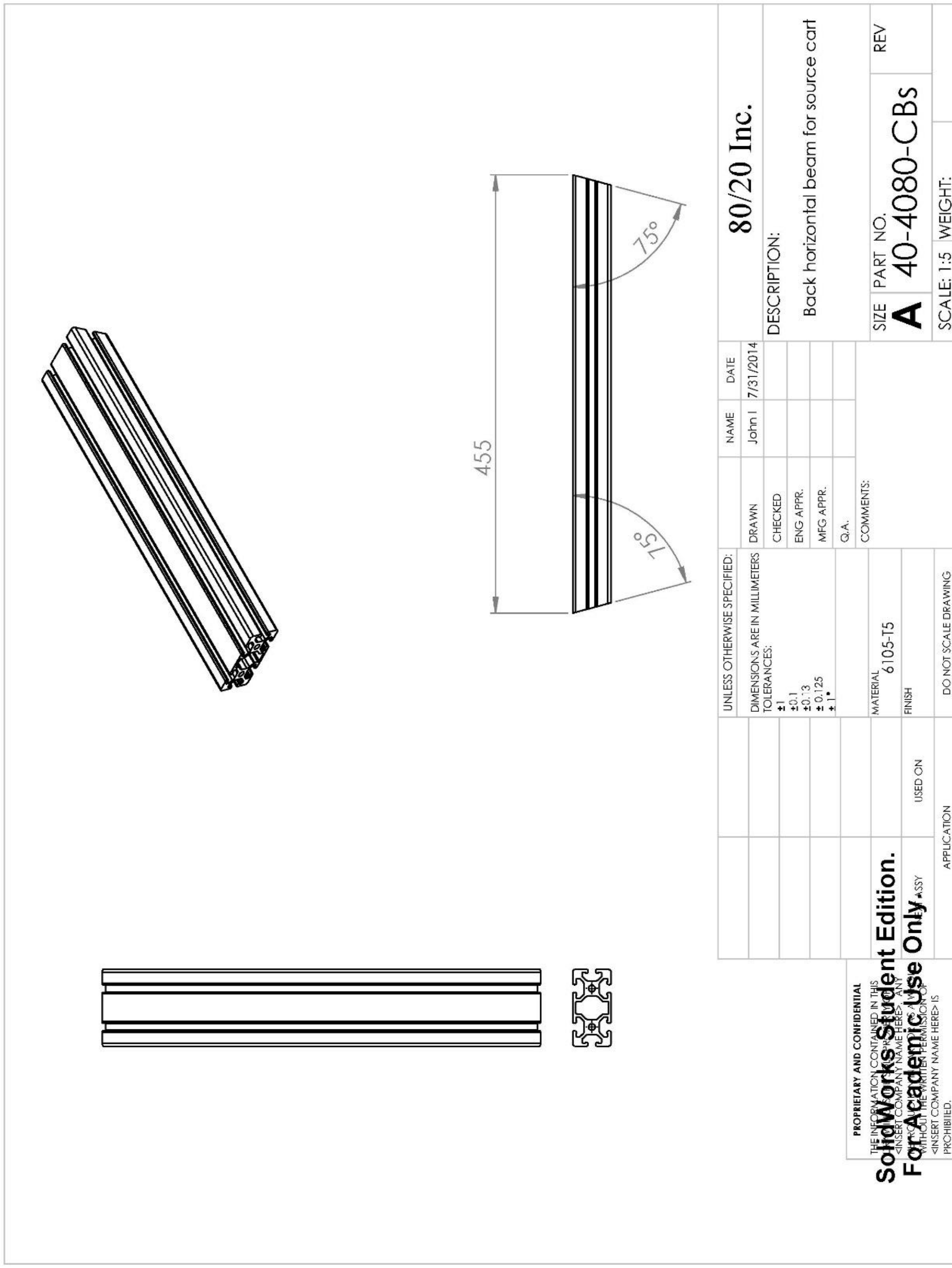
1
2
3
4
5


455
75°
75°
80/20 Inc.
DESCRIPTION:
Back horizontal beam for source cart
SIZE A
PART NO.
40-4080-CBs
REV
SCALE: 1:5
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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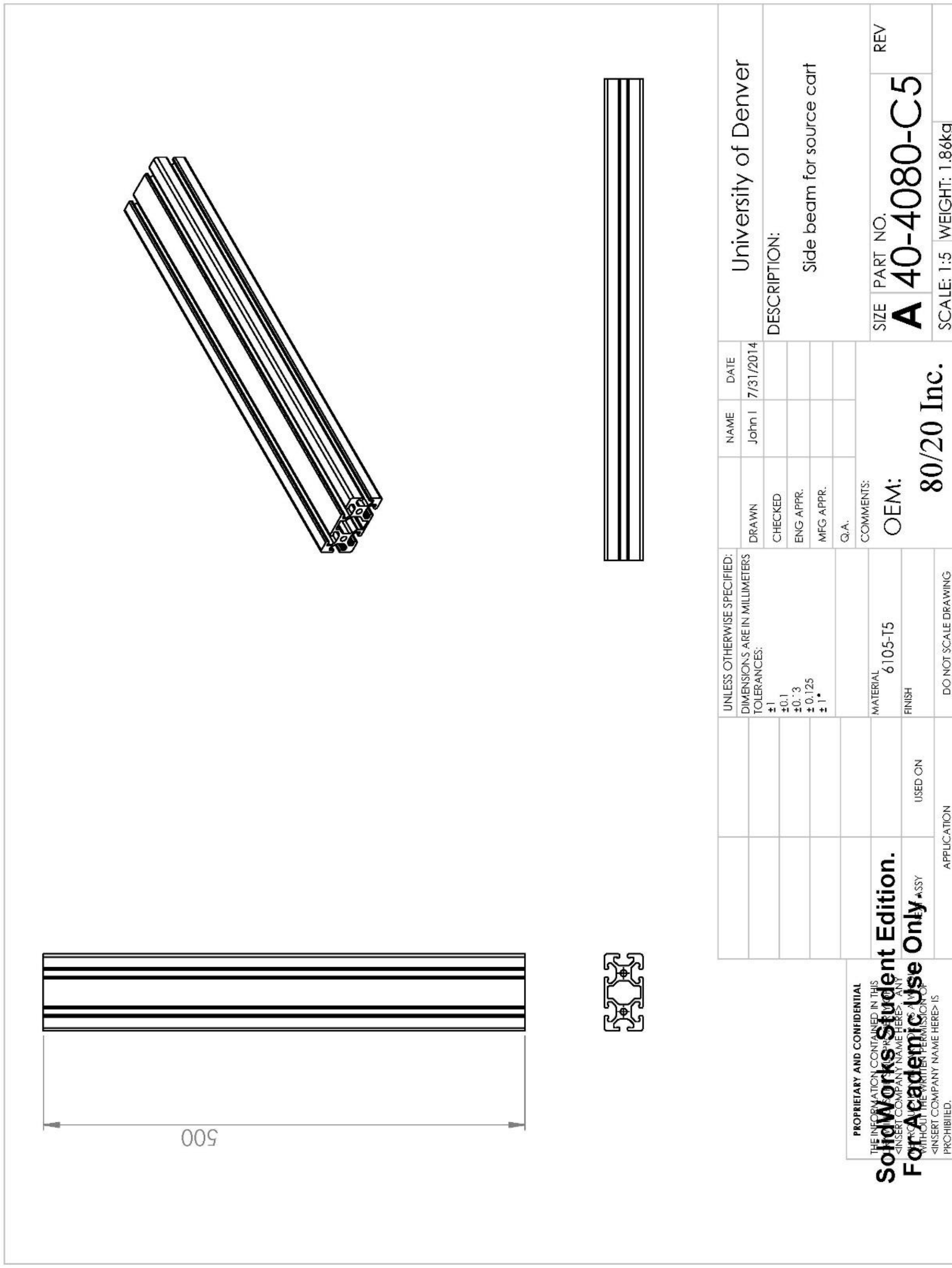
1
2
3
4
5


University of Denver
DESCRIPTION:
Side beam for source cart
SIZE A
PART NO. 40-4080-C5
REV
SCALE: 1:5
WEIGHT: 1.86kg
NAME
DATE
DRAWN John I 7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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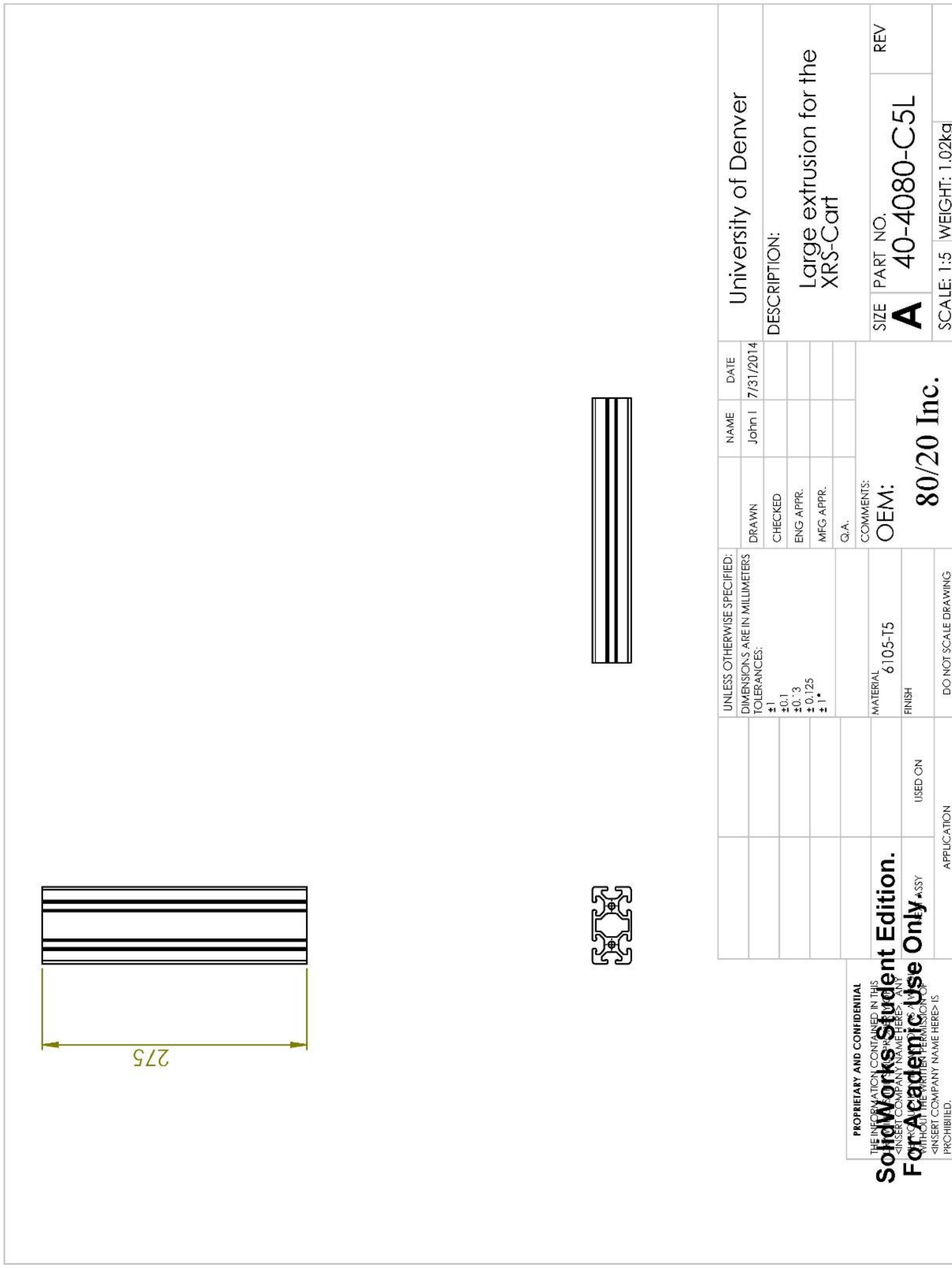
500
1
2
3
4
5


