AUBURN

UNIVERSITY

SAMUEL GINN

COLLEGE OF ENGINEERING

MECH 4240: Senior Design 1
ELEC 4980: Special Projects in Engineering

CORP_2 Teleoperated Lunar Regolith Excavator

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Operational Readiness Report

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ABSTRACT

A fast growing approach in determining the best design concept for a problem is to hold a competition in which the rules are based on requirements similar to the actual problem. By going public with such competitions, sponsoring entities receive some of the most innovative engineering solutions in a fraction of the time and cost it would have taken to develop such concepts internally. Space exploration is a large benefactor of such design competitions as seen by the results of X-Prize Foundation and NASA lunar excavation competitions [1].

The results of NASA's past lunar excavator challenges has led to the need for an effective means of collecting lunar regolith in the absence of human beings. The 2010 Exploration Systems Mission Directorate (ESMD) Lunar Excavation Challenge was created "to engage and retain students in science, technology, engineering, and mathematics, or STEM, in a competitive environment that may result in innovative ideas and solutions, which could be applied to actual lunar excavation for NASA." [2]. The ESMD Challenge calls for "teams to use telerobotics or autonomous operations to excavate at least 10kg of lunar regolith simulant in a 15 minute time limit" [2].

The Systems Engineering approach was used in accordance with Auburn University's mechanical engineering senior design course (MECH 4240) to develop a telerobotic lunar excavator, seen in Fig. 1, that fulfilled requirements imposed by the NASA ESMD Competition Rules. The goal of the senior design project was to have a validated lunar excavator that would be used in the NASA ESMD lunar excavation challenge.

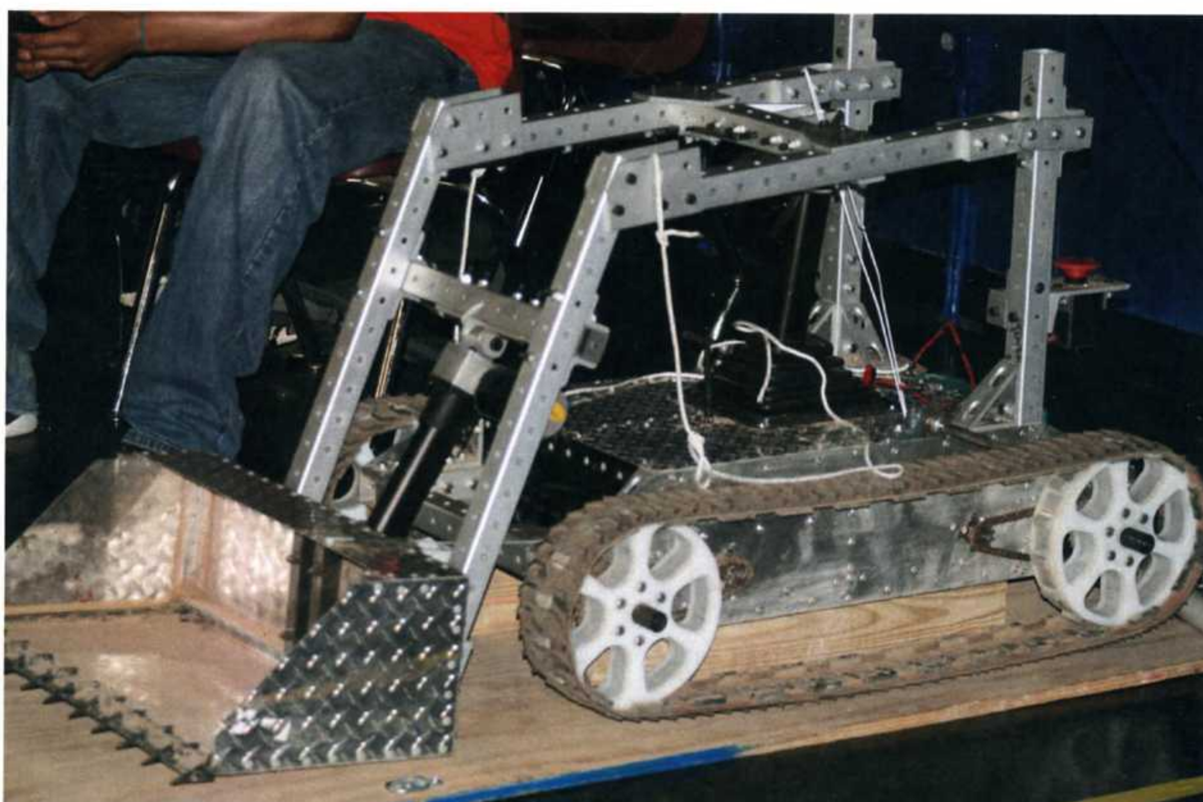

Figure 1: Excavator at NASA competition

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INTRODUCTION

The systems engineering design process involves following the Vee Chart, seen in Fig. 2, and applying the 11 system engineering steps, seen in Fig. 3, throughout the Engineering Design Process.

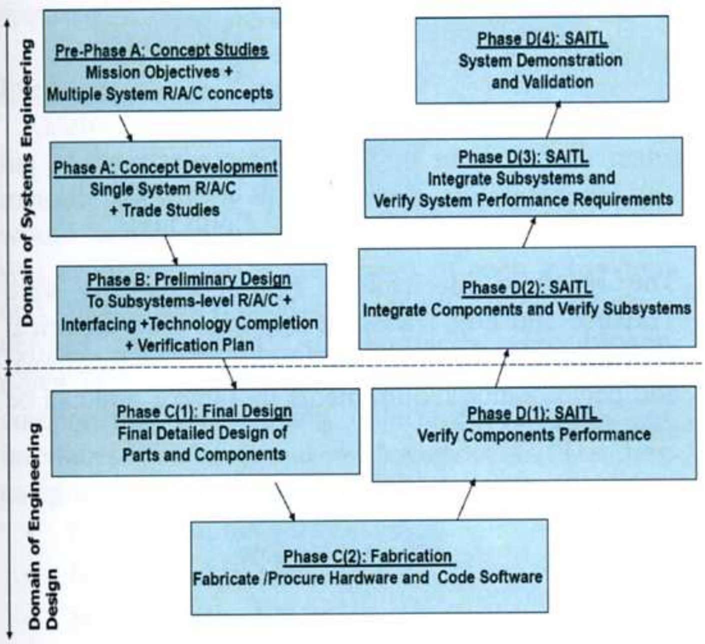

Figure 2: Systems Engineering Vee Chart [3]

