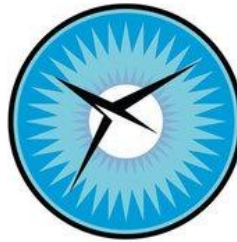# Final Design Report

Fall 2012 - EML4551

Florida Agricultural & Mechanical University / Florida State University College of Engineering

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I. Project Overview (Competition Proposal)

1.0　　　Abstract

This document describes the FAMU/FSU College of Engineering's proposed rover design for the 2013 RASC-AL Robo-Ops competition. The team consists of 6 undergraduate engineering students all with an interest in space exploration and a strong will to compete in this year's competition. Guidance and working facilities will be provided to the team by their main advisor, Dr. Jonathan Clark, and the STRIDe Lab, which operates under his direction.

A hexapedal locomotion platform forms the basis for the proposed rover, and grants the rover several key features which we believe will make it successful in completing the tasks of this year's competition. The rover also features a low degree of freedom Sample Extraction Module (SEM) designed specifically for the legged platform, an on-board Field Programmable Gate Array to consolidate logic operations (pulse-width modulation and decoding of motor signals), and a strategy for wireless control of the rover, which minimizes on-board computing requirements.

2.0　　　Team Leads and Facilities

Daniel Bucken, Mechanical Systems Lead – Daniel Bucken is a senior at Florida State University pursuing his BS in Mechanical Engineering. Over the past year he has been employed by the Center for Intelligent Systems, Controls and Robotics (CISCOR) as a research assistant. His work has focused on the design of robotic systems and the design of components for implementation of controls on existing platforms.

Ricardo Asencio, Electrical and Computing Systems Lead – Ricardo is a senior at Florida State University and is completing his degree in Computer Engineering. He recently completed a year-long internship with Intel Corporation in Folsom, California and plans to return for full-time work after graduation. At Intel, Ricardo had various roles but was primarily focused on system validation of modern application-specific IC's while running a complete software stack in a pre/post silicon environment. His interests include autonomous robotic systems and artificial intelligence.

STRIDe Lab, Working Facilities – Scansorial and Terrestrial Robotics and Integrated Design Lab was founded in 2007 by its director, team advisor Dr. Jonathan Clark, with the aim of developing robotic platforms which can challenge the agility and versatility of animals and insects. STRIDe Lab has worked extensively on the design and control of legged platforms and is well equipped for the task of developing a legged rover. The lab boasts several tools to aid in the manufacture of a rover including a laser cutter, composite material construction tools, extensive analysis and testing devices, and a capable machine shop available next door at the FAMU/FSU College of Engineering.

3.0　　　Rover Performance Summary

Mechanical		Electrical/Computing	
Stowed Dimensions:	86.9 cm x 70.8 cm x 46 cm	**On-Board Computing:**	Raspberry Pi
Weight:	40 kg	**Computing Power:**	700 MHz
Ground Clearance:	15 cm	**Logic Device:**	Xilinx Spartan-6 FPGA
Tipping Angle:	43.2°	**Operating System:**	Arch Linux
Claw Movement Speed:	4 cm/s	**Control Method:**	SSH
Predicted Top Speed:	0.8 m/s	**Networking:**	Verizon 4G LTE USB modem
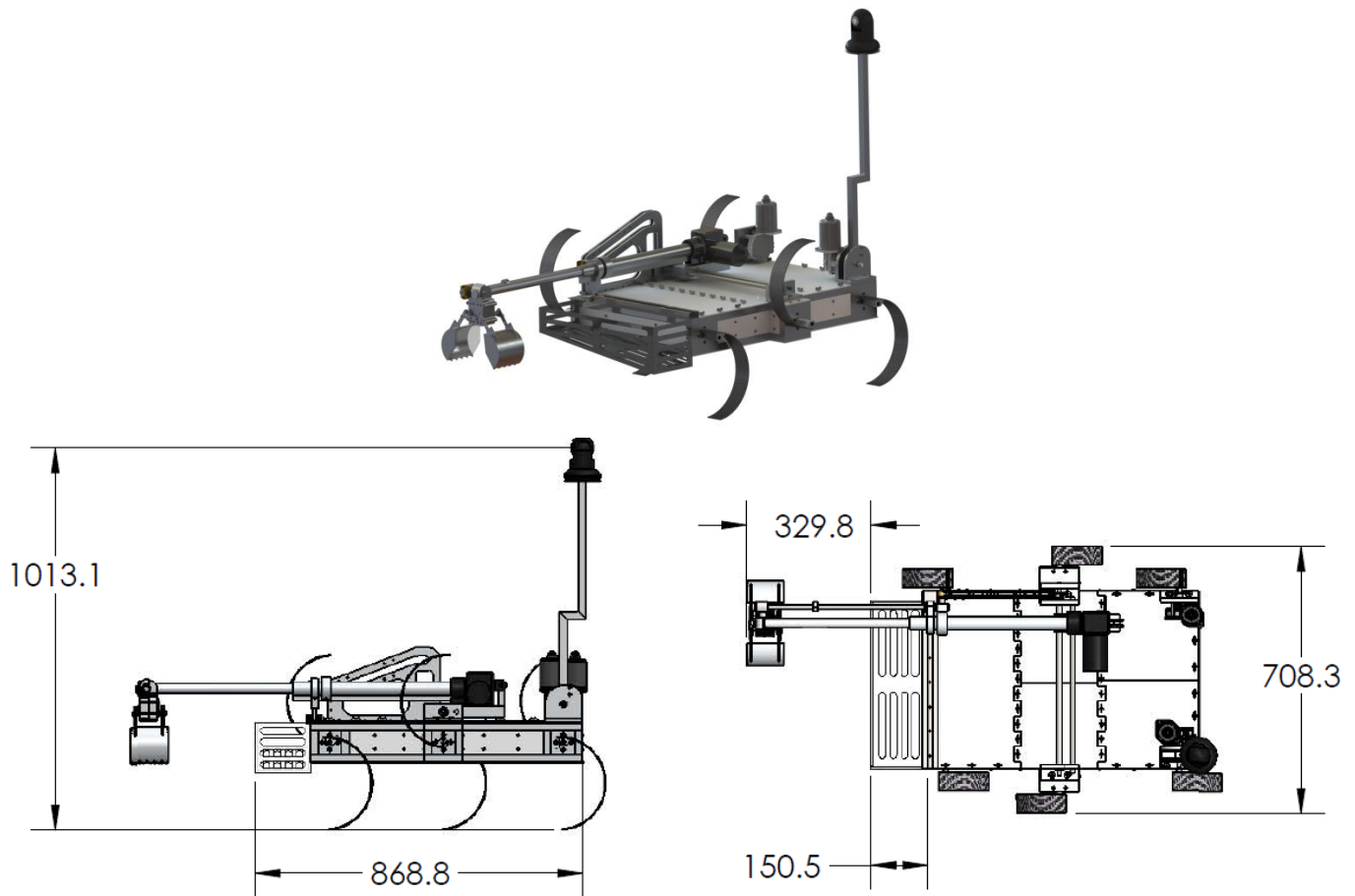
Figure 1 - A render (top) and key dimensions in mm (bottom) of the FAMU/FSU Robo-Ops Rover.

4.0   Functional Overview

Locomotion

The rover's drive system must allow it to quickly navigate a multitude of terrains, including steep inclines, large rocks, and sand. This system must also not consume too much power as to allow for at least one hour of rover operation.

The proposed design will implement six individually-actuated compliant legs for movement. The performance of this configuration on extreme terrains has been demonstrated by the RHex robot and by Hexcavator, a robot successfully developed at the FAMU/FSU College of Engineering for the 2012 NASA Lunabotics competition. The hexapedal platform was also chosen for its uniqueness to the Robo-Ops competition and to take advantage of the expertise of the project advisor, Dr. Jonathan Clark, who has extensive experience with the design and control of legged-robots.

The legs are 25 cm in diameter and will be constructed out of carbon fiber to provide adequate strength and the proper stiffness with the guidance and facilities of the STRIDe lab, where substantial research on the design of compliant legs for hexapedal robots has taken place. Each leg will be driven by an independently controlled Maxon RE-50 DC-motor attached to a GP-52 Maxon gearhead, which will implement a variable rotational speed algorithm during general movement of the rover. This algorithm is known as the Buehler clock and will be discussed further in the programming section of this proposal.

The hexapedal design is expected to perform favorably at the terrain of the JSC Rock Yard. The rover is designed to straddle objects up to 15 cm tall and sustain a tilt angle of 43.2° before tipping, allowing the rover to navigate large

obstacles with ease. Sand presents a challenge for wheeled rover designs, as seen with the fate of the Mars Exploration Rover Spirit, the rover's legged design grants it higher mobility in loose terrains. For example, Hexcavator navigated the fine "lunar regolith" of the 2012 Lunabotics competition with ease.

Sample Extraction

Our examination of the effectiveness of past years' sample extraction designs suggested that the quickest extraction times were achieved by teams with either low degree of freedom manipulators or very sophisticated control schemes; ease of control was thus determined to be the primary design consideration for the robotic arm.

The proposed arm design takes advantage of the fact that the legged locomotion platform results in a non-planar rover. The vertical mobility generally found in robotic arms was removed from the arm itself since this degree of freedom may be obtained via the legs of the rover. The arm employs a simple and reliable lead screw setup for motion along the width of the rover, and a long-stroke linear actuator to move the end effector along the length of the rover. Planar motion of the end effector in both directions will occur at speeds up to 4 cm/s. The range of motion in both directions is 30 cm, resulting in a 900 cm^2 operating area for the end effector.

The end effector is a hybrid pincer-scoop design. It utilizes two concave surfaces moved through pinching motion to capture the sample. This configuration combines the speed of scoop-style claws with the precision of a pincer. The scoops are toothed to enhance grip when used as a pincer and to lower the required force for the penetration of soil. The scoops also include clear rear surfaces to enhance visibility of an arm-mounted camera during positioning of the end effector. Each half of the pincer-scoop is actuated by a servo-driven fourbar mechanism. The resulting motion allows for grasping of objects up to 14 cm in diameter. The scoop-region has enough volume to enclose a spherical object 11 cm in diameter. This will allow our gripper to capture a rock within the size range specified in the design requirements.

1) Lead screw (A) moves linear actuator (B) in front of rock sample.

2) Linear actuator extended so gripper (C) is over the rock sample.

3) Gripper captures rock sample.

4) Lead screw moves linear actuator to far right.

5) Linear actuator retracted slightly. Cam-follower riser (D) engages.

6) Linear actuator is retracted further and rises via cam-follower path.

7) Gripper opens, dropping rock sample into basket (E).

8) Linear actuator may remain here or be returned to far left.

Figure 2 - SEM operation diagram outlining the sample extraction process.

The planar arm design requires special consideration with respect to sample storage as the container must be designed to allow access to the end effector while still fully constraining the samples. A passively controlled vertical degree of freedom was added in this design via a cam-follower system to allow the end effector to rise above the storage container and release the sample, as illustrated in Figure 2.

For the majority of sample extractions during the competition, the rover will simply lie down on the ground and the end effector will operate in the ground plane, which will allow for accurate and fast sample extraction. For samples not in the

ground plane shared by the rover, leg positions will be adjusted to orient the end effector's operating plane to contain the sample.

Electrical/Computing Systems

In order to minimize the required power consumption, a widely popular yet small ARM computer platform known as the Raspberry Pi will be used, which draws only 3.5 W of power. The Raspberry Pi is ultra-low-cost ($35), Linux-based, commercially available computer. The Raspberry Pi is at the center of our electrical system and will provide the foundation for the communication and control of the rover.

Raspberry Pi	
Architecture:	ARMv6I
SoC:	Broadcom BCM2835
CPU:	700 MHz ARM1176JZF-S core
Memory:	512 MB (shared with GPU)
Onboard storage:	SD / MMC / SDIO card slot
Network:	10/100 Ethernet (RJ45) via USB hub
Video:	Composite RCA, HDMI (Rev 1.3 & 1.4)
Power Rating:	700 mA (3.5 W)
Power Source:	5 volt via MicroUSB or GPIO header
Size:	85.60 mm× 53.98 mm
Weight:	45 g
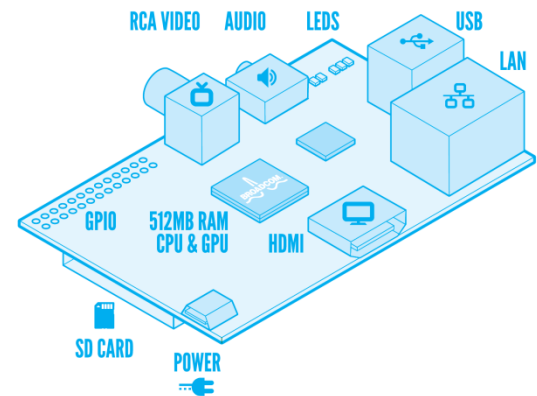
Figure 3 - Raspberry Pi specifications (left) and layout (right). (Image acquired from raspberrypi.org)

Interfacing the Raspberry Pi with a Field Programmable Gate Array (FPGA) will allow the team to develop the logic circuits needed to count the motor positions from the encoders. The selected FPGA board was a Xula2-LX25 made by Xess (Cost: $119). The Xula2 contains a Xilinx Spartan-6 FPGA and has a power consumption of approximately 2 ½ W which suits the low power profile of the design.

The logic circuits that will be implemented in the FPGA are decoders for counting motor positions and pulse width modulation (PWM) for motor driving, seen in **Figure 4**. The communication protocol used to communicate with the FPGA and the Raspberry Pi will be the Serial Peripheral Interface (SPI) as it is available on the Raspberry Pi pin-out. The decoders will simply count the quadrature encoded signal from the motor encoders and store the values in a register which can then be read by the Raspberry Pi. The PWMs will provide a square wave that drives the motors at the appropriate speed by altering the duty cycle. The duty cycle is set inside a register which will be written to by the Raspberry Pi.
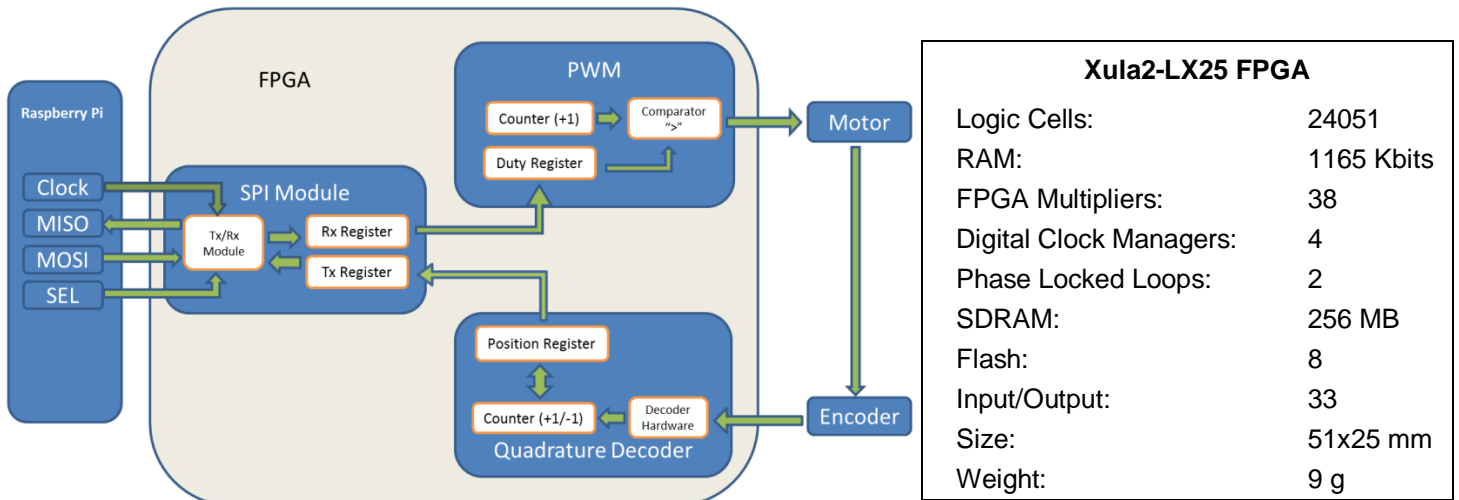
Figure 4 - FPGA block diagram (left) and specifications (right).

Control and Programming

The Operating System selected for the Raspberry Pi is Arch Linux ARM, which is a light Linux distribution with no Graphical User Interface and only the necessary drivers and processes are loaded at boot. This allows our user programs to use more CPU time as the OS scheduler has fewer processes which it must distribute CPU resources to. The General Compiler Compilation (GCC) and Vim (terminal text editor) were installed to create our development environment. The entire algorithm will be written in C. **Figure 5** illustrates how the locomotion algorithm works and is described below.
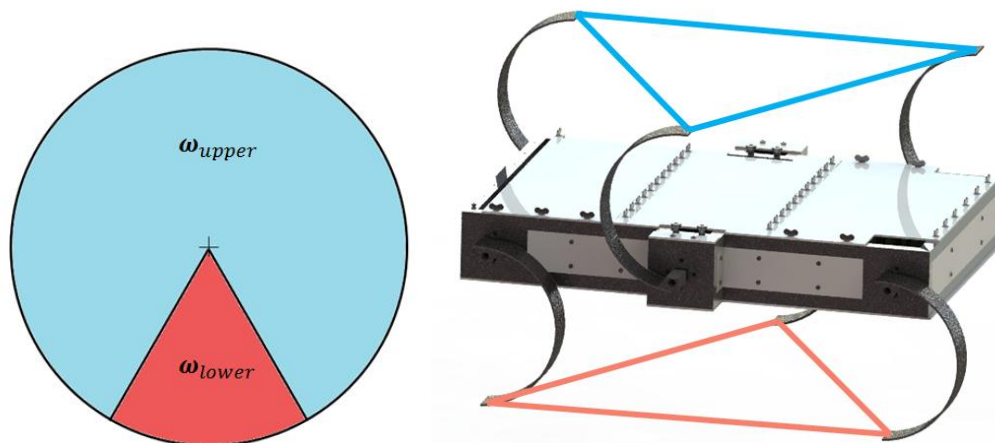
Figure 5 - Depiction of the Buehler algorithm. On the left are two rotational speed zones corresponding to the color-matched leg sets on the right.

In order to provide a walking motion the locomotion algorithm used is a Buehler clock. The Buehler clock has two phases. When a triplet of legs is in the blue phase (above) the angular velocity ω_{upper} is approximately five times faster than the velocity in the red phase ω_{lower}. The triplets connected by the blue and red lines in the diagram above should ideally be in the same position at any instance. However, small errors are unavoidable since it is possible for legs to be traversing different terrains simultaneously. This causes the leg rotational velocity to differ even if the same duty cycle is provided to drive both motors. For example, walking over a rock and traversing sand require different torques from each motor to achieve the same rotational velocity. The control algorithm used to correct this scenario is a Proportional Derivative (PD) algorithm which regulates the rotational velocity by increasing or decreasing the torque of each leg until the leg position matches the ideal position as calculated by the algorithm. When any motor is out of position the algorithm makes a torque correction proportional to how many positions it is behind or ahead of the ideal Buehler Clock. This allows every pair of leg to respond dynamically to the terrain it is currently traversing.

Communications

The communication hardware will mainly consist of the Verizon Wireless 4G LTE USB Modem 551L and the CradlePoint MBR1200B Mobile Broadband Router. The router has USB ports available for a wireless broadband modem connection. This modem-router configuration will allow multiple devices to connect via Ethernet to the router and send information over the wireless broadband network. The components that will require network access are the IP (Internet Protocol) cameras for video transfer and the Raspberry Pi for SSH (Secure Shell) access. A server will be set up, on campus, to receive the video feed from the cameras and control SSH access to the Raspberry Pi on the rover.
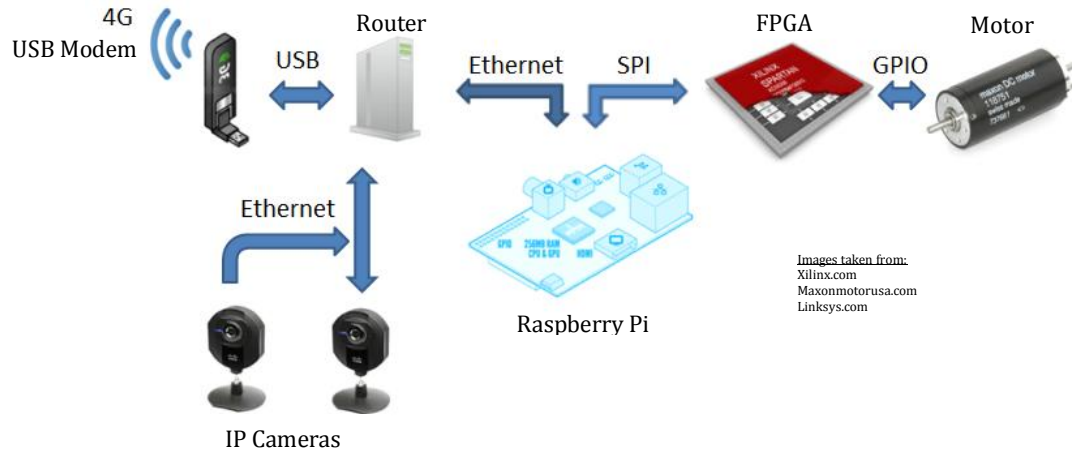
Figure 6 - Electrical system hardware interconnects.

The main vision component will be an overhead Internet Protocol (IP) camera that will sit atop the camera mast and have the ability to pan and tilt. More importantly, IP cameras are designed to handle video processing and compression and send the video over a network for remote viewing without the aid of a computer. A second IP camera will mount to the Sample Extraction Module to ensure an optimal viewing angle for the operator. The consequences of the time delay that are expected will be partially mitigated by making the rover semi-autonomous in its movements. Rather than having the operator directly control the rover's movements instantaneously; the operator will give the rover a command to walk a certain amount of steps; this will prevent the rover from stopping suddenly and toppling over. The arm will be controlled by the operator directly and will be subject to manual correction.

The SSH server and client are readily available on many Linux distributions and are a simple solution to remotely controlling the onboard computer. However, most wireless broadband carriers do not allow incoming SSH connections, but do allow outgoing SSH connections. A script was written that connects the Raspberry Pi to a local port on the campus server automatically at boot. This allows the server to then reverse-SSH into the Raspberry Pi and control the bash shell remotely. The operator can then access all of the scripts and programs written for control, calibration of the legs and error handling.

The Serial Peripheral Interface is a four wire interconnect that is used to communicate between discrete circuit components. The SPI protocol transmits information in bytes and is full Duplex, that is it receives and transmits a byte over the bus concurrently. The four communication signals are the bus clock (SCK), the select line (SSEL), MOSI (Master Output Slave Input), and MISO (Master Input Slave Output). When the select line is low the SPI slave reads a bit over the MOSI line while concurrently driving the MISO line at each and every rising edge of the bus clock as shown below.

5.0   Educational and Public Outreach Plan

The team currently maintains a Facebook page, a website, a YouTube channel, and an Instagram account to fulfill the electronic portion of the educational and public outreach (E/PO) requirements. The website is a primary hub for project documents and reports. It also contains information about all team members, sponsors, and an overview of the project itself. Most photos and videos of progress made will be posted on the team's Facebook page. Important photos and videos will also be featured on the team's website. The YouTube channel is used to feature all videos of progress and to

chronicle important project milestones and events. The Instagram account is used to provide impromptu picture-updates on team activity.

The team has future plans to participate in public outreach events at the Challenger Learning Center, the K-12 outreach facility of the Florida A&M University - Florida State University College of Engineering. The Challenger Learning Center has a theme of space exploration, and hosts family-friendly space-oriented events year-round. There is also planned an outreach event at a local middle school to engage students with the theme of robotic planetary exploration, using the team's rover as a set piece. Last year's Lunabotics team visited Swift Creek Middle School in Tallahassee, FL for a portion of their community outreach. Our current team and the school have agreed to continue this partnership to peak the children's interest in engineering and space exploration. We also plan to attend preview sessions for those looking to continue their education at our university. In doing so, we hope to inspire incoming students who are unsure of their planned field of study to enter the field of engineering.

6.0 Current Project Status

Task Name	Duration	Start	Finish
Design Refinement	7 days	Wed 12/19/12	Thu 12/27/12
Purchasing	66 days	Mon 11/5/12	Mon 2/4/13
Critical Components	30 days	Mon 11/5/12	Fri 12/14/12
Remaining Components	2 days	Fri 2/1/13	Mon 2/4/13
Manufacturing	75 days	Mon 11/5/12	Fri 2/15/13
Frame Fabrication	65 days	Mon 11/5/12	Fri 2/1/13
Machining	60 days	Mon 11/5/12	Fri 1/25/13
Leg Manufacturing	15 days	Wed 1/2/13	Tue 1/22/13
S.E.M Mounting	5 days	Mon 2/4/13	Fri 2/8/13
Camera Boom Mounting	5 days	Mon 2/4/13	Fri 2/8/13
Electrical Component Mounting	5 days	Mon 2/4/13	Fri 2/8/13
Final Assembly	5 days	Mon 2/11/13	Fri 2/15/13
Component Testing	48 days	Wed 1/2/13	Fri 3/8/13
S.E.M. Testing	10 days	Mon 2/18/13	Fri 3/1/13
Locomotion Control Development on Existing Platform	20 days	Wed 1/9/13	Tue 2/5/13
Locomotion Testing on Competition Platform	15 days	Mon 2/18/13	Fri 3/8/13
Wireless Control Testing	20 days	Mon 1/21/13	Fri 2/15/13
Video Testing and Refinement	20 days	Wed 1/2/13	Tue 1/29/13
System Testing	50 days	Mon 3/11/13	Fri 5/17/13
Sample Pickup Testing	15 days	Mon 3/11/13	Fri 3/29/13
Obstacle and Terrain Testing	15 days	Mon 4/1/13	Fri 4/19/13
Simulated Time-delay Testing and Practice	10 days	Mon 4/22/13	Fri 5/3/13
Competition Dry Runs	10 days	Mon 5/6/13	Fri 5/17/13
Control Algorithm Refinement	30 days	Mon 4/8/13	Fri 5/17/13
Automation	30 days	Mon 3/11/13	Fri 4/19/13
GUI Development	25 days	Mon 3/11/13	Fri 4/12/13
E/PO Events	90 days	Mon 1/14/13	Fri 5/17/13

Figure 7 - Project schedule outlining the manufacturing, purchasing and testing phases of the rover.

Currently, the full design of the rover has been completed, including all major electronic and mechanical components and mounting hardware. Development of the decoder and pulse width modulation logic on the FPGA board is under way and nearly complete; the team has been able to drive a motor using a Raspberry Pi and FPGA board. Wireless connectivity and control of the Raspberry Pi has been established over 3G and the team has been able to stream a webcam video over this connection. The team has also practiced forming carbon fiber legs on a small scale so that new legs can be constructed with minimum impact to schedule.

The major components and raw materials for the body and arm have been ordered. The square aluminum tubing for the frame of the rover has been cut and is scheduled to be welded by January. The various guides and parts for the SEM are undergoing CNC machining currently. Once these components are completed, they will be combined with the linear actuator that has already been received. Then, testing can begin.

II. Appendices

A. Competition Rules and Requirements

Competition Summary

The mission is to develop a planetary rover platform capable of exploring the NASA Johnson Space Center (JSC) Rock Yard. At the JSC Rock Yard, the rover must acquire and store specific rock samples spread across the rock yard. The rover must be controlled from the team's home campus over a commercially available cellular broadband connection. Teams must also connect with the general public throughout development using online social media, and community activities. Participation includes a potential grant worth a total of $10,000. Winning teams can receive up to $12,000 in cash prizes.

Requirements for 2012

Participation was established first by submitting a notice of intent to the competition stewards. Next, it was required that an 8 page proposal (was due December 9, 2012) to be eligible to become one of 8 teams chosen to compete. Being selected nets a team a $5,000 grant to construct the proposed rover, and all teams will be notified of their selection by December 19, 2012. The proposal was required to outline the team's plan for meeting the milestones of the competition (to be discussed later), and how the team's product will meet the following Rover Design Requirements outlined in the competition guidelines.

Rover specs for competition trim

In the rover's "Stowed configuration", meaning with all peripherals retracted, the rover must not exceed dimensions 1m x 1m x0.5m. The maximum mass (without payload) must not exceed 45kg, or else points will be deducted. No internal combustion engines are allowed, and the rover must be water-proof.

Rover performance and capability required

The rover must be capable of traversing obstacles at least 10cm tall, negotiate +/- 33% grades, and traverse level sand surfaces for at least 20 feet of distance. The areas of the JSC Rock Yard to be included in the competition are the Rock Field, Lunar craters, Sand Dunes, and the Mars Hill. The rover must selectively acquire at least five irregularly shaped rocks while traversing the JSC Rock Yard. The rocks are outlined as having diameters from 2 - 8 cm, masses from 20 - 150 gm, and be of different colors each corresponding to a point value. The rover must store and carry these rocks throughout the course. The JSC Rock Yard and the rocks of interest can be seen in Figure 8, below.

Figure 8.: Photo of JSC Rock Yard from NASA.com (left), and photo of colored rock samples from nianet.org (right).

Controls and Communications Requirement

As stated before, the rover must be remotely controlled from the team's home campus over a commercial cellular data network (ie. via wireless broadband card). Rover data must be sent from the rover itself to operators and spectators online. This data is required to consist of live video feed and some rover telemetry. The video feed must be capable of distinguishing color (rock samples), and must be recorded and posted on the team's website.

Requirements for 2013

After being selected to compete in the 2013 RASC-AL Robo-Ops competition, the team will be required to continuously document and broadcast rover development progress. These reports are required to outline how the team has met the aforementioned "milestones" of the competition. Next, each report will be introduced along with the milestones the team is expected to cover in that report.

Mid-Project Review Report + Video – due March 15, 2013

The purpose of this report is to display to the competition stewards that a team is on schedule to completing a rover capable of satisfying all design and performance requirements. This report consists of a five-page written portion and a YouTube video. The whole report must demonstrate the rover's present functionality and chronicle what is yet to come. Team must outline where they are with the project and how confident they are that their rover will be completed.

If the stewards feel that a team's report does not show this, they will be required to do a live follow-up web chat with the stewards to redeem themselves. Only after the stewards are satisfied with a team's progress will be awarded an additional $5,000 grant money be awarded to a team.

<u>Outreach Video – due May 17, 2013</u>

   Each team is required to conduct educational public outreach (E/PO) via the internet and in person. The use of Facebook, YouTube, and a team website are required for teams to host updates on rover development, relevant documents, and video. The outreach video itself is for teams to generate interest for the team itself, science, and space exploration in general, and must be posted on the team's website. Links to the team's website, E/PO pages, and the Rover's Camera Feed are all required to be submitted by May 17, 2013;

<u>Final technical report - due May 19, 2013</u>

   This report must summarize the completed rover itself and the whole development process. The only requirements given at this time are that it must be between 10-15 pages of information. The competition website says additional guidelines will be given to competing teams in February of 2013. A poster presentation will also be required for teams attending the 2013 Robo-Ops Competition in Houston, Texas.

B. Body Design

Due to the immense amount of research required to size a new robotic platform, our team decided it would be in our best interest to scale an existing and proven platform using its aspect ratio. The platform chosen was XRL, a hexapedal robot currently being utilized by STRIDe lab.

Our rover's major limiting dimension was the width, due to the size of the motors required to move this platform. The frame was then scaled using a width where two motors could be mounted across from one another and still have an appropriate clearance. From this, the length of the rover as well as the length of our legs was decided. The height of the frame was then minimized to be as small as possible while still allowing us to house all major electrical components in the interior of the frame.

The material chosen for the frame itself was 6065 hot extruded aluminum tubing with dimensions of 2 cm x 2 cm and a wall thickness of 2 mm. This provided the lightweight properties desired while still being able to undergo the stress and impacts of laying the robot down on rocky surfaces. This tubing will be welded together and have the aluminum motor mounts for locomotion welded to it as well. Along the underside of the frame are quarter-inch strips of aluminum that the electrical components will attach to via bolts and straps. This frame will be drilled for all components to attach to the top surface as well as for covers on all sides, as a sealed frame has been decided upon.