275
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.`3
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
University of Denver
DESCRIPTION:
Large extrusion for the XRS-Cart
SIZE
A
PART NO.
40-4080-C5L
REV
SCALE: 1:5
WEIGHT: 1.02kg
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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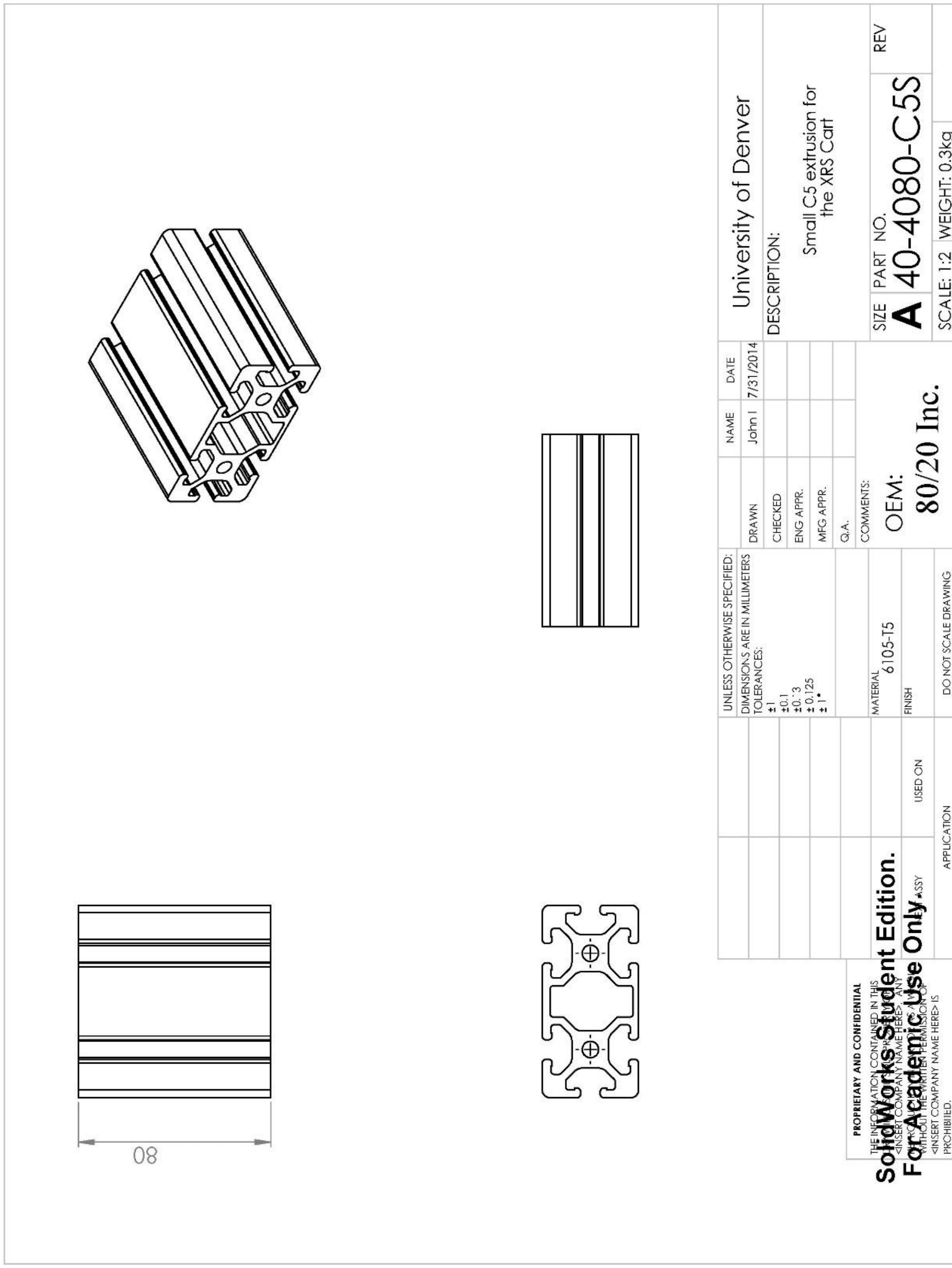
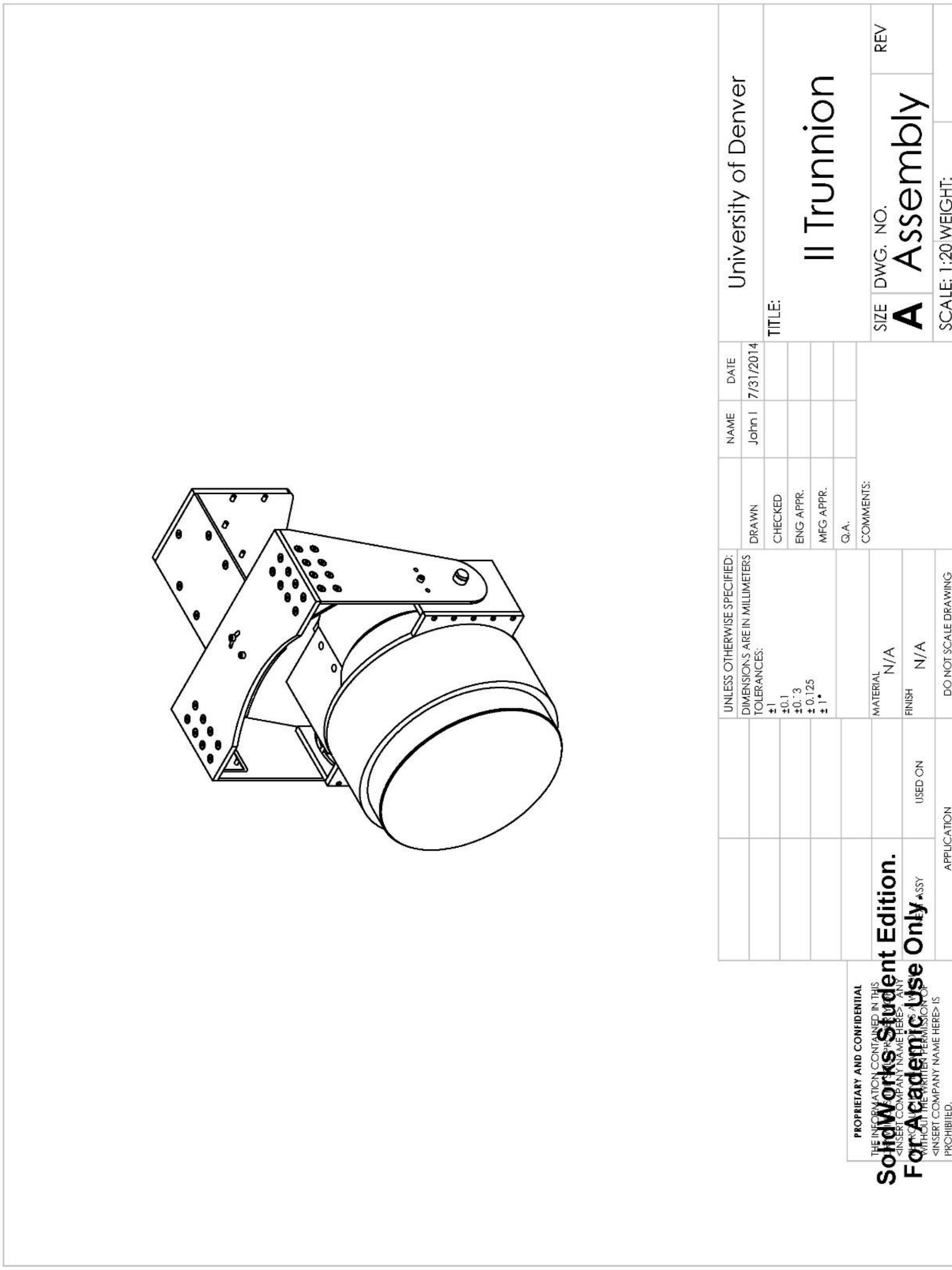
5
4
3
2
1



80
University of Denver
DESCRIPTION:
Small C5 extrusion for the XRS Cart
SIZE
A
PART NO.
40-4080-C5S
REV
SCALE: 1:2
WEIGHT: 0.3kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5


University of Denver
TITLE:
II Trunnion
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:20
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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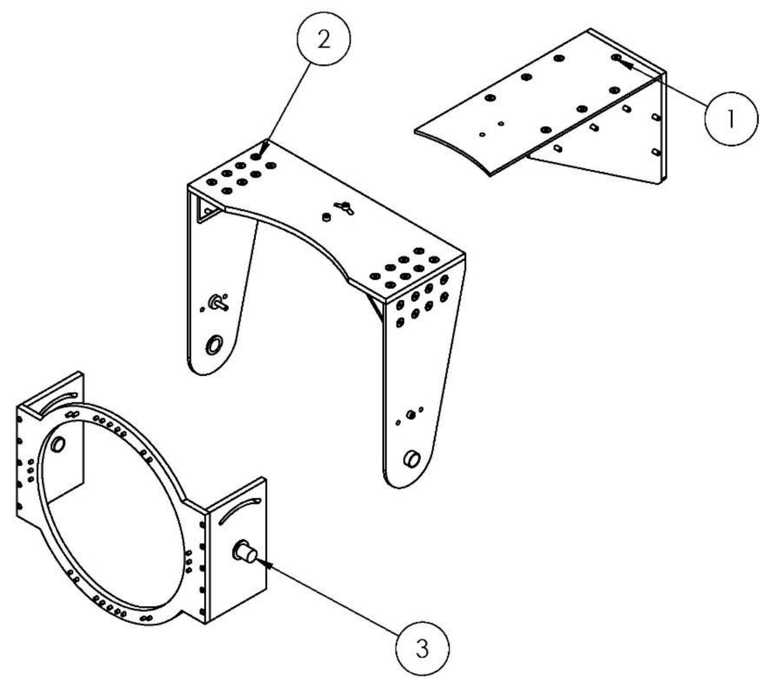
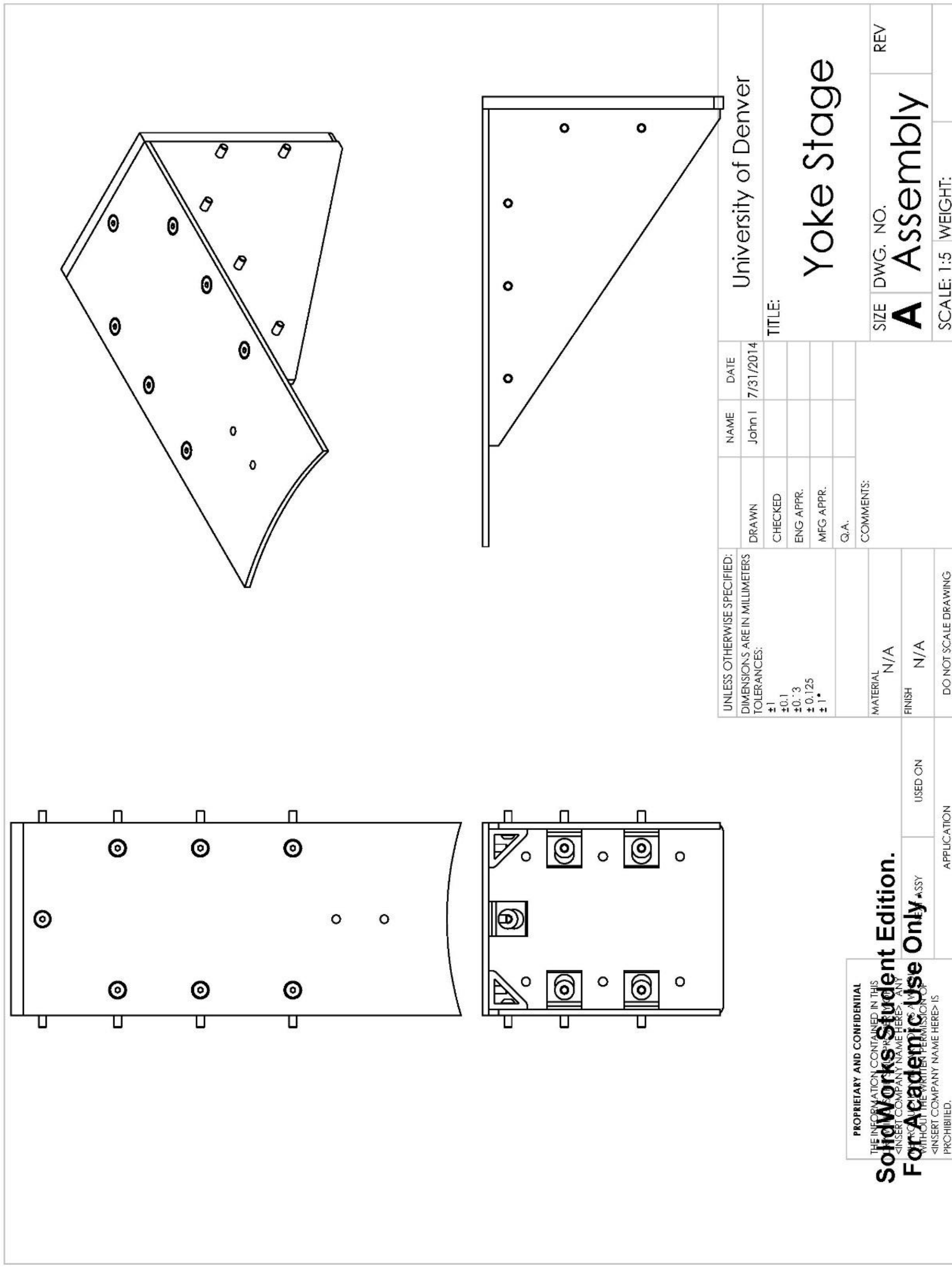
5
4
3
2
1

ITEM NO.	PART NUMBER	Default/ QTY.
1	Yoke Stage	1
2	Yoke	1
3	Hoop	1




University of Denver
TITLE:
Yoke Stage
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:5
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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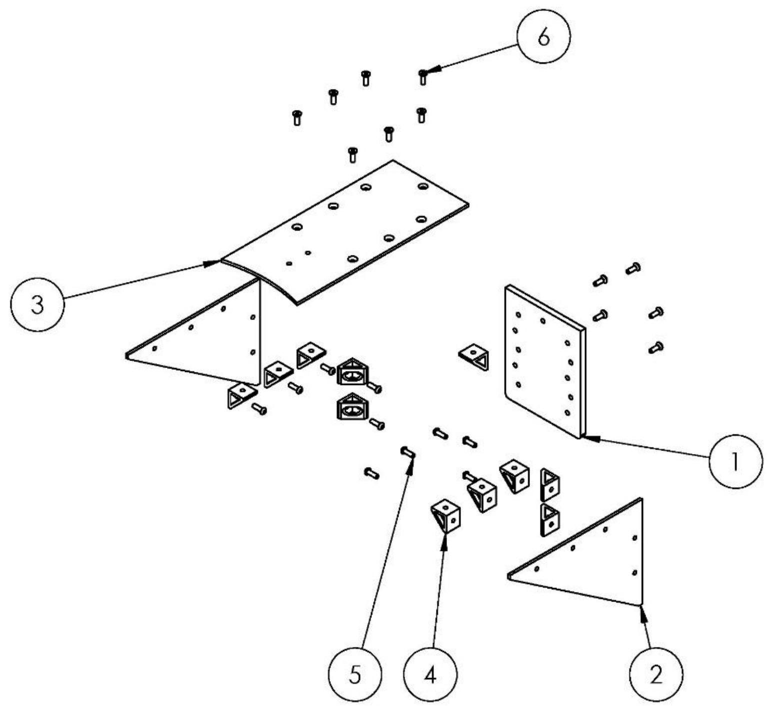

ITEM NO.	PART NUMBER	QTY.
1	AII-000	1
2	AII-001	2
3	AII-002	1
4	8020-40-4332	11
5	BH-M8X1.25X25	10
6	CS-M8X1.25X25	12

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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.`3
± 0.125
± 1°

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	John I	7/7/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

University of Denver

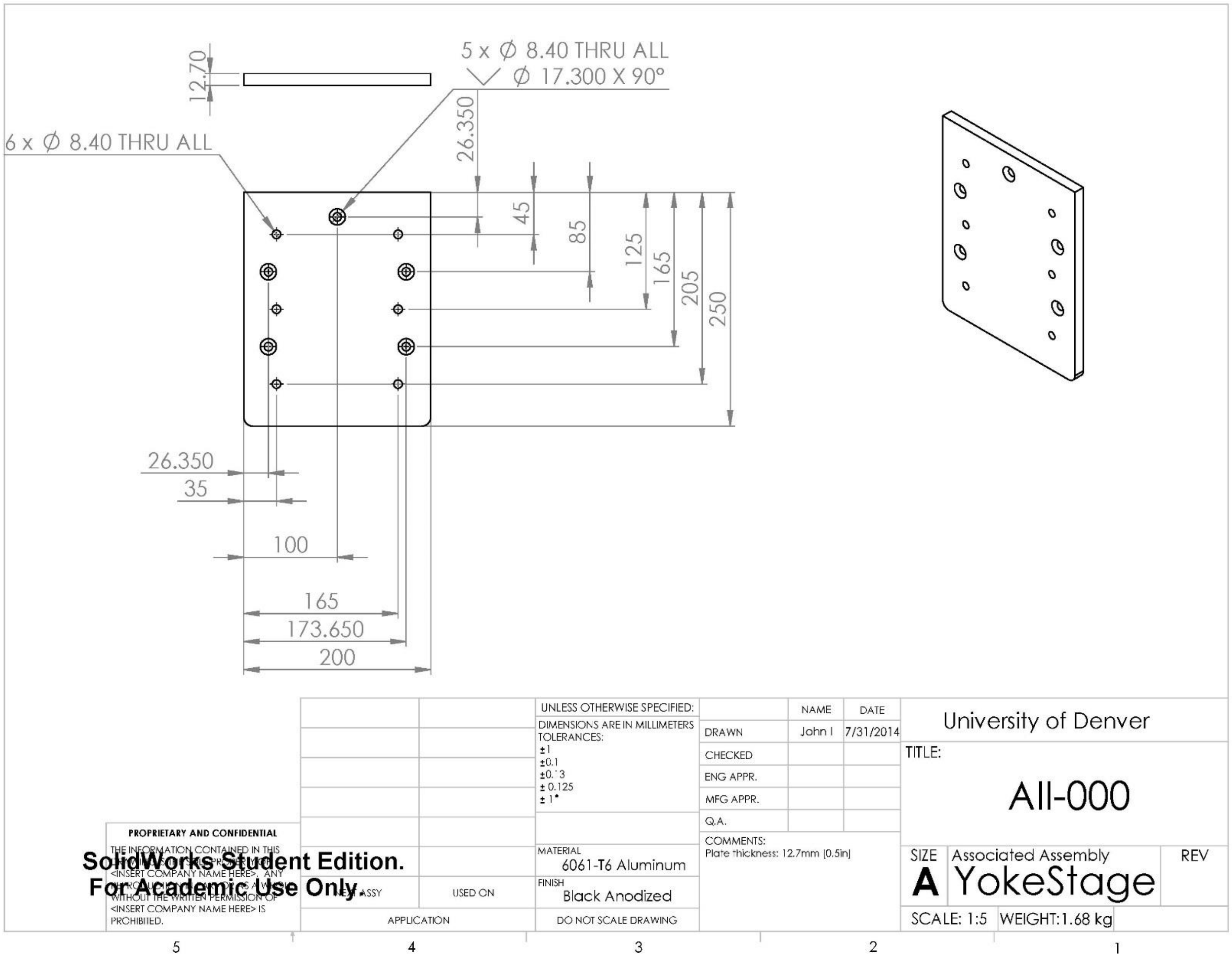
TITLE:

YokeStage

SIZE A | DWG. NO. Assembly | REV

SCALE: 1:10 WEIGHT:

5 4 3 2 1


5 x Ø 8.40 THRU ALL
Ø 17.300 X 90°
6 x Ø 8.40 THRU ALL
12.70
26.350
45
85
125
165
205
250
26.350
35
100
165
173.650
200
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate thickness: 12.7mm [0.5in]
University of Denver
TITLE:
AII-000
SIZE
A
Associated Assembly
YokeStage
REV
SCALE: 1:5
WEIGHT:1.68 kg
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
<INSERT COMPANY NAME HERE>. ANY
WITHOUT THE WRITTEN PERMISSION OF
<INSERT COMPANY NAME HERE> IS
PROHIBITED.
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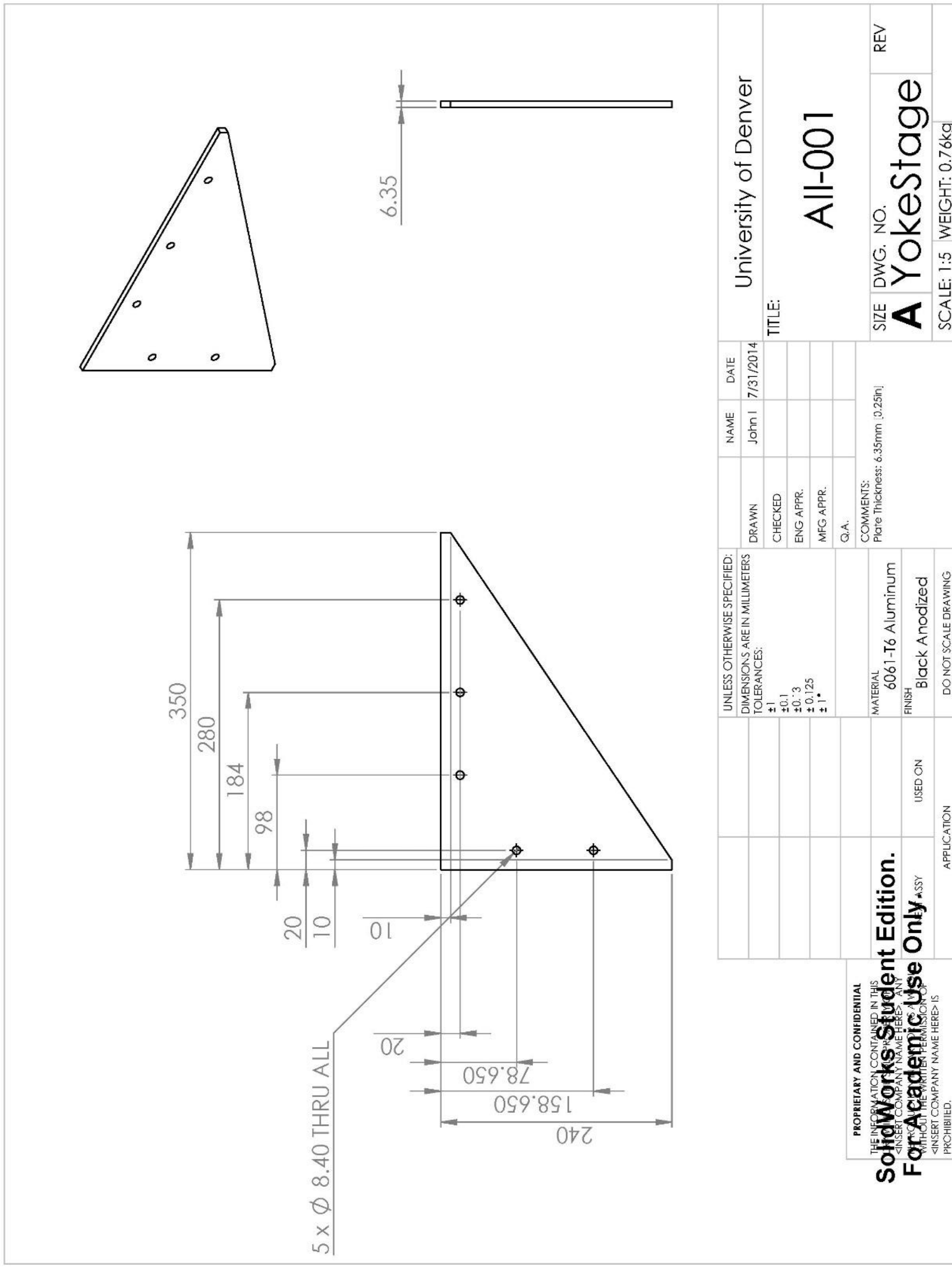
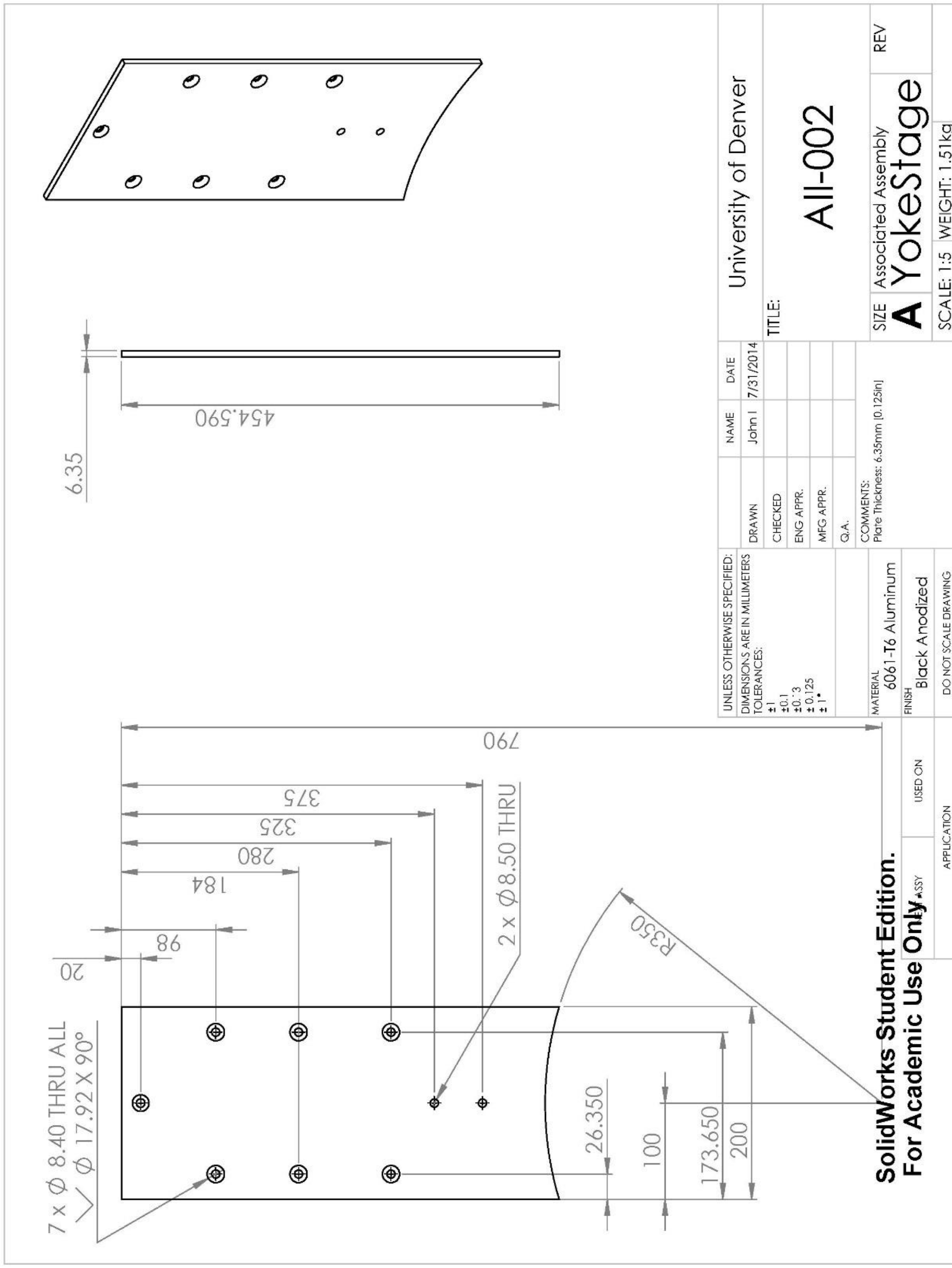
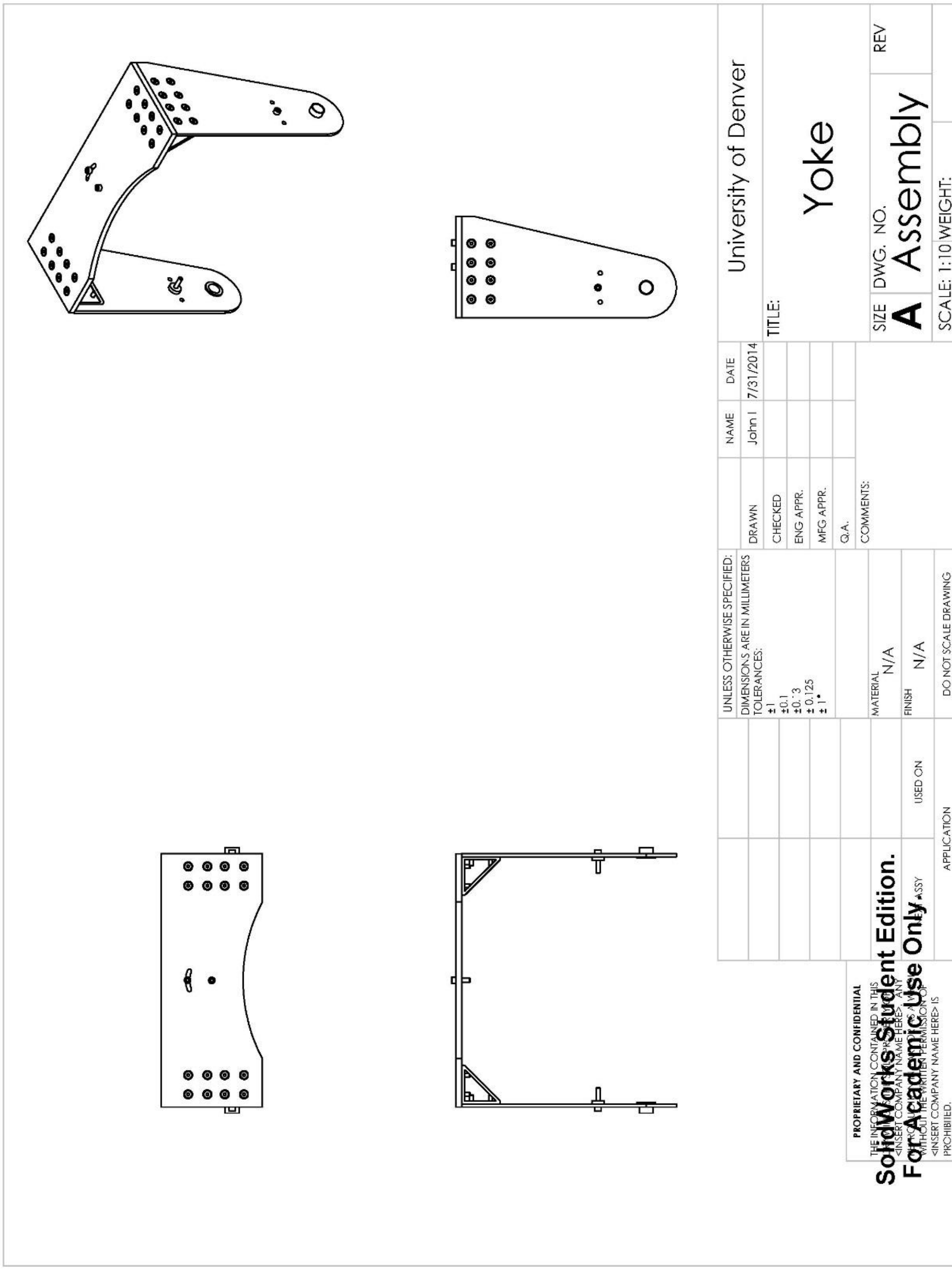
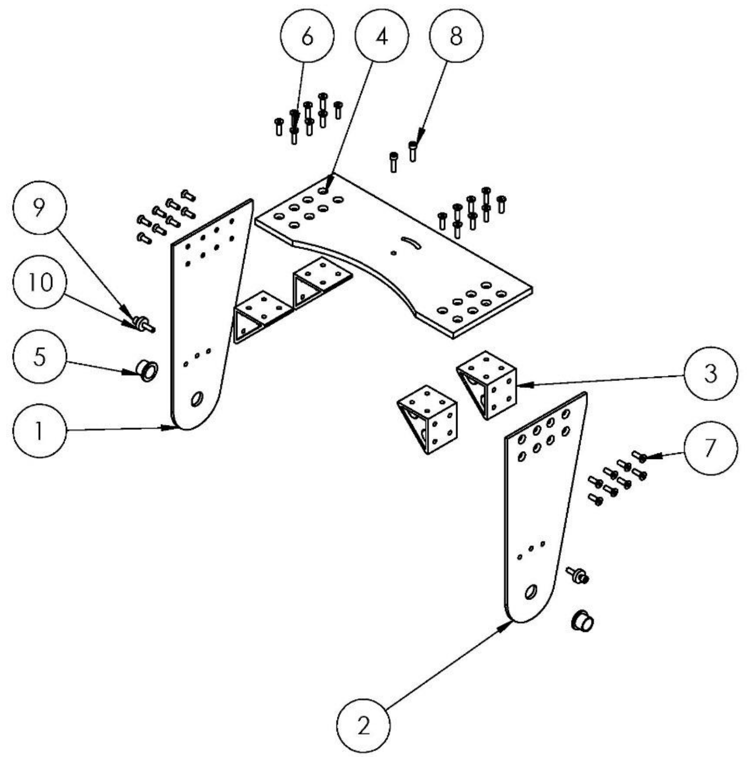
5
4
3
2
1


University of Denver
TITLE:
AII-001
SIZE
A
DWG. NO.
YokeStage
REV
SCALE: 1:5
WEIGHT: 0.76kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
NAME
DATE
John I
7/31/2014
COMMENTS:
Plate Thickness: 6.35mm (0.25in)
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
5 x Ø 8.40 THRU ALL
350
280
184
98
20
10
10
20
78.650
158.650
240
6.35



University of Denver
TITLE:
AII-002
SIZE
A
Associated Assembly
YokeStage
REV
SCALE: 1:5
WEIGHT: 1.51kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 6.35mm [0.125in]
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
SolidWorks Student Edition.
For Academic Use Only.
7 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
2 x Ø 8.50 THRU
R350
6.35
454.590
790
375
325
280
184
98
20
26.350
100
173.650
200


University of Denver
TITLE:
Yoke
SIZE A
DWG. NO.
Assembly
REV
SCALE: 1:10 WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5



ITEM NO.	PART NUMBER	QTY.
1	AII-004-Right	1
2	AII-004-Left	1
3	8020-40-4338	4
4	AII-003	1
5	Bushing	2
6	CS-M8X1.25X30	16
7	CS-M8X1.25X25	16
8	ISO 4762 M8 x 30 --- 30N	2
9	ISO 4762 M8 x 40 --- 28N	2
10	NylonWasher	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.˚3
± 0.125
± 1°

	NAME	DATE
DRAWN	John I	7/31/2014
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL N/A
FINISH N/A
DO NOT SCALE DRAWING
NEXT ASSY USED ON
APPLICATION

University of Denver

TITLE: Yoke

SIZE A DWG. NO. Assembly REV

SCALE: 1:10 WEIGHT:

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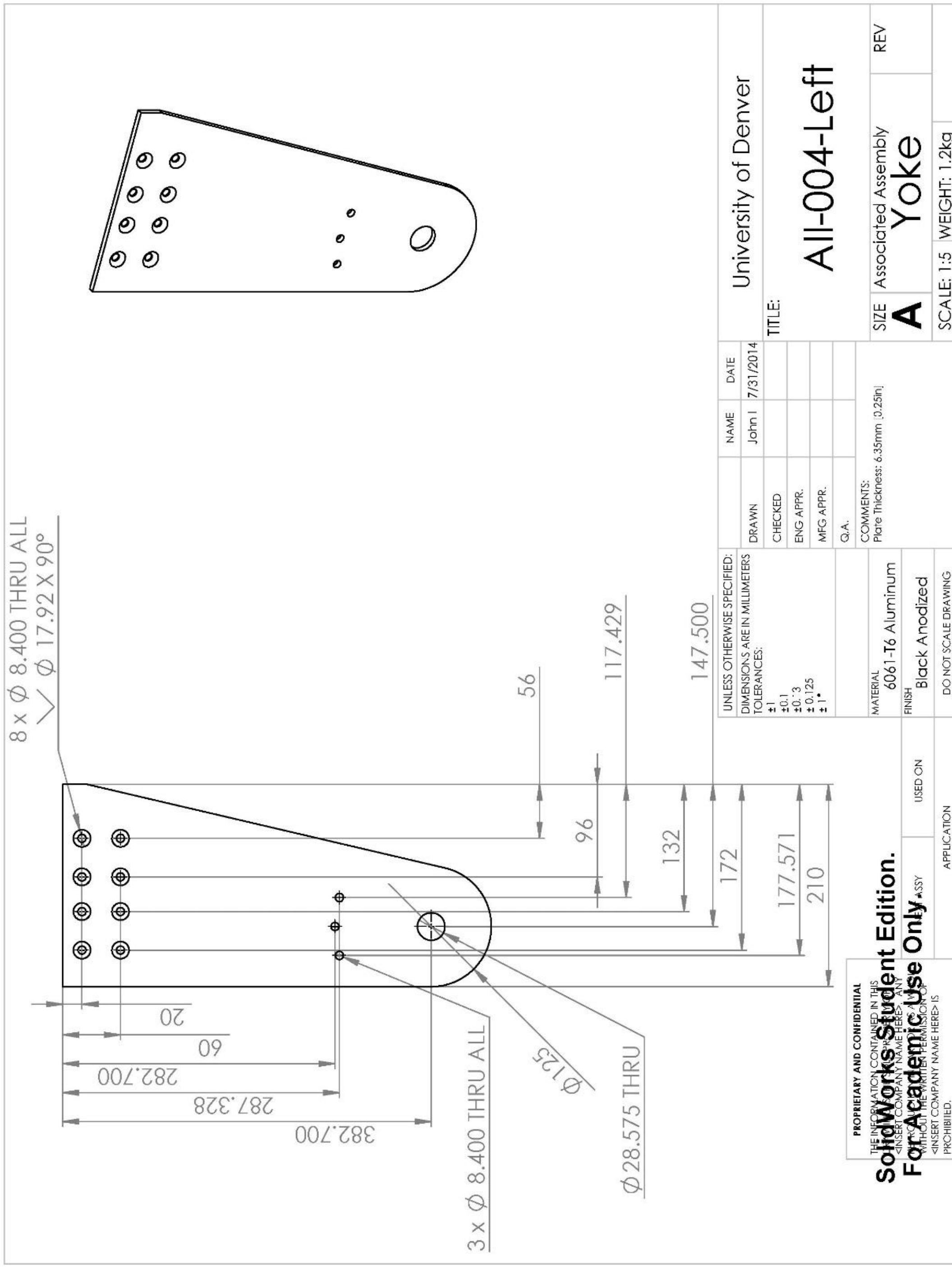
5 4 3 2 1



8 x Ø 8.400 THRU ALL
⌵ Ø 17.92 X 90°
56
96
117.429
132
147.500
172
177.571
210
20
60
282.700
287.328
382.700
3 x Ø 8.400 THRU ALL
Ø125
Ø28.575 THRU
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 6.35mm (0.25in)
University of Denver
TITLE:
All-004-Left
SIZE
A
Associated Assembly
Yoke
REV
SCALE: 1:5
WEIGHT: 1.2kg
PROPRIETARY AND CONFIDENTIAL
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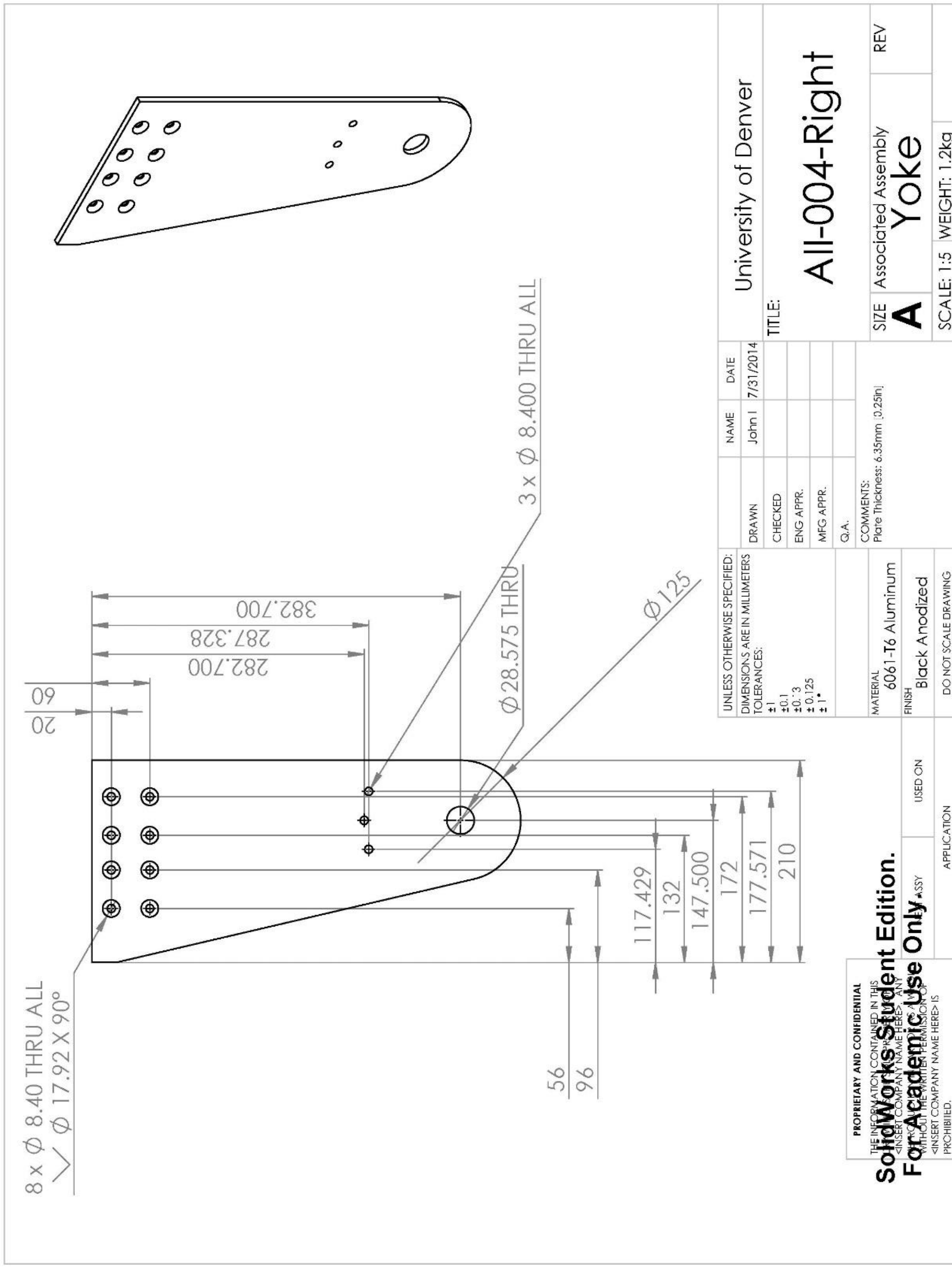

8 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
20
60
282.700
287.328
382.700
Ø28.575 THRU
3 x Ø 8.400 THRU ALL
Ø125
56
96
117.429
132
147.500
172
177.571
210
University of Denver
TITLE:
All-004-Right
SIZE A
Associated Assembly
Yoke
REV
SCALE: 1:5
WEIGHT: 1.2kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 6.35mm (0.25in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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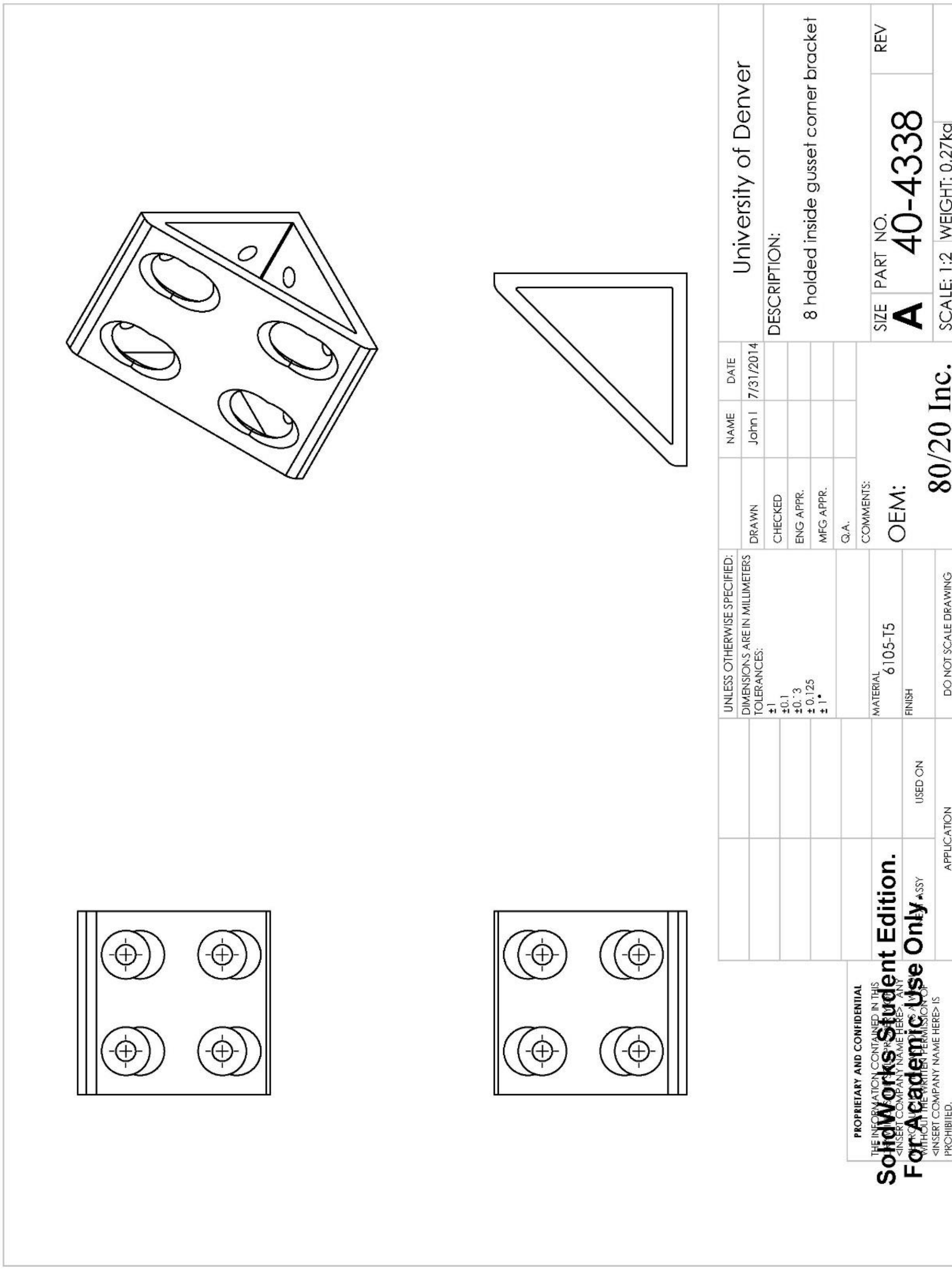
University of Denver
DESCRIPTION:
8 holded inside gusset corner bracket
SIZE
A
PART NO.
40-4338
REV
SCALE: 1:2
WEIGHT: 0.27kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
80/20 Inc.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6105-T5
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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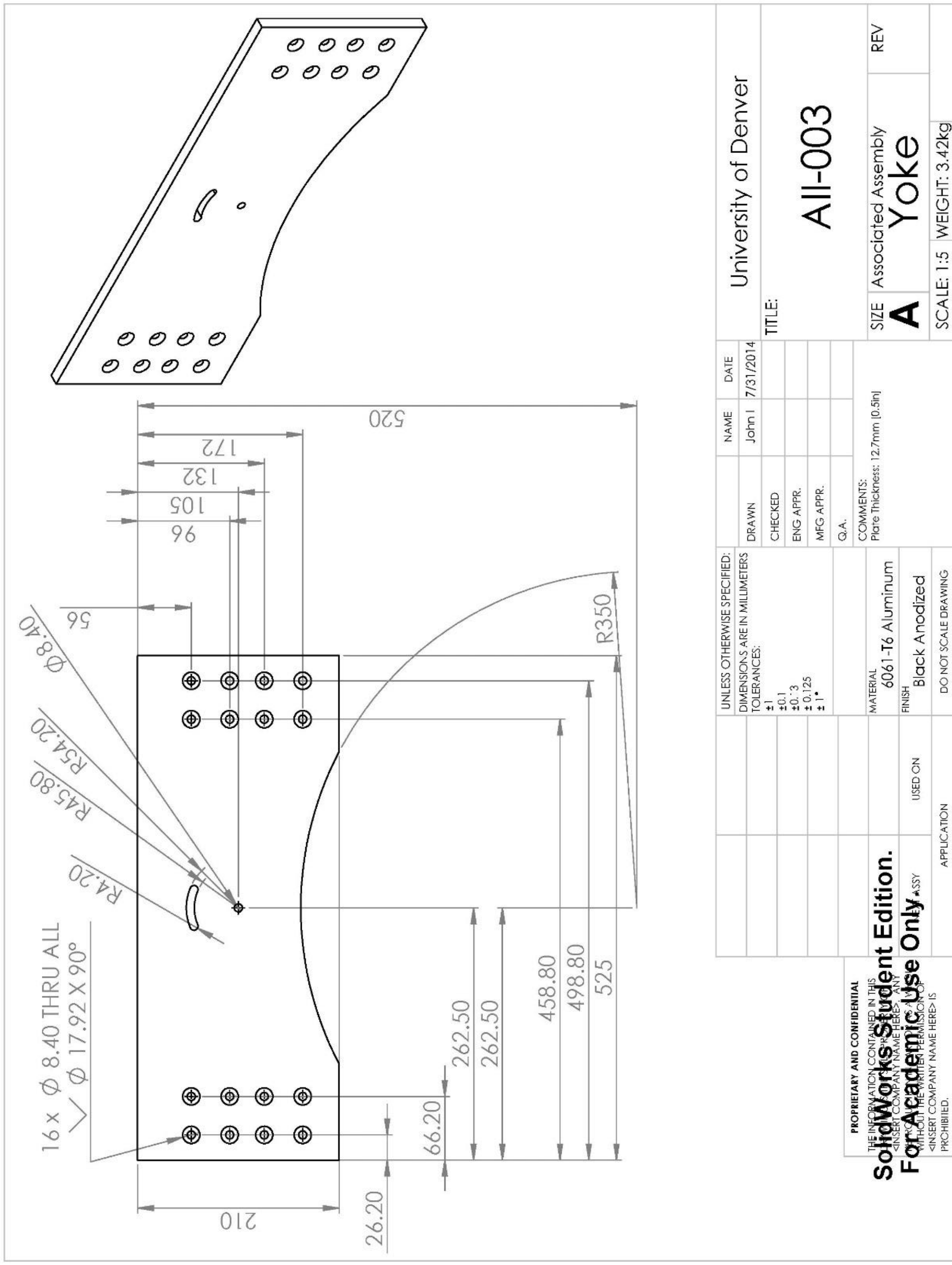
1
2
3
4
5