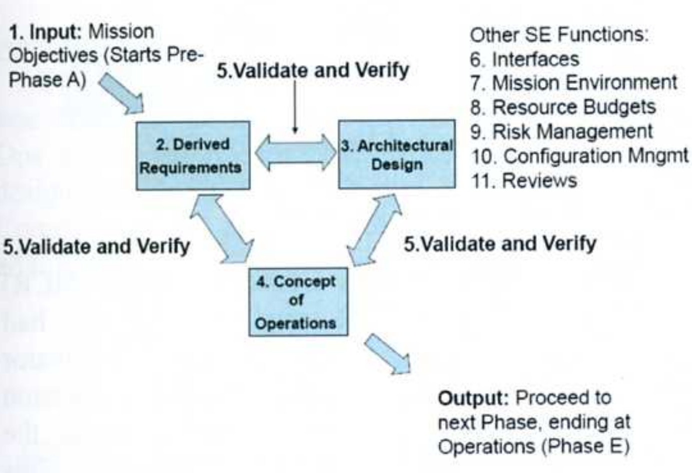

Figure 3: 11 Systems Engineering Functions [3]

The senior design course at Auburn University consists of splitting the systems engineering process into two consecutive semesters [4]. Pre-Phase A through Phase B of the Vee Chart typically occur in the first semester of senior design, and Phases C through D of the Vee Chart occur during the second semester of senior design [4].

The ESMD Challenge has been an ongoing project at Auburn University. Team Pumpernickel came onboard the ESMD Challenge project after Pre-Phase A through B had been completed. The previous group had designed and fabricated a prototype excavator for investigation of technology issues.

The prototype excavator underwent testing on "E-Day" at Auburn University, but it was decided that the prototype could not meet competition requirements by 24 May 2010. Team Pumpernickel decided the system requirements would best be met after redesign of the critical excavator subsystems. The overall Architectural Design and Concept of Operations remained the same in an effort to save time.

It is the goal of this paper to show the usage of systems engineering throughout the design and fabrication process of Team Pumpernickel's lunar excavator for the 2010 ESMD Lunabotics Mining Competition.

SYSTEMS ENGINEERING

Mission Objective:

The mission of this group is to enhance the prototype Lunar Excavator built by the previous design group. The excavator is designed to compete in the NASA ESMD Lunar Regolith Excavator Competition. The competition calls for a telerobotic lunar regolith excavator to compete for fifteen minutes.

Mission Environment

The environment for the excavator is theoretically the surface of the moon, however for competition purposes the environment will be a simulated lunar surface in a controlled climate on site at the Kennedy Space Station in Orlando, FL.

System Requirements

The fundamental system requirements were provided by NASA in the form of official field, game play, and technical rules for the ESMD mining competition, seen in Appendix A. Other system requirements were derived in addition to the ones provided by NASA based on **F**unctional, **P**erformance, **I**nterface, **V**erification, and **S**upplementary requirements of the system. A list of the most important derived system requirements can be seen in Table 1.

Table 1: System Requirements

F	The excavator shall collect, transport, lift, and deposit the lunar simulant
F	The excavator shall be operated via telecommunications
P	The excavator shall collect at least 10kg of simulant in 15 minutes
P	The excavator shall lift the simulant at least one meter above the surface of the playing field
I	The communication system shall interface with NASA's wireless network
V	The prototype excavator shall be tested according to the functional requirements on or before 26 February 2010
V	The final design of the system shall be verified according to the Competition Rule Book requirements on or before 03 May 2010
S	The excavation hardware must be equipped with an emergency stop
S	The excavation hardware must be able to operate under semi-lunar like conditions as described by Rule 25 of the Competition Rule Book [2]
S	The excavation system shall be designed, fabricated, and verified using less than $5000.00

The requirements for each subsystem and subsequent component were derived from the system requirements and will be discussed in further detail in each subsystem's appropriate section.

Concepts of Operations

The system was initially divided into two fields: Mechanical and Electrical, and the system Con-Ops were developed based on the system requirements. The mechanical Con-Ops were derived based primarily on the functional requirements in Table 1 and can be seen in Fig. 4.

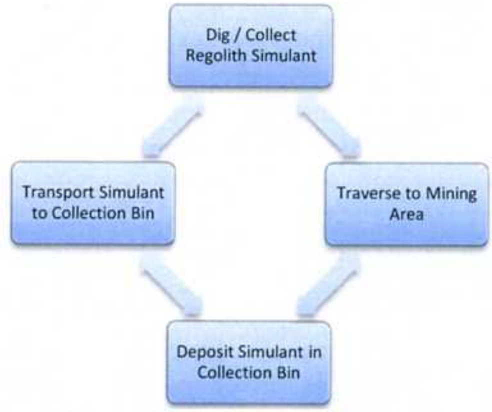

Figure 4: Mechanical Con-Ops

The resulting mechanical system Con-Ops were Traverse and Dig/Transport/Deposit. The Electrical Con-Ops were derived based primarily on functional and performance requirements in Table 1 and can be seen in Fig. 5.