The final modeled assembly of this part weighs less than 5 kg, which is acceptable for our competition maximum weight requirement. The tubing was purchased from a sponsor with an in-store credit, allowing us to keep our monetary grants for larger purchases. Its final dimensions are 72 cm long x 59.4 cm wide x 10.2 cm tall.
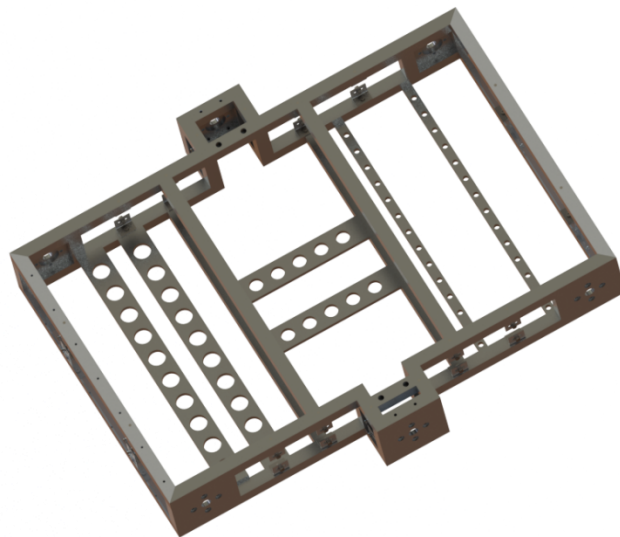
Figure 9 - The frame assembly with all mounting holes and brackets

As mentioned, the team has decided to have a sealed body. This was accomplished by encasing all sides with eighth-inch ABS plastic, which would keep the weight of this process to a minimum. The sides of the rover and underside will have the ABS bolted to them and will be caulked to provide a perfect seal. However, it is still necessary to access the internal components of the rover for testing, charging of batteries as well as fixing of any issues encountered. Because of this, the top has been designed to use a series quarter-turn screws pushing down on a gasket to provide the seal between the various panels and the frame. These screws will allow quick and tool-less access to the internals at any point in time. Figure 10 shows the frame with its panels in place with the cut outs for various pieces to be mounted to the top. The addition of these panels and fasteners brings the weight of the now sealed frame up to 7.6 kg.
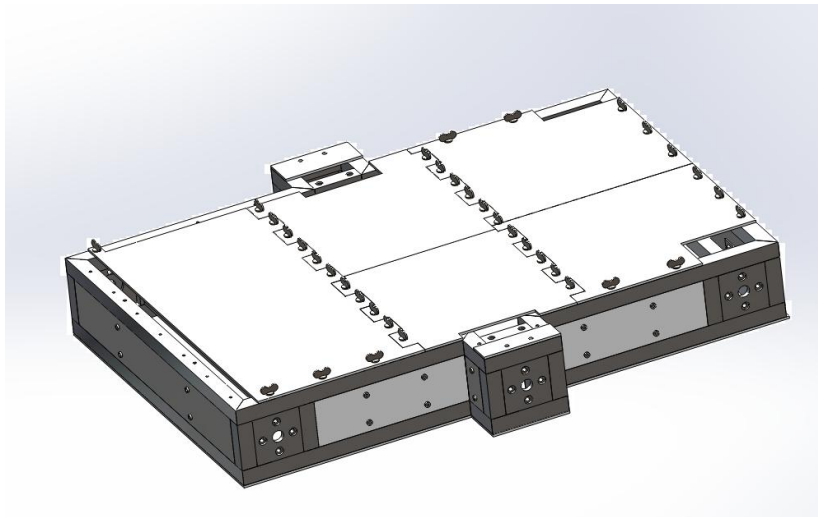
Figure 10 - The assembled frame with all ABS panels and mounting hardware

C. Drive Motors

Selecting the drive motors for our rover was a critical task, which then dictated the size of the rover and the proposed budget for all other systems, as they would be our most expensive purchase. To estimate the motor specifications that we would need, we turned to a research paper being done on dynamic scaling by our sponsor, the STRIDe lab. Using this information, we were able to obtain the desired data in Table 1 by scaling from the XRL platform. Our sponsor recommended the desired rotational speed as it is a fast walking gate, where the stiffness of the legs of the robot does not become problematic.

	Continuous Torque	**Stall Torque**	**Nominal Rotational Speed**
XRL	2.3 Nm	30.52 Nm	187 rpm
Desired	17.1 Nm	226.74 Nm	120 rpm
Selected	17.4 Nm	383.56 Nm	132 rpm

Table 1 - The torque values of the XRL platform, the scaled desired values and the values of the selected motors.

In looking for motors that could produce the desired specifications, there was only one company that could provide the motors in a relatively small and lightweight package. We ended up selecting Maxon Motors as our provider of this component of our system as they offered an educational discount to our group. To achieve this amount of torque and rotational speed, a RE-50 motor was chosen. This motor is a 24 Volt, 200 Watt motor that is coupled to a planetary gearbox with an encoder mounted to detect the motor's position. This combination provided the specifications in Table 2.

Supply Voltage	24 V
Power	200 W
Weight	1.9Kg
Encoder Counts/Revolution	108,500
Overall Length	207mm
Discounted Price (each)	$867.75

Table 2 - This table outlines the other key specifications of the selected drive motors.

These motors will cost the team a little over $6,000 for seven motors, including a spare. This is our largest purchase for the project but there was no other reasonable alternative. We also can rest assured that there will not be issues with these drives as Maxon is regarded as the industry standard and are known for their reliability.

D. SEM Design Requirements

The competition guidelines give few explicit requirements for the method by which teams pick up the samples (rocks), only specifying that:

"The rover must be capable of picking up irregularly-shaped rocks with maximum diameter of 2-8 cm and masses ranging from 20-150 grams. The rover must be capable of picking up at least five of these rocks and transporting them using the rover throughout the course."

In addition to these explicit requirements, the team has come up with several others to maximize the effectiveness of the Sample Extraction Module, or SEM. The primary design criteria will be presented here along with their justifications.

1. **The system must be easy to control.** During the team's concept generation phase, much research was conducted on the effectiveness of sample extraction designs and techniques from the teams of previous years. It was observed that the teams which performed the best in the competition either had low degree of freedom arm designs, such as the winning team from Worchester Polytechnic Institute who used an arm with only two rotational joints, or extremely sophisticated control schemes such as the second-place team from Caltech. At the advice of our advisor, Dr. Clark, we chose to avoid designs with multiple rotational joints and complicated dynamics, as they can take months to refine to acceptable precision.

2. **The reach of the system must be sufficient.** A legged robot cannot be as deliberate in its forward and backward movements as a wheeled robot can, as it is constrained to movement in finite increments. This means that the reach of the sample extraction system must be great enough to account for the minimum step size of the robot, so if the robot has a minimum step size of 8", the SEM must have a reach greater than 8" to ensure the sample can always be picked up.

3. **Autonomous operation of the system must be feasible.** Due to the substantial distance that will be present during the completion (Tallahassee, FL to Houston, TX) a significant time delay will be experienced between the user input, response of the robot, and seeing the action on the screen. As such, any actions that can be automated will save a significant amount of time. The SEM only needs to be user-controlled to navigate the claw to the sample of interest and to pick it up, the entire storage process of the sample can be automated. We looked for designs that would make this automation easy.

4. **The system must be reliable.** The design must allow for highly repeatable motion, low chance of failure, and the strength to survive the bumpy ride atop the legged rover.

Other noted design metrics are manufacturability as the device must be made in house by our machine shop, price to accommodate our budget, and weight to ensure we do not exceed the competition weight limit.

E. SEM Detailed Design

The chosen design for the SEM combines all of the above metrics to result in a design that should accomplish the task of picking up rocks samples both quickly and reliably. The proposed design takes advantage of the fact that the legged locomotion platform results in the body of the robot being non-planar. The vertical degree of freedom generally found in robotic arms was removed from the arm itself and compensated for through the use of the legs of the robot to vertically adjust the end effector. The arm employs a simple and reliable lead screw setup for motion along the width of the robot (X-axis), and a long-stroke linear actuator to move the end effector along the length of the robot (Z-axis). A cam-follower system is used as a passively-activated degree of freedom which allows the claw to rise over the sample bin during storage. Each of these sub-systems will be presented in detail in this section. All of the parts that comprise the system can be seen highlighted in red in Figure 11.
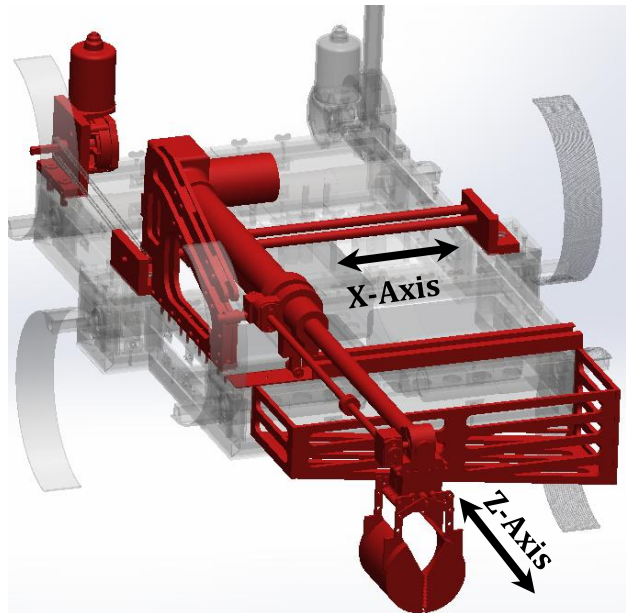
Figure 11 - Sample Extraction Module on rover
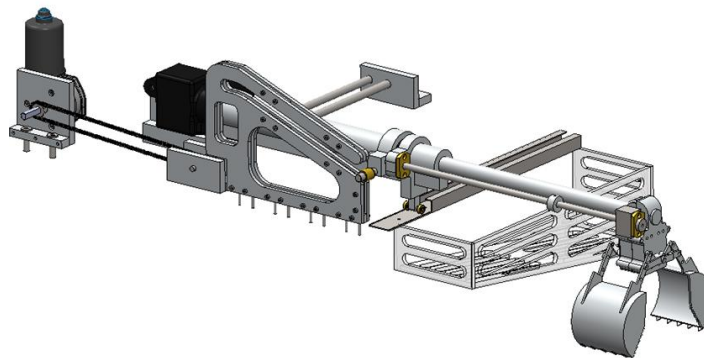
Figure 12 – Isolated Sample Extraction Module

X-Axis Movement
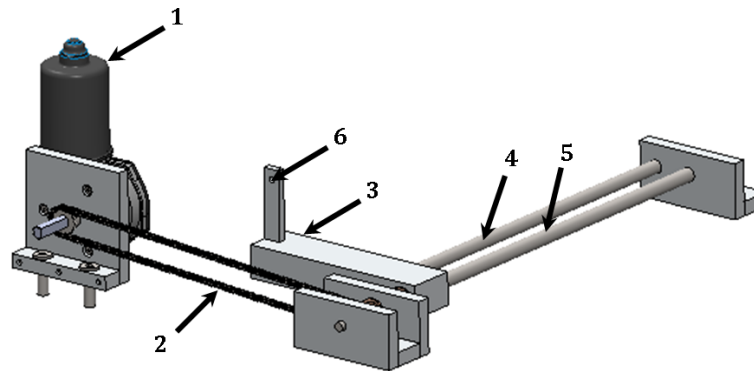
Figure 13 – X-Axis drive system

The x-axis drive system can be seen in Figure 13 and is a basic linear motion drive system based around an ACME ½" lead screw which offers a 1 inch-per-turn speed ratio (4). The lead screw meshes with a lead screw nut inserted into the carriage (3), which results in linear motion of the carriage whenever the lead screw is turned. The lead screw is driven by a high-torque geared DC motor (1) which offers 27 Nm of nominal torque. Connection between the lead screw and motor is made by a chain drive system comprised of a MISUMI chain and sprocket set (2) with a 1:1 speed ratio. The chain drive system was required due to spatial constraints; there was not enough room to couple the motor shaft to the lead screw directly. A 12mm diameter stainless-steel linear support shaft (4) guides an LMU12 linear bushing which is pressed into the carriage to ensure smooth motion. Double-shielded ball bearings are pressed into both mounts to support the lead screw, which will be machined down to 8mm at both ends to accommodate the drive sprocket and optical encoder.

A lead screw was chosen over a ball-screw because it does not require lubrication and has no internal moving parts which can be damaged by dirt or grit. A lead screw also undergoes far less backlash than a ball screw, resulting in more precise and more predictable system operation. All mounting plates will be machined in-house out of ½" aluminum. The mounting plates, carriage, linear support shaft, and bearings were all sized with a factor of safety of 2-6 based on Finite-Element Analysis, which will be described in Appendix H.

Table 3 – Important X-axis performance metrics.

X-Axis Performance Summary	
Movement Speed:	1.5 in/s
Traverse Distance:	12"
Drive Torque:	27 Nm
Positioning Precision:	512 counts/revolution

Z-axis Movement

Movement in the Z-axis, or "lengthwise" axis, is controlled by a long-stroke linear actuator, and mounts to the X-Axis carriage at (6) in Figure 13 which is a pin joint that allows the linear actuator to pivot. The specifications and dimensions of the linear actuator are listed in

Figure 14 and Table 4.

Table 4 – Z-Axis Performance Specifications

Z-Axis Linear Actuator	
Extension/Retraction Speed:	1.5 in/s
Useable Extension:	12"
Fully Extended Length:	34.9"
Fully Retracted Length:	20.9"
Actuating Force:	200 lbf
Rated Voltage:	12V
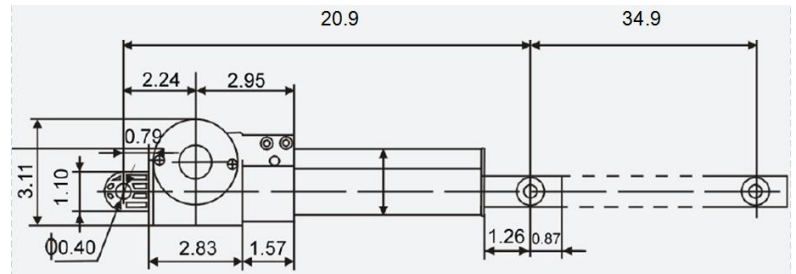
Figure 14 – Actuator dimensions in inches

The linear actuator is DC motor driven and can be controlled using the same pulse-width modulation as the drive motors. As of yet we have not selected a sensor to detect the position of the Z-Axis, but have found possible photoelectric and ultrasonic proximity sensors which meet our needs for under $50.

Sample Storage System

The planar arm design requires special considerations with respect to the storage of the sample, as the gripper needs to rise above the storage container in order to drop the sample inside. We investigated a sliding box design which would allow the box to lower enough for the gripper to drop sample inside, but found that the ground clearance of our rover was reduced to below the 10 cm minimum allowed by the competition. Our solution to the problem of raising the gripper is the addition of a passively-activated degree of freedom in the form of a cam-follower. The goal of the cam-follower is to couple the retraction of the linear actuator with pitching about the base of the actuator. The components that comprise the sample storage system are shown below.
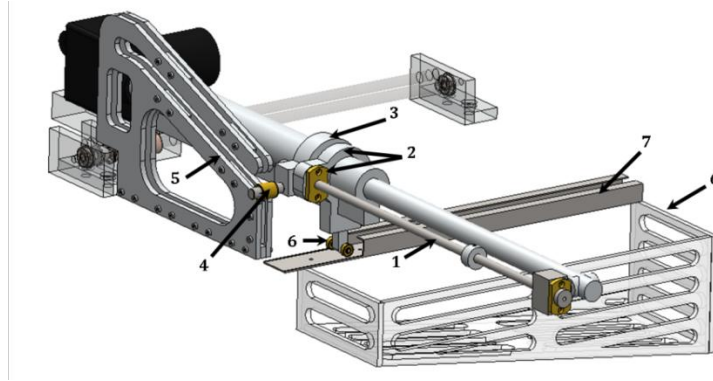
Figure 15 – Sample storage system

Operation of the sample storage system is fairly straightforward and will be automated. Once the sample has been captured in the gripper, the X and Z axes are positioned in the extreme "right-extended" position, as show in Figure 15. Storage is initiated by the retraction of the linear actuator (or Z-Axis), which causes the pushrod (1) to begin sliding through the linear bushing pressed into the fixed bracket (2). The sliding bracket (3) is attached to the end of the pushrod and thus begins to move backward also, this will cause the follower (4) to begin ascending the cam-slot (5). Once the linear actuator has been fully retracted it will be in the full pitch up position, shown in Figure X b), and the gripper will open to drop the sample directly into the storage bin (6). The process is then run in reverse to lower the gripper.

In order to ensure that the linear actuator cannot pitch and the gripper movement remains planar at all times other than storage, a rail (7) was designed for the front of the rover which constrains the rollers (6) attached to the fixed bracket (2). The rail/roller combination will prevent upward movement of the Z-Axis when the rover is not in the extreme "right-extended" position. Stainless-steel was chosen for the rail based on the failure of aluminum during an FEA simulation.
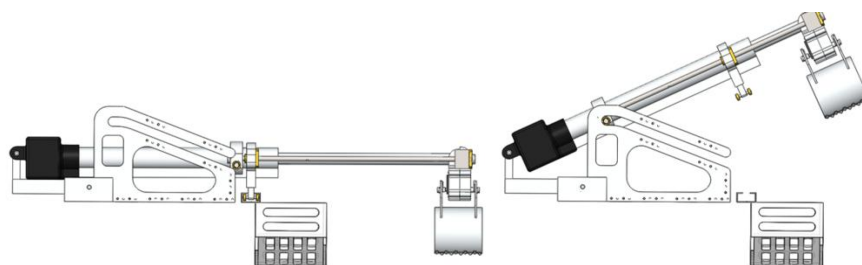
Figure 16 - a) Storage procedure starting position   b) End position

SEM Operation and Control

Control of the sample extraction module will be performed separate from the control of the movement of the rover itself, and will have a different operator. A camera will be mounted to the linear actuator just in front of the fixed bracket, (2) in Figure 15, for an optimal viewing angle of the gripper position, See Appendix P for camera specifications. It is expected from examination of competition footage that for the majority of samples the rover will be able to lie down on the ground and operate in the ground plane to extract the

sample. This would be the ideal case and allow for the fastest sample extraction times. In the event of uneven ground or obstructions that do not allow for this strategy, the legs will be used to position the sample within the operating plane of the gripper (which is coincident with the bottom of the rover's body). It is expected that the level of control required to hold the motors at an arbitrary angular position can be accomplished with the currently design electrical hardware, as holding the rover simply upright in the full standing position requires similar control and is necessary for operation. The difference will be the amount of current required to hold the motors in a loaded position. This will need to be tested carefully so as to not overload the motors. Inclinometers will be used to determine the angular orientation of the rover and to make adjustments as needed to acquire samples.

Current Status of SEM Hardware

As of this writing, all hardware required to construct the SEM has either been built and is in hand, is currently being machined, or has been ordered. Testing of the SEM module will begin in early January.

Figure 17 - Z-axis with storage system hardware attached.

F. Gripper Design

Overview

The sample extraction system needs a mechanical component to grasp rock samples at the end effector of the robotic manipulator. According to the competition guidelines, rock samples will vary in sizes and masses ranging from 2 - 8 cm in diameter and 20 - 150 g mass. The mechanism must be capable of acquiring largest rock sample discretely as points will be awarded for the selection of specific rocks. The component must be versatile in rock acquisition, and strong enough to endure competition environment.
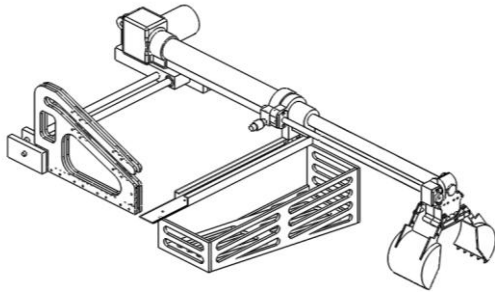
Figure 18: Complete Sample Extraction Module

The mechanism has been termed a gripper and is to be mounted to the end effector of the Sample Extraction Module (SEM, see Figure 18). In order for this gripper to mesh with the sample extraction system and the rover as a whole, it must be capable of interfacing with the main computing hardware. Since this component is also part of a remotely controlled system, it must not require more complexity to control/manipulate than the rest of the system's components. This is to maintain the fast sample acquisition times the team desires. This gripper must not consume too much power while operating, such that it does not jeopardize the rover from meeting the 1 hour operation time requirement of the competition.

Core Performance

The core system of this gripper is a single-actuated four bar mechanism. This mechanism will consist of grounded crank and rocker links connected by a coupler link. The coupler's motion is used for actual grasping, and this motion is optimized for large sample acquisition. The crank is driven by a single servo for positional control. Most commercial hobby grade servos can easily interface with wide variety of computing hardware, and relatively simple control algorithms may be employed to control them.

The grasping geometry consists of a hybrid design capable of both pinch and scoop action. Each pincer is a concave semi-enclosure, similar to an excavator bucket, attached to the coupler link. These buckets meet at their tips to create "pinch" action. When closed, the interior volume can potentially fully enclose a rock sample.

Preliminary Design

A solid model of the gripper design is pictured in Figure 19, below. The four bar mechanisms are planned to comprise of Aluminum links to keep weight down and strength up. The coupler-buckets are connected to a base enclosure via mirrored mechanisms on each side of the enclosure. The Driving Fourbar mechanisms are driven by two servos; one servo per bucket-driving mechanism. The Driven Fourbar mechanisms are passive, and exist for structural purpose only.
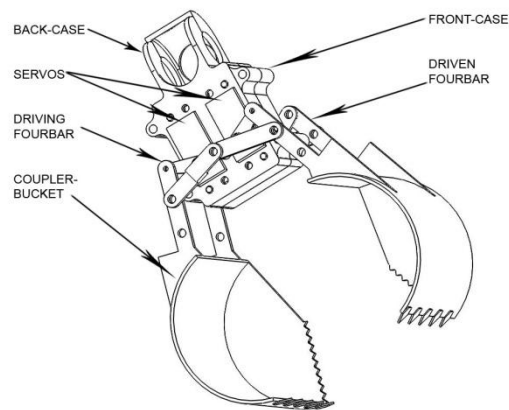
Figure 19: Solid model of gripper with key components annotated.

The base enclosure is a two halved enclosure that connects the gripper mechanism to the linear actuator in the SEM. The whole enclosure mounts directly to the linear actuator and houses the servos that rigidly mount to both halves of the enclosure. Passive cranks and all rocker links mount directly to the enclosure halves, and are to be fastened together via machine screws. The servo-driven cranks mount directly to the servos themselves. Link mounting holes are extruded from the enclosure to account for the spatial property of the mechanism.

Several grasp-enhancement features have been added to help improve the sample acquisition performance. Figure 20, below-left, shows the bucket mechanisms only and highlights two key features. Each bucket features interlocking teeth along the pinch-edge to increase clamping pressure when picking-up rocks. The sides of each bucket are serrated to increase friction if the sample is larger than the gripper, lengthwise. The gripper mouth opens to 14 cm wide, and interior bucket volume is large enough to enclose a 10 cm diameter sphere. Finally, a window will be placed on the rover-side faces of each bucket to enhance viewing of sample capture.

Figure 20: Bucket-driving mechanisms showing a couple enhancement features. The back void is to be replaced with clear viewing windows.

Further Development
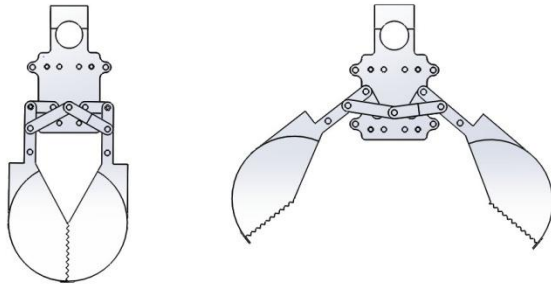
Figure 21: Depiction of the gripper mechanism with buckets opened (left) and closed (right).

Further analysis needs to be conducted on the performance of the designed gripper mechanism. Torque demand and joint reactions forces need to be calculated to figure the minimum size fasteners that can be used (to keep weight down). A Finite Element Analysis needs to be conducted on the solid model in order to determine the minimum link thickness possible without compromising the structural integrity of the mechanism.

A prototype will need to be fabricated and tested against the analytical results to unearth any unforeseen problems in the system. This will also help verify whether the mechanism provides enough mechanical advantage to utilize the servos on hand. The prototype will also be necessary to test and verify the servo control algorithm. The current plan is to finalize all design by mid-January based on the results of these analyses.

G. Camera Boom

During early vision tests, it was concluded that out main camera used to navigation and finding the target samples needs to be elevated above the rover. A low point of view restricted the ability to depict the colored samples in various terrains. In order to achieve the elevated view point, the rover's main camera will be located at the top of a camera boom. Due to the stored size constraints of the competition, the camera boom cannot be permanently fixed in its vertical position. The proposed design uses a single geared motor to raise the boom from the stored position to the vertical position where it will remain throughout the entire competition. When the boom is in its stored position it is laid horizontally across the top of the rover. At the start of the competition, the boom motor will be activated. When the boom has reached its vertical position it will come into contact with a backstop attached to the motor mount. The back torque on the motor will cause a sudden increase in the current supplied to the motor. The operator will be able to view current and voltage supplied to the motor which will be transmitted back from the rover. When the operator detects the increase in current, the power to the motor will be cut off. An alternative to the operator manually cutting off power to the motor is a programmed command which performs the same action, or a limiting switch which is activated when the boom reaches the vertical position. The optimal power cut off procedure will be determined during testing. The implementation of any power cut off method discussed negates the need to visually see the position of the boom, and the need of a position encoder which simplifies the rovers overall control algorithms.

A motor which was used for a different purpose by last year's Hexcavator team has been selected to raise the boom. The motor can produce a torque output of 23 N·m which is more than sufficient than the required 6 N·m required to raise the proposed boom design which is 62 cm in length, the camera mount, and selected camera. The main benefit of the selected motor is the gearbox it uses. The gearbox consists of a worm gear on the motor shaft which is mated to a spur gear on the gearbox output shaft. This gearbox design is extremely hard to back drive, meaning induced moments about the output shaft due to walking motion of the rover and the length of the boom will not be great enough to cause the boom to lower. The result of this is a reduction of weight and design complexity by negating the need for a locking mechanism to fix the boom in its vertical position. The motor mount will be made from the readily available half inch aluminum used in other parts of the rover. The boom will be constructed from the same tubing as the frame of the rover. The use of the same material as other components on the rover will reduce cost.

The current design does not have an active camera stabilizing system due to the large size and weight of systems currently available. A prototype of the boom will be constructed in early spring in order to perform tests to determine the need of an active or passive image stabilizing system. Figure 22 shows the camera boom design mounted on the rear left corner of the rover

Figure 22 - Camera boom mounted on the rear left corner of the rover.

H. Finite Element Analysis

The finite element method provided us with the verification of the strength of materials selected while ensuring us that our rover design would remain under its weight restriction. This analysis was done on several key components, which have been detailed below.

Body

The body of the frame was the first component that this method was applied to. While previous year's efforts to build a walking robot used aluminum tubing that had a thickness of over 3mm, we believed that weight could be saved in the making of a new frame. In the rovers walking process, the frame undergoes very little loading so we decided to verify the strength by putting the frame in far more extreme situations that would be possible. In Figure 23 one can see that the frame still has a factor of safety of 4 while undergoing a load of 50 lbf being pushed up on one of the robots legs. While this may seem as though a thinner tubing could have been used, the college of engineering machine shop has stated that they cannot weld any tubing thinner than this. It is also useful to have a large factor of safety on this part as it will take any impact from the terrain as the rover lays itself down.
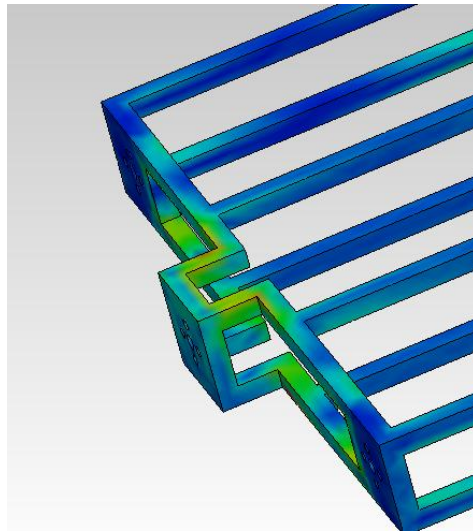
Figure 23 - The testing of the maximum conceivable force on a leg still provided a factor of safety of 4.

SEM Components

The sample extraction module has several components that were significantly influenced by the testing of these parts in simulation. The linear support rod, cam-follower rail and front guide rail all had finite element analysis done to assure the proper strength and weight properties.

The linear support rod is a critical part of the sample extraction module as it helps support the weight of the linear actuator and its load. It also removes the rotational degree of freedom the linear actuator's carriage would be capable of with just a lead screw in place. In doing this testing, the team was looking for a clear

material choice, diameter and whether a solid or hollow rod would be best suited. In doing this testing, the conclusion was reached to use a solid steel rod 12 mm in diameter. This allowed for the proper amount of support from the rod. The hollow rod was decided against for its added dimensions to the carriage, as it would have to have been bigger. The simulation can be seen in Figure 24 below.
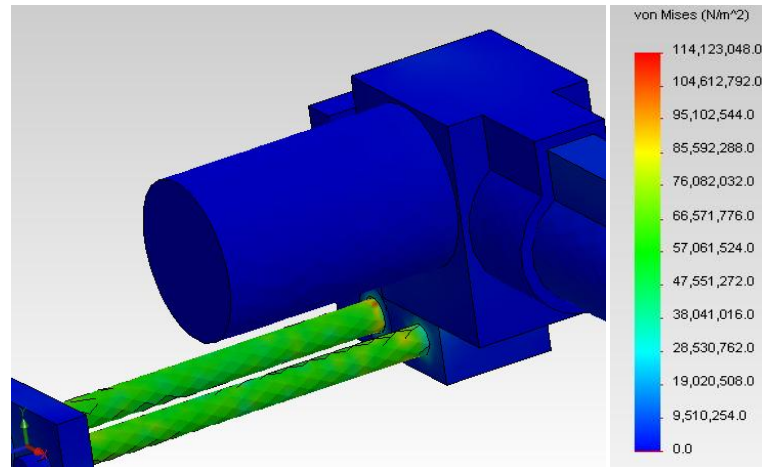
Figure 24 - The linear support rod is able to hold the weight of the actuator with a factor of safety of over 4.

The cam-follower rail was the next item of the sample extraction module to be tested. The purpose of this test was to ensure that the maximum load of the linear actuator (200 lbf) could be applied to the rail without failure while keeping weight to a minimum. Through the repeated testing of this part, the design of the holes machined into the rails was refined until a factor of safety of two was reached. The weight of the assembly was ultimately reduced to under 1 kg. The maximum stress occurred at the front most mount to the frame as seen in Figure 25. If for any reason, this factor of safety needed to be greater, the mounts to the frame could be made out of steel, as opposed to the aluminum mounts currently in use.
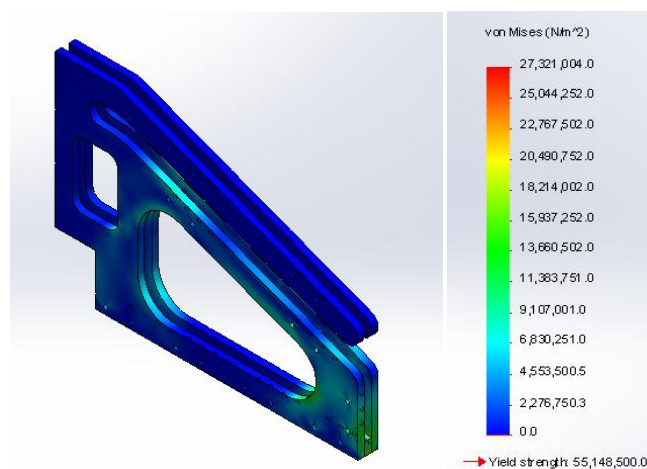
Figure 25 - The cam-follower rail loaded to 200 lbf still provided a factor of safety of 2.

The last component of the sample extraction module that undergoes large amounts of stress is the front guide rail. Due to potential video lag in the competition, the user may lay the rover down on the gripper. In this case, the rover would have half of its weight (max: 50 lbs) placed at one point along this rail. In testing, it was determined that the aluminum rail proposed would not be able to handle the stresses necessary. The team then decided to use a stainless steel rail to handle this. As seen in Figure 26, the rail has a factor of safety of over 6 in this situation.
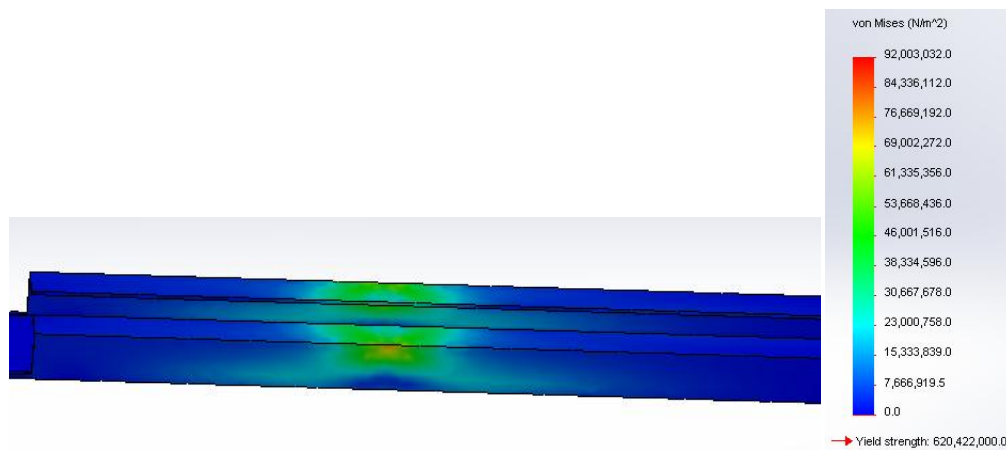
Figure 26 - The front guide rail with half of the rover's weight at a single point still had a factor of safety of over 6.

I.   Prototyping

In order to get a proper feel for our design, the team decided to prototype early in the semester so that problems could be discovered at an early stage. This later allowed the team to start the machining process earlier and with fewer problems. The prototyping consisted of building a mock frame and validating the design of the planar arm concept.

The frame dimensions were originally decided upon in the middle of September. Once this decision had been made, the team built a to-scale version of this frame out of wood to get a better feel for the size and how components could be housed within this frame. In this prototype were also place holders for size of the motors proposed at that point in the project. After some careful consideration, the frame was scaled up further to its current stage to help house the now larger motors and additional battery sources.