16 x Ø 8.40 THRU ALL
Ø 17.92 X 90°
Ø8.40
R54.20
R45.80
R4.20
56
96
105
132
172
520
R350
210
26.20
66.20
262.50
262.50
458.80
498.80
525
University of Denver
TITLE:
AII-003
SIZE A
Associated Assembly
Yoke
REV
SCALE: 1:5
WEIGHT: 3.42kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.3
± 0.125
± 1°
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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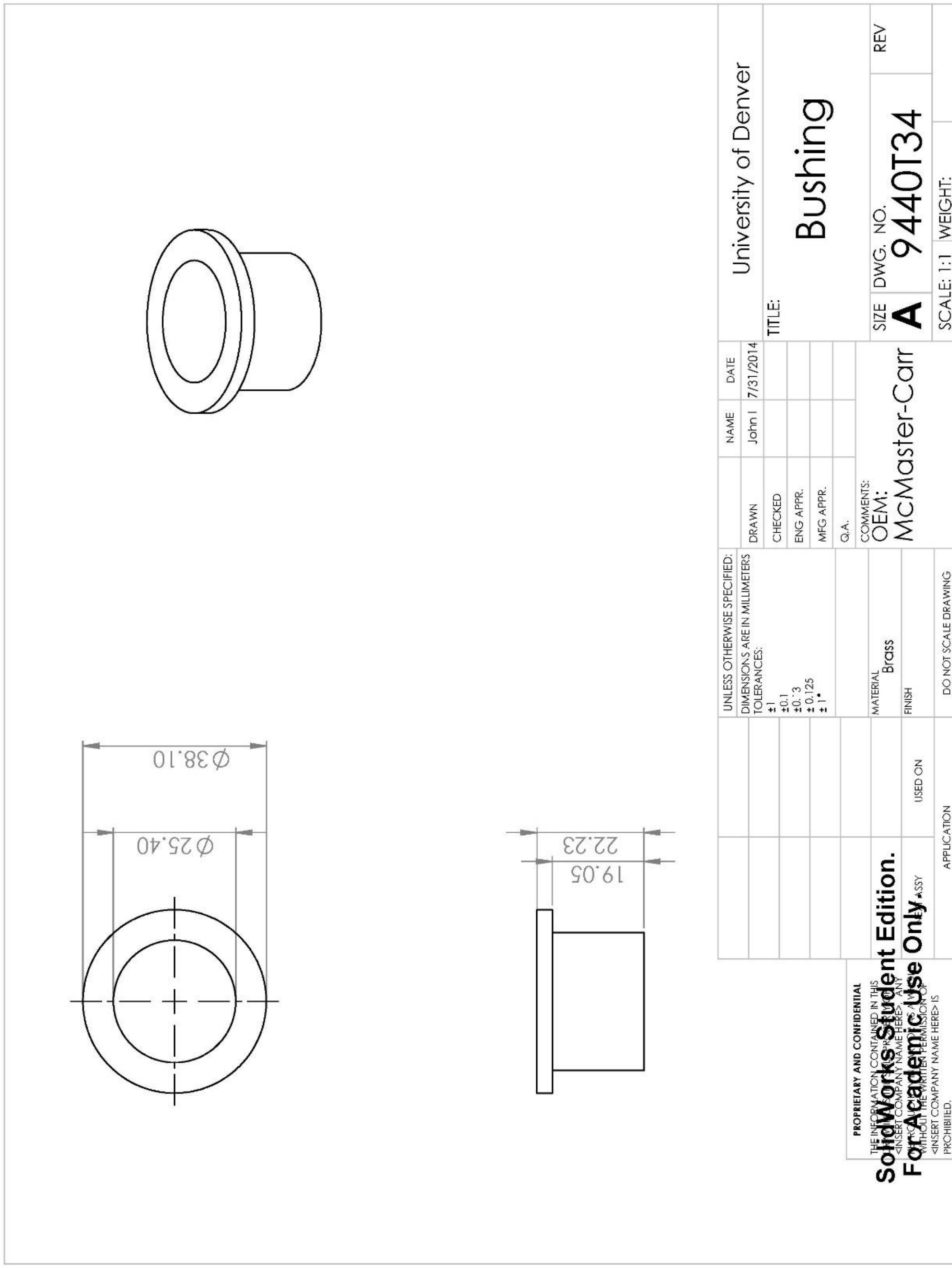
1
2
3
4
5


Ø38.10
Ø25.40
22.23
19.05
University of Denver
TITLE:
Bushing
SIZE
A
DWG. NO.
9440T34
REV
SCALE: 1:1
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
McMaster-Carr
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
Brass
FINISH
DO NOT SCALE DRAWING
APPLICATION
USED ON
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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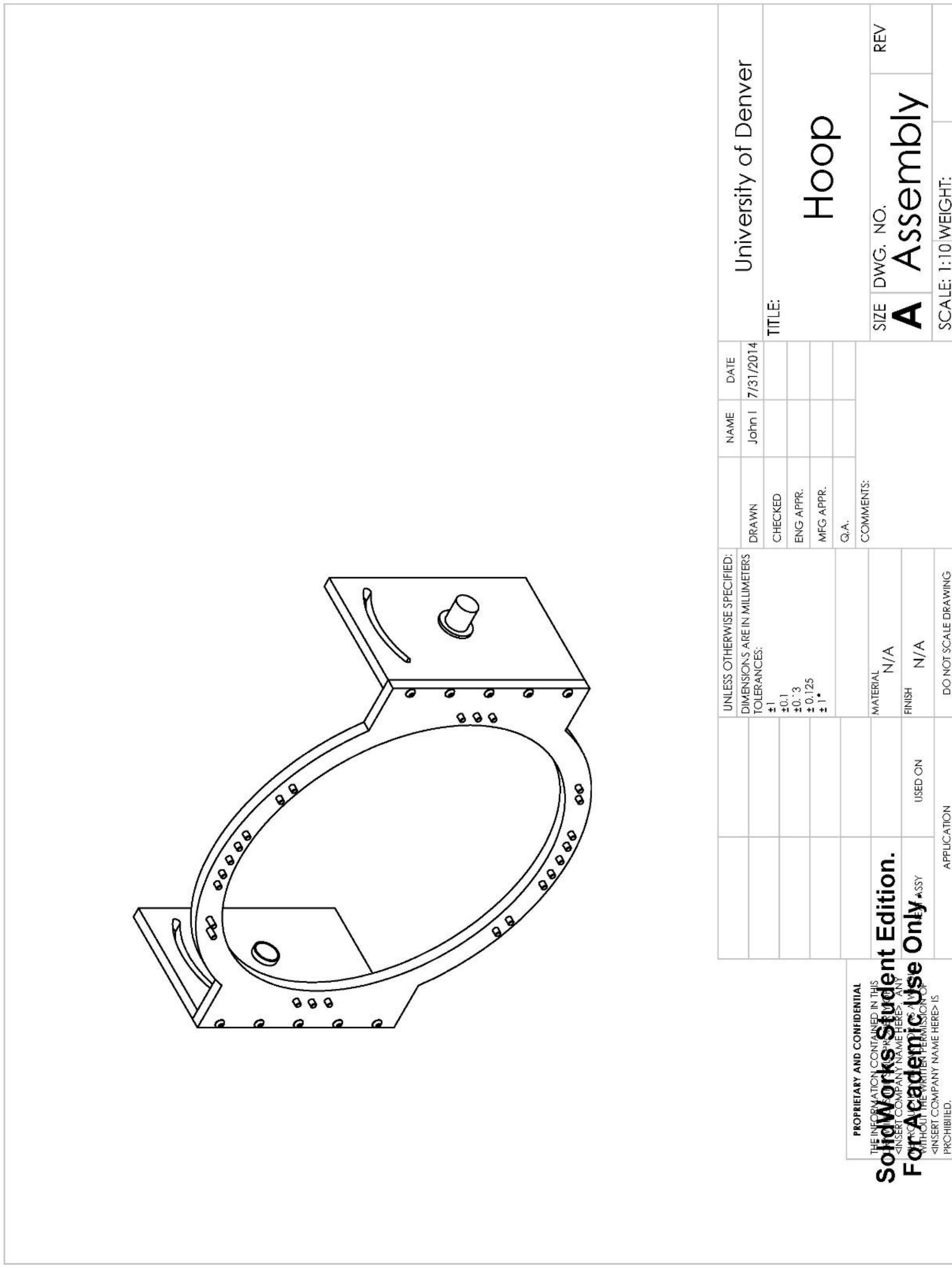
University of Denver
TITLE:
Hoop
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:10
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
APPLICATION
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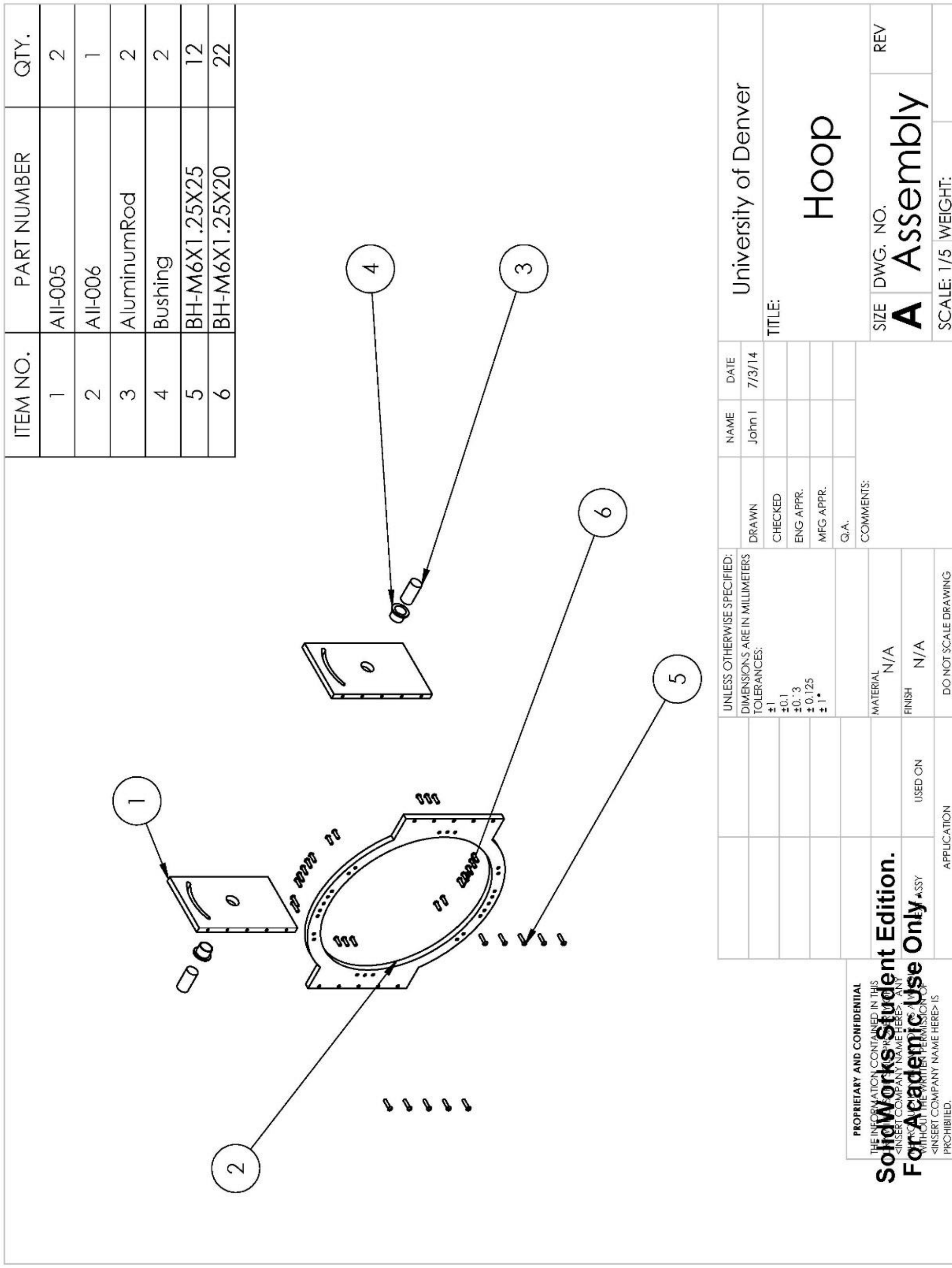
ITEM NO. | PART NUMBER | QTY.
1 | AII-005 | 2
2 | AII-006 | 1
3 | AluminumRod | 2
4 | Bushing | 2
5 | BH-M6X1.25X25 | 12
6 | BH-M6X1.25X20 | 22
1
2
3
4
5
6
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.`3
± 0.125
± 1°
NAME
DATE
DRAWN
John I
7/3/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
University of Denver
TITLE:
Hoop
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1/5
WEIGHT:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
USED ON
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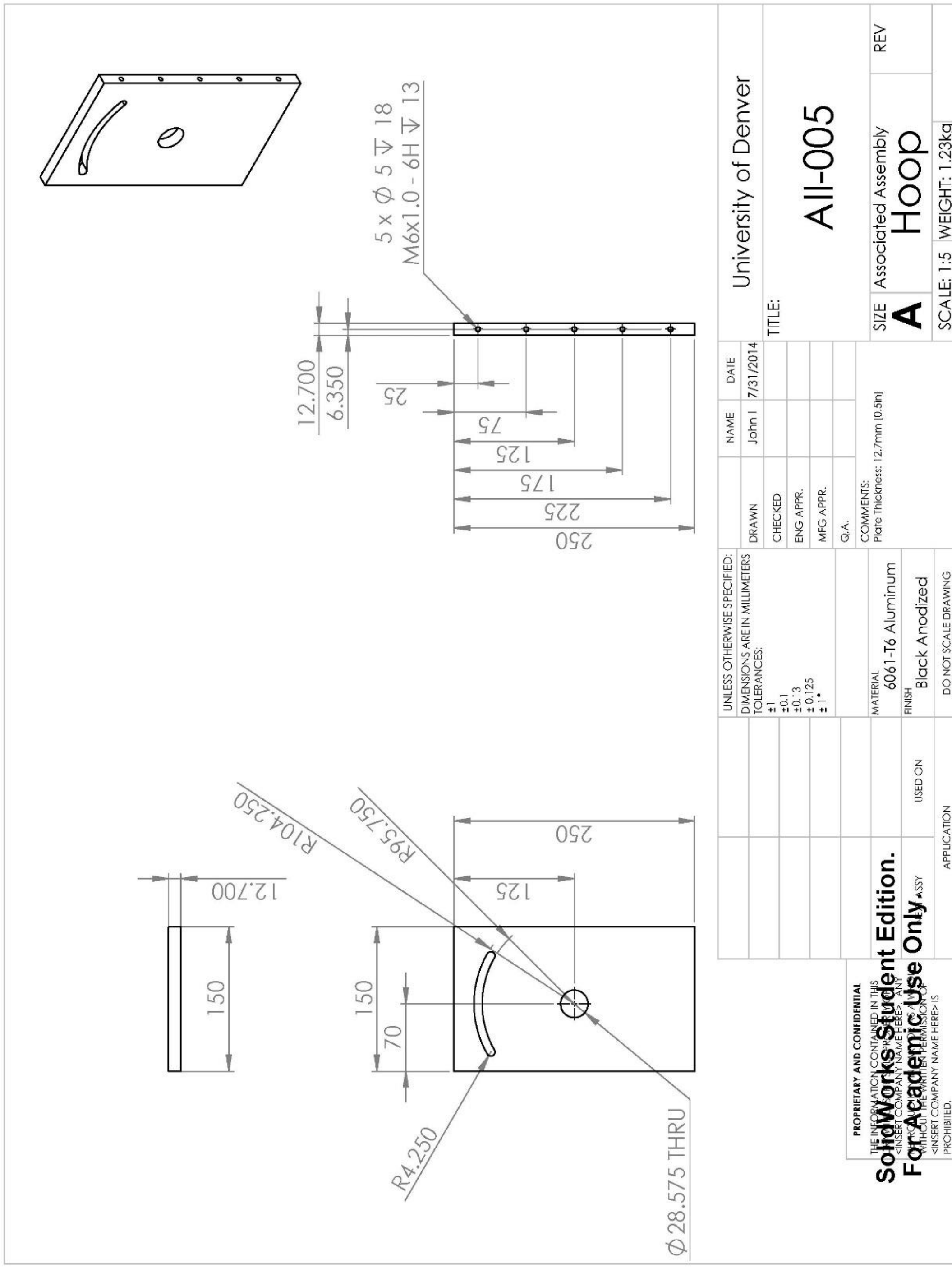