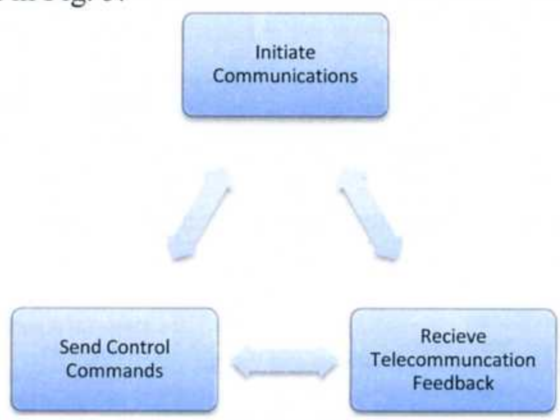

Figure 5: Electrical Con-Ops

Major Reviews:

Team Pumpernickel came onboard the ESMD project after the Mission Concept Review (MCR) and the Mission Design Review (MDR) as they had already taken place on the prototype excavator system. Team Pumpernickel made a key decision point after prototype testing which involved the redesign of the critical excavator subsystems. This was decided after cost/benefit analysis was performed on the proposed prototype modifications. Team Pumpernickel began construction of a new excavator immediately after prototype testing. Team Pumpernickel conducted a Preliminary Design Review (PDR) for the new excavator on 26 March 2010, which can be seen in Appendix B. The PDR addressed problems pertaining to the excavator and how system requirements would be met. The Critical Design Review is scheduled to take place on 3 May 2010 and the Readiness Review is scheduled to take place on 15 May 2010. The Critical Design Review will address remaining design proposals, and the Readiness Review will address remaining actions required for preparation of the ESMD competition

Interfaces

Before each subsystem was designed in detail, a list of interfaces was drawn up so that each team member knew how his subsystem and component(s) would have to interact with others. This interaction was accounted for in the design of each subsystem and consequently each component by becoming a derived requirement. All interfaces were broken down into five categories dependent on what two components were being interfaced, a table of interfaces can be found in Appendix C. The five categories where:

- Mechanical to Mechanical
- Mechanical to Mechatronic
- Mechanical to Electrical
- Electrical to Mechatronic
- Electrical to Electrical

Architectural Design and Development:

The overall architectural design of the excavator was developed using functional analysis of the Con-Ops of the excavator. The resulting architectural design included a Drive, Digger Arm, Frame, and Communication and Control subsystems. The architectural design layout can be seen in Fig. 6.

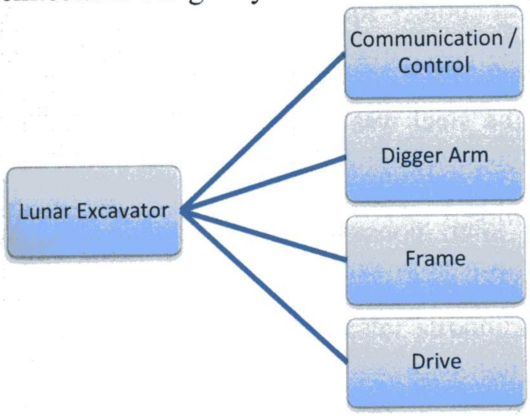

Figure 6: System Architectural Design

Frame Subsystem:

It was decided to use a frame system to which each subsystem could be attached and interfaced. The final frame proposal resulted in a body-on-frame design composed of 8020 Inc. aluminum components and aluminum exterior body panels.

The main focus for the new design of the frame subsystem was driven by increasing rigidity of the frame subsystem. This requirement was derived after the testing of the prototype excavator and the interfacing of the other subsystems. The prototype excavator's frame was composed of thin wall carbon fiber tubes joined by G-10 Garolite. The weak nature of hollow tubes caused deformations, as seen in Fig. 7, and the prototype frame subsystem did not meet rigidity requirements even after steps were taken to remedy such issues.

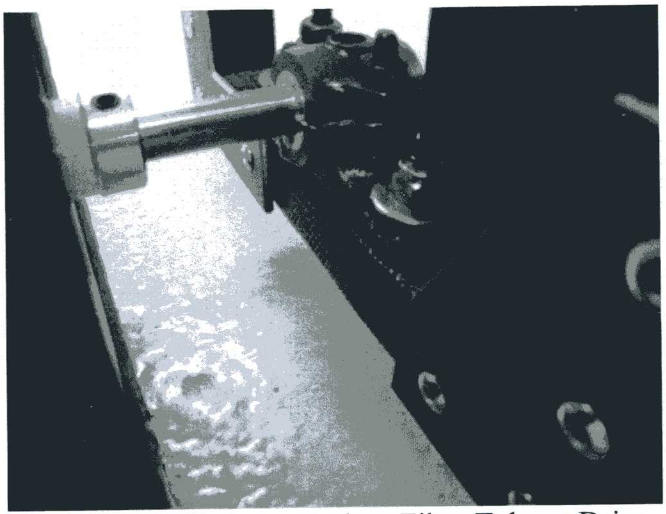

Figure 7: Bulging Carbon Fiber Tube at Drive Interface of Bearing Mount

The main focus for the new design was driven by increasing rigidity of the frame subsystem. Other driving derived requirements for the frame subsystem were:

The frame shall not weigh more than 30kg

- Derived from the overall weight requirement of the excavator system as per NASA Competition Rules [2]

- The frame shall not exceed 19.5"

  - Derived from the overall width requirement of the excavator system as per NASA Competition Rules [2]
- The frame subsystem shall be fabricated on or before 17 March 2010

The product hierarchy, seen in Fig. 8, was developed after analyzing the requirements imposed on the frame subsystem.

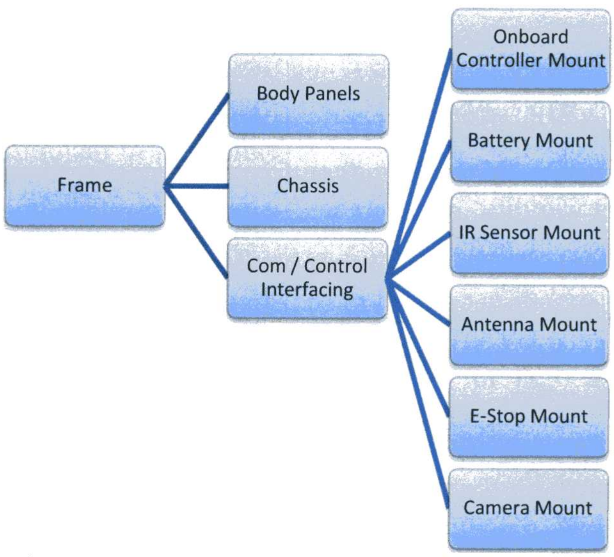

Figure 8: Frame Subsystem Product Hierarchy

Trade studies were conducted after the basic architectural design for the frame subsystem had been laid out. The most important trade study involved an investigation of Super Droid Robots, Inc. HD2 Treaded Tank Robot seen in Fig. 9 [5].