The validation of the arm design was done using a linear actuator and dc motor left from last year's team. They were attached to the mock-up frame created so that the proposed motion could be tested. This confirmed that the control of such an arm would have quick and easy control as originally thought. Due to this testing, we were able to move forward with the design and shortly after order the parts for this system. Both the frame and the arm can be seen in Figure 27.
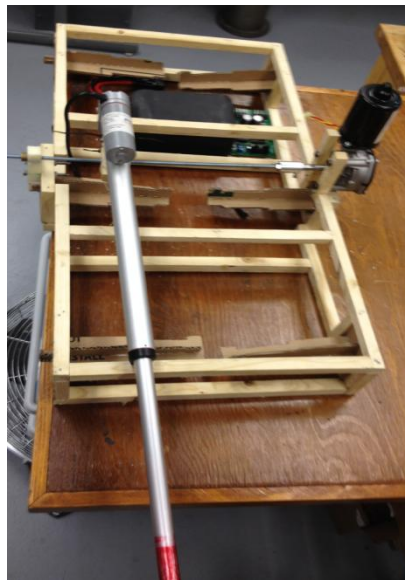
Figure 27 - The prototype of the frame and arm concept helped with design validation and visualizing placement of components.

The electrical and control side of this group also had to have a platform to test their proposed equipment on. This was done using last year's platform known as Hexcavator. Here they were able to test their new control hardware and algorithms without having to wait for the proposed rover to be built. The main advantage of using this platform to test was that it used similar motors to those being used on the proposed rover and the exact same encoders. This would ensure that there will be a relatively seamless transition from

one platform to the next. This platform was stripped of its old control hardware and is pictured in Figure 28 with select new hardware installed for testing.
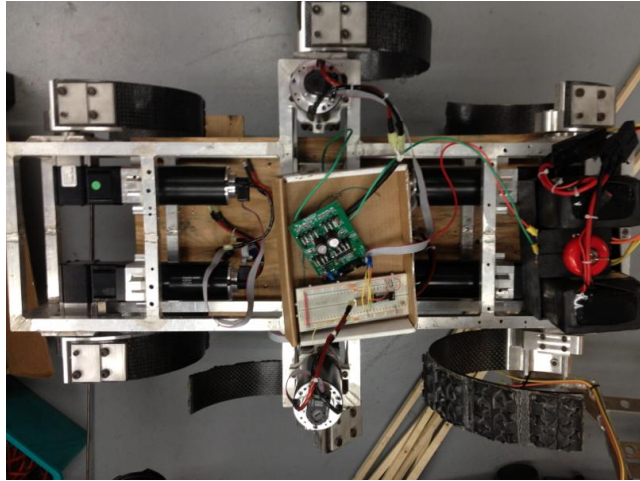
Figure 28 - Last year's platform set up for testing of new hardware configuration.

J.   Serial Peripheral Interface (SPI) Protocol

The team stated that communication between the Raspberry Pi and the Xula2 board will be accomplished with the use of the SPI communication protocol. It is a a 4 wire serial protocol that sends one bit of data per clock cycle over the communication lines. It allows for communication between two or more chips. The four wire protocol follows a single master and multiple slave system where the master is defined simply by its absolute control over communication between itself and each slave. The minimum four lines are the master input/slave output line (MISO), master output/slave input (MOSI), the serial clock (SCK), and the slave select (SSEL). The figure depicts a SPI communication system where there are three slaves. Notice that the SCK, MOSI, and MISO lines are all connected to each slave. Also notice that there a multiple slave select lines, each select line allows the bus master to communicate only with the desired slave. Each slave is required to have its own individual select line.
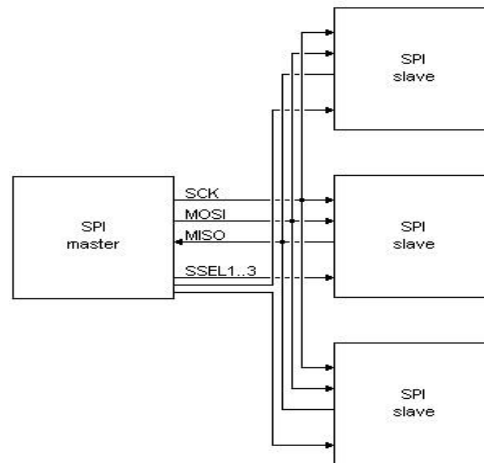
Figure 29 - One master, three slave system obtained from www.fpga4fun.com/SPI1.html

The figure below details how the SPI protocol operates during a single 8-bit data transfer. At 1, the master pulls the slave select line to logic level '0'. This initiates the transfer between the master and that particular slave. At 2, the master begins to toggle the serial clock, once for each bit transferred. SPI is a full duplex system, so for each bit that the master transmits to the slave, the slave transmits a bit of data to the master. At 3, the data transmission is complete so the master pulls the slave select line to logic level '1'. During this entire operation, every other slave select line is kept at logic level '1' so that they ignore the incoming data and transmit no data of their own.
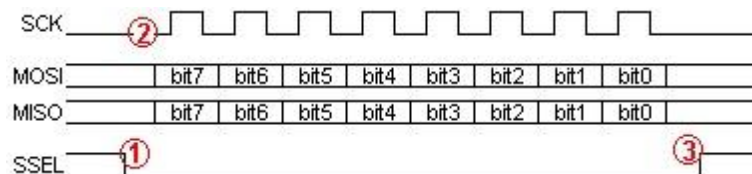
**Figure 30 - Typical SPI data transfer operation - obtained from
www.fpga4fun.com/SPI1.html**

K. Raspberry Pi Pinout

The Raspberry Pi has 26 general purpose input/output (GPIO) pins available. The figure below shows the layout and GPIO number of the pins. For the purposes of the team's particular application, GPIO7, GPIO8, GPIO9, GPIO10, GPIO 11, the 5V power and the numerous ground pins are used. GPIO pins seven through eleven are dedicated serial peripheral interface (SPI) bus pins that the team will use to facilitate communication between the Raspberry Pi and the Spartan-6 field programmable gate array (FPGA). GPIO 7 and GPIO 8 are the slave select lines that the Raspberry Pi will pull low, i.e. send a '0' to that line, to choose a slave to communicate with. Both of these pins are used as GPIO7 will be used to select the PWM module to transmit information to and GPIO8 will be used to select which of the decoders to receive information from. The rate at which the SPI bus is clocked at is determined by the Raspberry Pi via the SCKL (serial clock) pin. Prototyping with the Altera DE2 board has revealed that the SCKL will be able to achieve a frequency of 32 MHz, which will be more that fast enough for the team's purposes. The Raspberry Pi will send information to the PWM modules through the MOSI pin and receive information from the MISO pin.
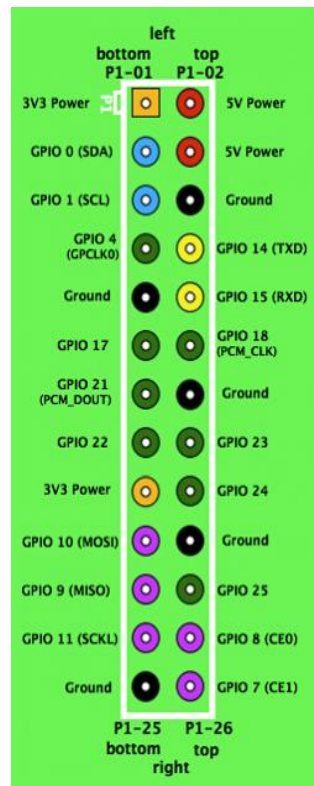
Figure 31 - Raspberry Pi pinout diagram, obtained from www.elinux.org/RPi_Low-Level_peripherals

L. Field Programmable Gate Array Board

The Xess Xula2 board houses the Xilinx Spartan VI - XC6SLX25 FPGA along with 8 Mbits of Flash memory, an onboard 12 MHz oscillator, and a 40-pin interface, 33 of which are general input/output pins. The Spartan-6 has 24,051 logic cells, four digital clock managers, and two phase lock loops (PLL).

While prototyping the FPGA circuit that consisted of six PWM modules, one SPI module, one decoder module, twelve AND gates and six NOT gates, the logic cells that were used was 245. Given that the circuit will be complete with only six more decoder modules, the team determined that 24,051 logic cells would far exceed the necessary logic cells for the circuit. The PLLs on the Spartan VI multiply the frequency of the 12 MHz oscillator to 255 MHz to achieve a 1 MHz PWM signal for precise control of the leg motors. The following equation was used to achieve this conclusion:

$$\frac{f_{clk}}{PWM\ Resolution} = PWM\ Frequency$$

With a duty cycle of eight bits, the resolution becomes 255. Substituting this value and the desired PWM frequency, the equation becomes:

$$\frac{f_{clk}}{255} = 1 MHz$$

$$fclk = 255 * 1 MHz = 255\ MHz$$

The Raspberry Pi will require five pins to communicate with the FPGA board via SPI; each of the six PWM modules will require two pins to transmit the PWM signal from the FPGA to the motors; and an additional seven pins will be required for the decoders in the FPGA to receive motor position data from the motor encoders. This sums to 24 pins out of the 33 GPIO pins available that the design will require. That leaves nine currently unused GPIO pins for any possible additions to the design before the available pins are exhausted.

Field Programmable Gate Array Circuit
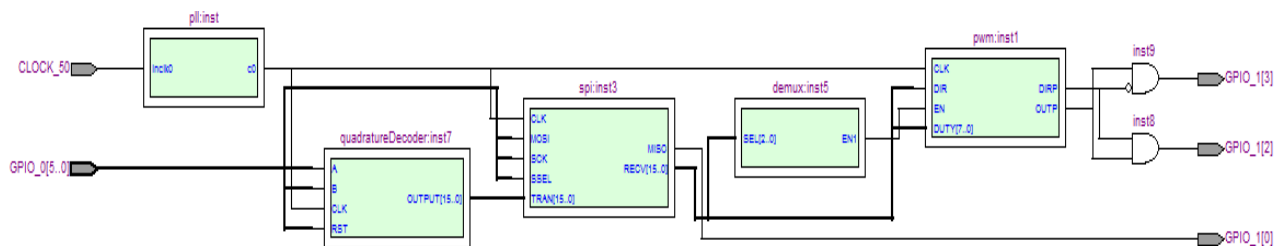
Figure 32 - Top level of the FPGA cicuit instantiated by the Quartus II Register Transfer Level (RTL) Viewer

The figure above gives a top level diagram of a portion of the circuit described in the very high speed integrated circuit hardware description language (VHDL) that the Spartan-6 will be programmed to implement. For simplicity and space, this portion of the circuit only depicts a single pulse width modulation (PWM) module and a single decoder module. When communicating with the FPGA circuit, the Raspberry Pi transmits two bytes of data which will represent different values based on what component is being communicated with. Generally though, the first byte will choose the motor rotation direction. The second byte will represent the duty cycle that the PWM will output to the motor driver and eventually the motor. When the decoder is chosen, the second byte will be ignored but still transmitted since SPI is full duplex.

M. Serial Peripheral Interface Module

The SPI module first synchronizes disparate clock frequencies input from the SPI serial clock and the PLL output clock by oversampling the SPI serial clock with the much faster PLL clock. Without synchronized clocks, the faster PLL clock would read a single transmitted bit multiple times during a much slower SPI clock cycle. The oversampling is accomplished by storing SCK, MOSI, and SEL into three separate two bit shift registers. When SCK changes from '0' to '1', then a rising edge on the serial clock has occurred and data on the MOSI and SEL lines are valid. The module counts the individual bits by counting the falling edges of SCK, that is when SCK changes from '1' to '0', while SEL is '0'. As long as the count of bits received from the Raspberry Pi is less than or equal to 16, the current bit on MOSI will be stored in a 16-bit shift register on the rising edge of SCK. This process works similarly for the current bit being transmitted via MISO except storages into the shift register occurs on the falling edge of SCK. Since the SPI protocol is full duplex, there must be data being transmitted in both the MISO and MOSI lines. Because the PWM module has nothing to transmit to the Raspberry Pi, the SPI module simply transmits two bytes of zeros to the Raspberry Pi, which will ignore those two bytes. When communication with the decoders is active, the SPI module will transmit two bytes of data representing the position of the motor to the Raspberry Pi.

Slave Selection

Traditionally, the SPI protocol has a single slave select line for each slave in the system. The Raspberry Pi has only two dedicated SPI slave select lines, which is not enough to select six PWMs and seven decoders. The team decided that one slave select line would be used for the PWM modules while the remaining line would select from among the decoder modules. A logic circuit that the team has named "demux" accomplishes the task of selecting an individual PWM or decoder from the modules. It reads the first byte transmitted by the Raspberry Pi and based on that value, transmits the appropriate data to and from the correct decoder and PWM.

N. Pulse Width Modulation
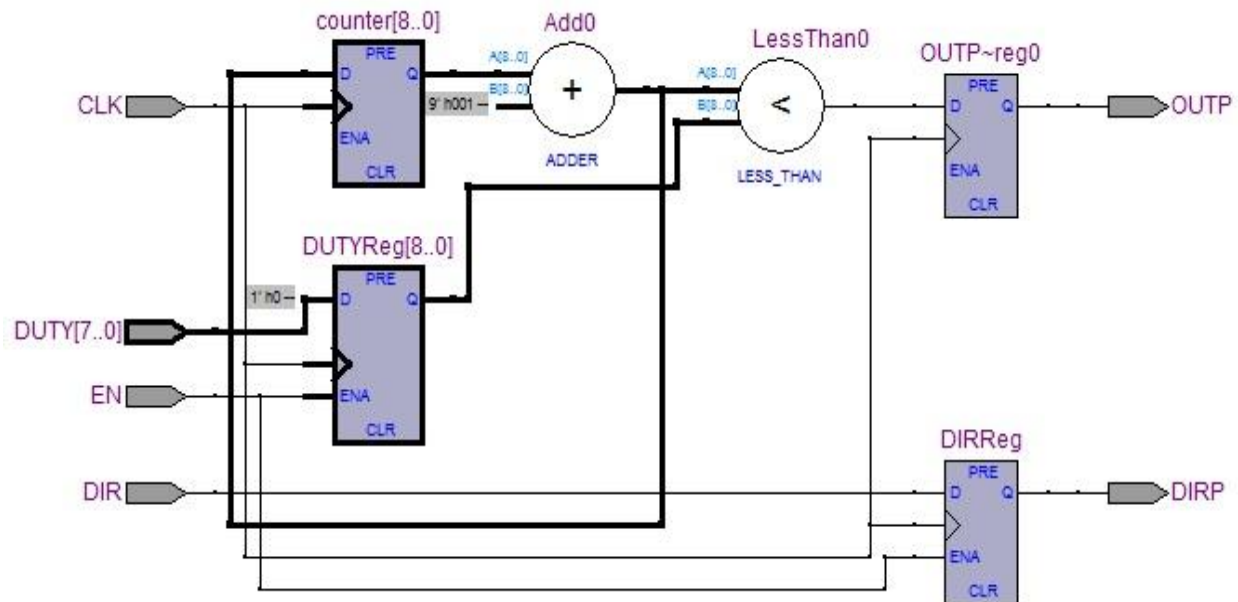
Figure 33 - PWM Module Instantiated by the Quartus II RTL Viewer

The PWM module consists of a nine bit counter, which consists of a register and an adder, a comparator, a duty register (DUTYReg), the direction register (DIRReg) and the PWM output register. The counter is a nine bit value that increments by one on each rising clock edge and runs continuously regardless of the module's activation state as determined by the enable line. The enable line determines the activation state of the module by enabling DUTYReg and DIRReg. DUTYReg stores the current duty of the PWM pulse being generated and outputs to the comparator the value of the duty cycle received from the Raspberry Pi when the enable line is logic level '1'. When the enable line is logic level '0', DUTYReg outputs zero. The register DIRReg is used to store a bit that will indicate the motor direction when enabled and high impedance otherwise. The comparator compares the value of the counter to that of the duty register. When the counter value is less than the duty register value, the module outputs a '1' until the counter value is greater than the value stored in DUTYReg, at this point the module outputs a '0' and it continues the process on every counter overflow. When the PWM module is disabled, the counter would always be less than the duty register since it is always zero and so the module will output '0'.

O. Decoder
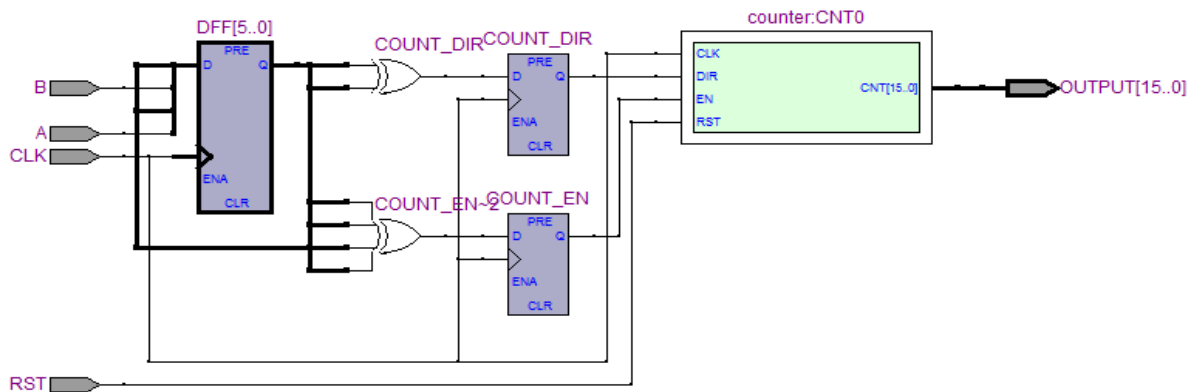
The preceding diagram depicts the decoder hardware that is used to count the quadrature encoded signals provided by the motor encoders. The counter is connected to the counter direction signal, COUNT_DIR, and the counter enable signal, COUNT_EN. If COUNT_EN is asserted, the counter will increment the count by one when COUNT_DIR is logic level '1' and decrement the count when COUNT_DIR is logic level '0'. Input signals A and B are 90° out of phase the count direction is dependent on how the signals are oriented to each other. If A precedes B, then the counter will ascend, if B precedes A, the counter will descend. That is assuming that the COUNT_EN signal is logic level '1'; if it is '0' then the count will not change. COUNT_EN is pulled to logic level '1' when a state change occurs in either of the input signals. The state change is detected by comparing the value of both signals before and after being stored in a flip flop. If the values are different, a change of state has occurred and the counter will become enabled.

The number of ticks in a single revolution of the motor in the prototyped decoder is currently set as 26,000. This requires at least 15 bits to represent in a binary counter and for reasons that will be made clear in the descending case; the counter is set to be 16 bits. This creates slight complications when the 25,999 count is reached since the counter does not automatically overflow and reset to zero. This is solved by comparing the counter value to 25,999. In the ascending direction, if the counter is greater than 25,999, it is set to 0; this would be the 26,000th tick and the motor would have made a complete revolution. In the descending direction, the counter is compared to zero. If it is less than zero, the counter is set to 25,999 and will continue to count down. This is the reason that a 16-bit counter has been implemented. Quartus uses the two's complement format to determine the sign of a number so if only 15 bits were used 25,999 would be considered a negative number since a one would be the most significant bit. In 16-bit binary, though, a zero is the most significant bit and 25,999 would be considered a positive number and the counter would count down.

Decoder Simulation

This is the simulation result from the decoders when provided a quadrature encoded signal on the inputs a_test and b_test. The signal ooutp is the register where the count value is stored. As can be seen in the

simulation figure, the output signal, ooutp increments every time signal a_test or b_test changes its state. If the changes in b_test preceded those of a_test, ooutp would decrement.
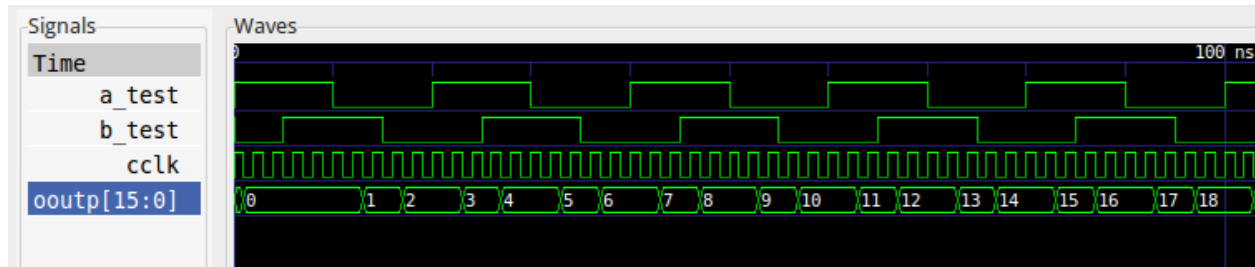
Figure 34 - Simulation waveform of the decoder module

SPI Protocol Slave Simulation

The following diagram is the result of simulation the SPI module of the team's FPGA circuit diagram. For this simulation, cclk represents the Xula2's onboard clock, mmiso is the MISO line, mmosi is the MOSI line, rrecv is the received data register, ssck is the SCK line, sssel is the SSEL line, and ttran is the transmitted data register. The data sent over the mmosi line will be stored by the rrecv register and the data sent over mmiso line will be stored in the ttran register. As can be seen, ssck pulses only while sssel is pulled to logic level '0', exactly what was expected of the SPI module. The master transmits on the mmosi line, from left to right, "1010 1010". In hexadecimal format this is AA, which is what the rrecv line displays after the transmission is completed. The slave transmits to the master via the mmiso line, from left to right, 1100 1010. In hexadecimal format this is CA, which is what the ttran line displays. Thus based on this and other simulations, the SPI module is determined to be functional.
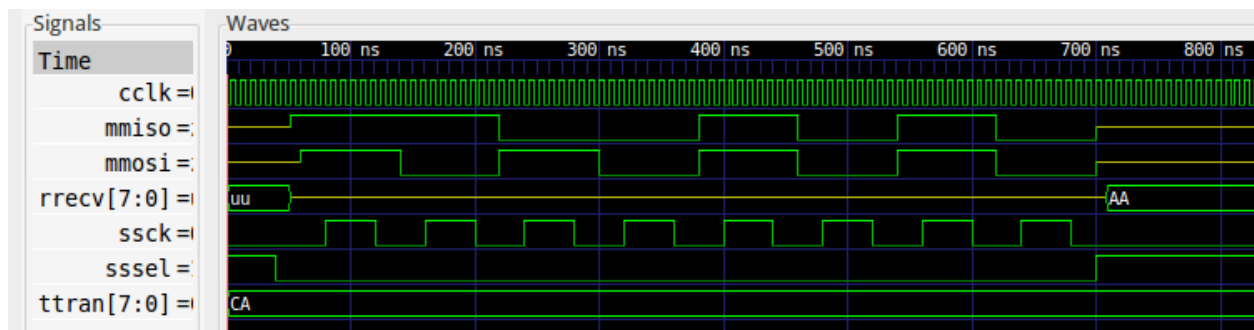
Figure 35 - Simulation waveform of the SPI module

P. Communications

Modem

The modem that was chosen for 3G/4G wireless connection is the Novatel USB551L. The wireless technology that it supports is 4G LTE and CDMA. It is backwards compatible with 3G networks which will be useful in case of loss of 4G connection. The system requirements specify that a 166 MHz processor and 128

MB of RAM are required. The Raspberry Pi easily exceeds these requirements. The modem also supports the Linux operating system. Its dimensions in centimeters are 8.79 x 3.51 x 1.19 and it weighs 34.9 grams.

Router

The Router selected was the CradlePoint MBR1200. This router allows us to plug in the Novatel USB551L modem into the router via USB for internet connectivity. The router then acts as a hub for us to connect our various devices to it via Ethernet. The router has 4 Ethernet ports available. We will use 2 Ethernet ports for the IP cameras and the third will be used to provide an internet connection for the Raspberry Pi to be able to communicate over the wireless network using SSH (Secure Shell). This allows us to remotely control the Raspberry Pi with the internet connection provided by the modem-router configuration. The router has a power consumption of 18W.

Cameras

The Foscam FI9820 is the pan and tilt internet protocol (IP) camera that will be mounted on the camera boom. It provides a 300° pan range and a 120° tilt range with a 50° viewing angle. This will give the operator a wide range of view to search for and identify the colored rocks during the competition. The camera also has a display resolution of 1280x720 and an image frame rate of 25fps - 30fps. More importantly however, is the camera's ability to compress the video feed using the H.264 video compression standard. That allows for remote viewing without the need of computation from the onboard computer, freeing clock cycles to be used for leg motor control. The camera also is equipped with an Ethernet port so that it can be connected into the greater communication network via the onboard router. The camera weighs 348 grams.

The second camera that will be used is the Ubiquiti Aircam Mini IP camera. It is a fixed camera that will be mounted at the front of the rover for optimal view of the arm and gripper when picking up the colored rocks. Like the FI9820, it compressed video with the H.264 compression standard and will not require the onboard computer for video processing and transmission. Also like the FI9820, it has an Ethernet port for connection into the communication network via the onboard router. Its maximum power consumption is 3 W and its frame rate is 30fps. The dimensions in centimeters are 5.5 x 5.5 x 12.5 and it weighs 166 grams.

Q. Environmental and Safety Concerns

Kill switches will be used during testing to ensure that the robot can be safely switched off if any unexpected behavior is observed. Proper precautions will be observed during the wiring of the rover's electrical systems to minimize the risk of shock. Goggles will be worn when testing the rover in sand or other loose terrains as there is a high likelihood of debris being flung by the rover's legs. Lithium Ion batteries will be the source of electrical power on the rover, as such, a team member will be present at all times during the charging process as there exists a fire hazard with batteries of this type. Extra caution will be exercised at public outreach events, where children will be in close proximity to the rover.

R. Arm Concepts

Pulley Arm Concept

   This arm concept design utilizes a pulley mechanism which moves a gripper along a track. Figure 8, below, shows the arm itself as a track which can be raised and lowered in reference to the ground, as well as pivoted about its base. The three degrees of freedom of the arm allows for a large reach area. When an object is picked up by the gripper, the arm can fold back over the robotic platform where it can release the object in to a collection-bin located on the top surface.
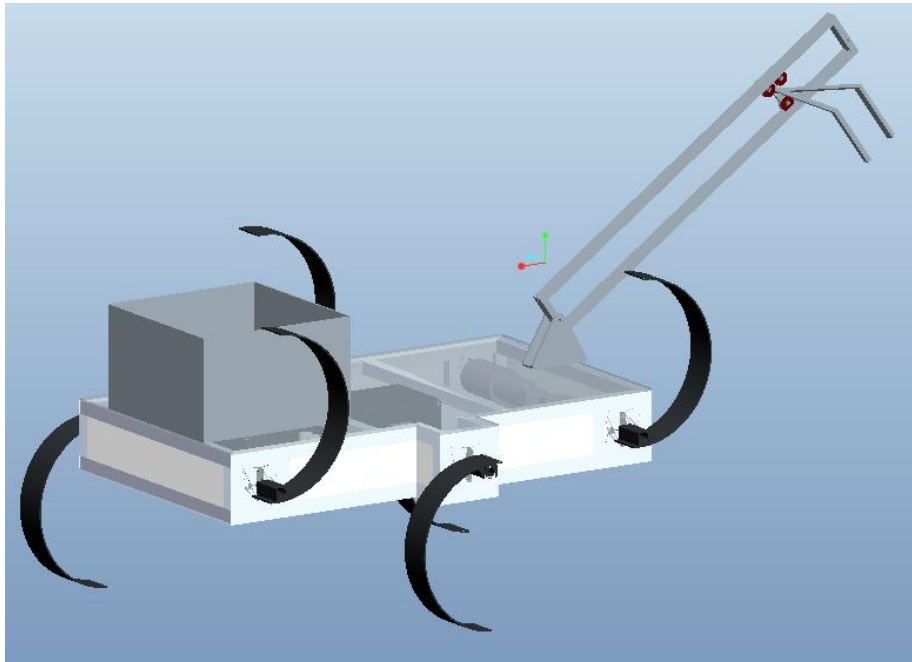
Figure 36: Pulley Arm Concept on the robotic platform with storage box.

   One of the benefits of this design is that almost any gripper/scoop design can be implemented on the arm. This allows for modifications to gripper designs to be easily made if design problems arise. Also, the three plane operation allows for a wider range of gripper positions when reaching for an object as opposed to an arm which operates in two planes.

   On the other hand, a downside to this design is that the pulley system is open to the elements. Debris can potentially become lodged in the track and seize motion of the gripper. This design also requires more complex control algorithms as opposed to an arm which operates in two planes.

Three Degree of Freedom Manipulator Concept

This robotic manipulator concept is a 3-DOF arm consisting of all revolute joints. It was evaluated that this is the minimum mobility necessary to manipulate specimens as required while maintaining versatility in how samples can be acquired. The joints are equivalent to a 2-DOF "shoulder", and a 1-DOF "elbow", with no "wrist" joint before the end-effector; servo or stepper motors may be used at each joint.
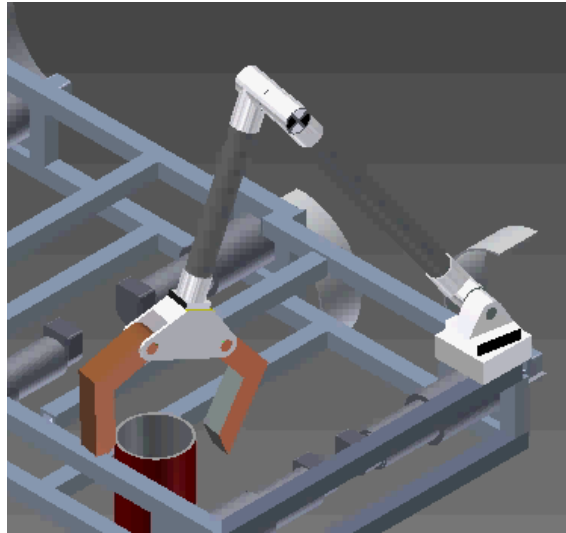
Figure 37: Robotic arm concept model generated using Autodesk Inventor Professional 2012. Gripper shown is generic and does not accurately represent gripper concepts generated.

Some key advantages of this concept is that its mobility allows access to a sample stowage compartment placed anywhere on the rover, and operate around any other instruments on top of the rover. Also, this arm can be mounted in front of or on top of the rover without jeopardizing its function. It is very compact in its stowed configuration, thus it easily meets the dimensional stowed rover configuration requirements.
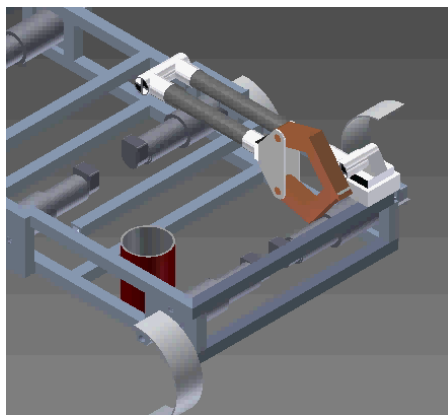
Figure 38: Robotic arm concept in stowed configuration. Model generated using Autodesk Inventor Professional 2012. Gripper shown is generic and does not accurately represent gripper concepts generated.

A major downside to this design is the complexity in controlling and/or automating the system. The number of motors that would be employed for the arm joints, and whatever gripper mechanism is implemented,

would require some relatively complex control algorithms to simplify the control scheme to something more user friendly.

Planar Arm Concept

This concept addresses the question: Is there a difference between a robotic arm designed for a wheeled robot and one designed for a legged robot?

A wheeled robot is "planar" in that it cannot adjust the vertical position of its body; on the other hand, it is clear that a legged robot is non-planar because it can adjust the height and even the angle of its body by manipulating the orientation of its legs. This arm concept takes advantage of this fact by removing the vertical degree of freedom generally found in robotic arms and instead utilizing the legs of the robot to adjust the vertical position and angle of the end effector. The result is an arm that is very simple to control, requiring only two linear motion axes. The figure below displays the axes of motion for this design (marked in red).
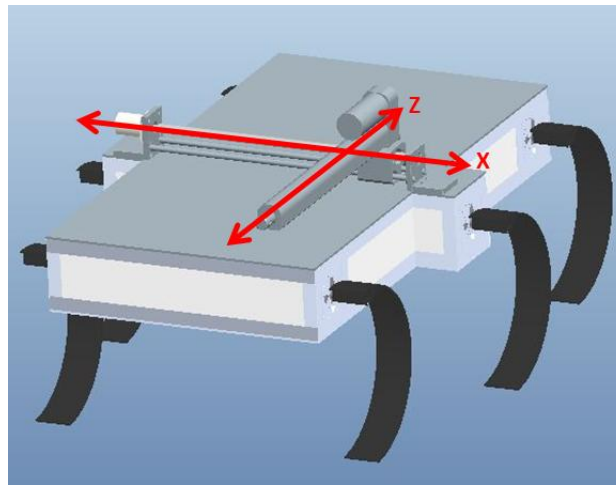
Figure 39: Depiction of the two axes of motion the Planar Arm Concept operates on.

The robot initiates the extraction process by lowering the plane of arm motion to the plane of the sample using the legs. In the above case, the sample (red ball), is located on flat ground so the robot simply lays all the way down, this is expected to be the case a majority of the time during the competition from examination of footage from previous years. The robot then positions the claw or end effector over the sample, captures it, and returns it to the storage container on the front of the robot. A scoop/pincer hybrid claw is shown above for demonstration purposes and is not the only possible claw configuration for use with this arm design. This sample extraction process is depicted in Figure 12 on the next page.
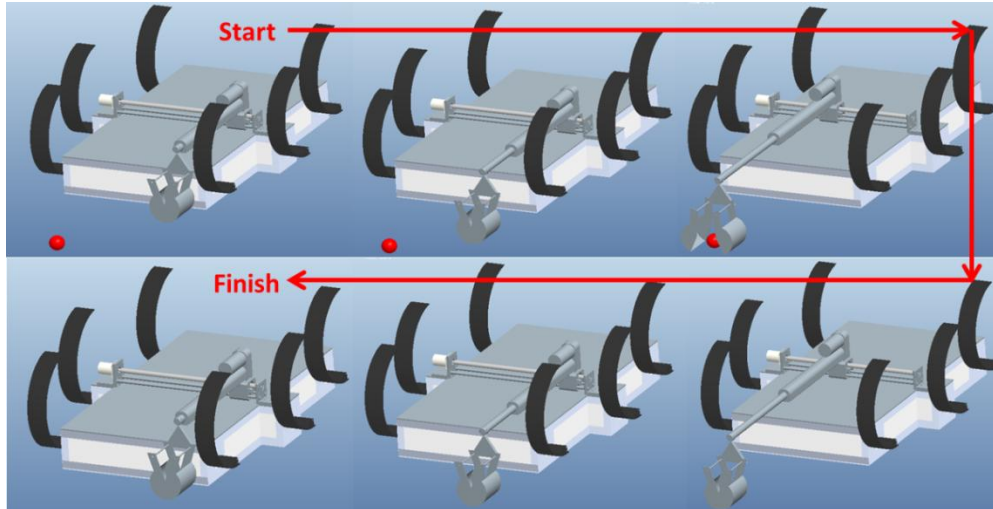
Figure 40: Step-by-step depiction of the Planar Arm Concept's sample extraction process.