University of Denver
TITLE:
AII-005
SIZE A
Associated Assembly
Hoop
REV
SCALE: 1:5
WEIGHT: 1.23kg
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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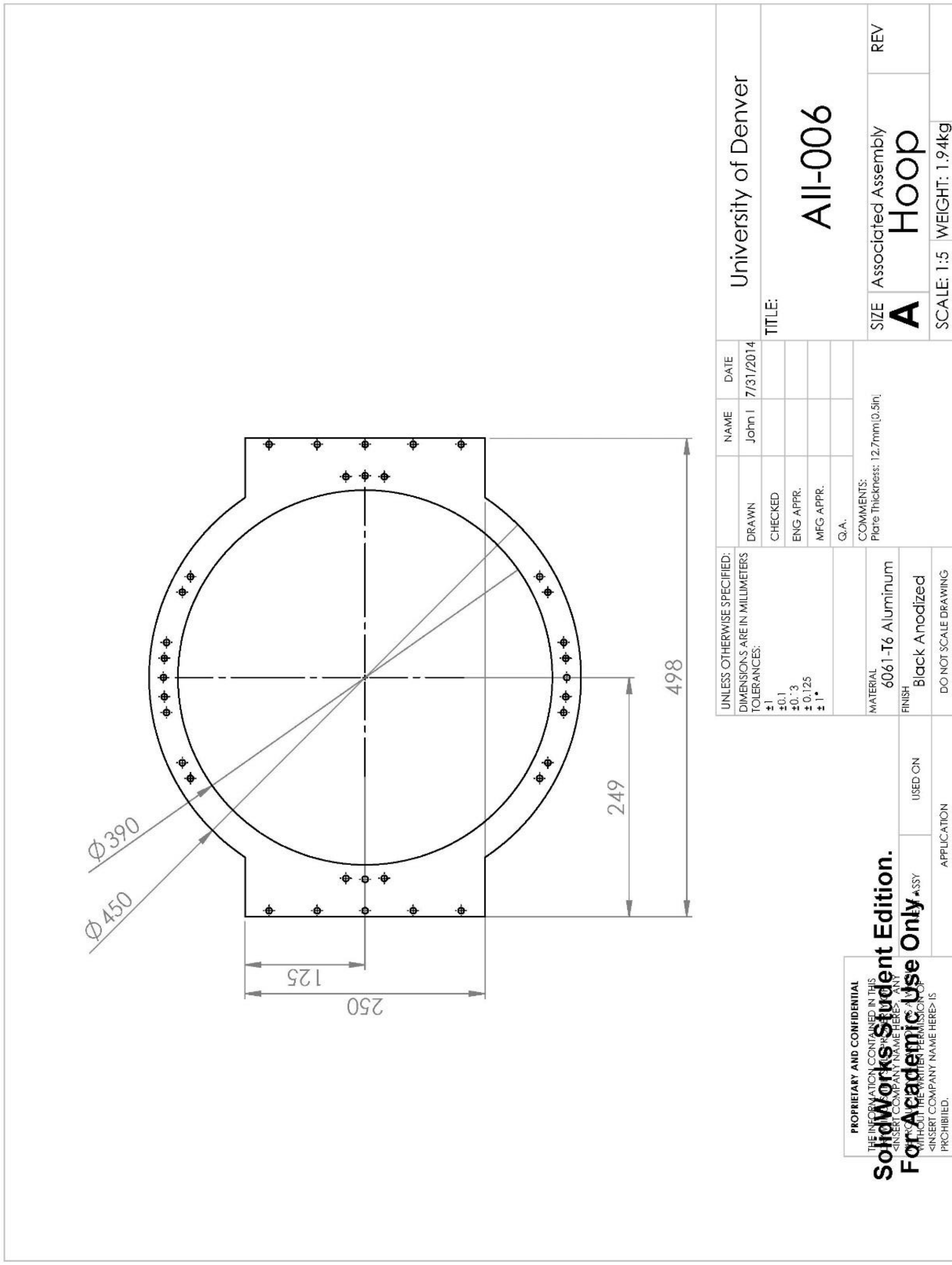
5 x Ø 5 ⊽ 18
M6x1.0 - 6H ⊽ 13
12.700
6.350
25
75
125
175
225
250
R104.250
R95.750
R4.250
Ø28.575 THRU
150
70


University of Denver
TITLE:
AII-006
SIZE
A
Associated Assembly
Hoop
REV
SCALE: 1:5
WEIGHT: 1.94kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm(0.5in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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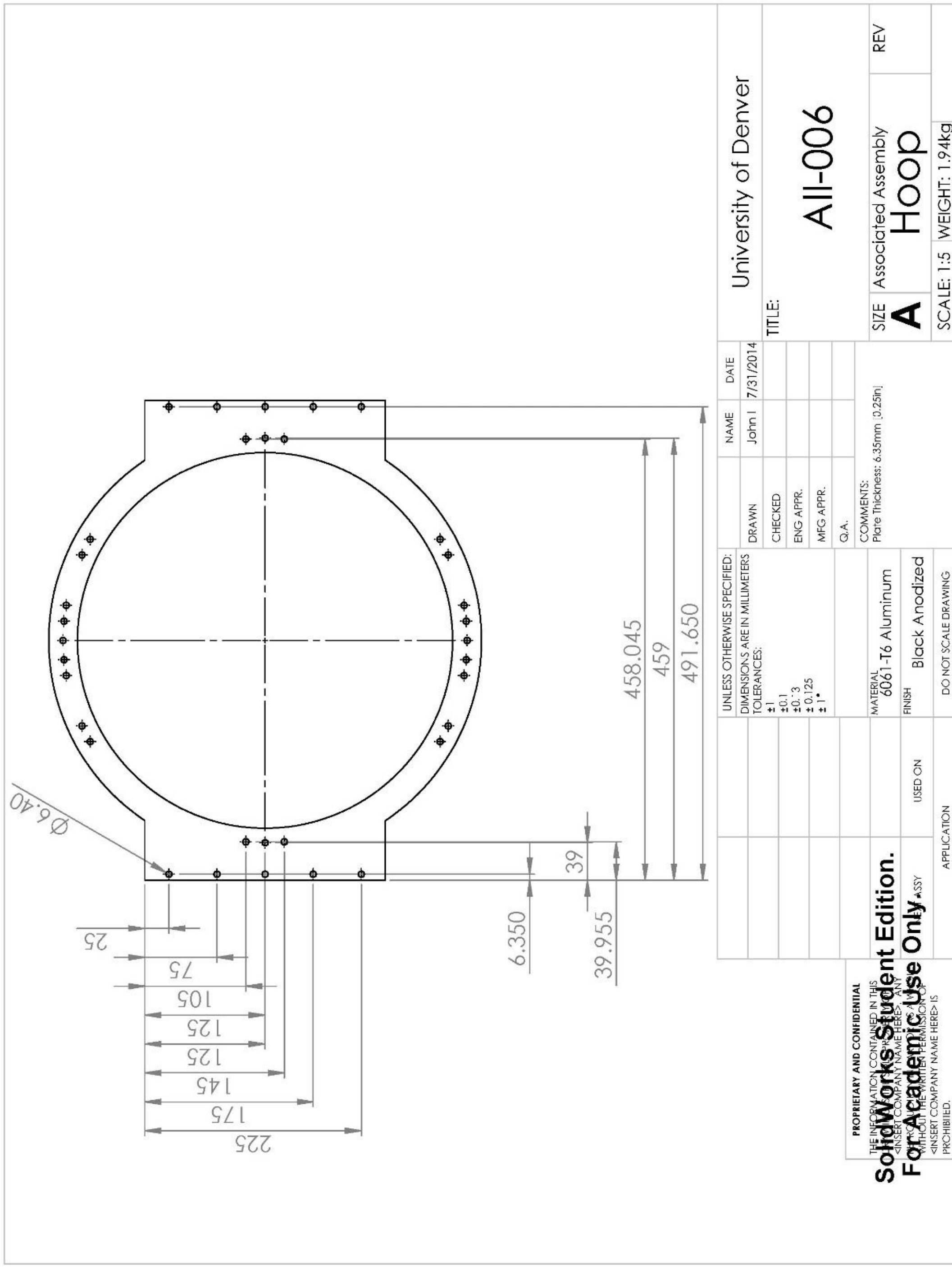
Ø390
Ø450
498
249
125
250
1
2
3
4
5



University of Denver
TITLE:
AII-006
SIZE A
Associated Assembly
Hoop
SCALE: 1:5
WEIGHT: 1.94kg
REV
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 6.35mm (0.25in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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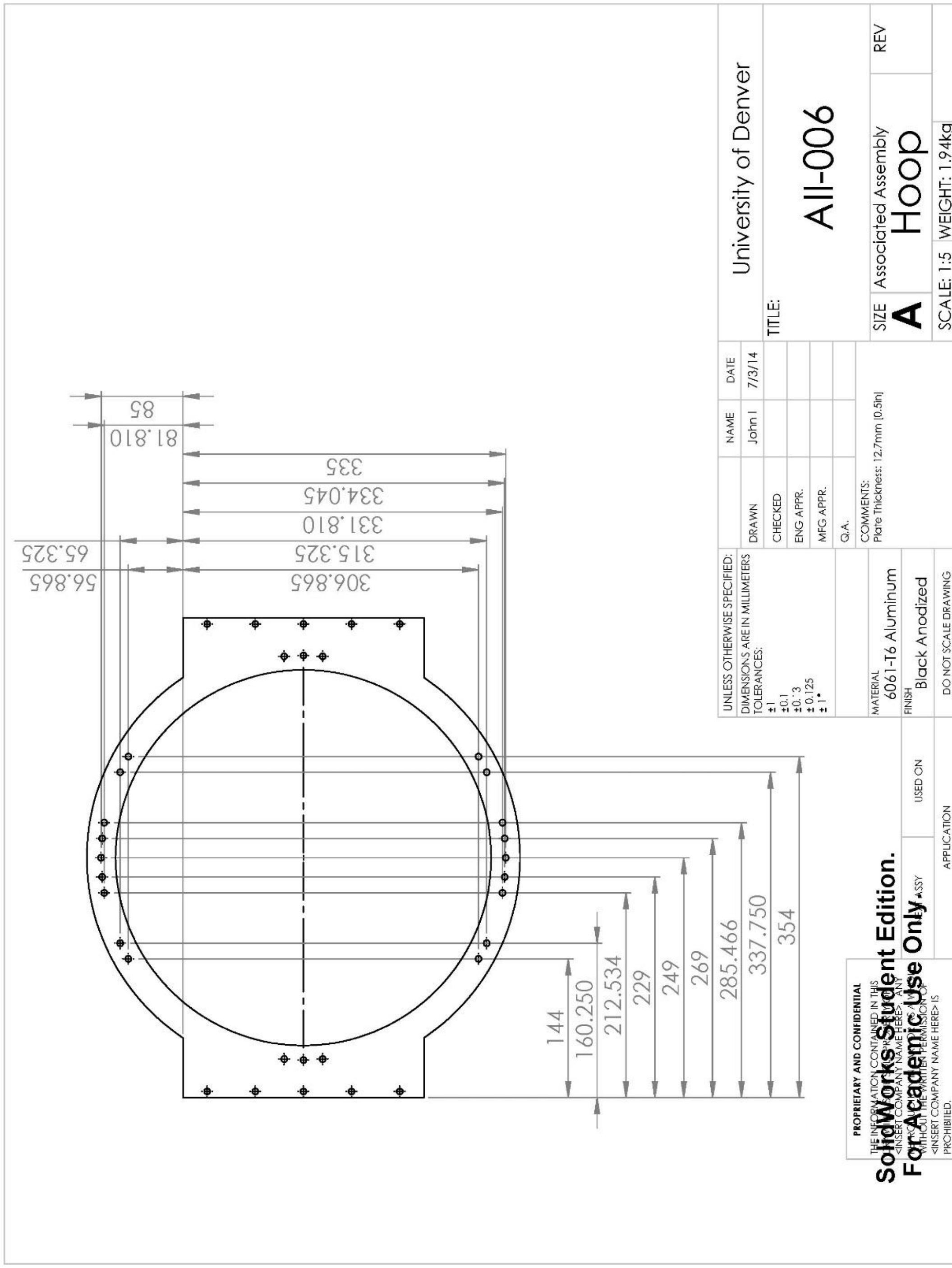
458.045
459
491.650
39
6.350
39.955
Ø6.40
25
75
105
125
125
145
175
225


University of Denver
TITLE:
AII-006
SIZE
A
Associated Assembly
Hoop
REV
SCALE: 1:5
WEIGHT: 1.94kg
NAME
DATE
DRAWN
John I
7/3/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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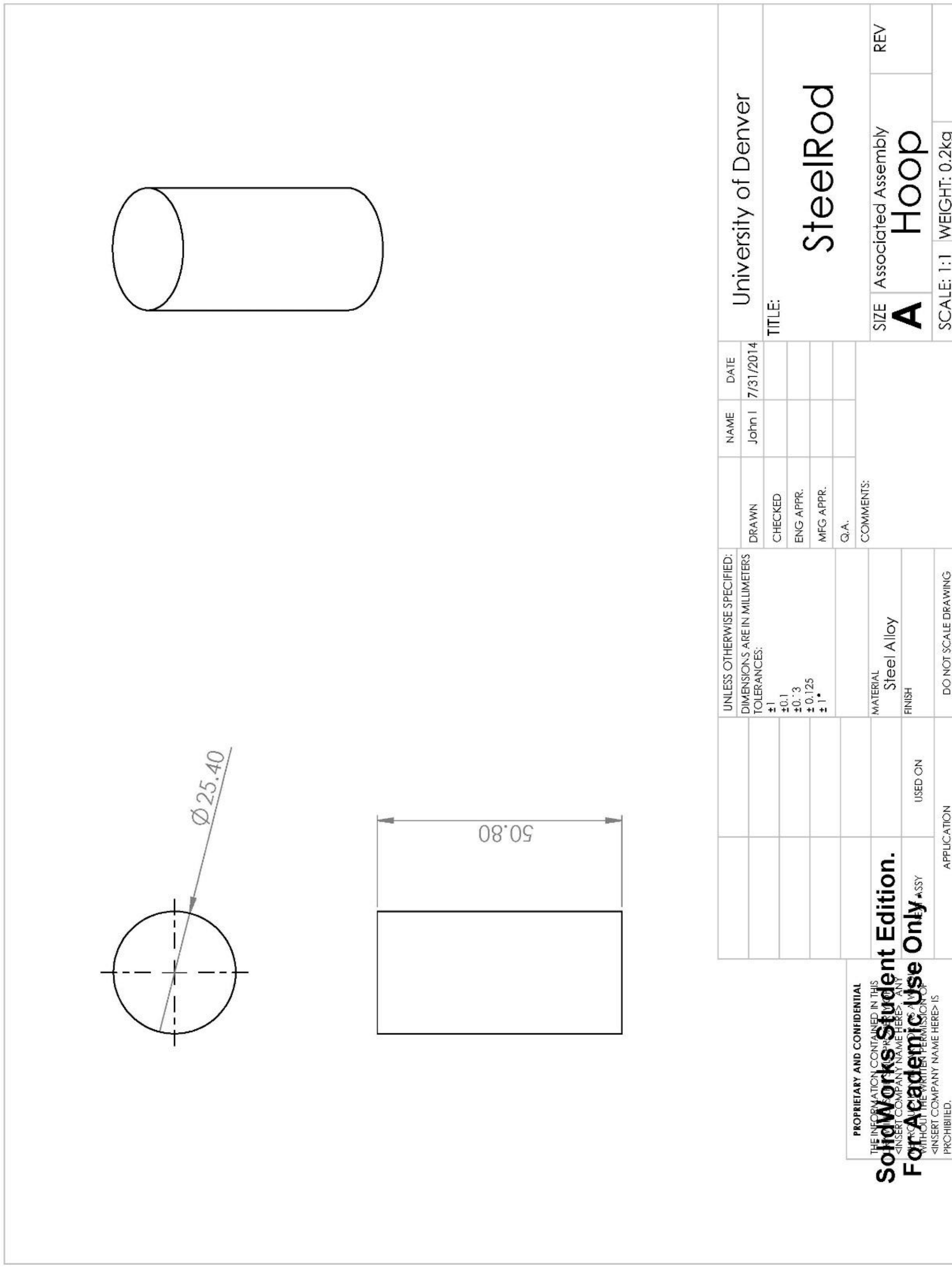
144
160.250
212.534
229
249
269
285.466
337.750
354
306.865
315.325
331.810
334.045
335
81.810
85
56.865
65.325
1
2
3
4
5