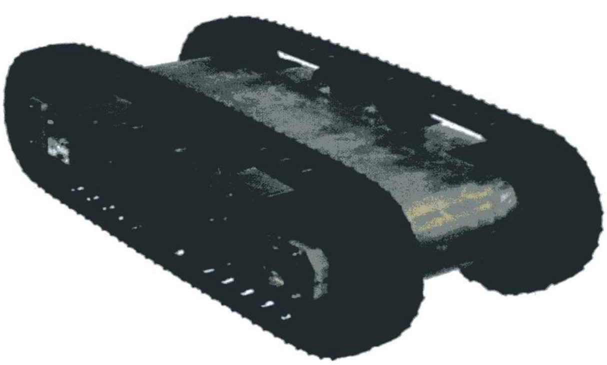

Figure 9: Super Droid Robots, Inc. HD2 Treaded Tank Robot [5]

The HD2 Robot consists of a welded aluminum frame to which the HD2 drive and control subsystems are interfaced [5]. One possibility for the design of not only the Frame but also the Drive and Com/Control subsystems of the new excavator involved purchasing the prefabricated HD2 Tank Robot. This option was deemed not feasible due to the price of the HD2 Tank. The HD2 Frame, Drive, and Com/Control subsystems would cost over $6000.00 in order to meet system requirements. This cost would not include the addition of the Digger Arm subsystem. Super Droid Robots, Inc. offers other smaller and less expensive prefabricated treaded tank robots, but these were deemed not feasible due to the inability to meet the performance requirements of the excavator system.

It was determined to design and fabricate a new frame after the trade studies were complete and after verification of the prototype excavator. The basic architectural layout was determined to mirror the prototype excavator's layout in order to reduce the design time. The driving requirement for the new frame design involved increasing frame rigidity. The design of the frame subsystem was based on

- Developing a decision matrix for determining the material to be used
- Conducting fabrication feasibility tests for frame joining options
- Researching the underlying design motives of the selected material for interfacing of other subsystems.

The material choices for the new frame consisted of either reusing old 8020 Inc. aluminum (www.8020.net) or using new steel. The size and profile of the steel was chosen such that weight of the steel components equaled the weight of the 8020 components. It was decided to use 8020 Inc. aluminum after constructing a decision matrix, which can be seen in Table 2.

Table 2: Frame Decision Matrix

	8020	Steel	Importance
Material Feature			
Rigidity / Strength	4.5	5	5
Ease of Interface	5	4	4
Cost	5	4	4
Use of Fasteners	1	4	3
Ease of Fabrication	5	3	4
Use of salvaged parts	5	1	5
Total	110.5	86	

Importance: 1 = Negligible, 5 = Significant
Material Capability: 1 = Poor, 5 = Excellent

The method for best joining the 8020 frame components was analyzed based on fabrication feasibility tests and the original intent of design for 8020. 8020 was originally designed to be bolted together, eliminating the need for welding [6]. Welding components, however, is lighter than using fasteners as with traditional 8020. The option of welding 8020 was eliminated after welding tests revealed extreme difficulty in welding.

The inherent design of 8020 was not only to eliminate welding and provide an easily fabricated base frame, but also to provide ease of attaching other components or subsystems to the base frame [6]. This was an influencing factor in choosing 8020 because it lent the easiest interfacing between the frame and the other subsystems. The Drive and Digger Arm subsystems need only take into account the available connecting options as quasi requirements.

The design of the body was based primarily on past prototype verification. The prototype verification revealed a lack of structural integrity between the interface of the Prototype Drive and the Prototype Frame subsystems. The resulting design of the body panels consisted of using aluminum sheet panels riveted to the base frame. The rivets were staggered providing greater structural strength to flat plate bending. Additional design decisions were made in an attempt to improve the Prototype Drive and Prototype Frame interface which will be further discussed in the Drive Subsystem section.

The aluminum sheet metal was determined satisfactory for serving as a base mount for the Com/Control subsystem. Proper steps need only be taken to ensure insulation for the Com/Control subsystem and to ensure wireless antenna reception. Battery mounts would be similar to the HD2 Tank, since the excavator batteries are identical to the HD2 Tank batteries. The controller and other PC boards would be mounted in the middle of the cavity in a similar fashion to the HD2 Tank, and the required kill switch would be added at a later time.

The resulting frame design consisted of a body-on-frame design fabricated out of salvaged 8020 Inc. aluminum HT slot frame parts joined using traditional fastening options (nuts and bolts) and a new aluminum sheet metal body. The resulting complete chassis can be seen in Fig. 10 and the body panels can be seen in Fig. 11.