<u>Advantages</u>

The operator will be controlling the robotic arm remotely and will guide the arm based on a low quality and low frame rate video, which will be delayed by several seconds. Every degree of freedom added to the arm will exponentially increase the time required to collect a sample with the arm, and as such, this arm has a significant advantage over the other proposed designs with respect to ease of control.

The number of motors or actuators required for the operation of an robotic manipulator is directly related to its weight, cost, and reliability. This design has the fewest number of required motors of the designs studied, thus it may have a slight edge in these categories (depending on specific hardware used). Also, the plane of the arm is located just above the top surface of the robot, which keeps the center of gravity low and results in a more stable robot. Finally, the end effector can be used to easily push away undesired rocks to isolate the target sample.

<u>Shortcomings/issues</u>

The design has several shortcomings and possible issues. The design requires that the storage box for the samples be mounted on the front of the robot, which would add to the length of the robot. As we are well under the maximum allowable dimensions specified by the competition, this is not an issue. Secondly, it is hard to predict how effective the legs will be in controlling the height of the robot, it may be the case that the robot is not stable at some intermediate positions between the prone and standing positions or that the resolution between these positions is too low for precise control. If this arm design is chosen, adequate control would be verified in the design of the electronics and a study would be performed to identify possible unstable positions.

S. Gripper Concepts

Pincer Style Claw

So called "pincer" style claws attempt to mimic the way relatively small objects are most commonly secured by the human hand. These claws generally consist of prongs or fingers which move towards each other to capture an object and prevent further motion through continuous application of force. This style of claw is good at picking up discreet objects but requires a relatively high level of precision from the manipulator it is attached to.

Figure 41: An example of a pincer-gripper. Image obtained from the Science in Seconds Blog.

Scoop Concept

There exist many versions of a "scoop" style sample/substance acquisition system, but they are all based on the idea of using the geometry (generally a concave surface) and the direction of gravity to capture and retain an object or substance. Scoops are generally used to pick up large quantities of a material and are not ideal for acquisition of discreet objects. Scoops can be operated successfully with much less precision than pincer style claws.

Figure 42: An excavator with the item of interest, its scoop, encircled.

Pincer/Scoop Hybrid

The scoop and pincer designs can be combined to form a claw that can pick up both discreetly and in bulk, is easy to control, and offers fairly high precision. A pincer/scoop hybrid claw moves two concave surfaces in a pinching motion to capture objects.
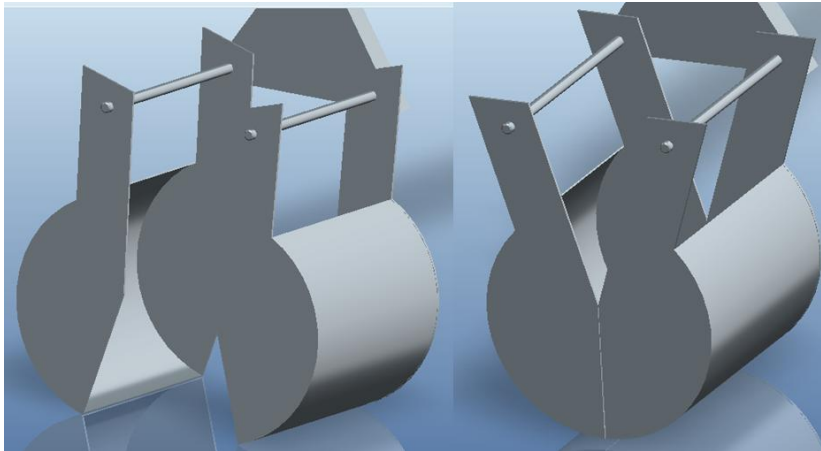
Figure 43: A solid model of the hybrid concept generated in Pro/Engineer software.

Universal Jamming Gripper Concept

This gripper concept utilizes not so common technique of picking up objects. Instead of having rigid moving members which grasp or scoop and object, this universal gripper conforms to the object in which it is grasping. The gripper consists of an ordinary latex party balloon filled with ground coffee. When the coffee-filled balloon is pressed onto the desired object to be picked up, the balloon and coffee conform to the object. At this point, a vacuum pump evacuates air from the balloon, solidifying the balloon, and thus gripping the object. This solidification is due to a "jamming transition" experienced by the coffee. When the air is vacated from the coffee filled balloon, the particulates of the coffee are pressed against each other causing them to resist slipping by one another or causing "jamming."

Figure 44: The universal gripper conforms to the shape of any object it is lifting to allow for a delicate yet firm grasp

This concept is very beneficial in that the gripper will not have to orient itself to the object being picked up, but rather simply press against it. Conventional grippers require the target object to be oriented a certain way between the contact points to be picked up. This concept has several flaws when it comes to implementation in the competition. Although the universal gripper excels at easily gripping objects, it will also grip objects adjacent to the target object. The vacuum seal of the gripper can be compromised by sharp objects which can puncture the latex balloon. Also, the lack of need for orientation to the target object results in the lack of ability to un-wedge objects from tight spaces.

T.   Camera Concepts

Internet Protocol (IP) Camera

IP cameras are typically used for surveillance purposes. For this reason, they feature the ability to pan and tilt. They also feature standard video transmission capabilities that can be remotely viewed from any personal computer (PC). These features are perfectly suited to the purposes of the competition. The standard pan/tilt ability of the camera would allow the rover operator to have a wide visual range. Another advantage to this type of camera is that it does not require any type of computational device; it is a completely standalone device. That is, it handles the video compression and processing by itself and then transmits the data. These cameras are also specifically built for outdoor use, which is where the competition will take place.

These capabilities do not come without a price, though, as IP cameras of this caliber are more expensive than standard webcams. Configuration of the device is also more complicated in that special care needs to be taken to ensure that all of the network values are correct. If the networking between the computer and the camera is not done correctly, then communication between the two would be impossible.

Figure 45: A typical IP camera (left) and webcam (right).

Standard Web Camera (Webcam)

The webcam is almost the complete opposite of the IP camera. It is cheaper and uses an onboard computer to handle video processing. There is also no need to worry about the correct network configurations since the onboard computer would take care of the communication aspect. As mentioned, this device would need an

onboard computer for its data processing. This has the potential to consume more power than the standalone IP camera solution. The video streaming would also not be as straightforward since webcams are not set up to automatically stream as IP cameras are. Furthermore, webcams are not built for use outdoors. They are primarily social cameras for use with Skype and other software which, in most cases, does not involve the camera being used outdoors.

U. On-Board Computing Systems

Raspberry Pi

The Raspberry Pi is a Linux based computer that is about the size of a credit card and is a possible solution for onboard computing for the camera. It has a 700 MHz clock, 256 MB of random access memory (RAM), 2 USB 2.0 ports, an Ethernet port, and power is supplied via 5 V micro-USB port. There are already many peripherals that have been verified to be compatible with the Raspberry Pi; one of the most important being USB 3G dongles. The dongle would allow the Raspberry Pi to connect to a 3G network. Unfortunately the USB ports that are standard do not supply enough power for 3G dongles so a powered USB hub will be required. Since the operating system is Linux, communication with the Raspberry Pi is fairly straightforward with the ability to access its shell account. As long as the IP address is known, the Raspberry Pi can be communicated with and controlled.

However, the Raspberry Pi does not have enough pins to control all 6 motors in both directions and read every decoder. There are several pulse width modulation ICs and decoders available in the market but many of them require too many pins and those that are serial interfaced are not capable of handling 6 motors. Reading several decoders through a serial interface will introduce delays in our control algorithm. Therefore, the appropriate solution is to create the logic using an FPGA. This allows us to create the logic to control and read position from every motor in one compact design. The FPGA will have a serial interface which we will connect to the Raspberry Pi.
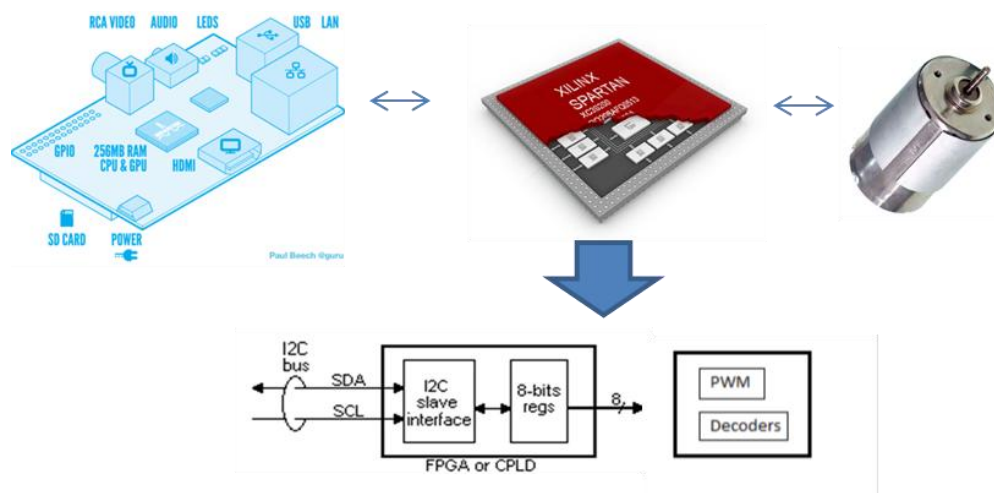
V. Budget and Bill of Materials

| Item	Vendor	Part Number	Price	Qty	Total
20x20mm 2mm thick 2m long Aluminum Tubing	Misumi	A6063-K20X20-20-2-2000	$ 17.78	5	$88.90
Sprocket for chain	Misumi	SP15B15-P-8	$ 11.49	1	$11.49
Sprocket for chain	Misumi	SP15B16-P-10	$ 11.49	1	$11.49
Linear Bushing (flanged)	Misumi	LHFC10	$ 7.25	3	$21.75
Double Sheilded Bearing	Misumi	B605ZZ	$ 1.77	2	$3.54
Rotary Shaft	Misumi	SFRMGN12-40.0-F20.0-B17-PMC10	$ 10.84	1	$10.84
Slider linear bushing	Misumi	MPBZ40-25	$ 12.61	2	$25.22
Riser shaft	Misumi	SFRMGQ6-20.0-F6.2-P5-T6.2-Q5-KC4-A12	$ 10.99	1	$10.99
Riser Linear Bushing	Misumi	SHBR12-25	$ 4.80	1	$4.80
Double Sheilded Bearing (for sprocket shaft)	Misumi	FL608ZZ	$ 4.83	3	$14.49
Linear Bearing with flange (x arm direction)	Misumi	LHFC12	$ 7.65	1	$7.65
Linear Shaft 10cm Diameter	Misumi	SFJ10-510	$ 9.52	1	$9.52
Linear Shaft 12cm Diameter	Misumi	SFJ12-460	$ 10.57	1	$10.57
4x2x60 cm steel square tubing	Misumi	SUS304-PKH40X20-40-20-1.5-600	$ 39.73	1	$39.73
Ultra Low Head Screw	Misumi	CBSTSE6-25	$ 4.20	7	$29.40
Chain	Misumi	CHE15-148	$ 18.83	1	$18.83
Key For Shaft	Misumi	KESF2-12	$ 3.92	1	$3.92
5052 aluminum pipe (gripper)	Misumi	A5052-PHN-110-5-100	$ 13.32	1	$13.32
Shipping and Tax for Misumi Parts			$ 60.97	1	$60.97
Acme Round Nut	McMaster Carr	95072A420	$ 32.98	1	$32.98
Acme Threaded Rod	Mcmaster Carr	99030A300	$ 26.68	1	$26.68
L Brackets	McMaster Carr	15275A51	$ 0.63	36	$22.68
8-32 1 1/4 Inch Long Screw	McMaster Carr	91251A201	$ 8.55	1	$8.55
8-32 3/8 Inch Long Screw	McMaster Carr	91251A192	$ 11.16	1	$11.16
8-32 Machine Screw Hex Nuts	Mcmaster Carr	90480A009	$ 1.49	2	$2.98
M6x25 Low Head Screw	McMaster Carr	92855A622	$ 13.00	3	$39.00
M10x30 Low Head screw	Mcmaster Carr	92855A759	$ 7.95	1	$7.95
3/4" Aluminum Plate	McMaster Carr	8975K334	$ 39.34	1	$39.34
1" Aluminum Plate	McMaster Carr	8975K335	$ 51.61	1	$51.61
1 1/4" Aluminum Plate	McMaster Carr	8975K323	$ 43.38	1	$43.38
M4x12 Low Head Screw	McMaster Carr	92855A413	$ 4.55	2	$9.10
M4x35 Low Head Screw	McMaster Carr	92855A428	$ 9.05	1	$9.05
M5x25 Low Head Screw	Mcmaster Carr	92855A428	$ 8.89	1	$8.89
1/4" Aluminum (3ftx1ft)	McMaster Carr	9246K44	$ 48.26	1	$48.26
1' x 2' 1/8" sheet of ABS Plastic	Mcmaster Carr	8586K361	$ 14.07	5	$70.35
Carbon Fiber	Mcmaster Carr	8711T31	$ 27.37	15	$410.55
Quarter-Turn Screws	Mcmaster Carr	94170A540	$ 13.44	3	$40.32
Linear Acuator	Progressive Automation		Donated	1	$0.00
Drive Motors	Maxon Motors	see attched specs	$ 867.00	7	$6,069.00
IP Camera	Foscam	F19820	$ 84.99	1	$84.99
IP Camera for SEM	Ubiquiti	Aircam Mini IP Camera	$ 100.00	1	$100.00
Raspberry Pi	Raspberry Pi Corp		$ 35.00	1	$35.00
FPGA	Xess	Xula2	$ 119.00	1	$119.00
Router	CradlePoint	MBR1200	$ 168.95	1	$168.95
Modem	Novatel	551L	$ 199.00	1	$199.00
Batteries	Battery Space	High Power Polymer Li-Ion Battery: 37V 21Ah	$ 936.95	2	$1,873.90
Servo Motors	Pololu	i00600	$ 289.00	2	$578.00
Wiring, Connections	DigiKey		$ 150.00	1	$150.00
Travel			$3,000.00	1	$3,000.00

Total: $13,658.09

W. Drive Motor Specifications

RE 50 ⌀50 mm, Graphite Brushes, 200 Watt
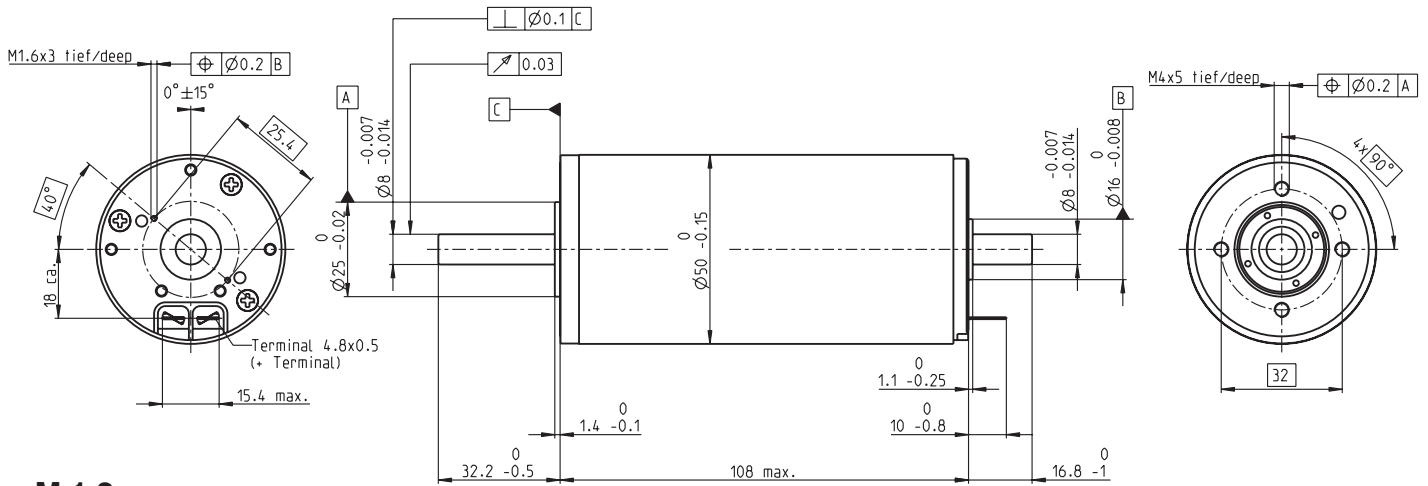
M 1:2

- 🟥 Stock program
- ⬜ Standard program
- ⬜ Special program (on request)

Article Numbers

Motor Data		370354	370355	370356	370357
Values at nominal voltage					
1 Nominal voltage	V	24	36	48	70
2 No load speed	rpm	5950	5680	4900	2760
3 No load current	mA	236	147	88.4	27.4
4 Nominal speed	rpm	5680	5420	4620	2470
5 Nominal torque (max. continuous torque)	mNm	405	418	420	452
6 Nominal current (max. continuous current)	A	10.8	7.07	4.58	1.89
7 Stall torque	mNm	8920	8920	7370	4340
8 Starting current	A	232	148	78.9	17.9
9 Max. efficiency	%	94	94	94	92
Characteristics					
10 Terminal resistance	Ω	0.103	0.244	0.608	3.9
11 Terminal inductance	mH	0.0717	0.177	0.423	2.83
12 Torque constant	mNm/A	38.5	60.4	93.4	242
13 Speed constant	rpm/V	248	158	102	39.5
14 Speed / torque gradient	rpm/mNm	0.668	0.638	0.666	0.638
15 Mechanical time constant	ms	3.75	3.74	3.78	3.74
16 Rotor inertia	gcm^2	536	560	542	560

Specifications

Thermal data
17 Thermal resistance housing-ambient   3.8 K/W
18 Thermal resistance winding-housing   1.2 K/W
19 Thermal time constant winding   71.7 s
20 Thermal time constant motor   1370 s
21 Ambient temperature   -30…+100°C
22 Max. permissible winding temperature   +125°C

Mechanical data (preloaded ball bearings)
23 Max. permissible speed   9500 rpm
24 Axial play at axial load   < 11.5 N   0 mm
                 > 11.5 N   0.1 mm
25 Radial play   0.03 mm
26 Max. axial load (dynamic)   30 N
27 Max. force for press fits (static)   150 N
     (static, shaft supported)   6000 N
28 Max. radial loading, 15 mm from flange   110 N

Other specifications
29 Number of pole pairs   1
30 Number of commutator segments   15
31 Weight of motor   1100 g

Values listed in the table are nominal.
Explanation of the figures on page 49.

Industrial version with radial shaft seal ring
(resulting in increased no-load current)

Operating Range
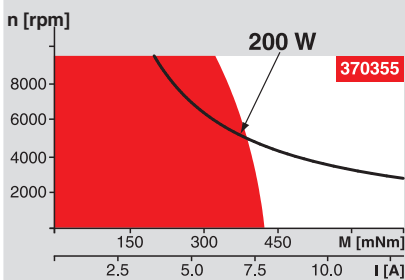
Comments

🟥 **Continuous operation**
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

⬜ **Short term operation**
The motor may be briefly overloaded (recurring).

—— **Assigned power rating**

maxon Modular System   Overview on page 16 - 21

Planetary Gearhead
⌀52 mm
4 - 30 Nm
Page 245

Planetary Gearhead
⌀62 mm
8 - 50 Nm
Page 247
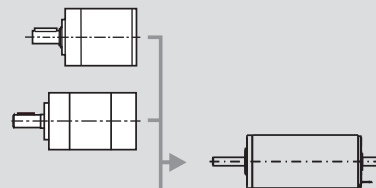
Recommended Electronics:
ESCON 50/5	Page 292
EPOS2 50/5	313
EPOS2 70/10	313
EPOS3 70/10 EtherCAT	319
ADS 50/10	373
ADS_E 50/10	373
Notes	**18**

Encoder HEDS 5540
500 CPT,
3 channels
Page 277

Encoder HEDL 5540
500 CPT,
3 channels
Page 279

**Industrial Version IP54
Encoder HEDL 9140**
Page 282

Brake AB 44
Page 334

End cap
Page 335

Planetary Gearhead GP 52 C ⌀52 mm, 4–30 Nm
Ceramic Version

M 1:4

Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel
Bearing at output	preloaded ball bearings
Radial play, 12 mm from flange	max. 0.06 mm
Axial play at axial load < 5 N	0 mm
> 5 N	max. 0.3 mm
Max. permissible axial load	200 N
Max. permissible force for press fits	500 N
Sense of rotation, drive to output	=
Recommended input speed	< 6000 rpm
Recommended temperature range	-15…+80°C
Extended range as option	-40…+100°C
Number of stages	1 2 3 4
Max. radial load, 12 mm from flange	500 N 700 N 900 N 900 N

■ Stock program
□ Standard program
▢ Special program (on request)

Article Numbers

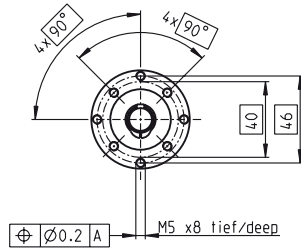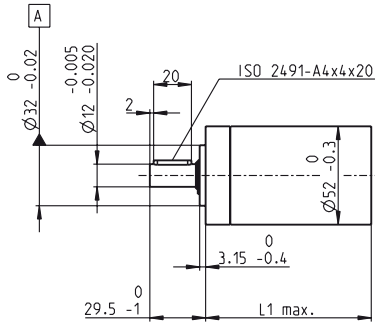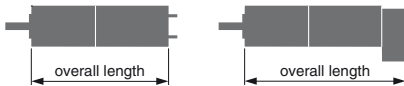| Gearhead Data			223080	223083	223089	223094	223097	223104	223109
1	Reduction		3.5 : 1	12 : 1	43 : 1	91 : 1	150 : 1	319 : 1	546 : 1
2	Reduction absolute		$^7/_2$	$^{49}/_4$	$^{343}/_8$	91	$^{2401}/_{16}$	$^{637}/_2$	546
10	Mass inertia	gcm²	20.7	17.6	17.3	16.7	17.3	16.8	16.4
3	Max. motor shaft diameter	mm	10	10	10	10	10	10	10
Article Numbers			**223081**	223084	223090	223095	223099	**223105**	223110
1	Reduction		4.3 : 1	15 : 1	53 : 1	113 : 1	186 : 1	353 :1	676 : 1
2	Reduction absolute		$^{13}/_3$	$^{91}/_6$	$^{637}/_{12}$	$^{338}/_3$	$^{4459}/_{24}$	$^{28561}/_{81}$	676
10	Mass inertia	gcm²	12	16.8	17.2	9.3	17.3	9.4	9.1
3	Max. motor shaft diameter	mm	8	10	10	8	10	8	8
Article Numbers				**223085**	223091	223096	223101	223106	223111
1	Reduction			19 : 1	66 : 1	126 : 1	230 : 1	394 : 1	756 : 1
2	Reduction absolute			$^{169}/_9$	$^{1183}/_{18}$	126	$^{8281}/_{36}$	$^{1183}/_3$	756
10	Mass inertia	gcm²		9.5	16.7	16.4	16.8	16.7	16.4
3	Max. motor shaft diameter	mm		8	10	10	10	10	10
Article Numbers				223086	223092	223098	223102	223107	223112
1	Reduction			21 : 1	74 : 1	156 : 1	257 : 1	441 : 1	936 : 1
2	Reduction absolute			21	$^{147}/_2$	156	$^{1029}/_4$	441	936
10	Mass inertia	gcm²		16.5	17.2	9.1	17.3	16.5	9.1
3	Max. motor shaft diameter	mm		10	10	8	10	10	8
Article Numbers				223087	**223093**		223103	223108	
1	Reduction			26 : 1	81 : 1		285 : 1	488 : 1	
2	Reduction absolute			26	2197/27		15379/54	4394/9	
10	Mass inertia	gcm²		9.1	9.4		16.7	9.4	
3	Max. motor shaft diameter	mm		8	8		10	8	
4	Number of stages		1	2	3	3	4	4	4
5	Max. continuous torque	Nm	4	15	30	30	30	30	30
6	Intermittently permissible torque at gear output	Nm	6	22.5	45	45	45	45	45
7	Max. efficiency	%	91	83	75	75	68	68	68
8	Weight	g	460	620	770	770	920	920	920
9	Average backlash no load	°	0.6	0.8	1.0	1.0	1.0	1.0	1.0
11	Gearhead length L1	mm	49.0	65.0	78.5	78.5	92.0	92.0	92.0

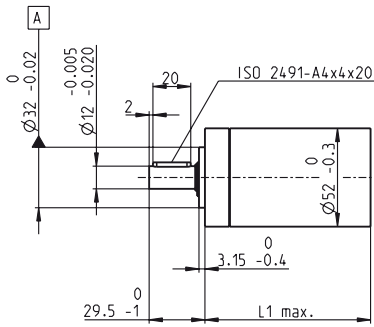

overall length   overall length

maxon Modular System

+ Motor	Page	+ Sensor	Page	Brake	Page	Overall length [mm] = Motor length + gearhead length + (sensor/brake) + assembly parts						
RE 40, 150 W	82					120.1	136.1	149.6	149.6	163.1	163.1	163.1
RE 40, 150 W	82	MR	273			131.5	147.5	161.0	161.0	174.5	174.5	174.5
RE 40, 150 W	82	HED_ 5540	276/278			140.8	156.8	170.3	170.3	183.8	183.8	183.8
RE 40, 150 W	82	HEDL 9140	281			174.1	190.1	203.6	203.6	217.1	217.1	217.1
RE 40, 150 W	82			AB 28	330	156.2	172.2	185.7	185.7	199.2	199.2	199.2
RE 40, 150 W	82			AB 28	331	164.2	180.2	193.7	193.7	207.2	207.2	207.2
RE 40, 150 W	82	HED_ 5540	276/278	AB 28	330	173.4	189.4	202.9	202.9	216.4	216.4	216.4
RE 40, 150 W	82	HEDL 9140	281	AB 28	331	184.6	200.6	214.1	214.1	227.6	227.6	227.6
RE 50, 200 W	83					157.1	173.1	186.6	186.6	200.1	200.1	200.1
RE 50, 200 W	83	HED_5540	277/279			177.8	193.8	207.3	207.3	220.8	220.8	220.8
RE 50, 200 W	83	HEDL 9140	282			219.5	235.5	249.0	249.0	262.5	262.5	262.5
RE 50, 200 W	83			AB 44	334	219.5	235.5	249.0	249.0	262.5	262.5	262.5
RE 50, 200 W	83	HEDL 9140	282	AB 44	334	232.5	248.5	262.0	262.0	275.5	275.5	275.5
EC 40, 170 W	157					132.4	148.4	161.9	161.9	175.4	175.4	175.4
EC 40, 170 W	157	HED_5540	277/279			155.8	171.8	185.3	185.3	198.8	198.8	198.8
EC 40, 170 W	157	Res 26	287			159.8	175.8	189.3	189.3	202.8	202.8	202.8
EC 40, 170 W	157			AB 32	332	175.1	191.1	204.6	204.6	218.1	218.1	218.1
EC 40, 170 W	157	HED_5540	277/279	AB 32	332	198.5	214.5	228.0	228.0	241.5	241.5	241.5

Planetary Gearhead GP 52 C ⌀52 mm, 4–30 Nm

Ceramic Version

M 1:4

Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel
Bearing at output	preloaded ball bearings
Radial play, 12 mm from flange	max. 0.06 mm
Axial play at axial load	< 5 N 0 mm
	> 5 N max. 0.3 mm
Max. permissible axial load	200 N
Max. permissible force for press fits	500 N
Sense of rotation, drive to output	=
Recommended input speed	< 6000 rpm
Recommended temperature range	-15…+80°C
Extended range as option	-40…+100°C
Number of stages	1 2 3 4
Max. radial load, 12 mm	
from flange	500 N 700 N 900 N 900 N

		Stock program
		Standard program
		Special program (on request)

Article Numbers							
		223080	223083	223089	223094	223097	223104	223109

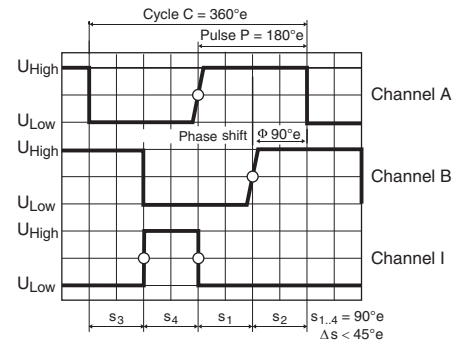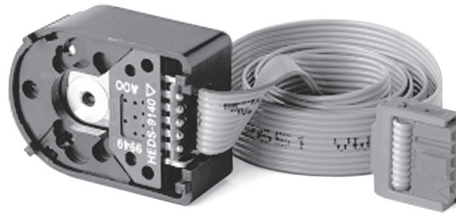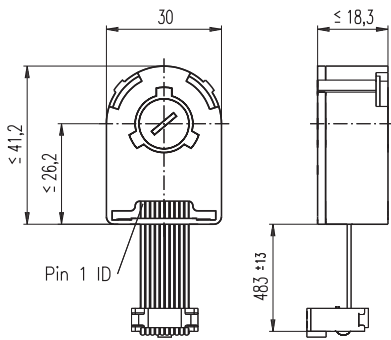| Gearhead Data								
1	Reduction		3.5 : 1	12 : 1	43 : 1	91 : 1	150 : 1	319 : 1	546 : 1
2	Reduction absolute		$7/2$	$49/4$	$343/8$	91	$2401/16$	$637/2$	546
10	Mass inertia	gcm^2	20.7	17.6	17.3	16.7	17.3	16.8	16.4
3	Max. motor shaft diameter	mm	10	10	10	10	10	10	10
	Article Numbers		223081	223084	223090	223095	223099	223105	223110
1	Reduction		4.3 : 1	15 : 1	53 : 1	113 : 1	186 : 1	353 : 1	676 : 1
2	Reduction absolute		$13/3$	$91/6$	$637/12$	$338/3$	$4459/24$	$28561/81$	676
10	Mass inertia	gcm^2	12	16.8	17.2	9.3	17.3	9.4	9.1
3	Max. motor shaft diameter	mm	8	10	10	8	10	8	8
	Article Numbers			223085	223091	223096	223101	223106	223111
1	Reduction			19 : 1	66 : 1	126 : 1	230 : 1	394 : 1	756 : 1
2	Reduction absolute			$169/9$	$1183/18$	126	$8281/36$	$1183/3$	756
10	Mass inertia	gcm^2		9.5	16.7	16.4	16.8	16.7	16.4
3	Max. motor shaft diameter	mm		8	10	10	10	10	10
	Article Numbers			223086	223092	223098	223102	223107	223112
1	Reduction			21 : 1	74 : 1	156 : 1	257 : 1	441 : 1	936 : 1
2	Reduction absolute			21	$147/2$	156	$1029/4$	441	936
10	Mass inertia	gcm^2		16.5	17.2	9.1	17.3	16.5	9.1
3	Max. motor shaft diameter	mm		10	10	8	10	10	8
	Article Numbers			223087	223093		223103	223108	
1	Reduction			26 : 1	81 : 1		285 : 1	488 : 1	
2	Reduction absolute			26	$2197/27$		$15379/54$	$4394/9$	
10	Mass inertia	gcm^2		9.1	9.4		16.7	9.4	
3	Max. motor shaft diameter	mm		8	8		10	8	
4	Number of stages		1	2	3	3	4	4	4
5	Max. continuous torque	Nm	4	15	30	30	30	30	30
6	Intermittently permissible torque at gear output	Nm	6	22.5	45	45	45	45	45
7	Max. efficiency	%	91	83	75	75	68	68	68
8	Weight	g	460	620	770	770	920	920	920
9	Average backlash no load	°	0.6	0.8	1.0	1.0	1.0	1.0	1.0
11	Gearhead length L1	mm	49.0	65.0	78.5	78.5	92.0	92.0	92.0

overall length   overall length

maxon Modular System

+ Motor	Page	+ Sensor	Page	Brake	Page	Overall length [mm] = Motor length + gearhead length + (sensor/brake) + assembly parts						
EC 45, 150 W	158					160.3	176.3	189.8	189.8	203.3	203.3	203.3
EC 45, 150 W	158	HEDL 9140	281			175.9	191.9	205.4	205.4	218.9	218.9	218.9
EC 45, 150 W	158	Res 26	287			160.3	176.3	189.8	189.8	203.3	203.3	203.3
EC 45, 150 W	158			AB 28	331	167.7	183.7	197.2	197.2	210.7	210.7	210.7
EC 45, 150 W	158	HEDL 9140	281	AB 28	331	184.7	200.7	214.2	214.2	227.7	227.7	227.7
EC 45, 250 W	159					193.1	209.1	222.6	222.6	236.1	236.1	236.1
EC 45, 250 W	159	HEDL 9140	281			208.7	224.7	238.2	238.2	251.7	251.7	251.7
EC 45, 250 W	159	Res 26	287			193.1	209.1	222.6	222.6	236.1	236.1	236.1
EC 45, 250 W	159			AB 28	331	200.5	216.5	230.0	230.0	243.5	243.5	243.5
EC 45, 250 W	159	HEDL 9140	281	AB 28	331	217.5	233.5	247.0	247.0	260.5	260.5	260.5
EC-max 40, 120 W	171					137.1	153.1	166.6	166.6	180.1	180.1	180.1
EC-max 40, 120 W	171	MR	273			153.0	169.0	182.5	182.5	196.0	196.0	196.0
EC-max 40, 120 W	171	HEDL 5540	281			160.5	176.5	190.0	190.0	203.5	203.5	203.5
EC-max 40, 120 W	171			AB 28	329	177.1	193.1	206.6	206.6	220.1	220.1	220.1
EC-max 40, 120 W	171	HEDL 5540	281	AB 28	329	200.5	216.5	230.0	230.0	243.5	243.5	243.5
EC 60 flat, IP 00	198					89.8	105.8	119.3	119.3	132.8	132.8	132.8
EC 60 flat, IP 54	198					94.8	110.8	124.3	124.3	137.8	137.8	137.8
EC 60 flat, IP 00	198	MILE				90.8	106.8	120.3	120.3	133.8	133.8	133.8
EC 60 flat, IP 54	198	MILE				94.8	110.8	124.3	124.3	137.8	137.8	137.8
EC 90 flat, 90 W	199					81.4	97.4	110.9	110.9	124.4	124.4	124.4