Ø25.40
50.80
University of Denver
TITLE:
SteelRod
SIZE
A
Associated Assembly
Hoop
REV
SCALE: 1:1
WEIGHT: 0.2kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
Steel Alloy
FINISH
DO NOT SCALE DRAWING
USED ON
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SolidWorks Student Edition.
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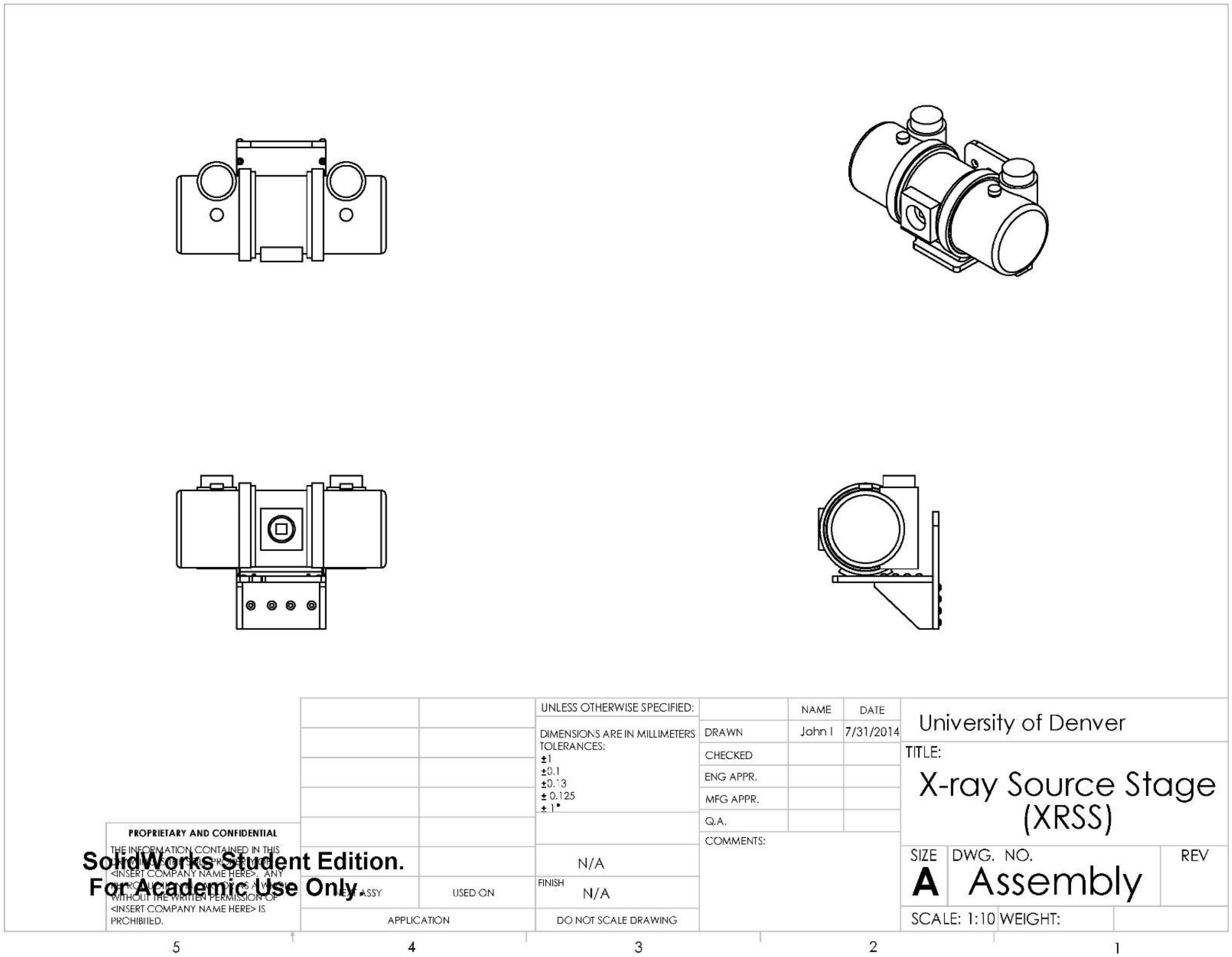

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.13
± 0.125
± 1°
N/A
FINISH
N/A
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
University of Denver
TITLE:
X-ray Source Stage
(XRSS)
SIZE
A
DWG. NO.
Assembly
REV
SCALE: 1:10
WEIGHT:
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS
<INSERT COMPANY NAME HERE>. ANY
WITHOUT THE WRITTEN PERMISSION OF
<INSERT COMPANY NAME HERE> IS
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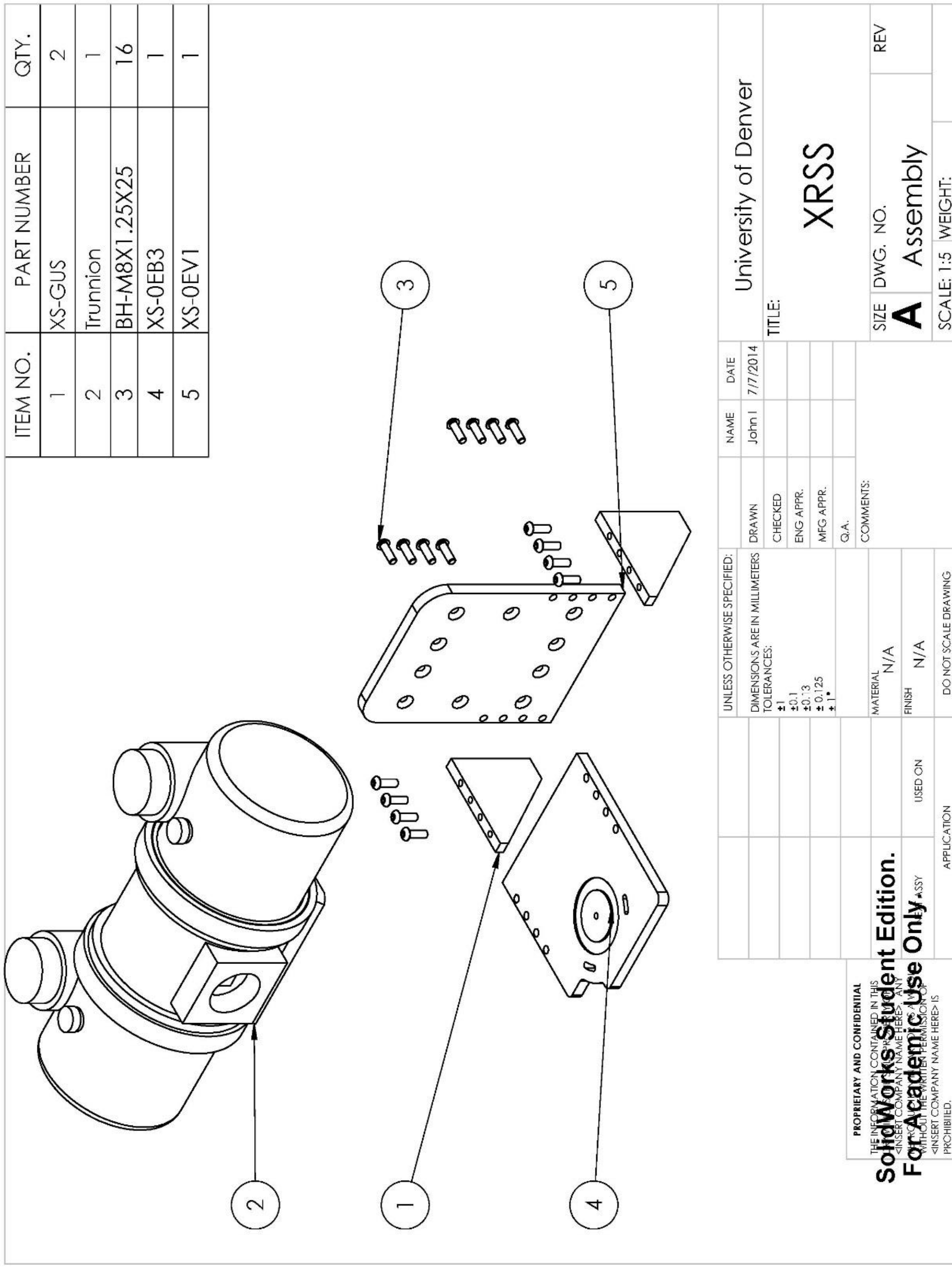
NEXT ASSY
USED ON
APPLICATION
5
4
3
2
1


ITEM NO. | PART NUMBER | QTY.
1 | XS-GUS | 2
2 | Trunnion | 1
3 | BH-M8X1.25X25 | 16
4 | XS-0EB3 | 1
5 | XS-0EV1 | 1
University of Denver
TITLE:
XRSS
SIZE A
DWG. NO.
Assembly
REV
SCALE: 1:5
WEIGHT:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/7/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
N/A
FINISH
N/A
DO NOT SCALE DRAWING
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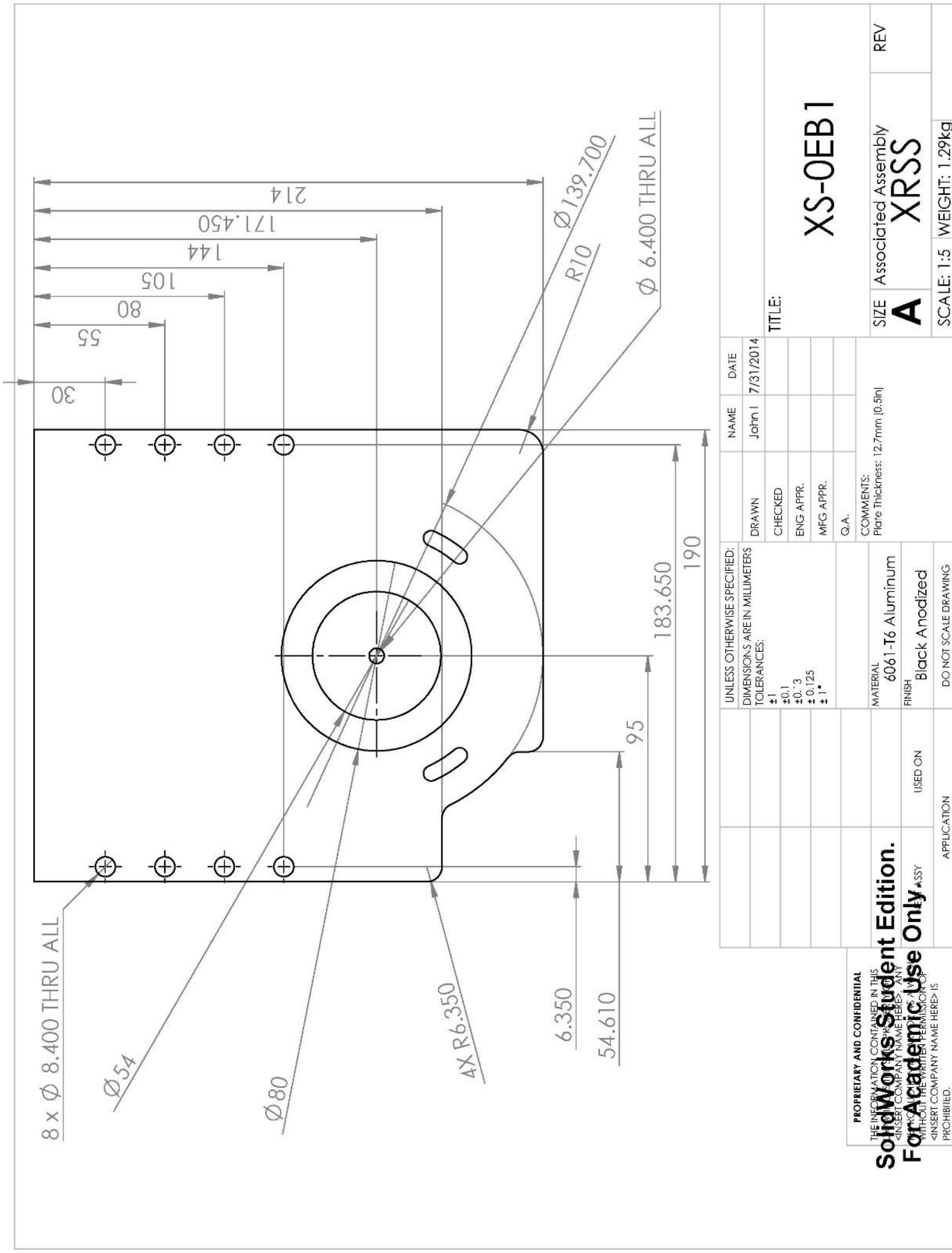