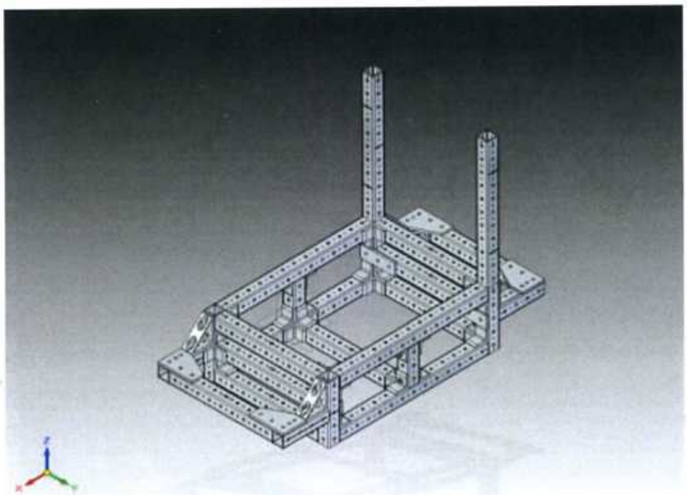

Figure 10: Body-on-Frame design for the Excavator

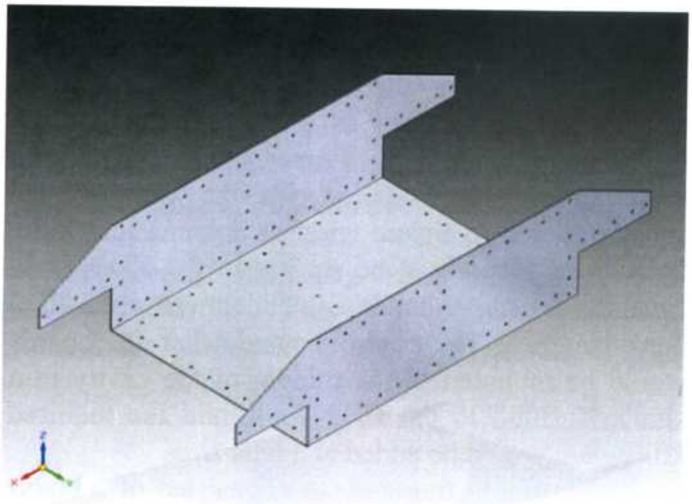

Figure 11: Body Panels for Frame Subsystem

The frame components and subsystems were verified before manufacturing based on component mating, overall dimensions, structural integrity, and approximate weight using Solid Edge. The components were then manufactured and installed piecewise. The resulting frame subsystem can be seen in Fig. 12.

Figure 12: Assembled Frame Subsystem

The interfaces of the Frame subsystem with the Drive and Com/Control subsystems were verified, and will be discussed in the "Subsystem – Subsystem Verification" section. A bill of materials for the frame subsystem can be found in Table D.1 of Appendix D.

Drive System:

In order for the excavator to complete its tasks it must be able to move. Additionally with the excavator weighing as much as it does or can the drive system must also be robust. The outcome of the design process led us to settle on a simple track drive system. The system consists of one tread for each side, along with one motor per wheel; giving us a total of four motors. The power transmission is achieved by employing a chain and sprocket gear system. The main advantages to this system are zero degree turning radius, ability to traverse multiple terrains, and simplicity of design.

The main focus for the drive subsystem was driven by increasing the turning torque provided by the motors during zero degree turns. Other driving derived requirements for the drive subsystem were:

- The drive wheels shall not be mounted directly on the motors
- The treads shall be properly tensioned and aligned
- The wheel shafts shall be supported such that they experience minimum deflections

The product hierarchy, seen in Fig. 13, was developed after analyzing the requirements imposed on the drive subsystem.

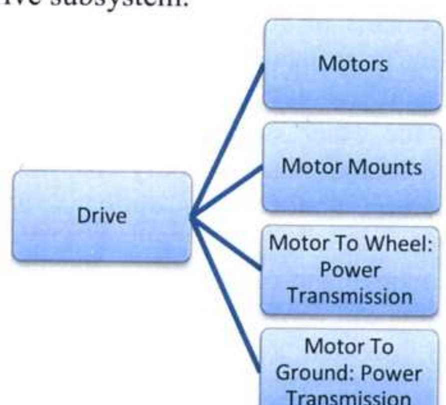

Figure 13: Drive Subsystem Product Hierarchy

Once the product hierarchy and interfaces were derived the design of the drive system was undertaken. The first thing that needed to be done was to assess the performance of the drive system that the prototype excavator used. The prototype had two motors that were directly attached to two drive wheels that drove the treads. The vehicle turned by simply having one side go forward while the other side goes in reverse, this type of steering is called skid steer. Additionally the prototype had both motors mounted directly to the side panels with no internal support. Once the system was finally installed in accordance with the previous design it was obvious that the design would not work, there was too much deflection in the system which made it impossible for the treads to remain on the wheels for any substantial amount of time. An example of such deflection is shown in Fig. 14

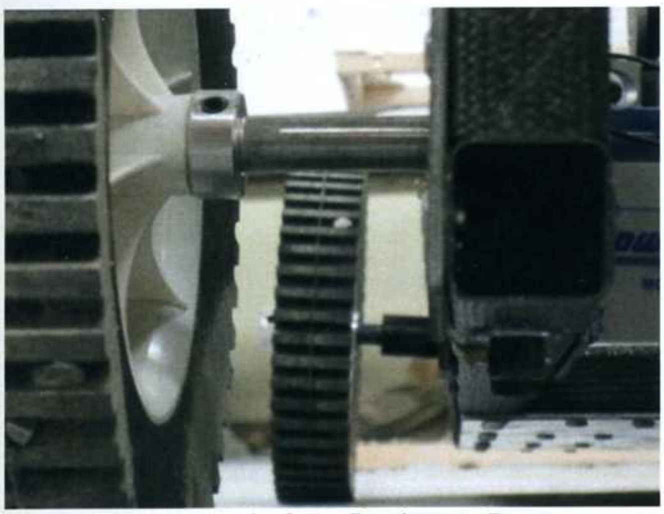

Figure 14: Shaft Deflection on Prototype

The main issues arose in the mounting of the motors, power transmission, and the mounting of the drive shafts. Solutions to all of these problems were discovered and will be discussed shortly. "E-Day" was used for verification purposes; the performance of the excavator was sub-par to say the least. Now that a base had been established for the drive system and it was noted that a new design was required. The next task was brainstorming and coming up with several options; then narrowing those down to a group that are both feasible and efficient in providing the motion for the excavator. Once brainstorming was complete and the list narrowed only three options remained.

- Improving upon the treaded design that was employed on the prototype
- Changing to a traditional drive system similar to what most cars employ
- Switching to a multi-wheeled system that uses skid steer for turning

As mentioned, one choice was a traditional drive system similar to what most cars use today. What this would entail is a four wheel system with the rear two wheels being driven by independent motors and the front two wheels would be the steering wheels, and would turn just like the front wheels in a traditional automobile. The power transmission from motor to drive wheel would be accomplished by a chain and sprocket system. A major cause for concern was the design of the steering linkages, with the timeline being what it is for this project a complete design of a complex steering system would be impractical. Additionally with only four wheels a limited amount of surface area for the excavator to ride on, this could permit the excavator to sink into the regolith and render it motionless. Lastly, and maybe the most important argument against this design is cost, this design does not call for the use of many parts, if any from the prototype. Taking into account these three main concerns it was decided that this design was not a good fit for this application so it was discarded.