May 2012 edition / subject to change

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422

Cycle C = 360°e
Pulse P = 180°e

U_High
U_Low
Channel A

U_High
Phase shift Φ 90°e
U_Low
Channel B

U_High
U_Low
Channel I

s_3 s_4 s_1 s_2   s_{1..4} = 90°e
Δs < 45°e

Direction of rotation cw (definition cw p. 48)

■ Stock program
□ Standard program
▨ Special program (on request)

Article Numbers

	110512	110514	110516	110518
Type				
Counts per turn	500	500	500	500
Number of channels	3	3	3	3
Max. operating frequency (kHz)	100	100	100	100
Max. speed (rpm)	12 000	12 000	12 000	12 000
Shaft diameter (mm)	3	4	6	8

overall length

overall length

maxon Modular System

+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead		
RE 50, 200 W	83							128.7
RE 50, 200 W	83	GP 52, 4 - 30 Nm	246					●
RE 50, 200 W	83	GP 62, 8 - 50 Nm	247					●
RE 65, 250 W	84							157.3
RE 65, 250 W	84	GP 81, 20 - 120 Nm	248					●
EC 32, 80 W	156					78.4		
EC 32, 80 W	156	GP 32, 0.75 - 4.5 Nm	234			●		
EC 32, 80 W	156	GP 32, 0.75 - 6.0 Nm	236/238			●		
EC 32, 80 W	156	GP 32 S	255-257			●		
EC 40, 170 W	157						103.3	
EC 40, 170 W	157	GP 42, 3.0 - 15 Nm	242				●	
EC 40, 170 W	157	GP 52, 4.0 - 30 Nm	245				●	
EC-max 30, 40 W	168					62.6		
EC-max 30, 40 W	168	GP 32, 1 - 6 Nm	238			●		
EC-max 30, 40 W	168			AB 20	328	101.7		
EC-max 30, 40 W	168	GP 32, 1 - 6 Nm	238	AB 20	328	●		
EC-max 30, 40 W	168	GP 32 S				●		
EC-max 30, 40 W	168	GP 32, 4.0 - 8.0 Nm	239					
EC-max 30, 60 W	169					84.6		
EC-max 30, 60 W	169	GP 32, 4.0 - 8.0 Nm	239					
EC-max 30, 60 W	169	GP 42, 3 - 15 Nm	243			●		
EC-max 30, 60 W	169			AB 20	328	120.4		
EC-max 30, 60 W	169	GP 42, 3 - 15 Nm	243	AB 20	328	●		
EC-max 40, 70 W	170						81.4	
EC-max 40, 70 W	170	GP 42, 3 - 15 Nm	243				●	
EC-max 40, 70 W	170			AB 28	329	121.4		
EC-max 40, 70 W	170	GP 42, 3 - 15 Nm	243	AB 28	329	●		
EC-max 40, 120 W	171					111.4		
EC-max 40, 120 W	171	GP 52, 4 - 30 Nm	246			●		
EC-max 40, 120 W	171			AB 28	329	140.8		
EC-max 40, 120 W	171	GP 52, 4 - 30 Nm	246	AB 28	329	●		

Technical Data

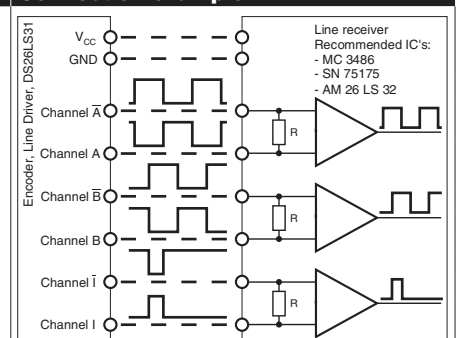|	
Supply voltage V_{CC}	5 V ± 10%
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90°e ± 45°e
Signal rise time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	180 ns
Signal fall time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	40 ns
Index pulse width	90°e
Operating temperature range	-40…+100°C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250 000 rad s^{-2}
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

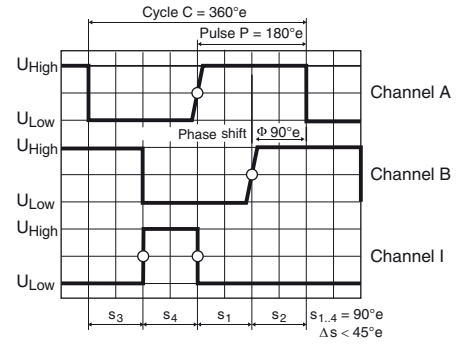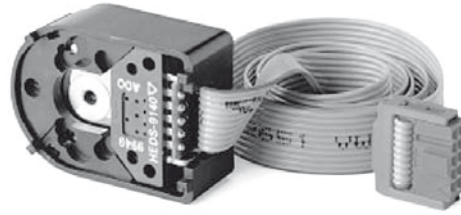The index signal I is synchronised with channel A or B.

Pin Allocation

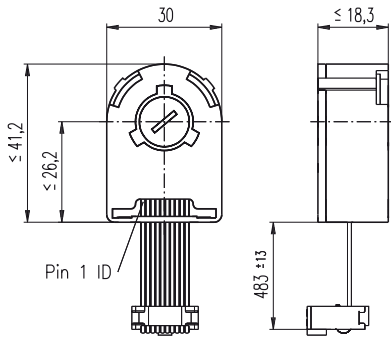2 1
10 9

1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\overline{A}$
6 Channel A
7 Channel $\overline{B}$
8 Channel B
9 Channel $\overline{I}$ (Index)
10 Channel I (Index)

Pin type DIN 41651/
EN 60603-13
flat band cable AWG 28

Connection example

Encoder, Line Driver, DS26LS31

V_{CC}
GND
Channel $\overline{A}$
Channel A
Channel $\overline{B}$
Channel B
Channel $\overline{I}$
Channel I

R

Line receiver
Recommended IC's:
- MC 3486
- SN 75175
- AM 26 LS 32

Terminal resistance R = typical 120 Ω

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422

Cycle C = 360°e
Pulse P = 180°e

Channel A
Channel B
Channel I

Phase shift Φ 90°e

s_3 s_4 s_1 s_2 $s_{1..4} = 90°e$ $\Delta s < 45°e$

Direction of rotation cw (definition cw p. 48)

■ Stock program
□ Standard program
▨ Special program (on request)

Type			
Counts per turn	500	500	500
Number of channels	3	3	3
Max. operating frequency (kHz)	100	100	100
Max. speed (rpm)	12 000	12 000	12 000
Shaft diameter (mm)	3	4	6

maxon Modular System

+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead
RE 25	77/79					75.3
RE 25	77/79	GP 26/GP 32	231/234			●
RE 25	77/79	KD 32, 1.0 - 4.5 Nm	240			●
RE 25	77/79	GP 32, 0.75 - 6.0 Nm	235/237			●
RE 25	77/79	GP 32 S	255-257			●
RE 25, 20 W	79			AB 28	330	105.8
RE 25, 20 W	79	GP 26/GP 32	231/234	AB 28	330	●
RE 25, 20 W	79	KD 32, 1.0 - 4.5 Nm	240	AB 28	330	●
RE 25, 20 W	79	GP 32, 0.75 - 6.0 Nm	235/237	AB 28	330	●
RE 25, 20 W	79	GP 32 S	255-257	AB 28	330	●
RE 35, 90 W	81					91.7
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	234			●
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	236/237			●
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	239			●
RE 35, 90 W	81	GP 42, 3.0 - 15 Nm	242			●
RE 35, 90 W	81	GP 32 S	255-257			●
RE 35, 90 W	81			AB 28	330	124.3
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	234	AB 28	330	●
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	236/237	AB 28	330	●
RE 35, 90 W	81	GP 42, 3.0 - 15 Nm	242	AB 28	330	●
RE 35, 90 W	81	GP 32 S	255-257	AB 28	330	●
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	239	AB 28	330	●
RE 40, 150 W	82					91.7
RE 40, 150 W	82	GP 42, 3.0 - 15 Nm	242			●
RE 40, 150 W	82	GP 52, 4.0 - 30 Nm	245			●
RE 40, 150 W	82			AB 28	330	124.3
RE 40, 150 W	82	GP 42, 3.0 - 15 Nm	242	AB 28	330	●
RE 40, 150 W	82	GP 52, 4.0 - 30 Nm	245	AB 28	330	●
A-max 26	102-108					63.1
A-max 26	102-108	GP 26, 0.5 - 4.5 Nm	231/232			●
A-max 26	102-108	GS 30/GP 32	233/236			●
A-max 26	102-108	GP 32, 0.75 - 6.0 Nm	235/238			●
A-max 26	102-108	GS 38, 0.1 - 0.6 Nm	241			●
A-max 26	102-108	GP 32 S	255-257			●
A-max 32	110/112					82.3
A-max 32	110/112	GP 32, 0.75 - 6.0 Nm	236/238			●
A-max 32	110/112	GS 38, 0.1 - 0.6 Nm	241			●
A-max 32	110/112	GP 32 S	255-257			●

Technical Data

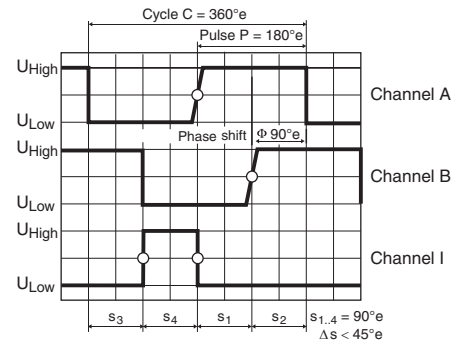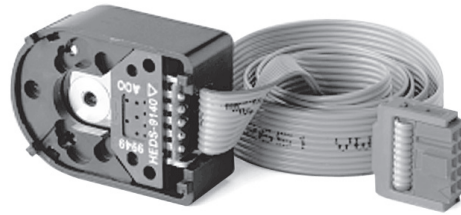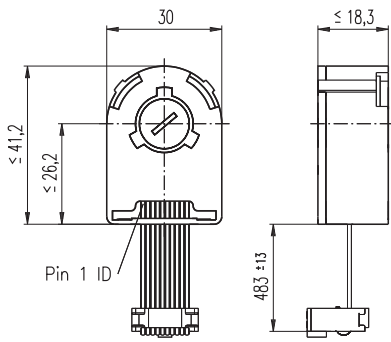|	
Supply voltage V_{CC}	5 V ± 10%
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90°e ± 45°e
Signal rise time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	180 ns
Signal fall time (typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	40 ns
Index pulse width	90°e
Operating temperature range	-40…+100°C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250 000 rad s⁻²
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

The index signal I is synchronised with channel A or B.

Pin Allocation

1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\overline{A}$
6 Channel A
7 Channel $\overline{B}$
8 Channel B
9 Channel $\overline{I}$ (Index)
10 Channel I (Index)

Pin type DIN 41651/
EN 60603-13
flat band cable AWG 28

Connection example

Line receiver
Recommended IC's:
- MC 3486
- SN 75175
- AM 26 LS 32

Terminal resistance R = typical 120 Ω

Encoder HEDL 5540 500 CPT, 3 Channels, with Line Driver RS 422

Pin 1 ID

Cycle C = 360°e
Pulse P = 180°e

U_{High}
U_{Low} — Channel A

Phase shift Φ 90°e

U_{High}
U_{Low} — Channel B

U_{High}
U_{Low} — Channel I

s_3 s_4 s_1 s_2 $s_{1..4} = 90°e$
$\Delta s < 45°e$

Direction of rotation cw (definition cw p. 48)

Stock program
Standard program
Special program (on request)

Article Numbers

	110512	110514	110516

Type

Counts per turn	500	500	500
Number of channels	3	3	3
Max. operating frequency (kHz)	100	100	100
Max. speed (rpm)	12 000	12 000	12 000
Shaft diameter (mm)	3	4	6

maxon Modular System

+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead	
RE 25	78					63.8	
RE 25	78	GP 26/GP 32	231/234			●	
RE 25	78	KD 32, 1.0 - 4.5 Nm	240			●	
RE 25	78	GP 32, 0.75 - 6.0 Nm	235/237			●	
RE 25	78	GP 32 S	255-257			●	
RE 25, 20 W	78			AB 28	330	94.3	
RE 25, 20 W	78	GP 26/GP 32	231/234	AB 28	330	●	
RE 25, 20 W	78	KD 32, 1.0 - 4.5 Nm	240	AB 28	330	●	
RE 25, 20 W	78	GP 32, 0.75 - 6.0 Nm	235/237	AB 28	330	●	
RE 25, 20 W	78	GP 32 S	255-257	AB 28	330	●	
EC-4pole 22	175					70.1	
EC-4pole 22	175	GP 22/GP 32	227/238			●	
EC-4pole 22	175	GP 32 S	255-257			●	
EC-4pole 22	176					87.5	
EC-4pole 22	176	GP 22/GP 32	227/238			●	
EC-4pole 22	176	GP 32 S	255-257			●	
EC-4pole 30	177					67.6	
EC-4pole 30	177	GP 32, 4.0 - 8.0 Nm	239			●	
EC-4pole 30	177	GP 42, 3 - 15 Nm	243			●	
EC-4pole 30	177			AB 20	328	104.0	
EC-4pole 30	177	GP 32, 4.0 - 8.0 Nm	239	AB 20	328	●	
EC-4pole 30	177	GP 42, 3 - 15 Nm	243	AB 20	328	●	
EC-4pole 30	178					84.6	
EC-4pole 30	178	GP 32, 4.0 - 8.0 Nm	239			●	
EC-4pole 30	178	GP 42, 3 - 15 Nm	243			●	
EC-4pole 30	178			AB 20	328	121.0	
EC-4pole 30	178	GP 32, 4.0 - 8.0 Nm	239	AB 20	328	●	
EC-4pole 30	178	GP 42, 3 - 15 Nm	243	AB 20	328	●	
EC-i 40, 50 W	190					49.0	
EC-i 40, 50 W	190	GP 32, 1 - 6 Nm	238			●	
EC-i 40, 50 W	190	GP 32 S	255-257			●	
EC-i 40, 70 W	191					59.0	
EC-i 40, 70 W	191	GP 32, 1 - 6 Nm	238			●	
EC-i 40, 70 W	191	GP 32 S	255-257			●	

Technical Data

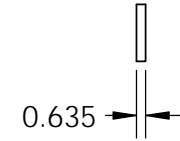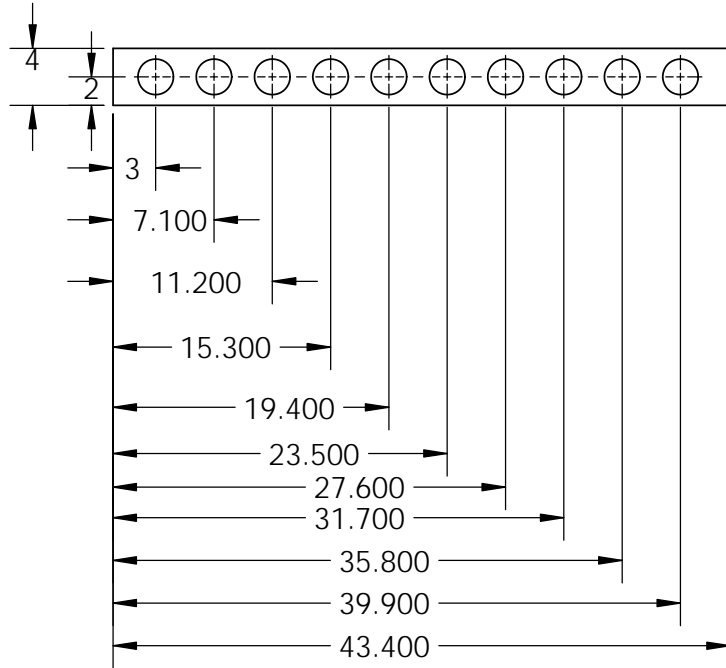|	
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driver used:	DS26LS31
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(typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	180 ns
Signal fall time	
(typically, at C_L = 25 pF, R_L = 2.7 kΩ, 25°C)	40 ns
Index pulse width	90°e
Operating temperature range	-40…+100°C
Moment of inertia of code wheel	≤ 0.6 gcm²
Max. angular acceleration	250 000 rad s⁻²
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 Counts per turn, 2 Channels

The index signal I is synchronised with channel A or B.

Pin Allocation

1 N.C.
2 V_{CC}
3 GND
4 N.C.
5 Channel $\overline{A}$
6 Channel A
7 Channel $\overline{B}$
8 Channel B
9 Channel $\overline{I}$ (Index)
10 Channel I (Index)

Pin type DIN 41651/
EN 60603-13
flat band cable AWG 28

Connection example

Line receiver
Recommended IC's:
- MC 3486
- SN 75175
- AM 26 LS 32

Encoder, Line Driver, DS26LS31

V_{CC}
GND
Channel $\overline{A}$
Channel A
Channel $\overline{B}$
Channel B
Channel $\overline{I}$
Channel I

Terminal resistance R = typical 120 Ω

X. Drawings

2 REQUIRED

4
2

3
7.100
11.200
15.300
19.400
23.500
27.600
31.700
35.800
39.900
43.400

0.635

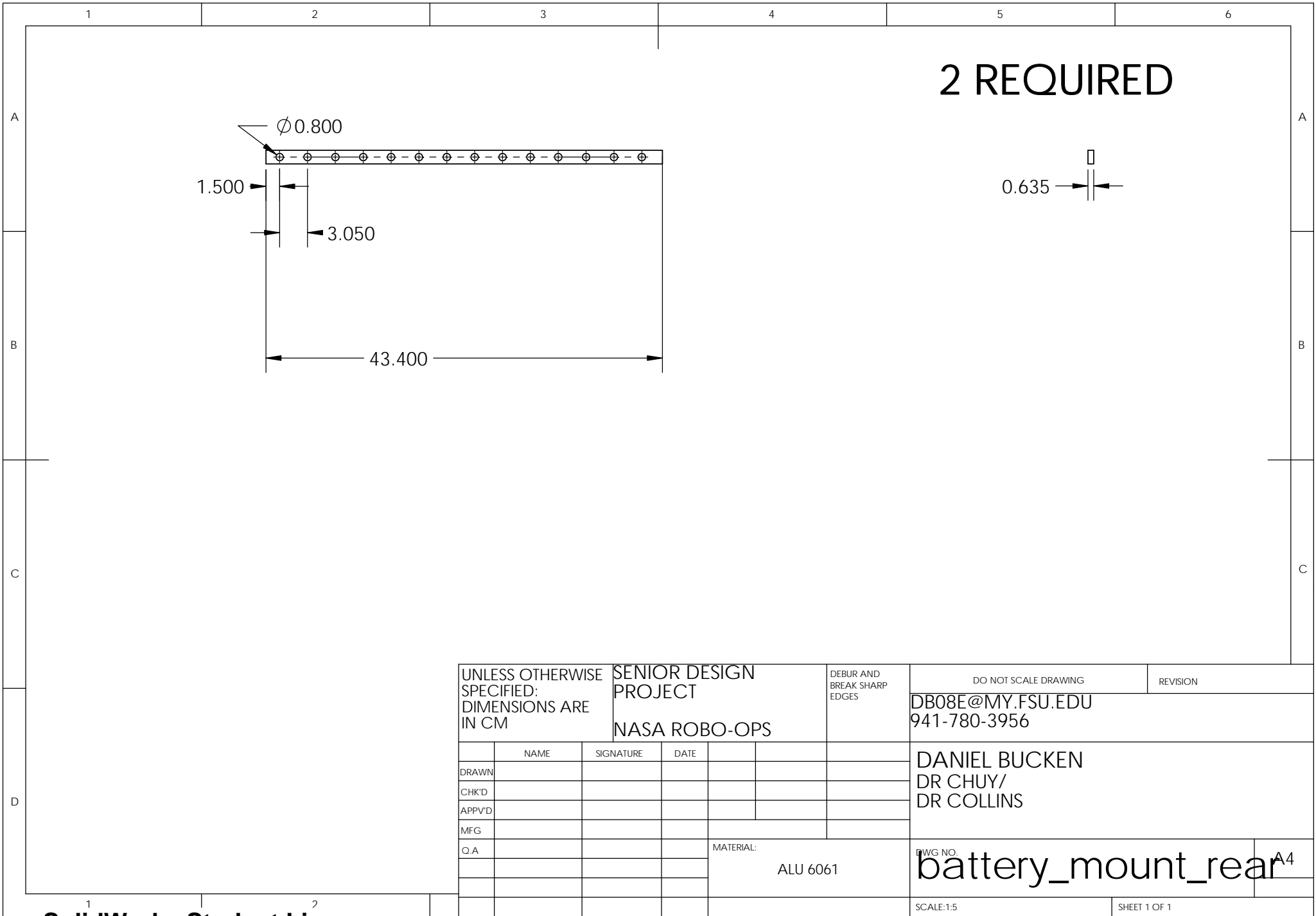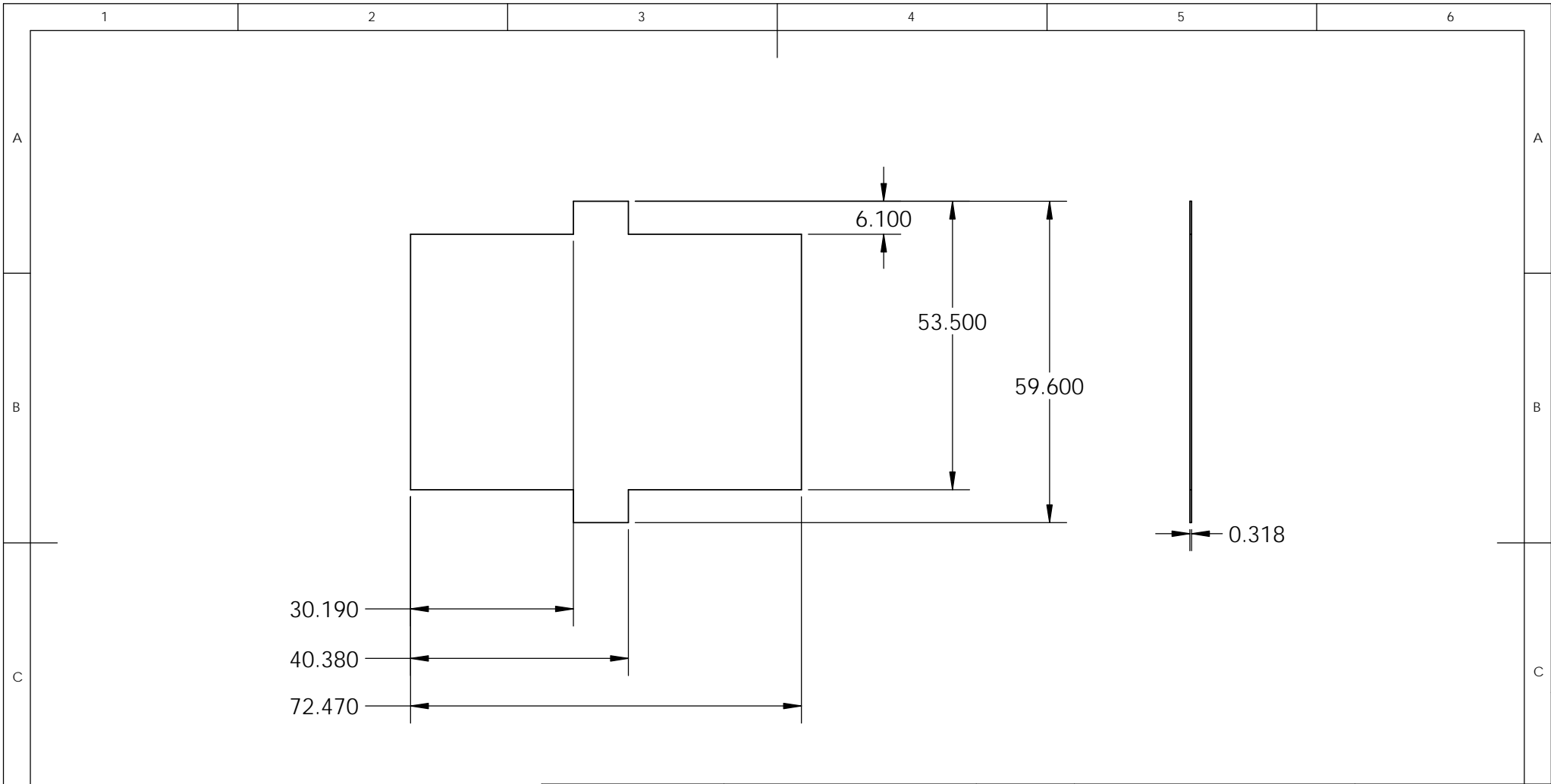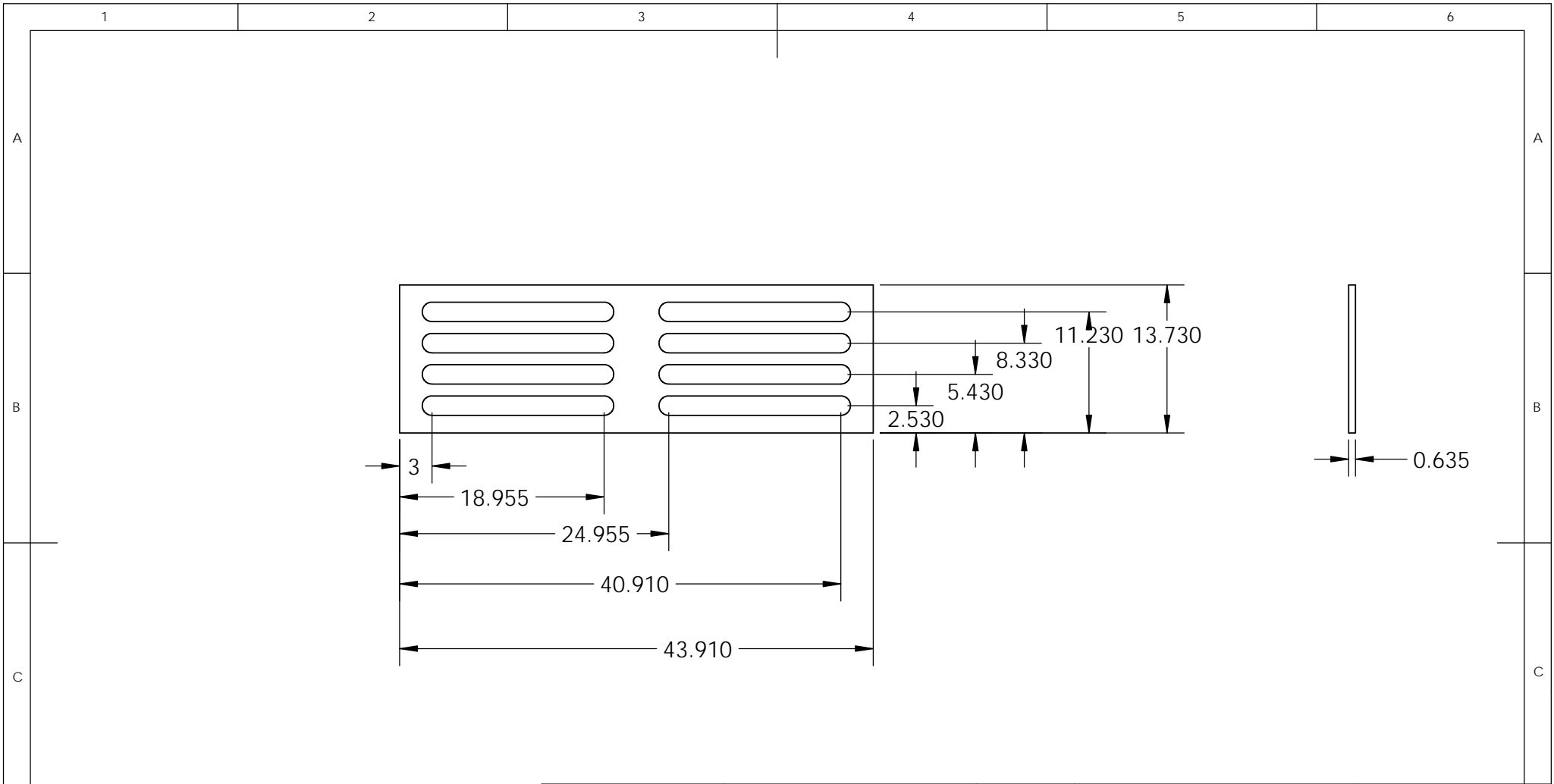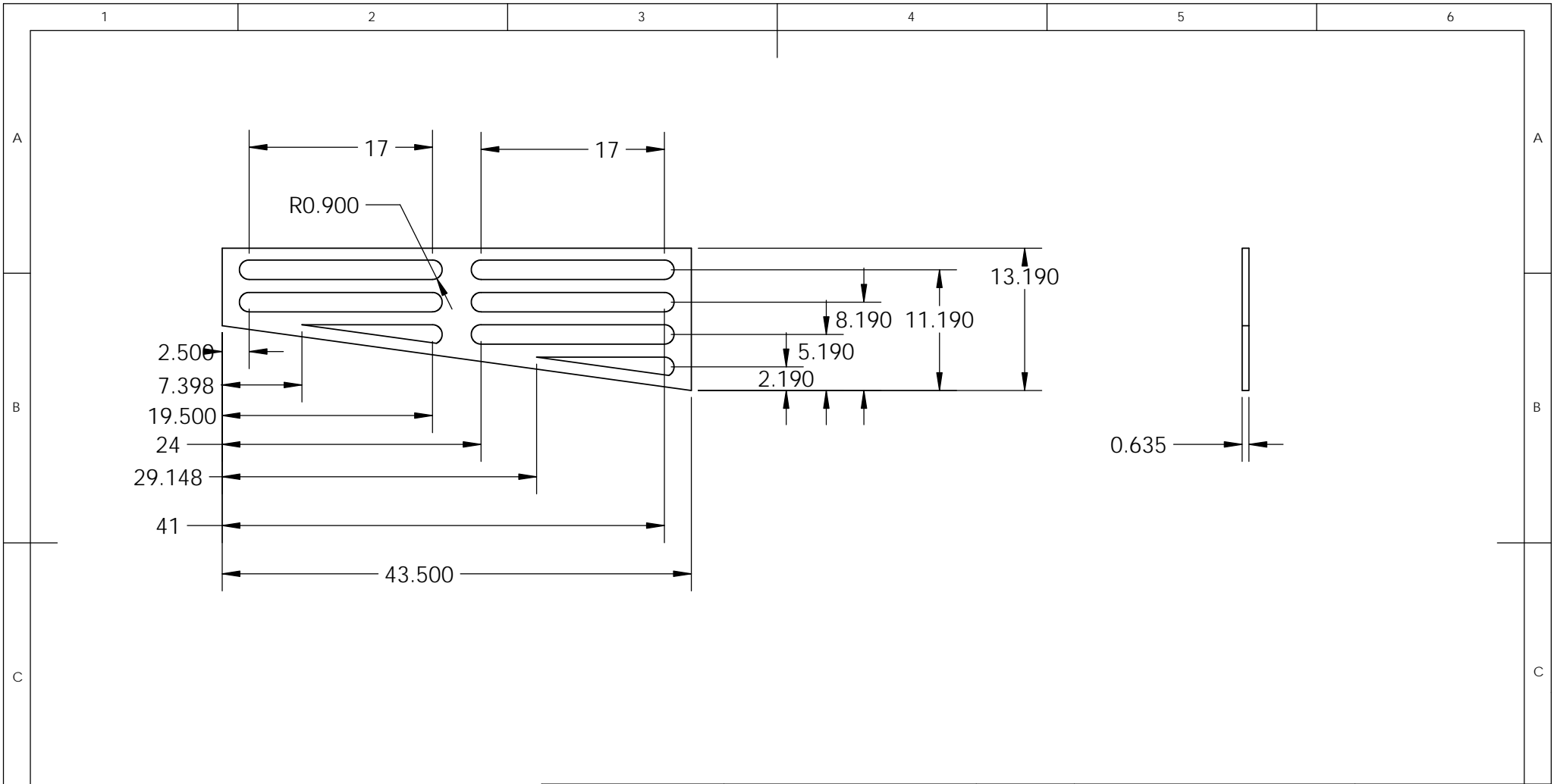|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

DB08E@MY.FSU.EDU
941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
battery_mount_front