214
171.450
144
105
80
55
30
Ø139.700
R10
Ø 6.400 THRU ALL
8 x Ø 8.400 THRU ALL
Ø54
Ø80
4X R6.350
6.350
54.610
95
183.650
190
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
TITLE:
XS-OEB1
SIZE
A
Associated Assembly
XRSS
REV
SCALE: 1:5
WEIGHT: 1.29kg
PROPRIETARY AND CONFIDENTIAL
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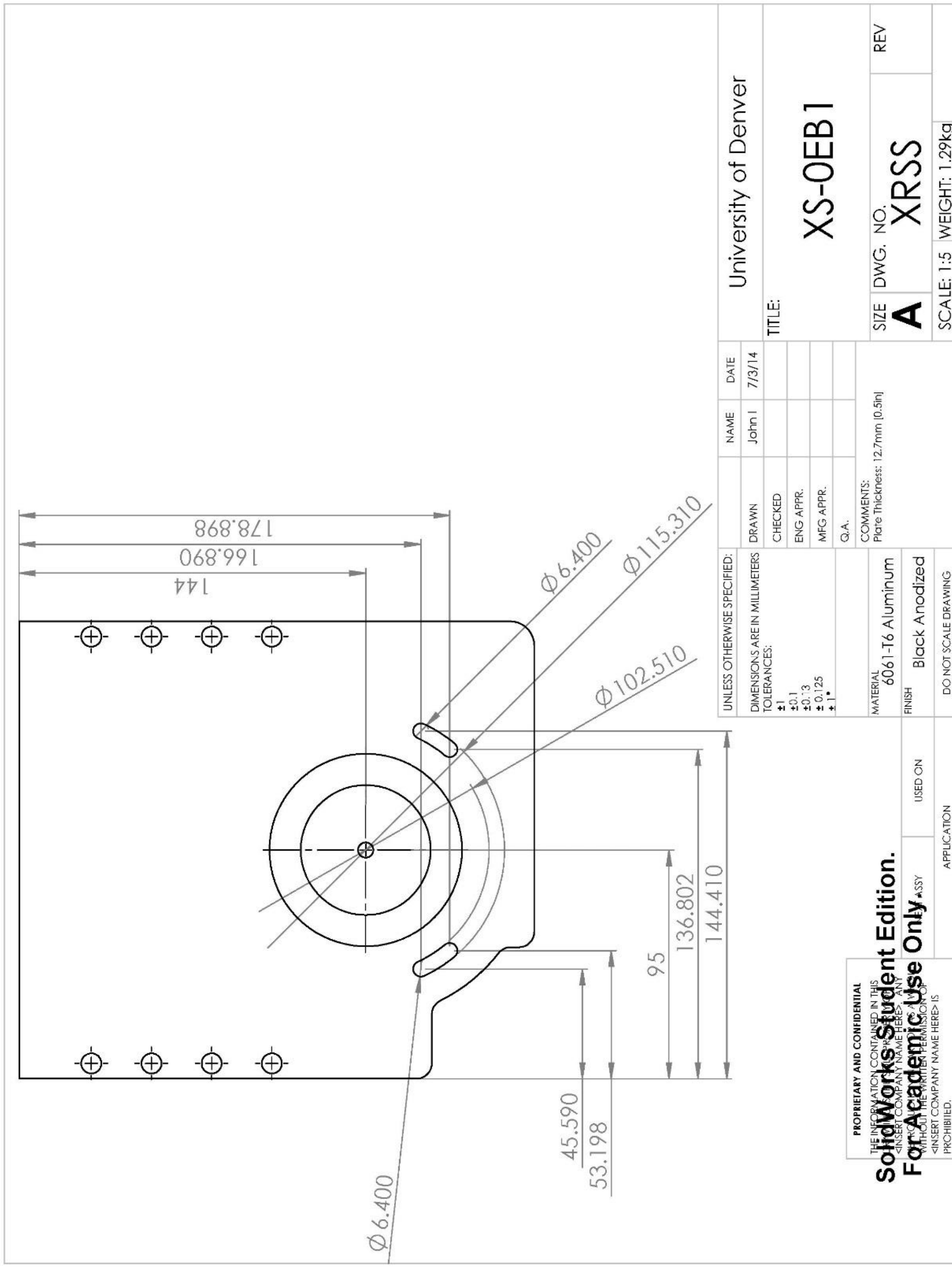

University of Denver
TITLE:
XS-OEB1
SIZE A
DWG. NO. XRSS
REV
SCALE: 1:5
WEIGHT: 1.29kg
NAME
DATE
DRAWN
John I
7/3/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm (0.5in)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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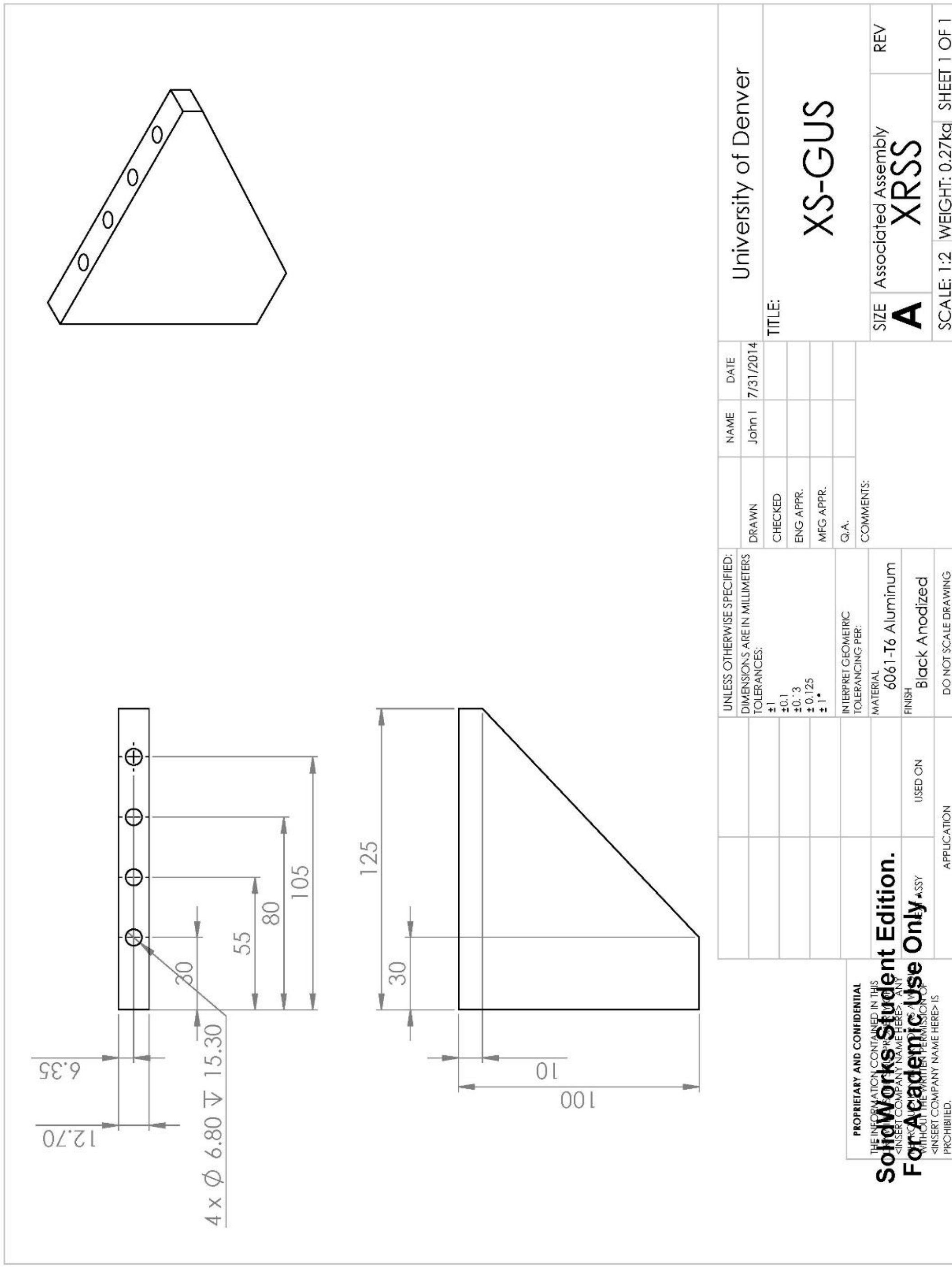
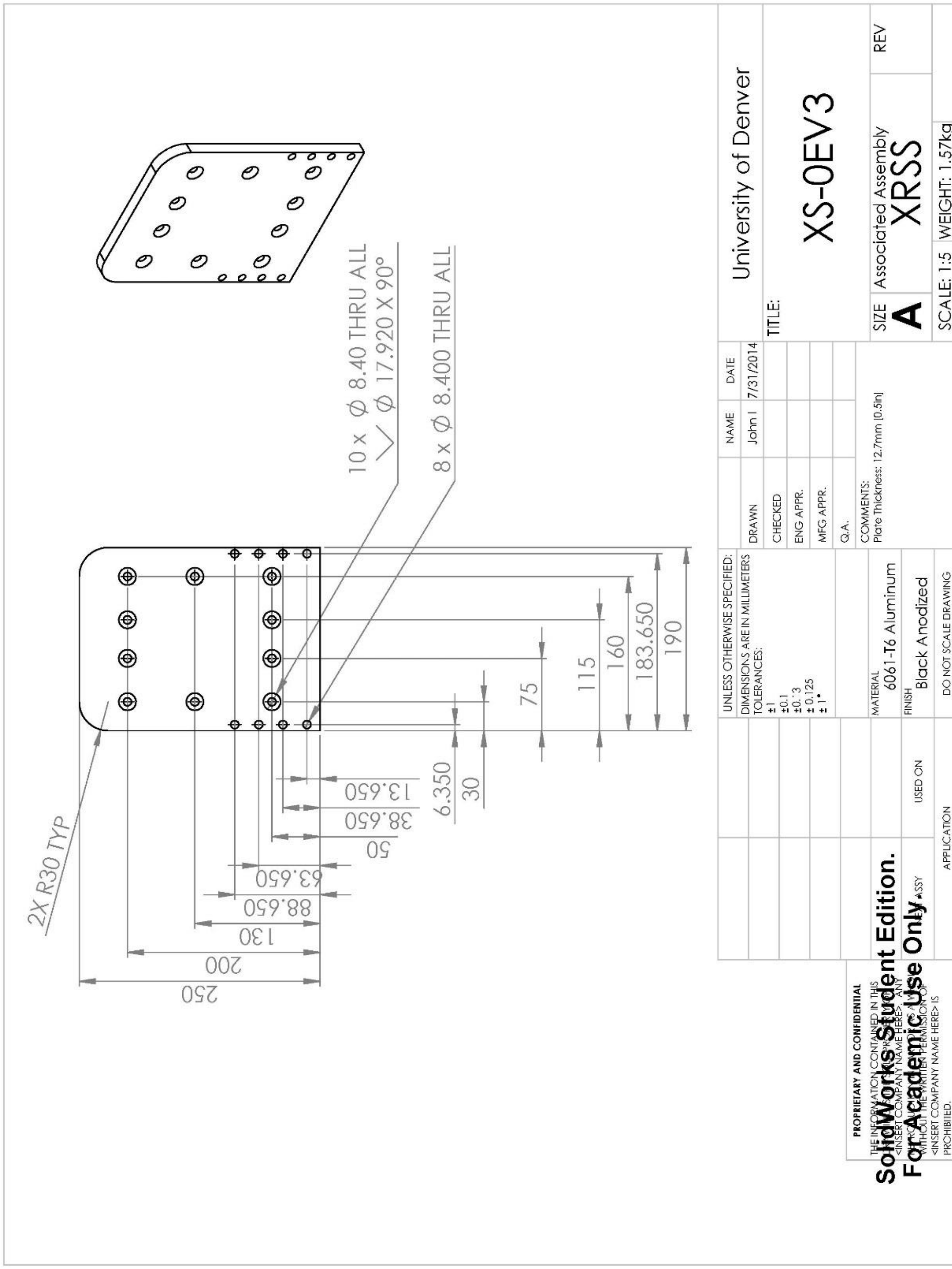
178.898
166.890
144
Ø6.400
Ø115.310
Ø102.510
136.802
144.410
95
45.590
53.198
Ø6.400
1
2
3
4
5



4 x Ø 6.80 ⊽ 15.30
12.70
6.35
30
55
80
105
125
30
10
100
University of Denver
TITLE:
XS-GUS
SIZE
A
Associated Assembly
XRSS
REV
SCALE: 1:2
WEIGHT: 0.27kg
SHEET 1 OF 1
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
±1
±0.1
±0.°3
± 0.125
± 1°
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
1
2
3
4
5



University of Denver
TITLE:
XS-0EV3
SIZE A
Associated Assembly
XRSS
REV
SCALE: 1:5
WEIGHT: 1.57kg
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Plate Thickness: 12.7mm [0.5in]
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
6061-T6 Aluminum
FINISH
Black Anodized
DO NOT SCALE DRAWING
USED ON
APPLICATION
NEXT ASSY
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
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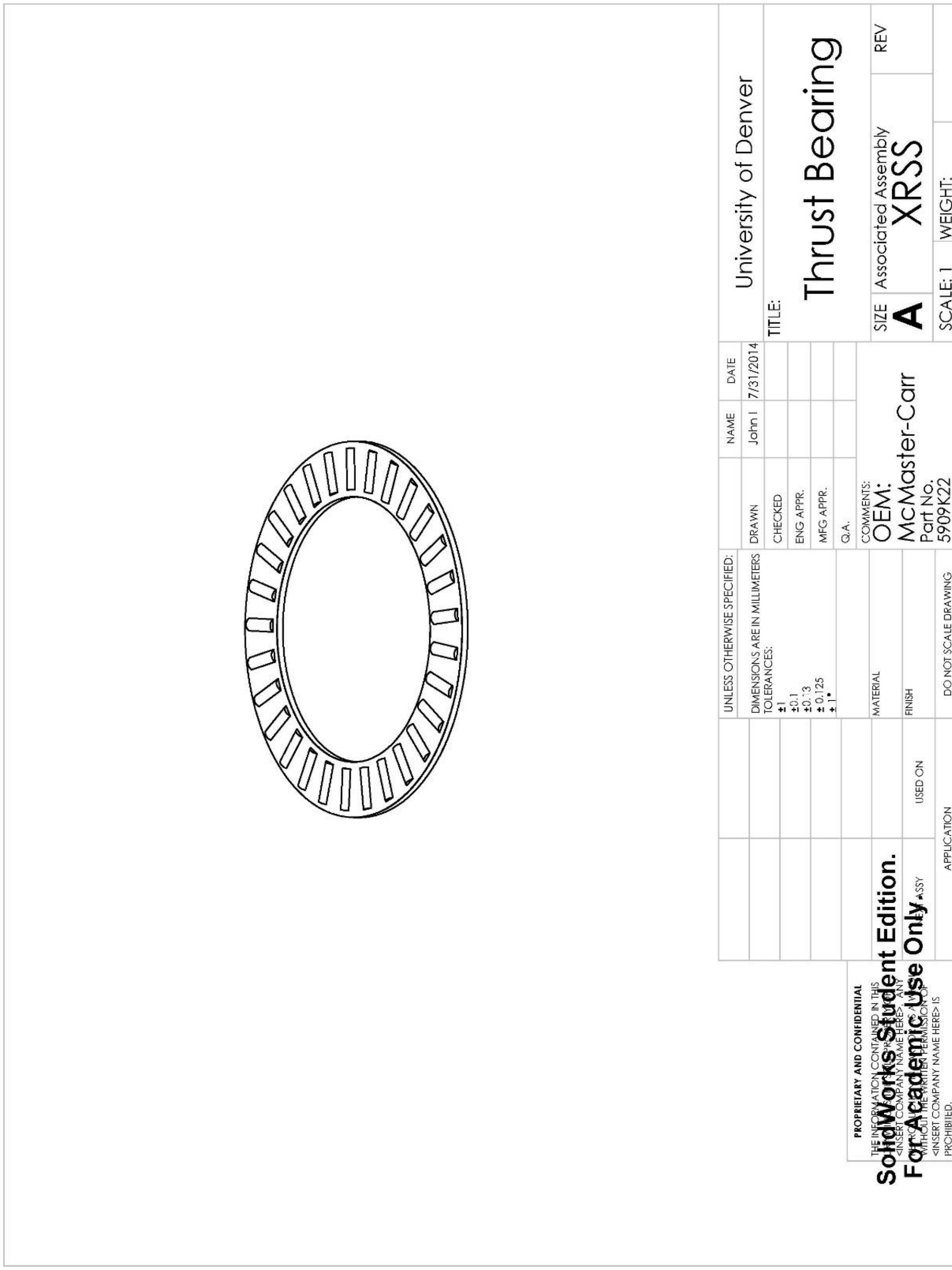
10 x Ø 8.40 THRU ALL
Ø 17.920 X 90°
8 x Ø 8.400 THRU ALL
2X R30 TYP
250
200
130
88.650
63.650
50
38.650
13.650
6.350
30
75
115
160
183.650
190


University of Denver
TITLE:
Thrust Bearing
SIZE
A
Associated Assembly
XRSS
REV
SCALE: 1
WEIGHT:
NAME
DATE
DRAWN
John I
7/31/2014
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
OEM:
McMaster-Carr
Part No.
5909K22
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
MATERIAL
FINISH
DO NOT SCALE DRAWING
USED ON
APPLICATION
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