The other alternative discussed was a multi wheeled system that uses skid steer. This system is similar to the previous alternative in that it uses four wheels to support the weight of the excavator and two motors to provide the power; however where this system differs is in the steering. This design calls for the use of skid steer, which as discussed earlier is the use of differential velocities to turn a vehicle. The main concerns with this design were the lack of surface area, also there was large concern about turning in regolith with this system. Since it only has two motors when the excavator went to turn it was believed that it would simply dig itself into the dirt since the front wheels would essentially dig into the regolith instead of skidding over the top as desired. This system also required for all of the parts to be purchased and most of the parts from the prototype to be scrapped. Taking into account the budget and the concern over turning it was decided that this system too was unacceptable.

The next step was developing a detailed design of the drive system and components after an architectural design had been decided. Since a tread system was to be employed many of the parts from the prototype were able to be salvaged. Among those parts was a tread set that the previous group had purchased along with the wheels that were machined to match the timing of the treads. Also able to be taken were the two motors that they had purchased to drive the treads. The previous team had purchased a set of treads from Super Droid Robots, Inc as seen in Fig. 15 and instead of purchasing the wheels as well they machined them in our on-campus machine shop.

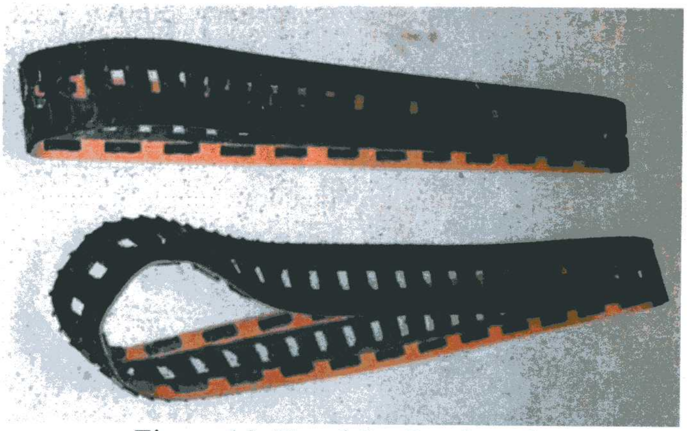

Figure 15: Tread Set Purchased

Now is really where the design of the current system began, as mentioned above there were some major issues with the prototype system that had to be corrected. So the initial task was to solve those issues so that the system could be tested to set a baseline for performance. There are several key solutions that are implemented in the current design to eliminate the issues that were experienced with the prototype. Among those are internal motor mounts to eliminate motor deflections, the side panel which serves as the interface between the drive and frame systems, being made out of aluminum in order to reduce deflections, and also the addition of a chain and sprocket power transmission system. The chain and sprocket is by far the most crucial addition, the old design would not produce enough torque for the excavator to turn on any practical surface. The motors that were installed in the prototype were decided upon by looking at how fast they could propel the excavator strictly forward and reverse so it had great speed but could not turn. So in order to increase the torque a 10 tooth drive gear, 30 tooth sprocket, and 10 feet of #35 ANSI chain were purchased and installed in the system as shown in Fig. 16 and Fig.17.

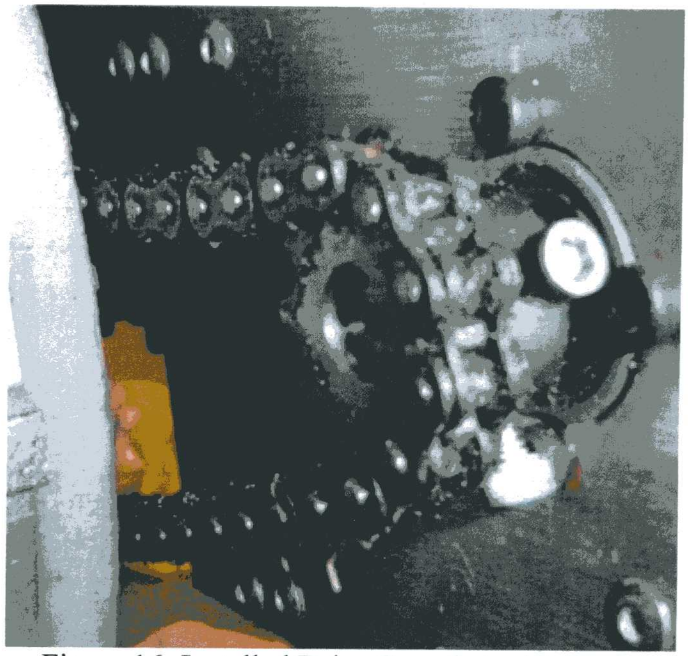

Figure 16: Installed Drive Sprocket with Chain

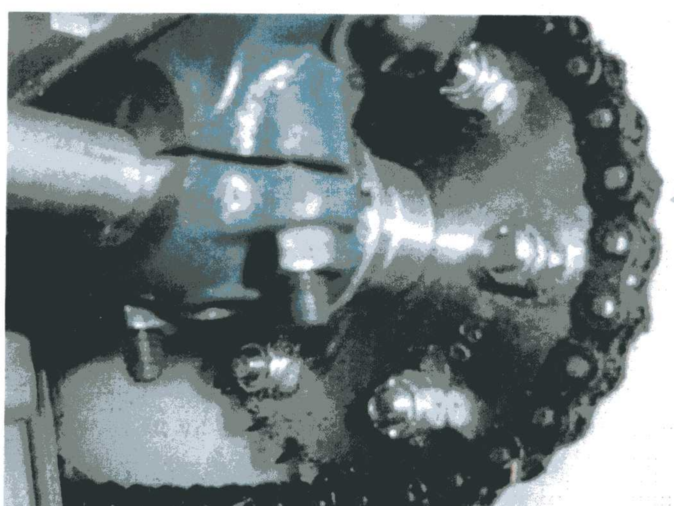

Figure 17: Installed Wheel Sprocket with Chain

This not only produced a 3:1 reduction in the drive system but also allowed for the motors to not be directly mounted to the drive wheels, which was a design requirement. Now that the drive wheels were no longer mounted directly to the motors the issue of shaft deflections could be easily addressed, the solution that was chosen was to use solid shafts that would run the width of the excavator, both the driven wheels and the un-driven wheels would ride on these shafts and spin freely. The last of the major issues with the previous design was the tension of the treads; the supplier was contacted and provided the information on the amount of tension the treads should be under. Next a tensioning system was to be designed that would keep a constant tension in the system. The result was an idler pulley attached to a rotational spring that would allow for flexibility in the treads while still keeping them in constant tension. This design can be seen in Fig. 18. So through these design alterations and additions all of the initial concerns with the design were resolved.