A4

SCALE:1:5

SHEET 1 OF 1

2 REQUIRED

4
2
3
6.500
10
13.500
17
20.190
0.635

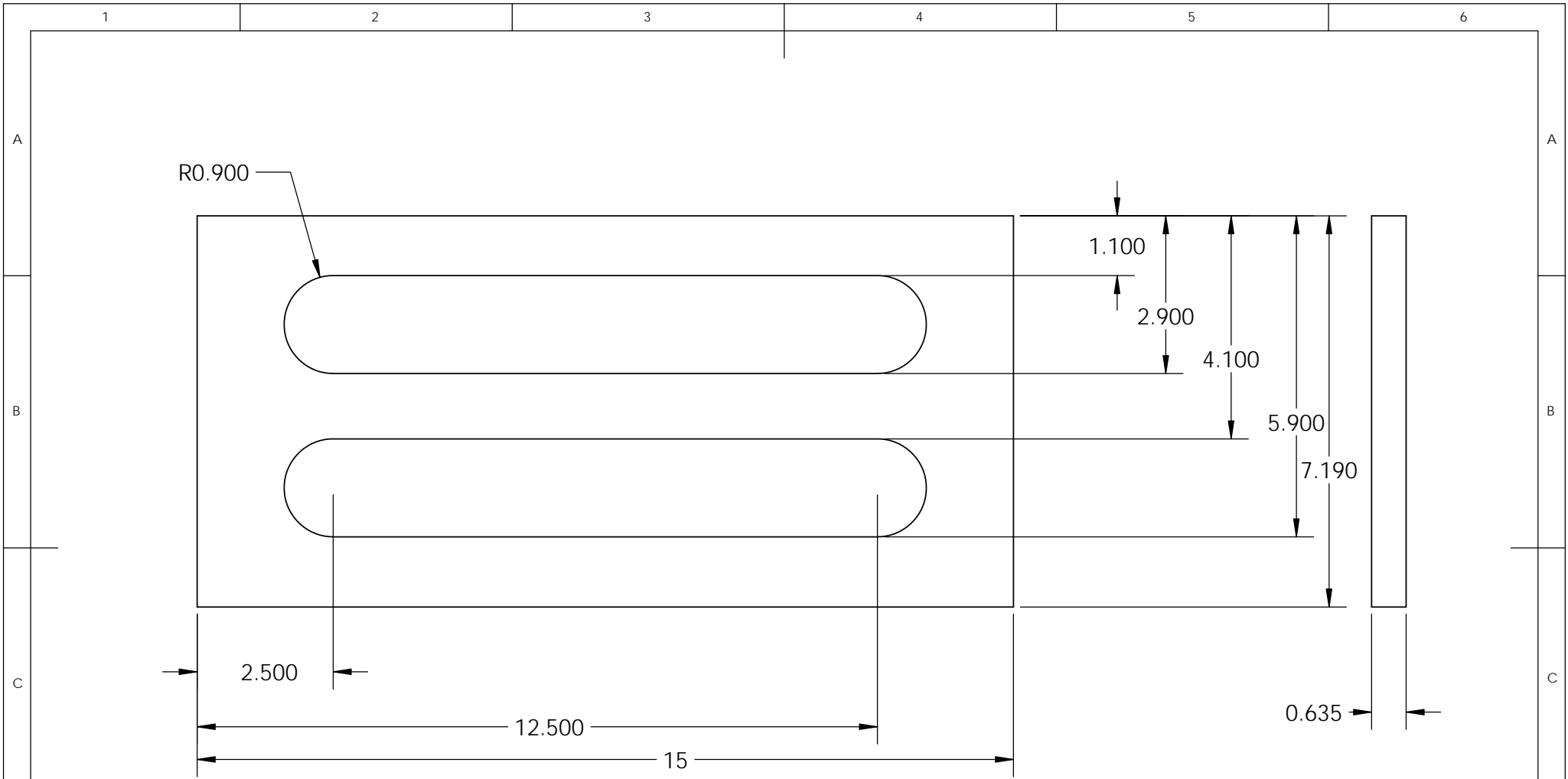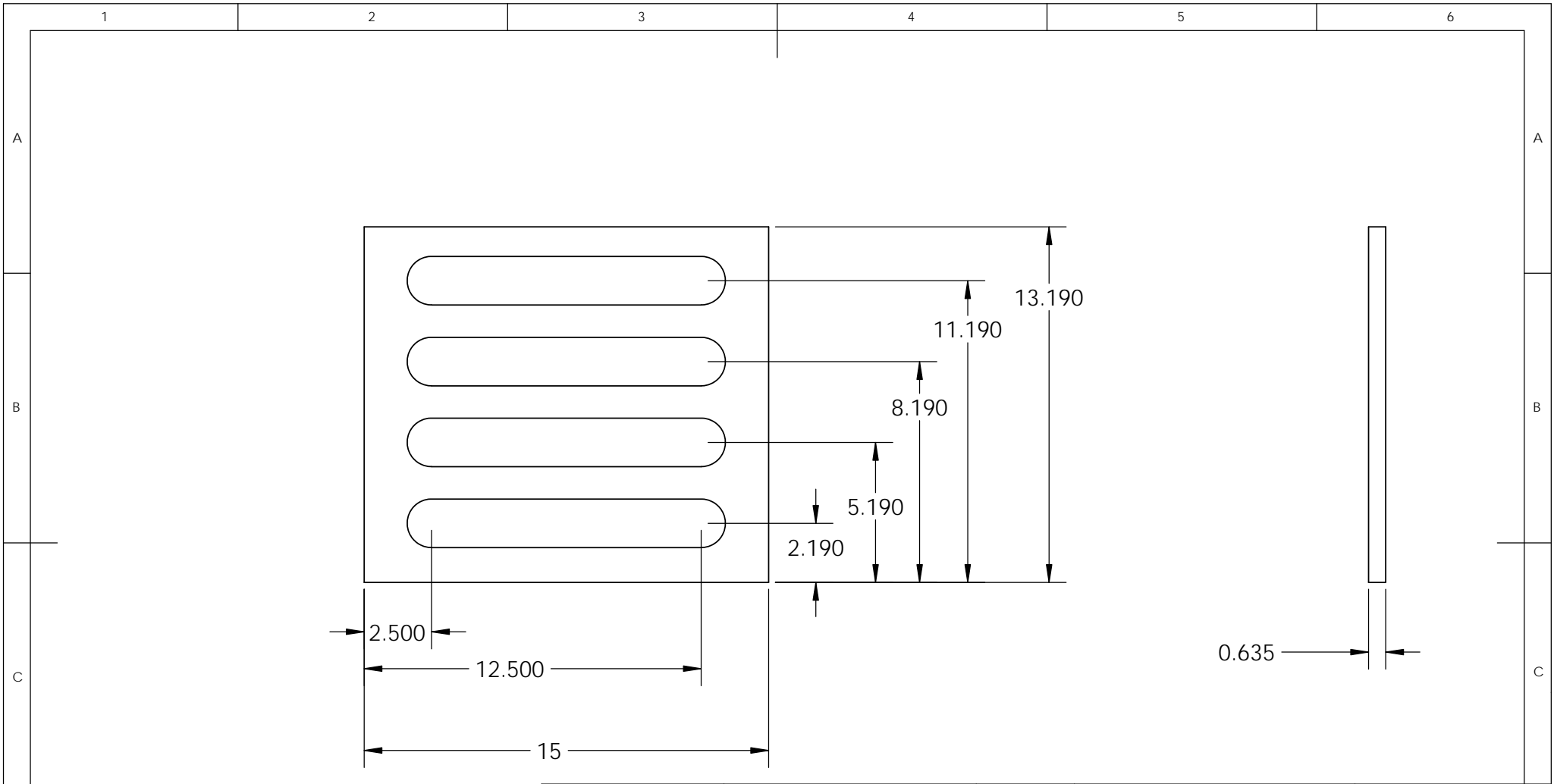|	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
battery_mount_mid

A4

SCALE:1:2

SHEET 1 OF 1

| | 1 | 2 | 3 | 4 | 5 | 6 |

2 REQUIRED

⌀ 0.800

1.500

3.050

43.400

0.635

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
battery_mount_rear

A4

SCALE:1:5   SHEET 1 OF 1

6.100

53.500

59.600

0.318

30.190

40.380

72.470

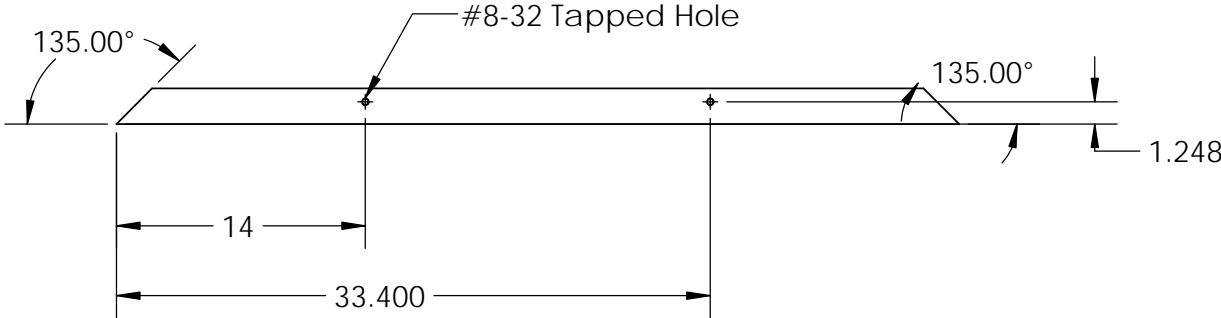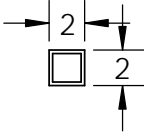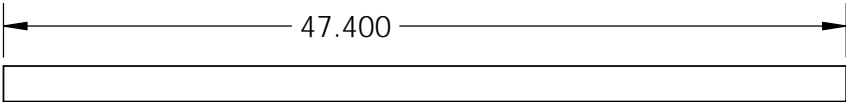|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ABS PLASTIC

DWG NO.

belly_plate

A4

SCALE:1:10

SHEET 1 OF 1

11.230 13.730
8.330
5.430
2.530
3
18.955
24.955
40.910
43.910
0.635

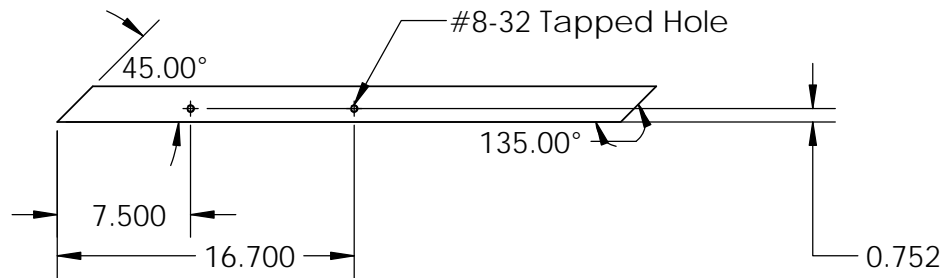|	NAME	SIGNATURE	DATE				
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A							

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
box_bttm

A4

SCALE:1:5   SHEET 1 OF 1

17

17

R0.900

13.190

8.190 11.190

5.190

2.190

2.500

7.398

19.500

24

29.148

41

43.500

0.635

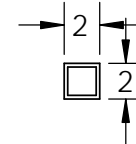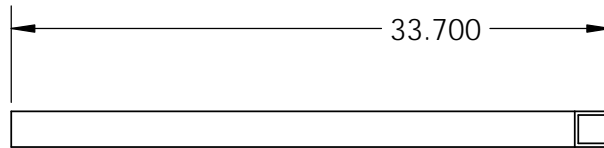|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
PLEXI

DWG NO.

box_front

A4

SCALE:1:5

SHEET 1 OF 1

R0.900

1.100
2.900
4.100
5.900
7.190

2.500
12.500
15
0.635

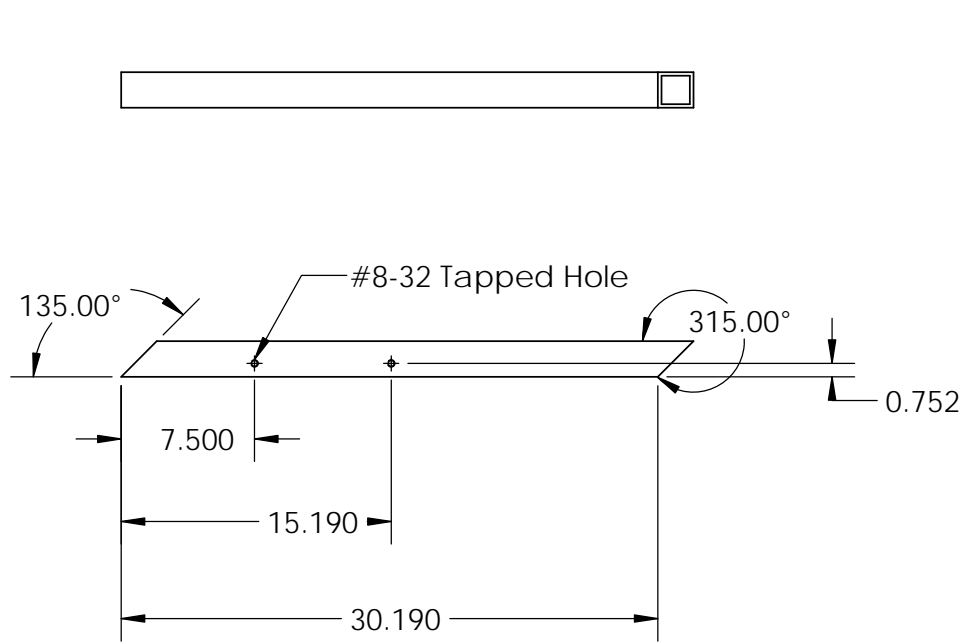|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
PLEXI

DWG NO.

box_side_1

A4

SCALE:1:1

SHEET 1 OF 1

13.190

11.190

8.190

5.190

2.190

2.500

12.500

15

0.635

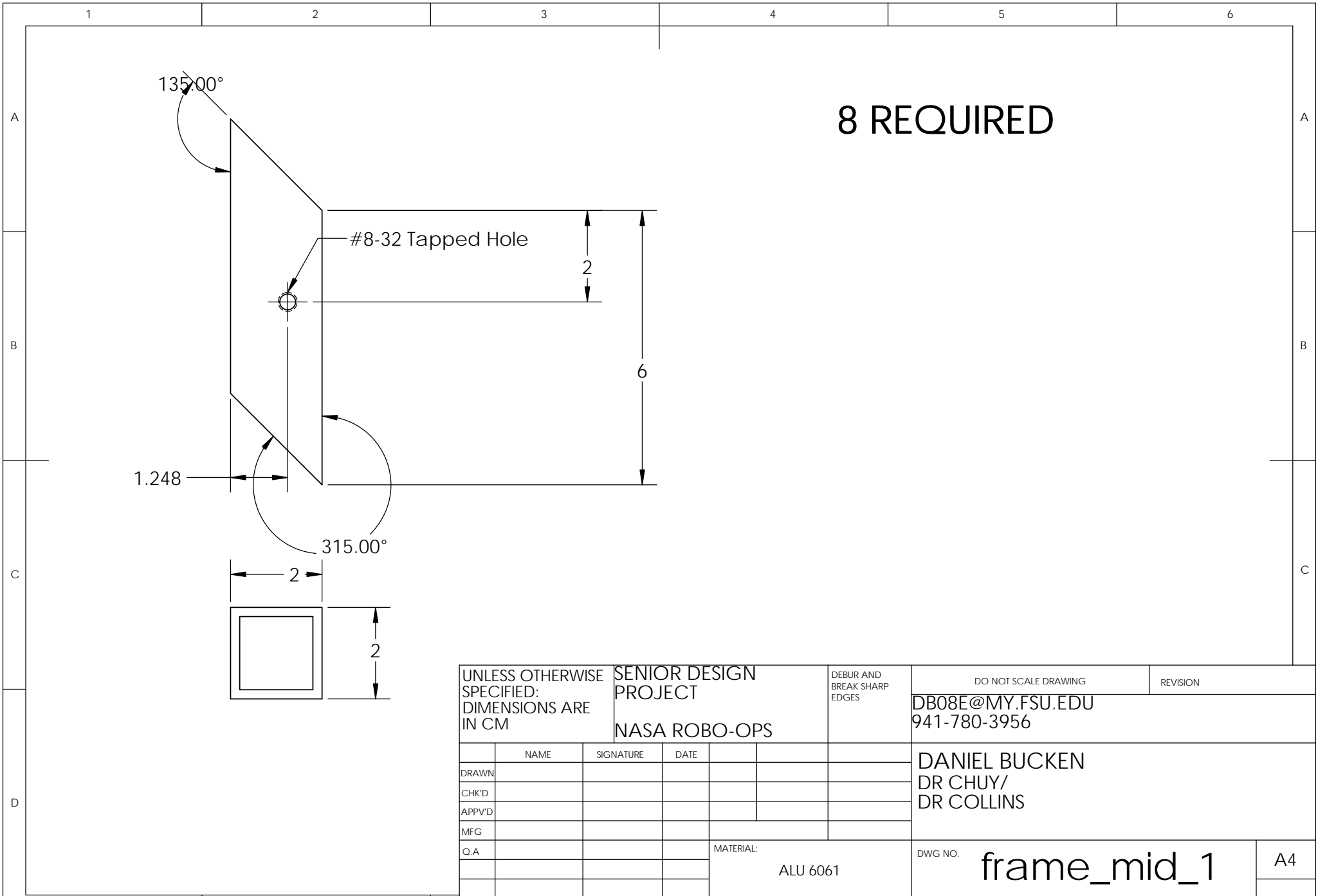|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
PLEXI

DWG NO.

box_side_2

A4

SCALE:1:2　　SHEET 1 OF 1

4 REQUIRED

47.400

2

2

#8-32 Tapped Hole

135.00°

135.00°

1.248

14

33.400

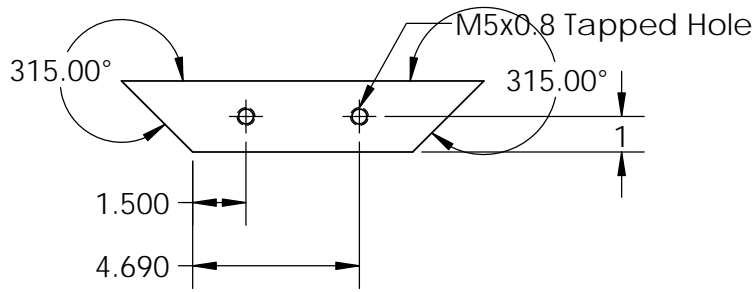|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
frame_front_bar

A4

SCALE:1:5

SHEET 1 OF 1

4 REQUIRED

33.700

2
2

45.00°

#8-32 Tapped Hole

135.00°

7.500

16.700

0.752

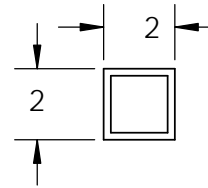|	NAME	SIGNATURE	DATE				
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A							

UNLESS OTHERWISE SPECIFIED:
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SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG. NO.
frame_long_back

A4

SCALE:1:5

SHEET 1 OF 1

135.00°

#8-32 Tapped Hole

315.00°

0.752

7.500

15.190

30.190

2

2

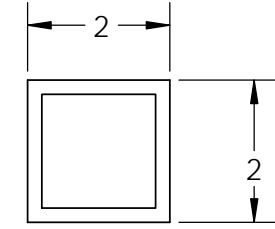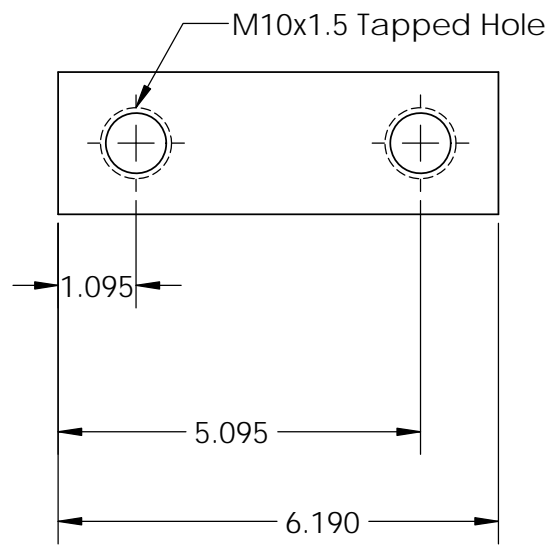|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
frame_long_front

A4

SCALE:1:5

SHEET 1 OF 1

135.00°
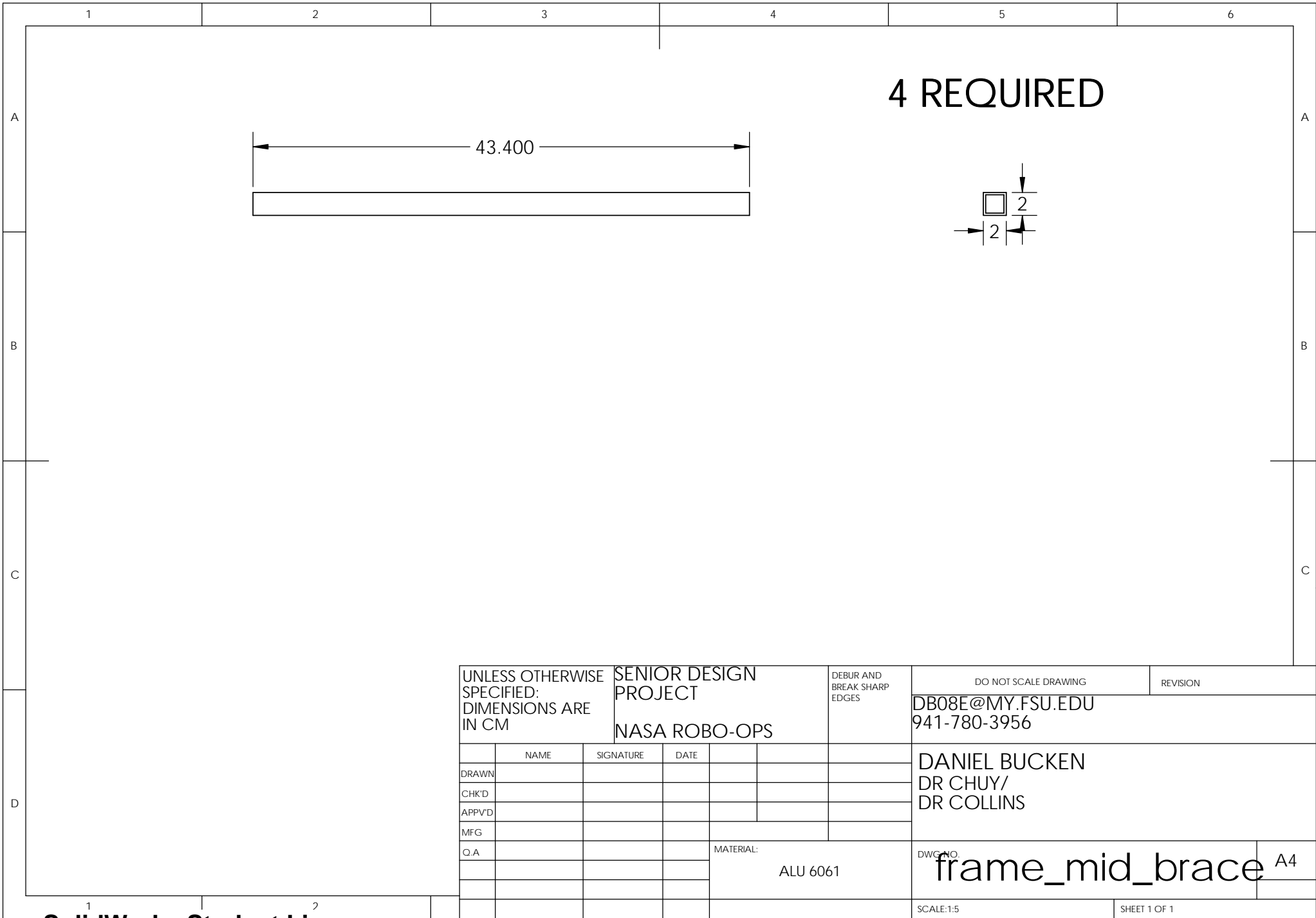
8 REQUIRED

#8-32 Tapped Hole

2

6

1.248

315.00°

2

2

		UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN CM	SENIOR DESIGN PROJECT	DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DB08E@MY.FSU.EDU
941-780-3956

	NAME	SIGNATURE	DATE			
DRAWN						DANIEL BUCKEN
CHK'D						DR CHUY/
APPV'D						DR COLLINS
MFG						
Q.A				MATERIAL:		

ALU 6061

DWG NO.

frame_mid_1

A4

SCALE:1:1   SHEET 1 OF 1

M5x0.8 Tapped Hole

315.00°   315.00°

1

4 REQUIRED

1.500

4.690

10.190

2

2

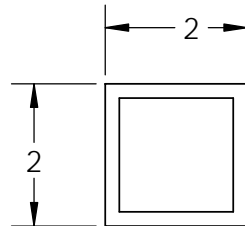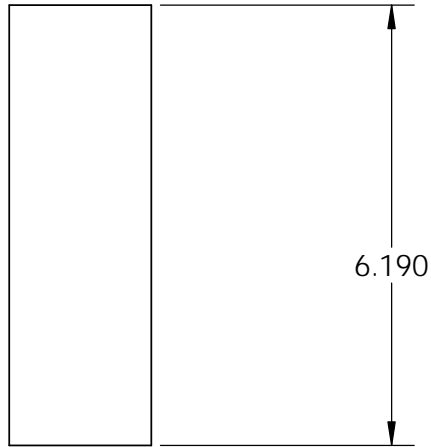|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
frame_mid_2

A4

SCALE:1:2   SHEET 1 OF 1

2 REQUIRED

M10x1.5 Tapped Hole

2

2

1.095

5.095

6.190

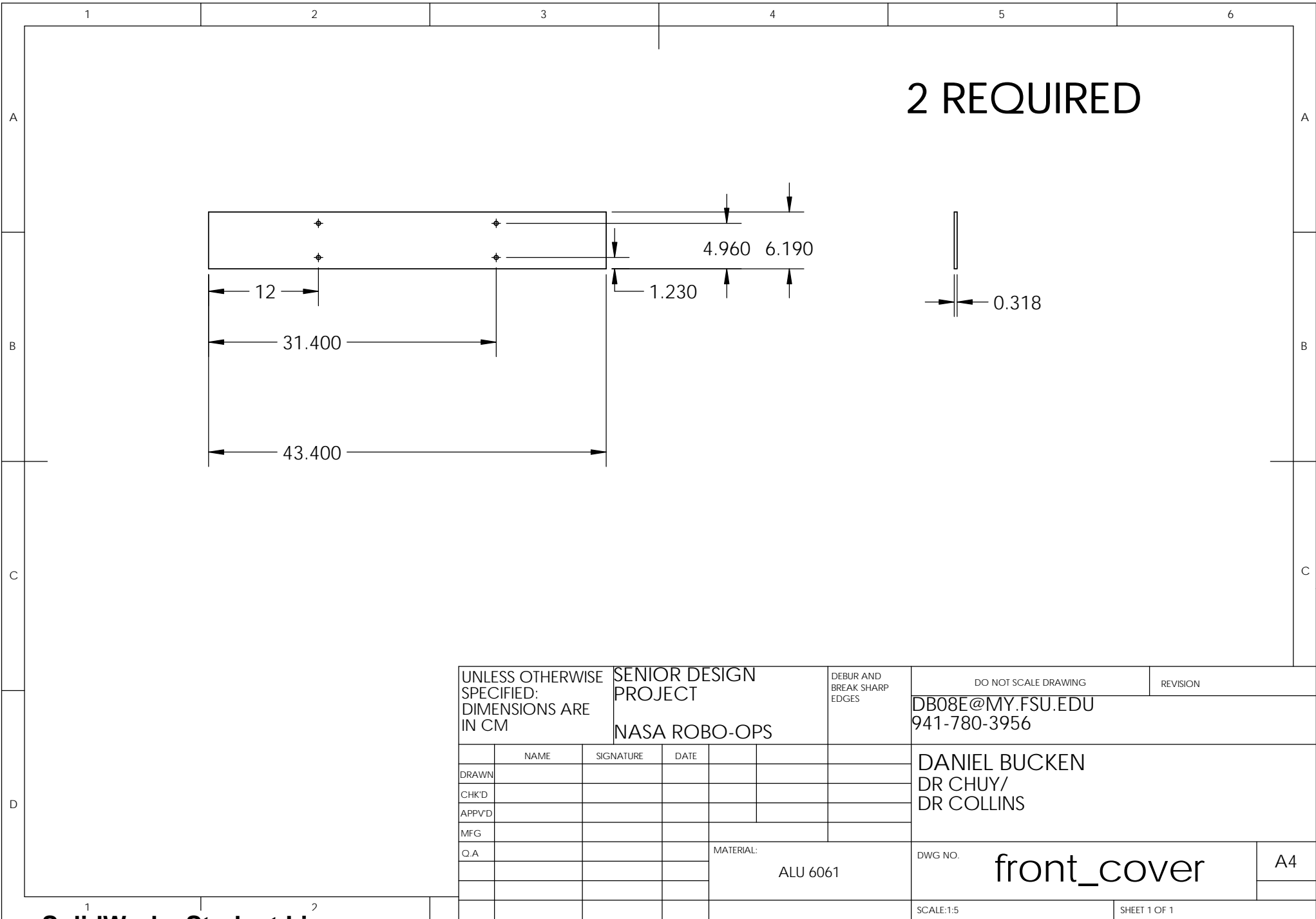|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
frame_mid_brace_2

A4

SCALE:1:1

SHEET 1 OF 1

4 REQUIRED

43.400

2

2

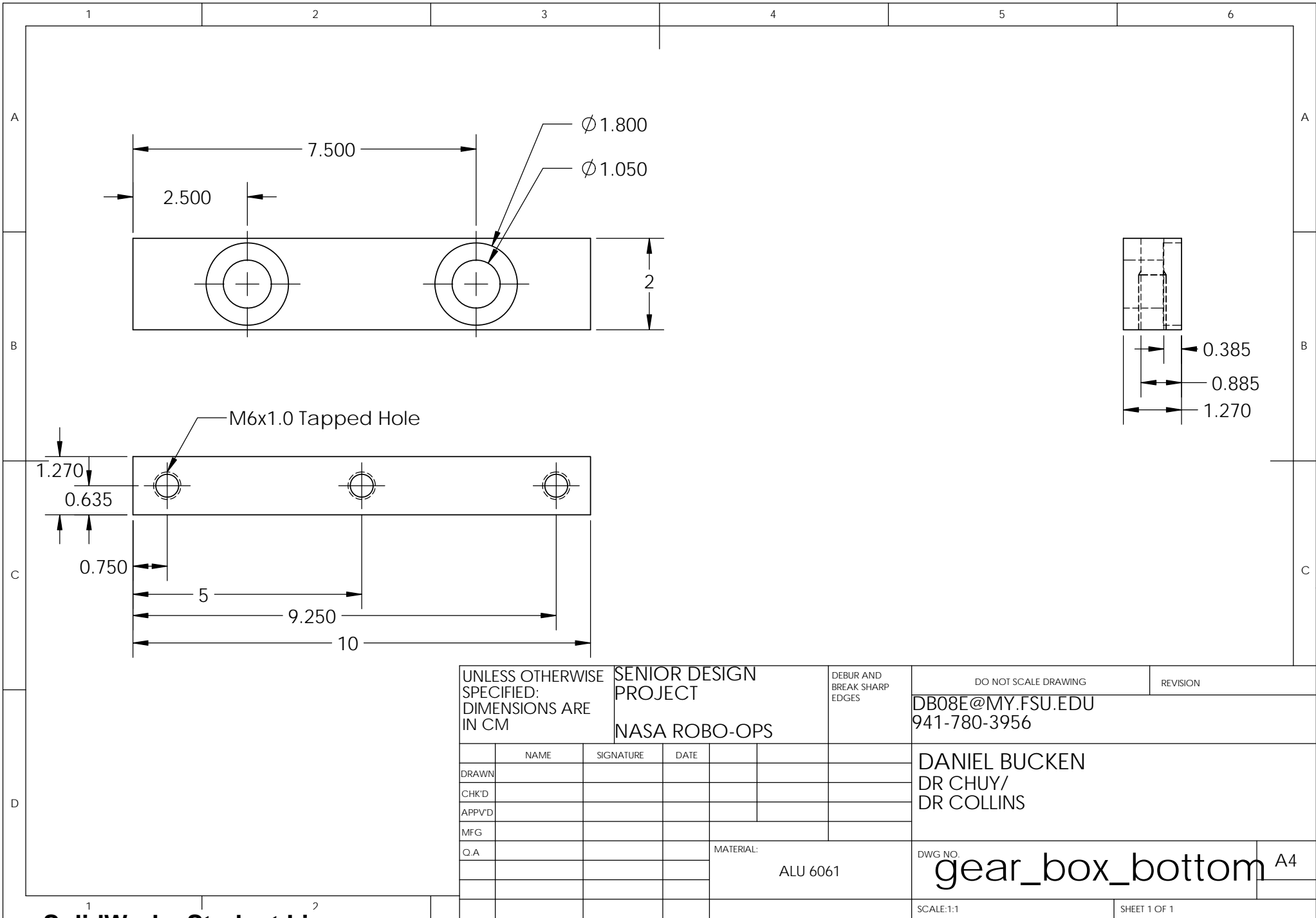|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ALU 6061

DWG NO.
frame_mid_brace

A4

SCALE:1:5

SHEET 1 OF 1

16 REQUIRED

6.190

2

2

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ALU 6061

DWG NO.