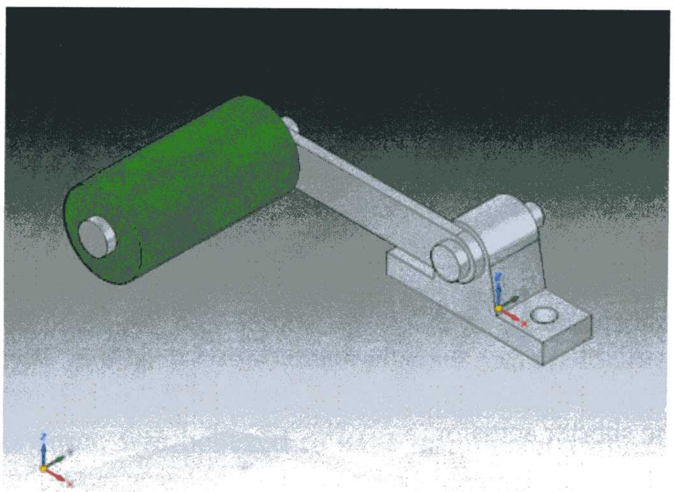

Figure 18: Design of Tensioning Device

Once the system was installed it was taken for a test run and performed admirably on most surfaces, however the excavator still experienced some difficultly turning in rougher terrain. In order to address this, the design was revisited and several trade studies were performed. The ultimate decision made was to purchase two additional motors resulting in the excavator having all four wheels driven. This would provide more than adequate turning torque in all surfaces. Since part of the design of the frame was for it to be "open" there was plenty of room for this addition. A full bill of material for the drive system can be found in Table D.2 of Appendix D.

Unfortunately, since the drive system has not been entirely installed the verification of it has yet to be fully preformed. However through previous tests and trade studies this design is thought to be sufficient for any terrain that the excavator could experience, on this planet or any other.

Digger Arm:

The design of the Digger Arm subsystem was driven by the following derived requirements:

- The Digger Arm shall lift the simulant at least 1m
- The Digger Arm shall collect at least 10 kg
- The Digger Arm shall be fabricated with salvaged parts

The product hierarchy, seen in Fig. 19, was developed after analyzing the requirements imposed on the Digger Arm subsystem.

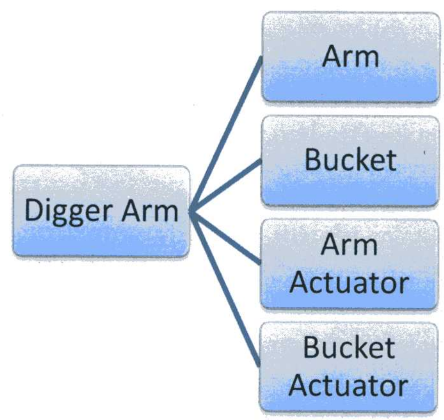

Figure 19: Digger Arm Subsystem Product Hierarchy

The Digger Arm subsystem was separated into two components, the Arm Boom and Bucket components.

Arm Boom:

The design of the Arm Boom subsystem was driven by the following derived requirements:

- The pivot point of the bucket subsystem shall lift higher than 1.15m

- The Arm/Boom actuator shall not exceed 1300 lbs dynamic load

There were many concepts of the digger arm which were sorted through for a possible design. The forklift, overhead scoop and dump, front end loader, and back hoe were all designs which were under consideration as a possible design to use on the excavator. The Forklift is front heavy and consisted of many parts. The overhead scoop and dump required a greater field of vision and is likely to miss the dumping bin. In order to operate the back hoe, the excavator had to be very heavy; it required more actuators, and a smaller bucket. Considering the alternatives, the team decided to use a front end loader.

We designed the front end loader to be simple and effective. After the design of the first concept, it was noticed that speed was a huge problem. This problem was caused mainly because of the height where the bucket arm is pivoted in accordance to where it is pivoted on the bucket, see Fig. 20.

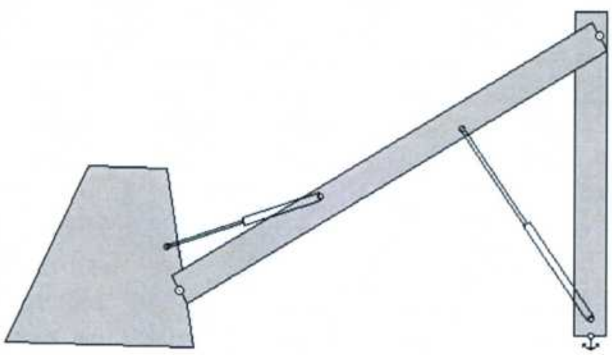

Figure 20: Prototype Arm Design

To have a design which could handle the moment caused by an instant stop of the excavator while it is traveling at full speed and also rise faster than the conceptual design, the height of the arm's pivot position must be reduced, see Fig. 21.