frame_vertical

A4

SCALE:1:1

SHEET 1 OF 1

2 REQUIRED

4.960 6.190

1.230

12

31.400

43.400

0.318

	NAME	SIGNATURE	DATE				
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A							

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SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING
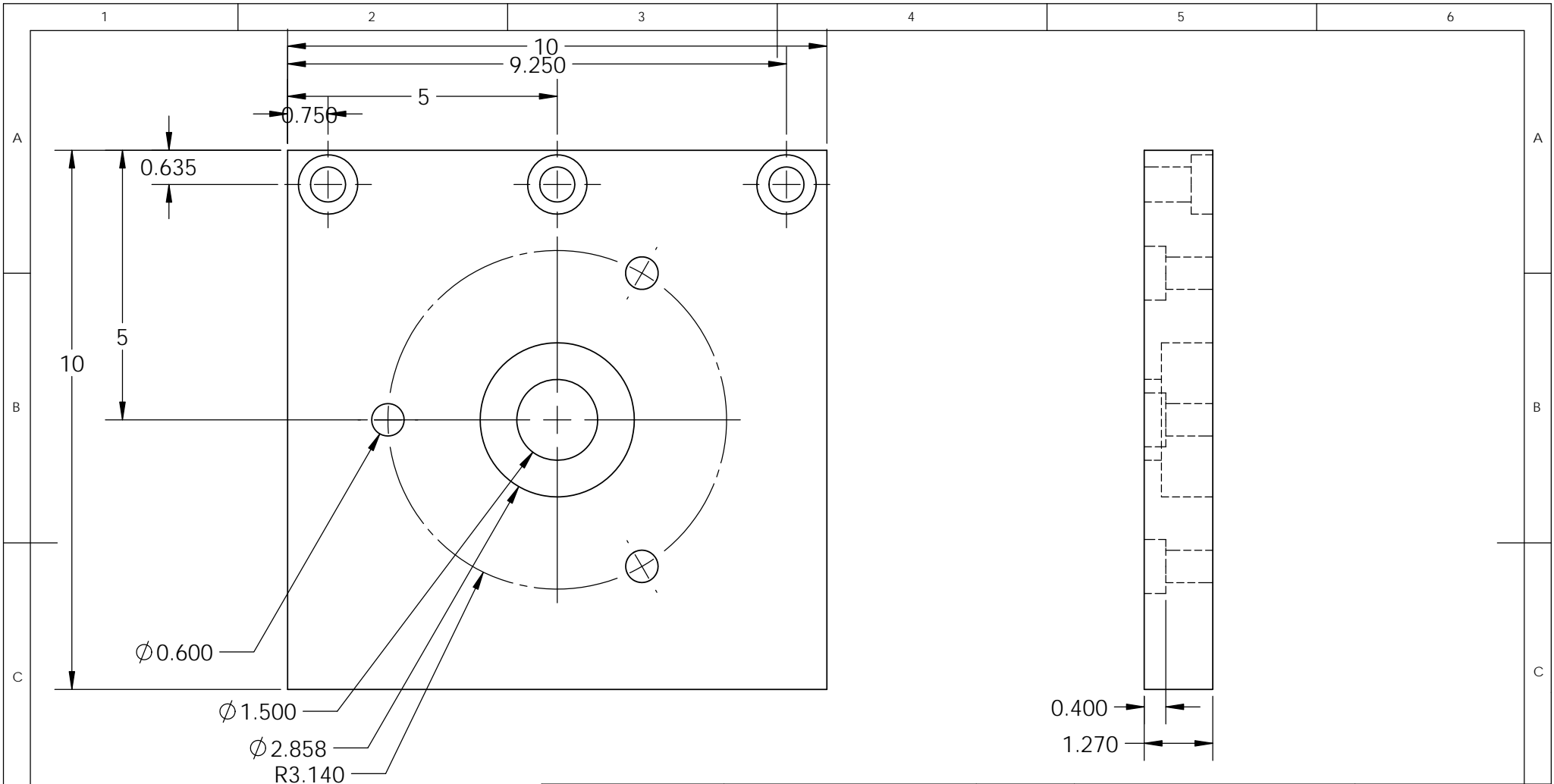
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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ALU 6061

DWG NO.

front_cover

A4

SCALE:1:5

SHEET 1 OF 1

⌀1.800

⌀1.050

7.500

2.500

2

0.385

0.885

1.270

M6x1.0 Tapped Hole

1.270

0.635

0.750

5

9.250

10

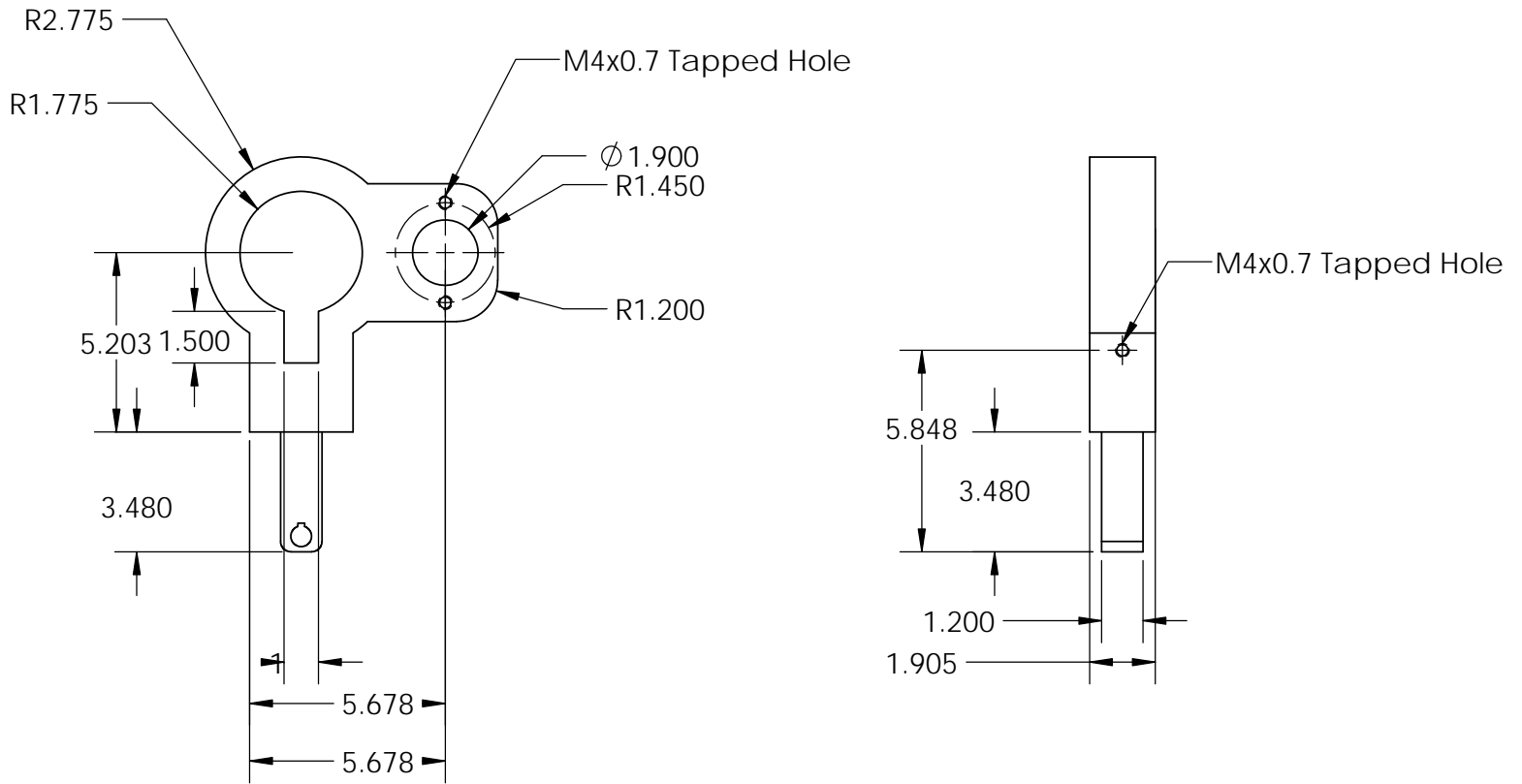|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CM

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DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
gear_box_bottom   A4

SCALE:1:1   SHEET 1 OF 1

10
9.250
5
0.750
0.635
10
5
Ø 0.600
Ø 1.500
Ø 2.858
R3.140

0.400
1.270

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
gear_box_side

A4

SCALE:1:1

SHEET 1 OF 1

R.787

M4x0.7 Tapped Hole

19 CM
FOR BEARING

∅.563

1.063

1.969

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

SENIOR DESIGN PROJECT

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DEBUR AND BREAK SHARP EDGES

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 2024

DWG NO.

grip_pin

A4

SCALE:1:2

SHEET 1 OF 1

R2.775

R1.775

M4x0.7 Tapped Hole

⌀1.900
R1.450

R1.200

5.203 1.500

3.480

5.678

5.678

M4x0.7 Tapped Hole

5.848

3.480

1.200

1.905

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

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DR COLLINS

MATERIAL:
ALU 6061

DWG NO.

guide_1

A4

SCALE:1:2

SHEET 1 OF 1

7.874				
5.489				
1.969				

.669
1.531
1.575
2.441
3.210
11.732

	NAME	SIGNATURE	DATE				
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A							

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DR COLLINS

MATERIAL:
ALU 2024

DWG NO.
GUIDE_1_NEW

A4

SCALE:1:2

SHEET 1 OF 1

4.790

CLEARANCE M4(2 PLACES)
THRU

0.730

1.125

3.665

1.270

M4x0.7 Tapped Hole   THRU

4 REQUIRED

0.500

1.750

3.040

4.290

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DEBUR AND BREAK SHARP EDGES

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941-780-3956
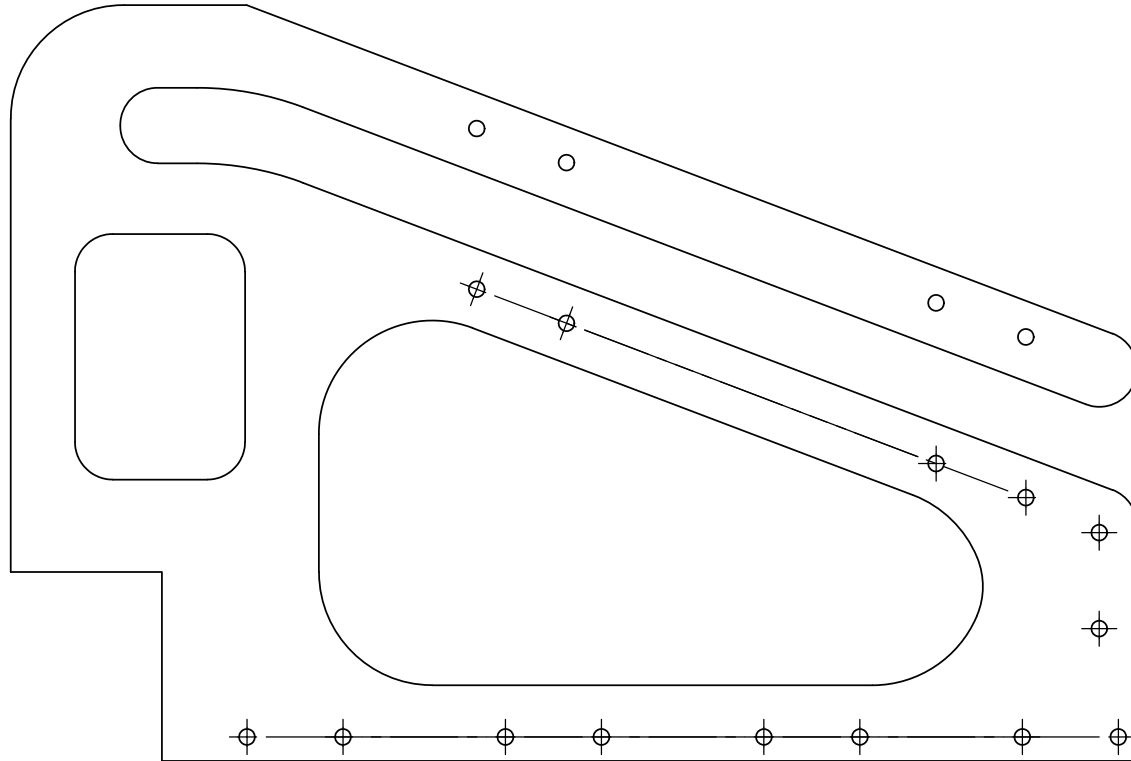
DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 2024

DWG NO.
GUIDE_1_RAIL

A4

SCALE:2:1   SHEET 1 OF 1

1.886

.287

.500

M4x0.7 Tapped Hole

THRU

.197

.689

1.197

1.689

5 REQUIRED

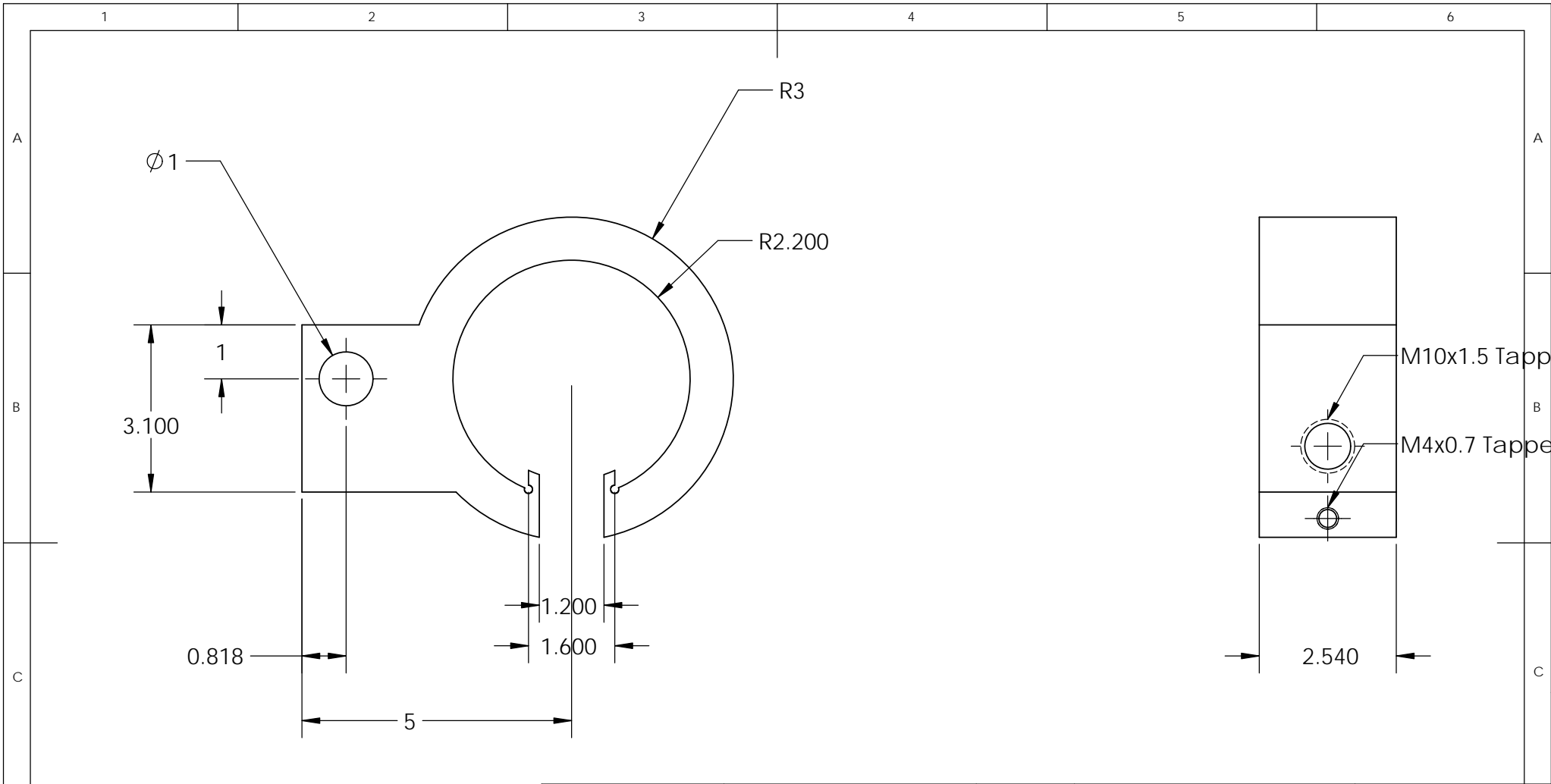|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

SENIOR DESIGN PROJECT

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DEBUR AND BREAK SHARP EDGES

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ALU 2024

DWG NO.
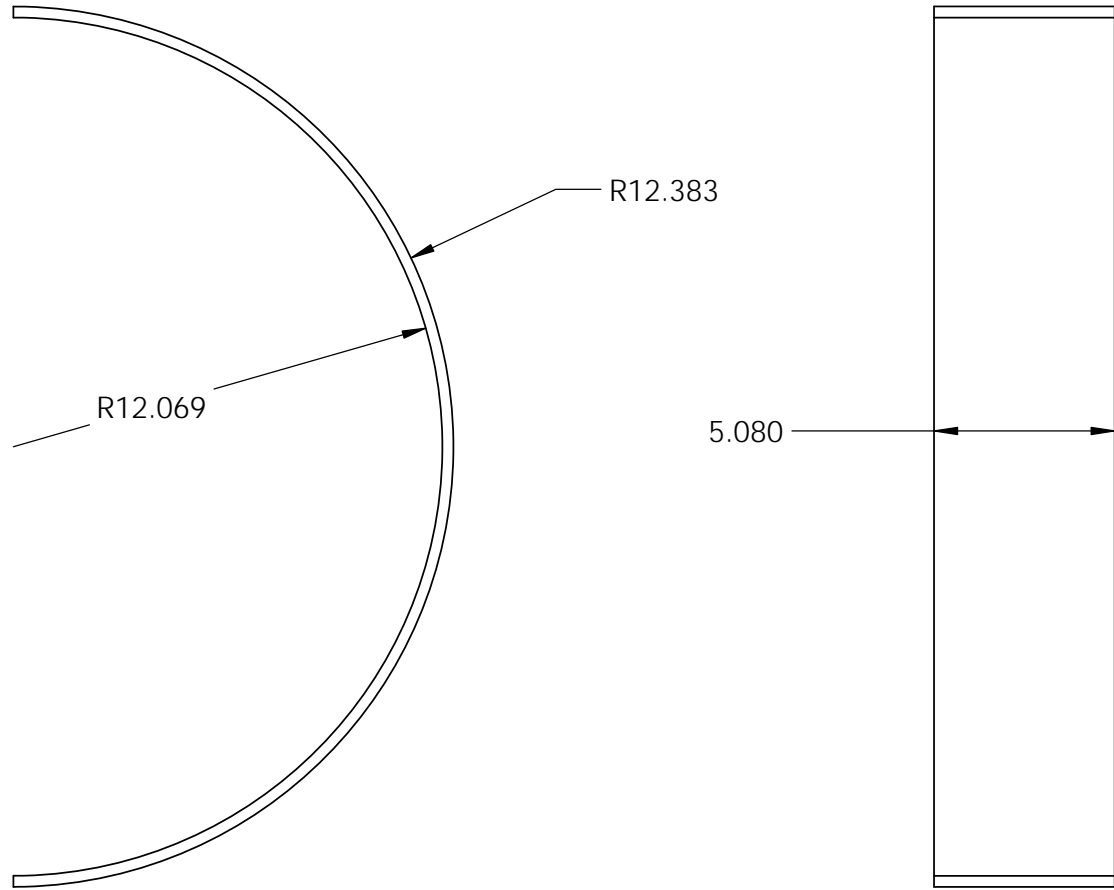GUIDE_1_RAIL_TOP

A4

SCALE:2:1

SHEET 1 OF 1

Only difference between guide_1
is clearance hole location

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							DB08E@MY.FSU.EDU 941-780-3956	
		NASA ROBO-OPS						
	NAME	SIGNATURE	DATE				DANIEL BUCKEN DR CHUY/ DR COLLINS	
DRAWN								
CHK'D								
APPV'D								
MFG								
Q.A				MATERIAL: ALU 2024			DWG NO. GUIDE_2_NEW	A4
							SCALE:1:2	SHEET 1 OF 1

R3

∅1

R2.200

1

3.100

0.818

1.200

1.600

5

2.540

M10x1.5 Tapped

M4x0.7 Tapped

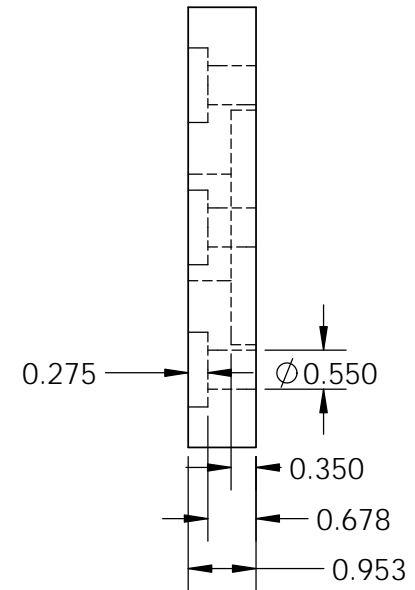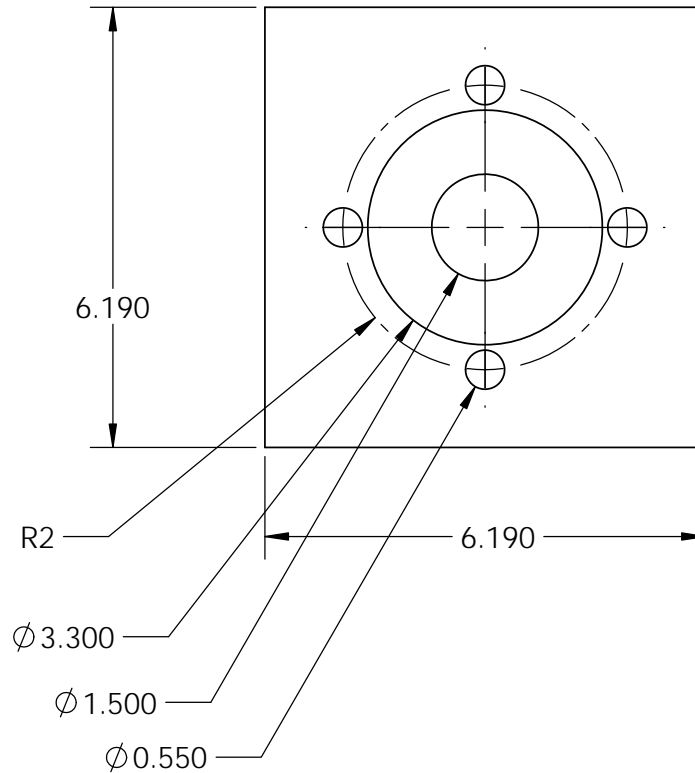|	NAME	SIGNATURE	DATE				
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A							

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DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
guide_move

A4

SCALE:1:1   SHEET 1 OF 1

6 REQUIRED

R12.383

R12.069

5.080

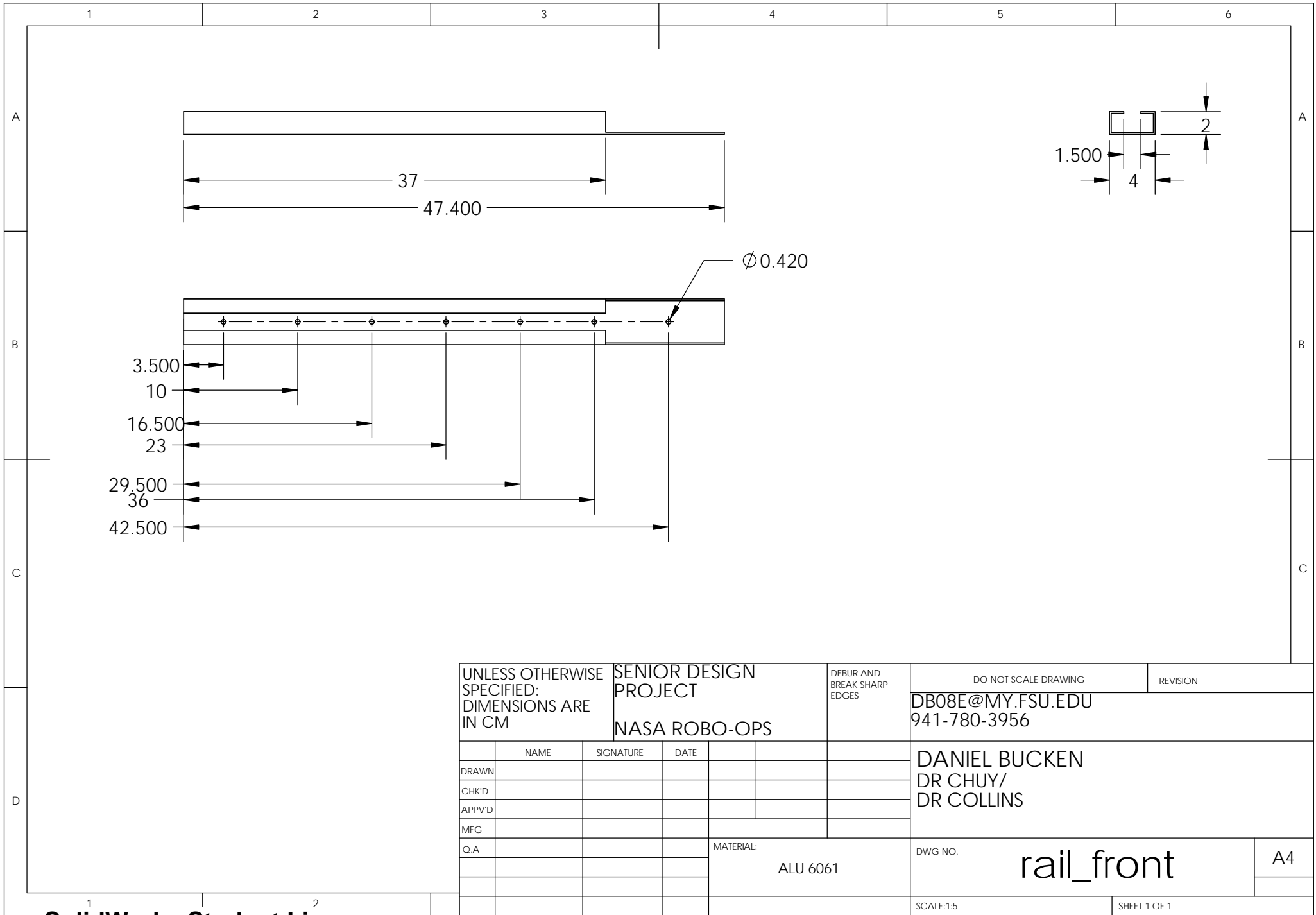|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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SENIOR DESIGN PROJECT

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
carbon fiber

DWG NO.

leg

A4

SCALE:1:5   SHEET 1 OF 1

6 REQUIRED

R2

⌀3.300

⌀1.500

⌀0.550

6.190

6.190

0.275

⌀0.550

0.350

0.678

0.953

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	NASA ROBO-OPS			DB08E@MY.FSU.EDU 941-780-3956		

	NAME	SIGNATURE	DATE			DANIEL BUCKEN DR CHUY/ DR COLLINS	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A			MATERIAL:		DWG NO.		
			ALU 6061		motor_mount		A4

SCALE:1:1   SHEET 1 OF 1

		A4

Dimensions and notes visible:

- 37
- 47.400
- ∅0.420
- 2
- 1.500
- 4
- 3.500
- 10
- 16.500
- 23
- 29.500
- 36
- 42.500

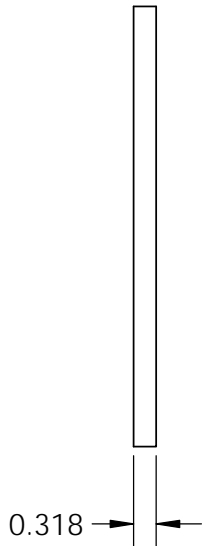|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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SENIOR DESIGN PROJECT

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.

rail_front

SCALE:1:5

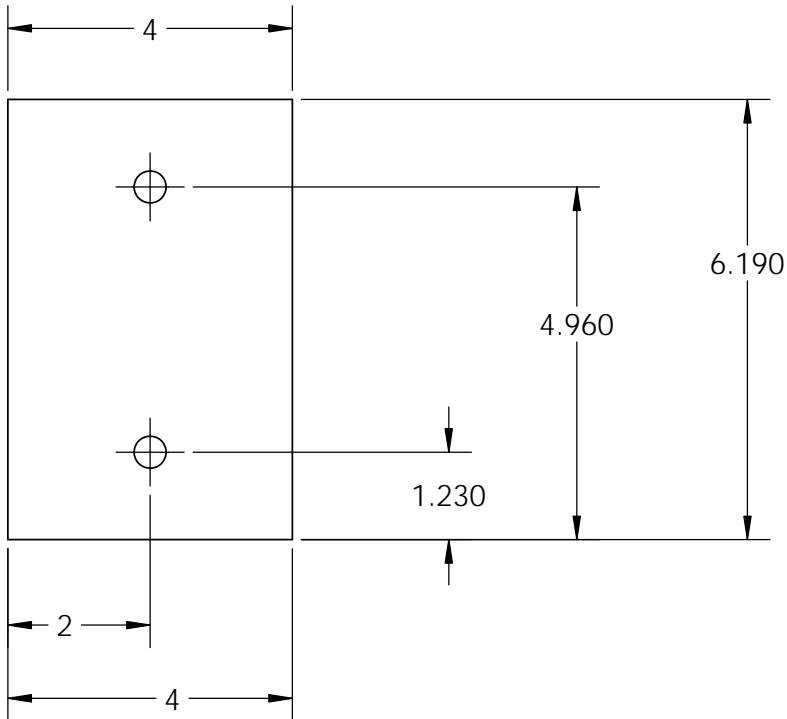SHEET 1 OF 1

⌀2.500

⌀1

M4x0.7 Tapped Hole

1.270

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	NASA ROBO-OPS			DB08E@MY.FSU.EDU 941-780-3956		

	NAME	SIGNATURE	DATE			DANIEL BUCKEN DR CHUY/ DR COLLINS		
DRAWN								
CHK'D								
APPV'D								
MFG								
Q.A				MATERIAL: ALU 6061		DWG NO. ROD_BLOCK		A4

SCALE:2:1   SHEET 1 OF 1

4 REQUIRED

4

6.190

4.960

1.230

2

4

0.318

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ABS PLASTIC

DWG NO.

side_cover

A4

SCALE:1:1

SHEET 1 OF 1

2 REQUIRED

⌀ 0.450

6.190

4.960

1.230

5.490

14.690

0.318

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DR COLLINS

MATERIAL:
ABS PLASTIC

DWG NO.
side_cover_2

A4

SCALE:1:2

SHEET 1 OF 1

2 REQUIRED

⌀0.450

6.190

4.960

1.230

6.810

14.500

20

0.318

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ABS PLASTIC

DWG NO.

side_cover_3

A4

SCALE:1:2

SHEET 1 OF 1

A | 1 | 2 | 3 | 4 | 5 | 6
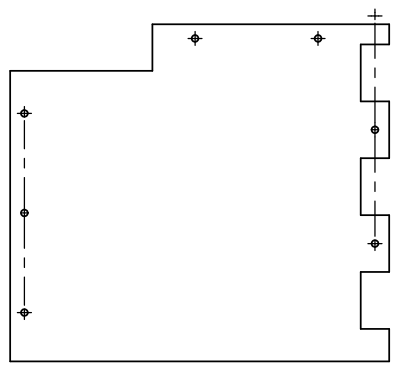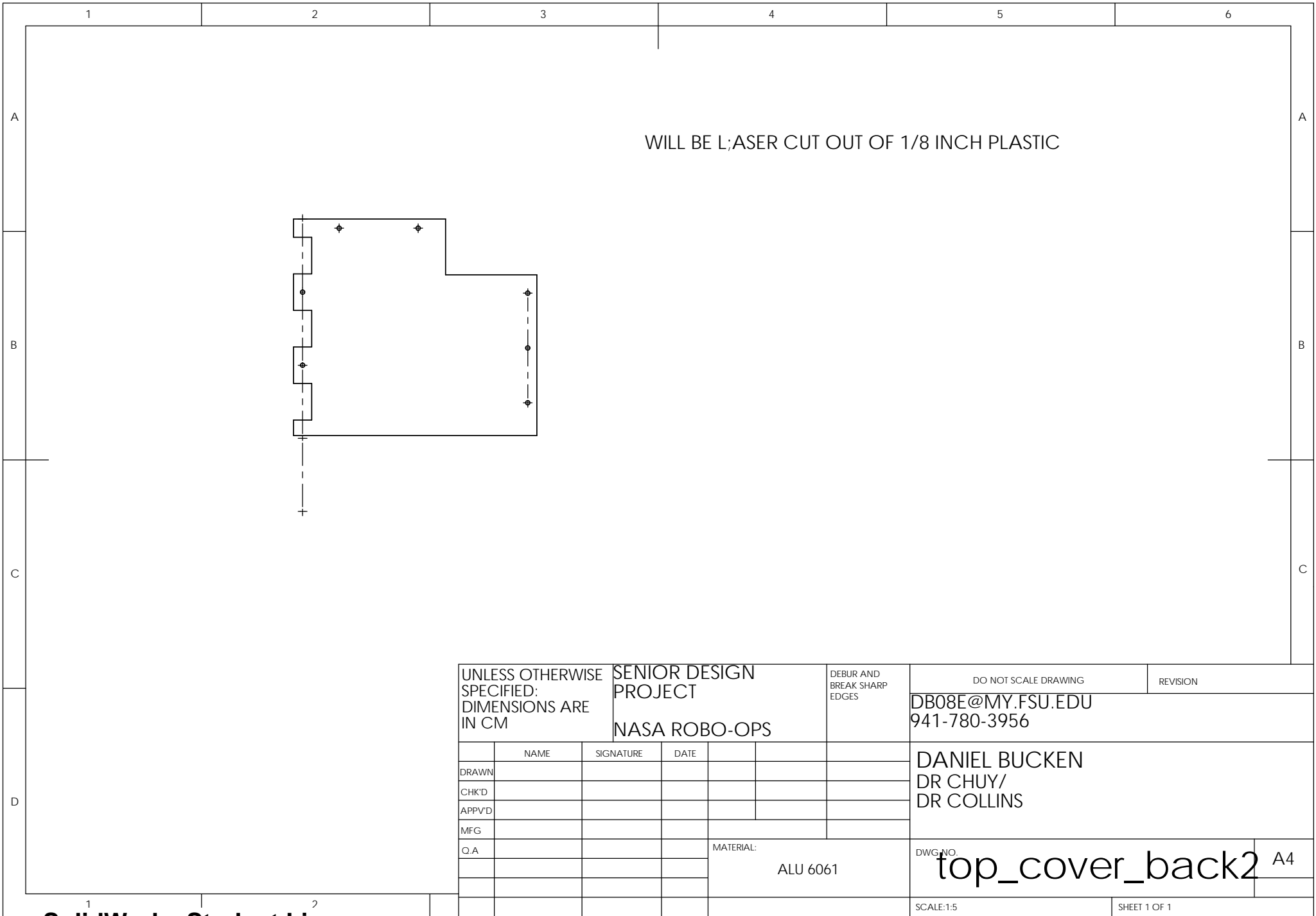
WILL BE LASER CUT OUT OF 1/8 INCH PLASTIC

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN CM	SENIOR DESIGN PROJECT		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NASA ROBO-OPS			DB08E@MY.FSU.EDU 941-780-3956	

	NAME	SIGNATURE	DATE			DANIEL BUCKEN DR CHUY/ DR COLLINS	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: ALU 6061		DWG NO. top_cover_back	A4

SCALE:1:5 | SHEET 1 OF 1

WILL BE L;ASER CUT OUT OF 1/8 INCH PLASTIC

	1	2	3	4	5	6

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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
top_cover_back2   A4

SCALE:1:5   SHEET 1 OF 1

2

3.400

4

2

1.390

2

9

16

20.140

22.140

0.318

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

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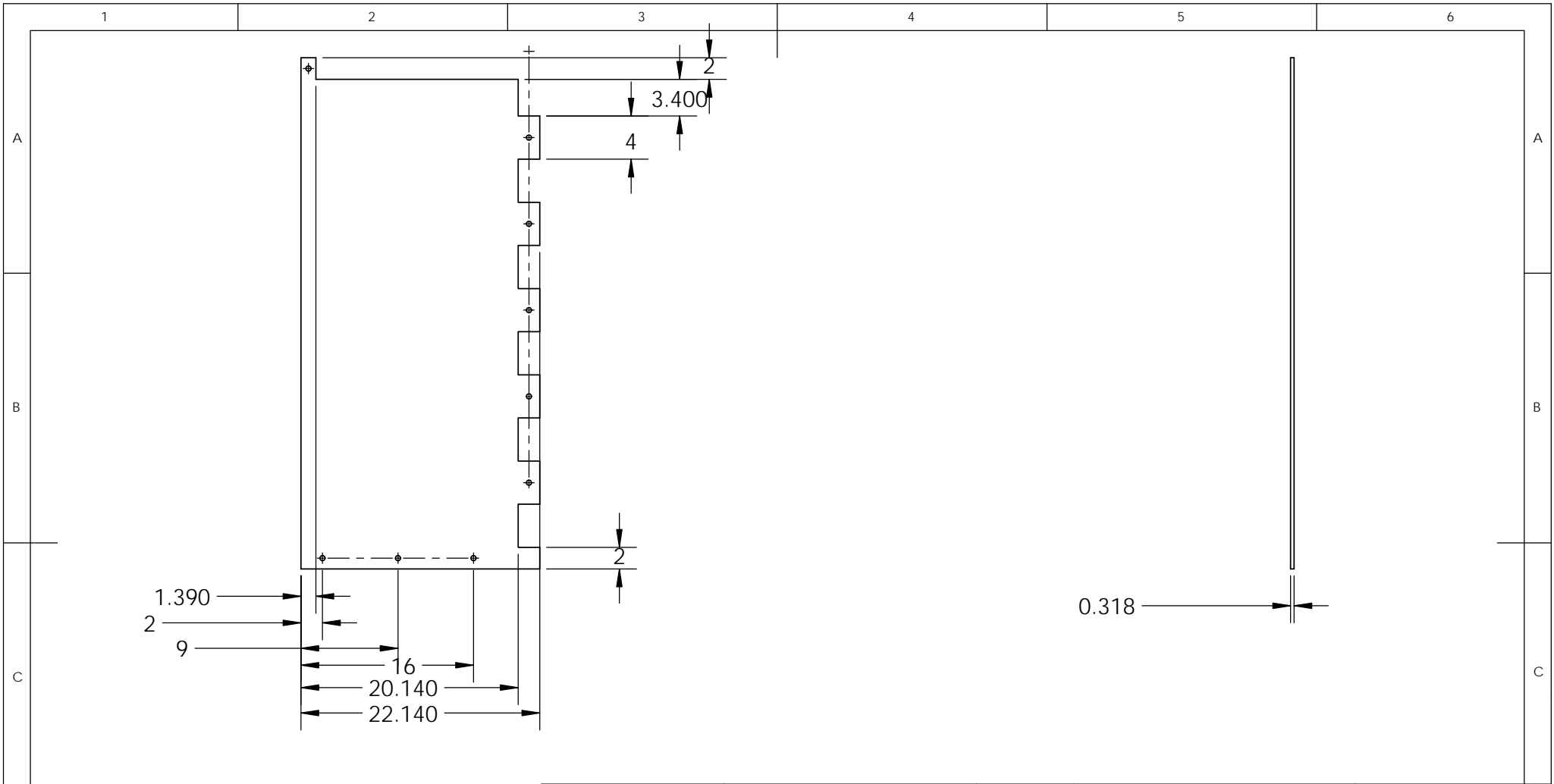
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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ABS PLASTIC

DWG NO.
top_cover_front

A4

SCALE:1:5

SHEET 1 OF 1

A   B   C   D

1   2   3   4   5   6

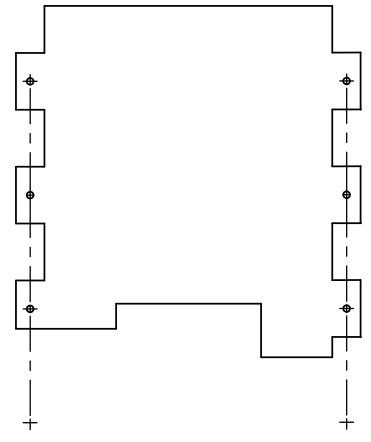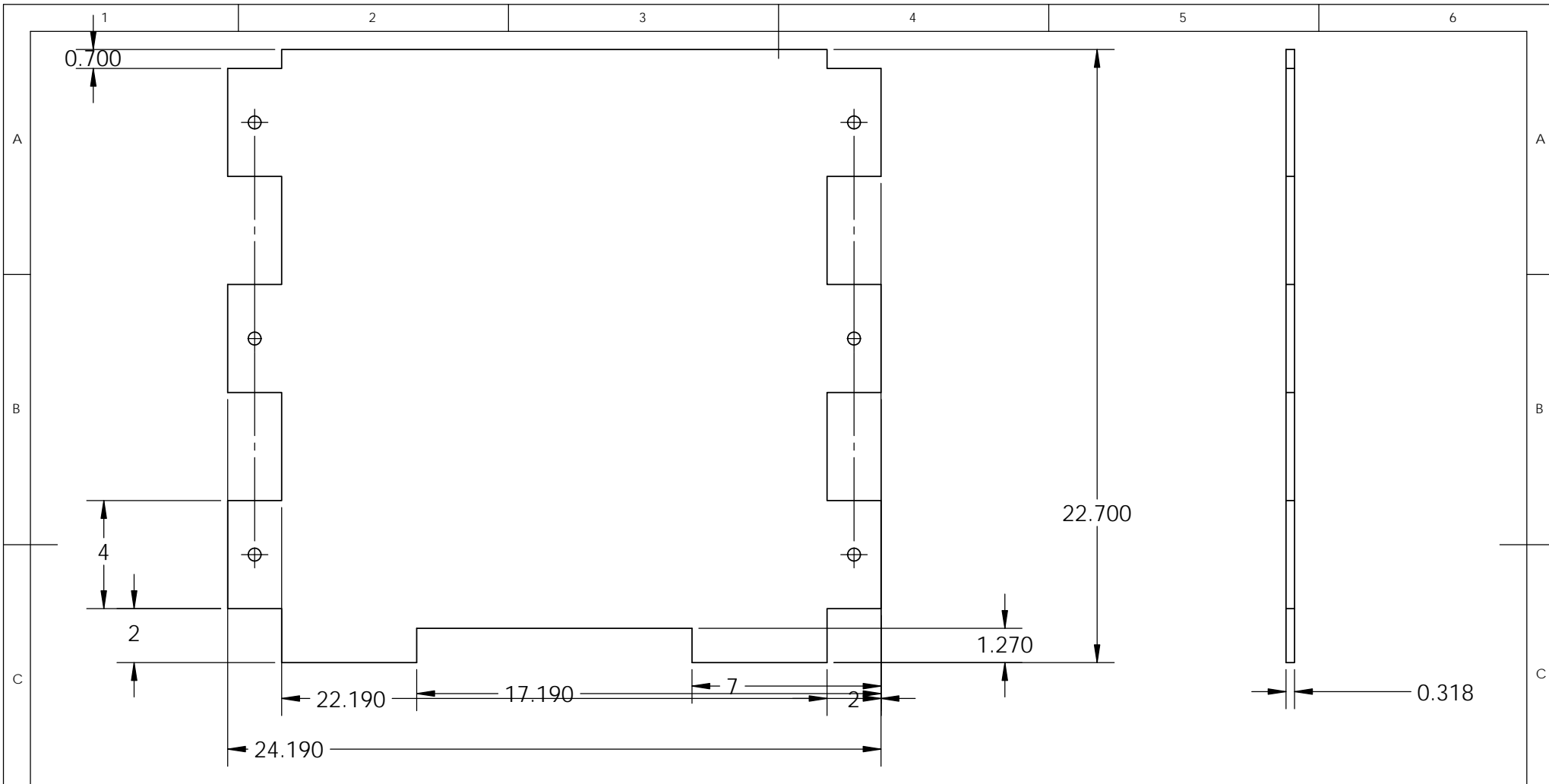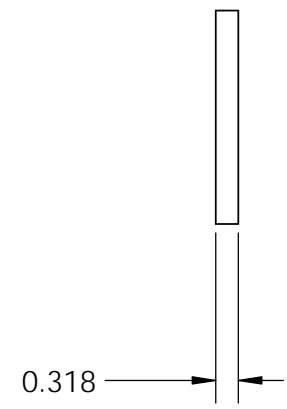| | 1 | 2 | 3 | 4 | 5 | 6 |

WILL BE LASER CUT OUT OF 1/8 INCH PLASTIC

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN CM	SENIOR DESIGN PROJECT		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING		REVISION
	NASA ROBO-OPS			DB08E@MY.FSU.EDU 941-780-3956		

	NAME	SIGNATURE	DATE			DANIEL BUCKEN DR CHUY/ DR COLLINS
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: ALU 6061	DWG NO. top_cover_mid2	A4

SCALE:1:5 | SHEET 1 OF 1

0.700

22.700

1.270

0.318

4

2

22.190

17.190

7

2

24.190

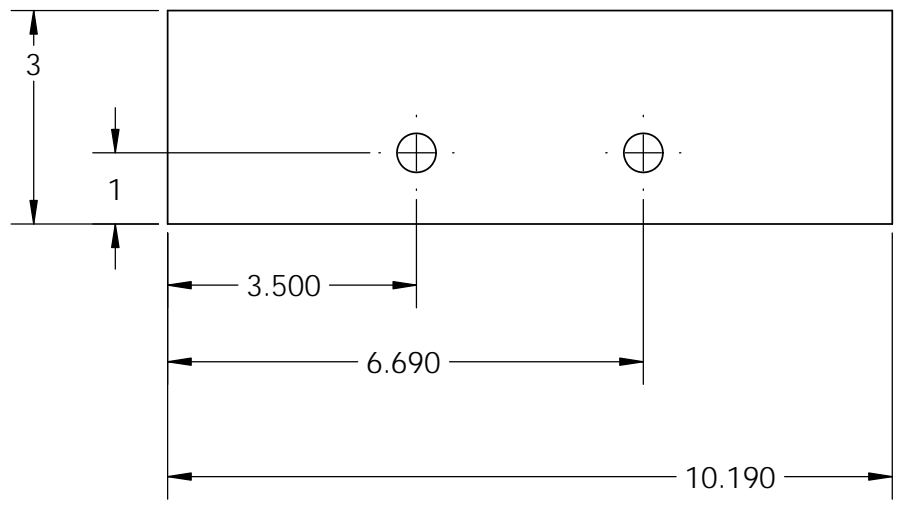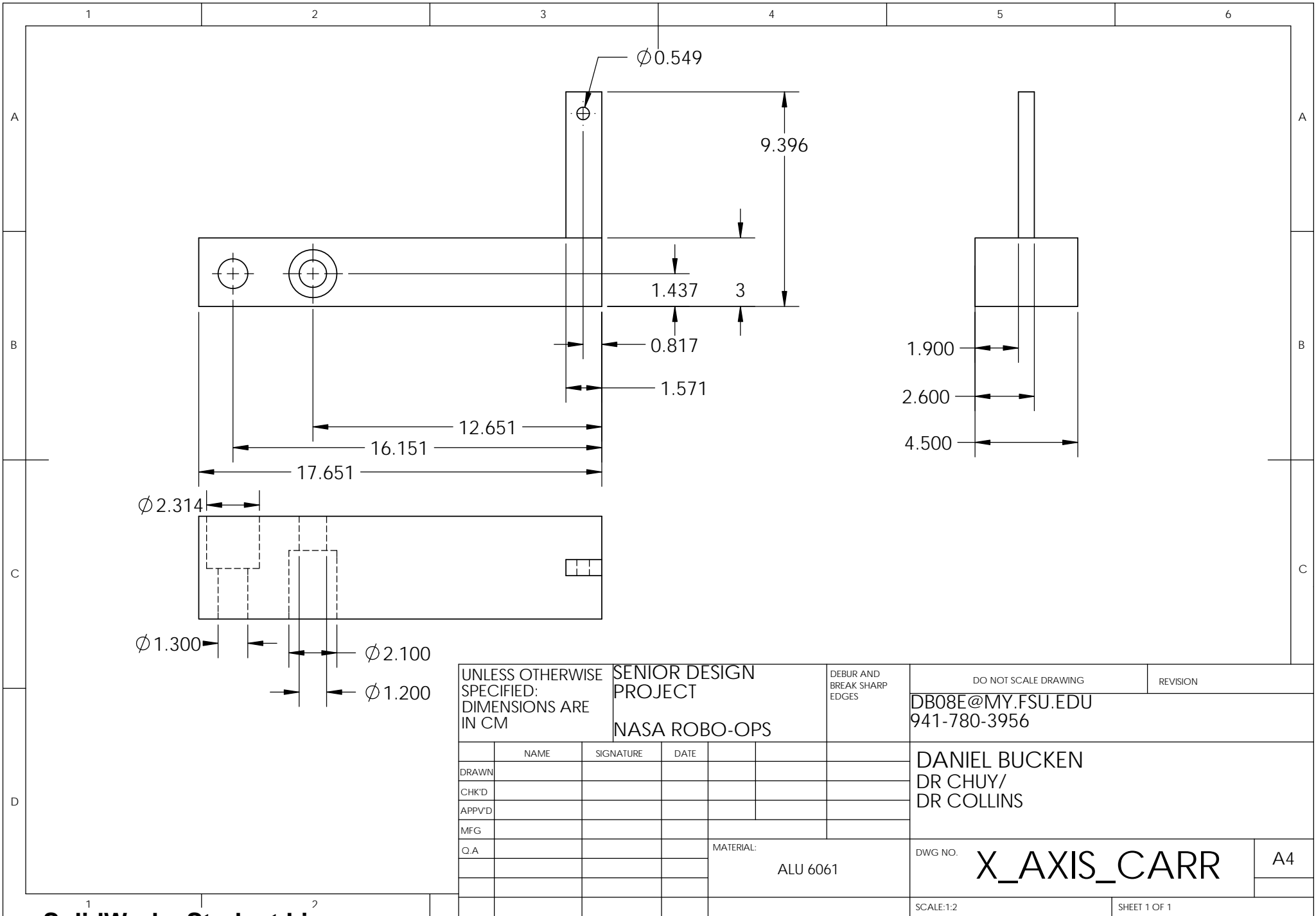|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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DR COLLINS

MATERIAL:

ABS PLASTIC

DWG NO.

top_cover_mid

A4

SCALE:1:2

SHEET 1 OF 1

2 REQUIRED

3

1

3.500

6.690

10.190

0.318

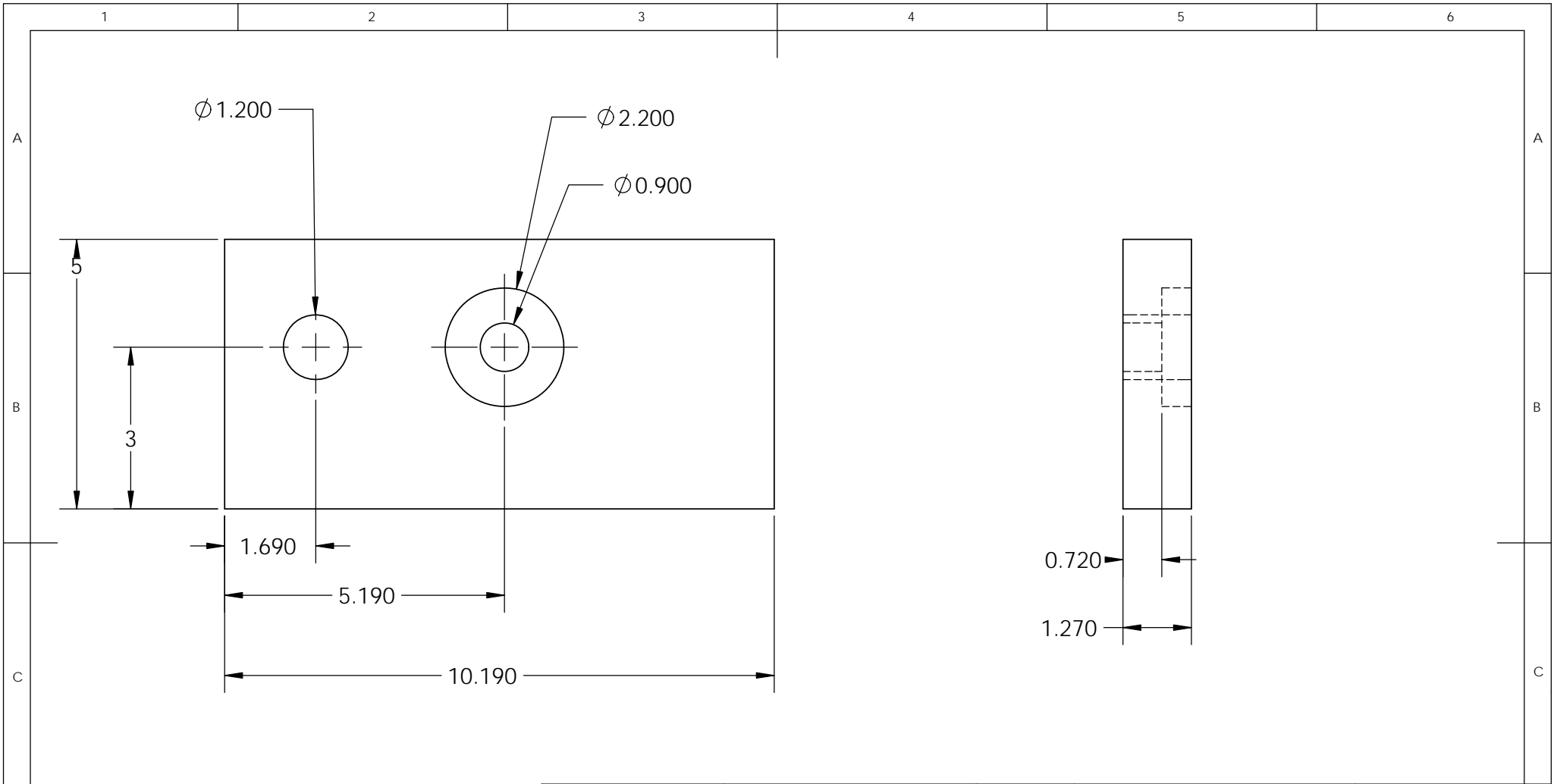|	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

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DIMENSIONS ARE IN CM

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DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ABS PLASTIC

DWG NO.

Top_cover_side1

A4

SCALE:1:1

SHEET 1 OF 1

⌀0.549

9.396

1.437   3

0.817

1.571

1.900

2.600

4.500

12.651

16.151

17.651

⌀2.314

⌀1.300

⌀2.100

⌀1.200

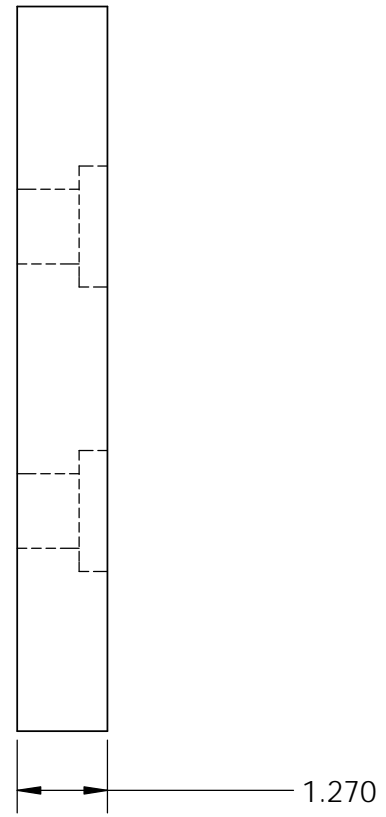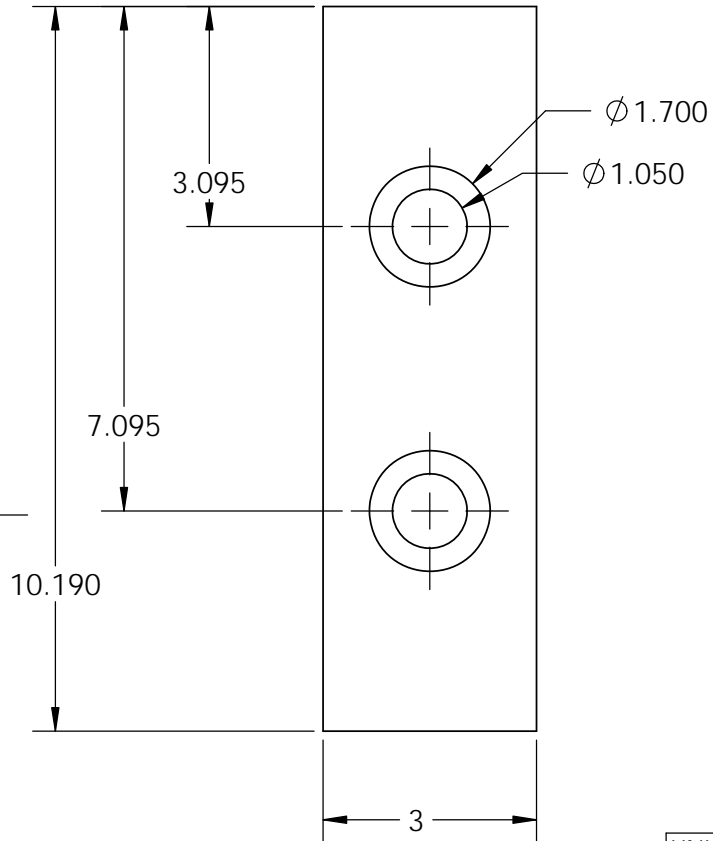|	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

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SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

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941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
X_AXIS_CARR

A4

SCALE:1:2   SHEET 1 OF 1

Ø1.200

Ø2.200

Ø0.900

5

3

1.690

5.190

10.190

0.720

1.270

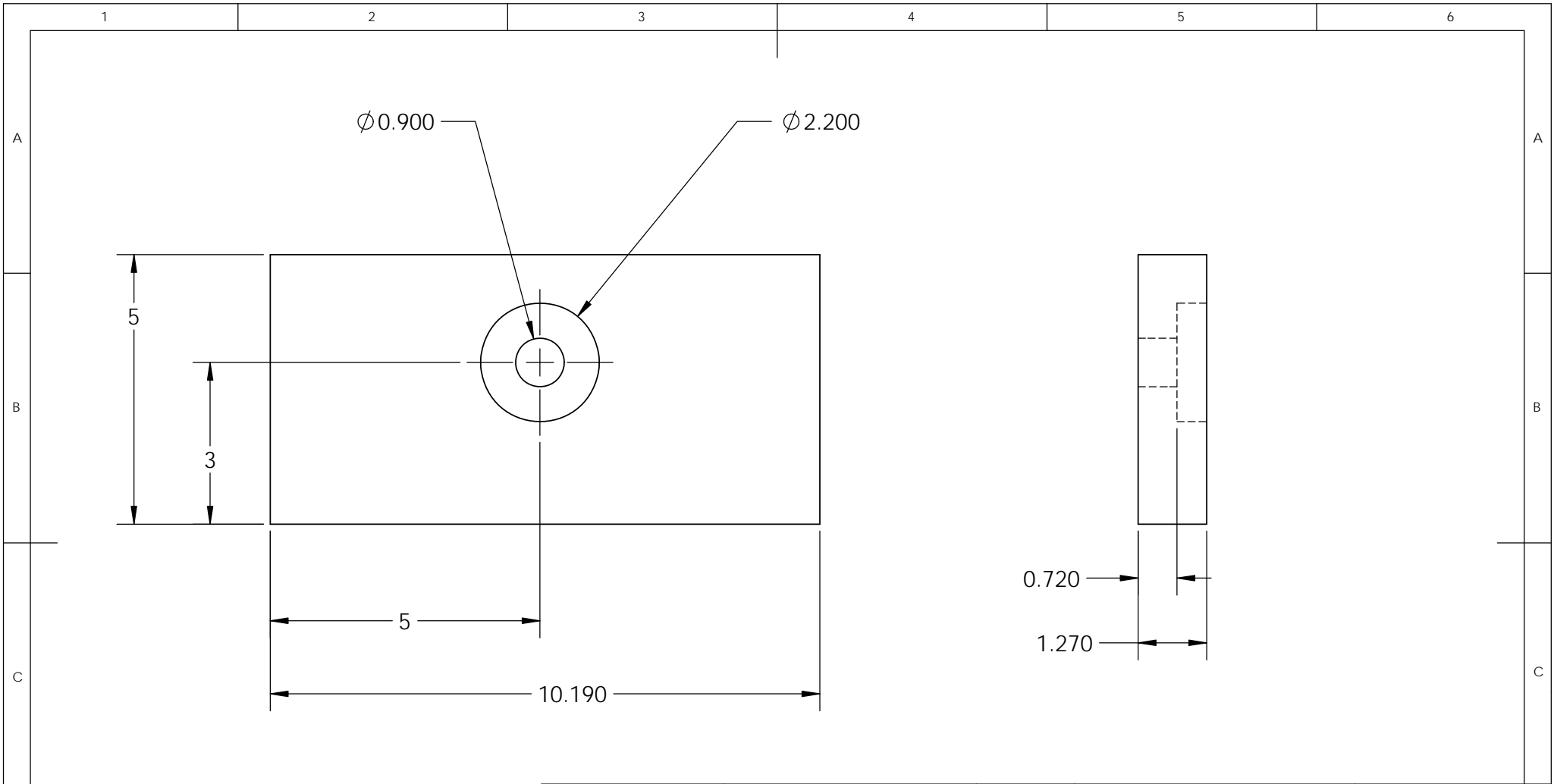|	NAME	SIGNATURE	DATE				
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A							

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CM

SENIOR DESIGN PROJECT

NASA ROBO-OPS

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

DB08E@MY.FSU.EDU
941-780-3956

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:

ALU 6061

DWG NO.

x_axis_mount1

A4

SCALE:1:1

SHEET 1 OF 1

2 REQUIRED

Ø 1.700
Ø 1.050

3.095

7.095

10.190

3

1.270

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

DANIEL BUCKEN
DR CHUY/
DR COLLINS

MATERIAL:
ALU 6061

DWG NO.
x_axis_mount2

A4

SCALE:1:1

SHEET 1 OF 1

Ø 0.900

Ø 2.200

5

3

5

10.190

0.720

1.270

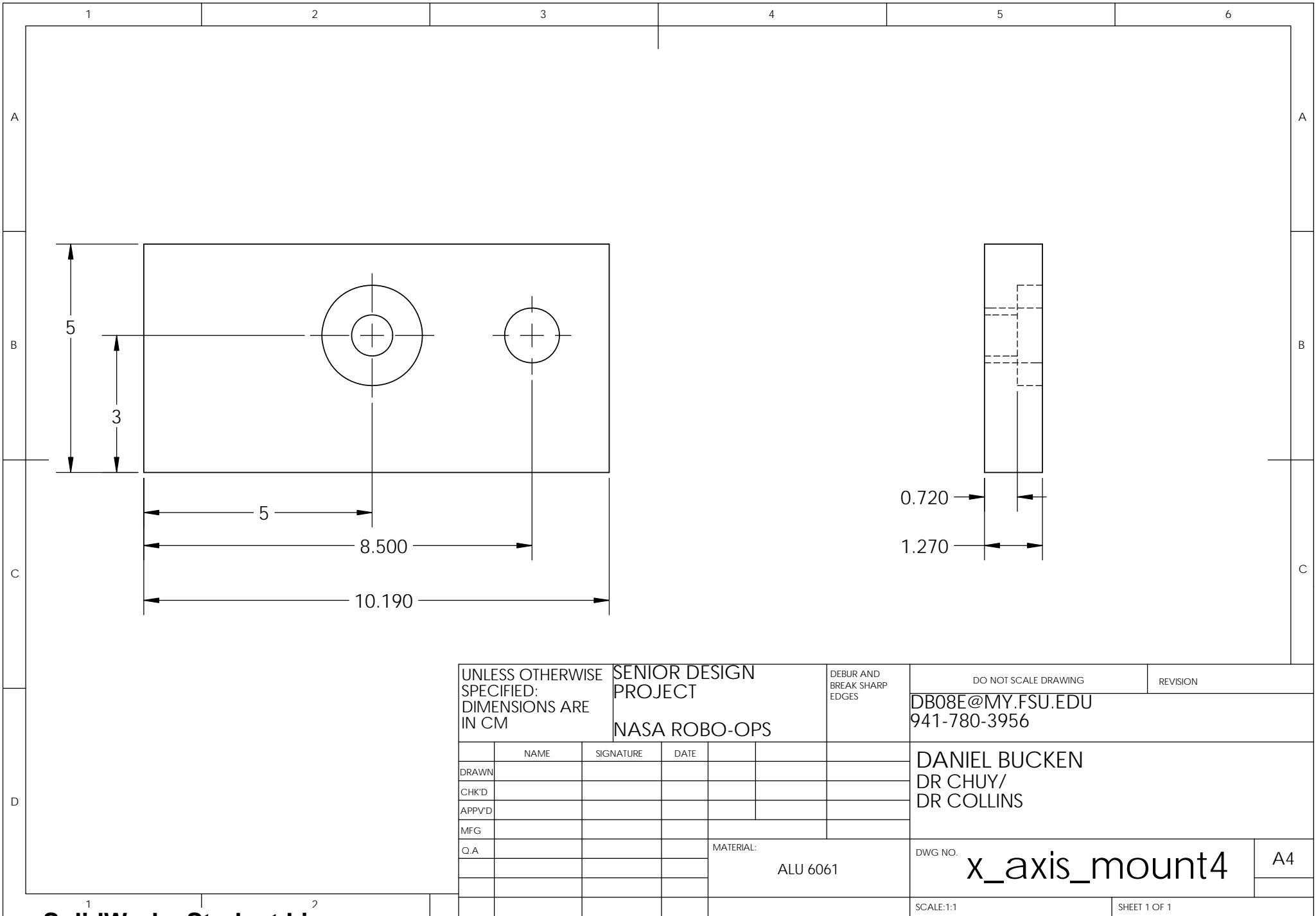|	NAME	SIGNATURE	DATE			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN CM	SENIOR DESIGN PROJECT			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NASA ROBO-OPS				DB08E@MY.FSU.EDU 941-780-3956	
DRAWN					DANIEL BUCKEN DR CHUY/ DR COLLINS	
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL:		DWG NO.	
			ALU 6061		x_axis_mount3	A4
					SCALE:1:1 SHEET 1 OF 1	

1	2	3	4	5	6	

5

3

5

8.500

10.190

0.720

1.270

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN CM	SENIOR DESIGN PROJECT		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NASA ROBO-OPS			DB08E@MY.FSU.EDU 941-780-3956	

	NAME	SIGNATURE	DATE			DANIEL BUCKEN DR CHUY/ DR COLLINS
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: ALU 6061		DWG NO. x_axis_mount4	A4

SCALE:1:1   SHEET 1 OF 1