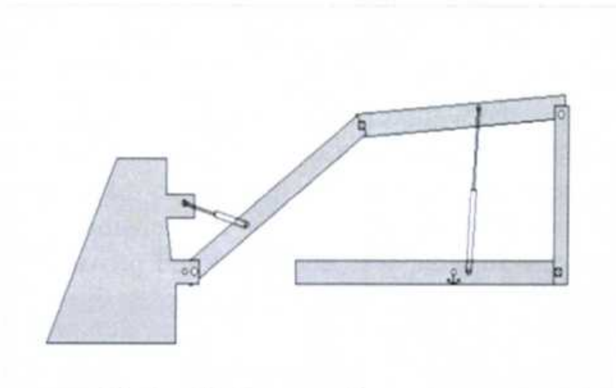

Figure 21: Proposed Arm Design

Reducing the height of the pivot position caused other problems which had to be solved. One problem was not being able to reach the dumping bin. Because of the reduced height of the pivot position, when lifting the arm we needed a longer length to reach the dumping bin. This was a simple solution but the longer length causes us to have to use a shorter bucket because of the length restrictions in the rules of the competition. If we position the shorter actuator accordingly, we are able to make the rise time three times faster, load size heavier, and also maintain a stop of the excavator when traveling at full speed. The actuator which we currently have is offered with a shorter stroke length but unfortunately, it is on backorder and will not be available before the subsystem design deadline. Fig. 22 shows the assembly of the arm on the frame and the shorter actuator.

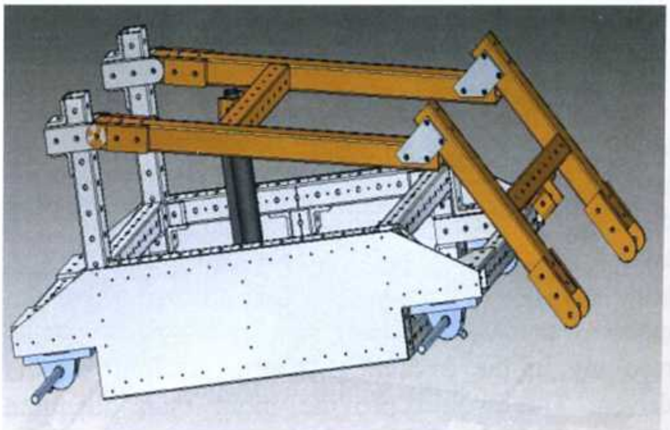

Figure 22: Proposed Arm Interfacing

For competition deadlines, we were able to come up with a design which could use our current actuator while the shorter actuator is being ordered. To do this we increased the height of the pivot which is used to connect the actuator to the arm. A Bill of Materials may be found in Table D.3 of Appendix D.

Bucket:

The bucket system's derived requirements stem from the requirements imposed upon the Digger Arm subsystem and the Prototype Excavator Bucket subsystem. The prototype bucket design consisted of a Garolite G-10 bucket that was attached to the main arm via a steel shaft as seen in Fig. 23.

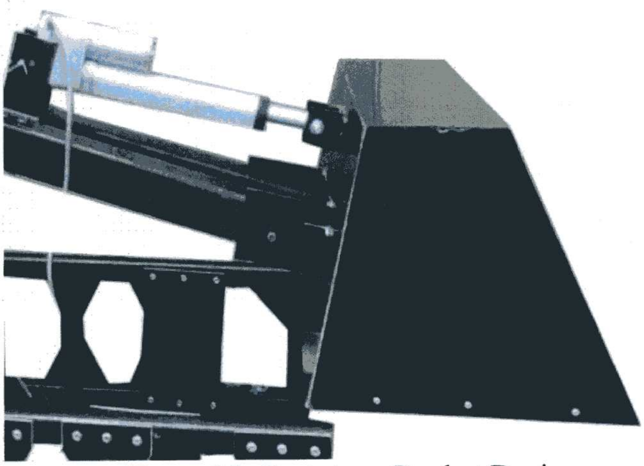

Figure 23: Prototype Bucket Design

This design was not verified due to the Prototype Frame and Drive subsystem testing. The design, however, was believed to have insufficient stiffness and robustness for digging and accidents.

The new design was driven by the requirements of being sturdy yet lightweight. In order for the Digger Arm subsystem to effectively collect and deposit the most simulant in one trip, the bucket must be of minimal weight. The following were the additional key driving requirements pertaining to the design of the Bucket subsystem.

- The Bucket shall dig with at least 22 kPa at the tip of the bucket
    - Requirement derived from regolith simulant technical paper [7]
- The collected regolith shall not cause the rover to tip forward
- The bucket shall pitch forward at least 145 degrees with respect to the horizontal
- The bucket actuator shall support no more than 500 lbs

After the architectural design of the subsystem had been laid out, trade studies were performed and critiqued according to the system and bucket subsystem requirements. The primary focus of the trade studies dealt with medium to large scale front end loader components such as the Bobcat loader bucket seen in Fig. 24.

Figure 24: Bobcat Loader Bucket [8]

The operation of a front end loader was also observed, providing valuable insight into the design of a bucket system. The use of teeth, maximum pitch angle, and actuator position on the bucket were observed in operation and taken into account during the design process. Teeth increase the pressure at the digging point, thus reducing the amount of force needed to penetrate the surface of the simulant. The bucket design was to imitate that which industry has already proven, only on a smaller scale.

A decision matrix was used to determine how the remaining requirements would be satisfied. The bucket decision matrix can be seen in Table 3.

Table 3: Bucket Decision Matrix

	Steel	AL	B-O-F	Importance
Property				
Rigid / Strength	5	2	3.5	4
Weight	1	5	4.5	5
Fab/ Install Ease	4.5	4	3.5	2
Total	34	41	43.5	

Importance: 1 = Negligible, 5 = Significant
Material Capability: 1 = Poor, 5 = Excellent

The results of the decision matrix indicated that an aluminum bucket with a sub frame would best suit the bucket design based on the derived requirements. The actuator attachment to the bucket was designed based on front end loader observations, the required pitch angle, and maximum available force from the bucket actuator. The available digging force was calculated to ensure it met the derived requirement. The results of the process consisted of a bucket made of aluminum sheet metal with an aluminum sub frame, steel cutting blade with teeth, 8020 compatible interfacing components, and placement of the actuator approximately 3" from the bottom pivot. The Solid Edge CAD assembly of the bucket can be seen in Fig. 25.

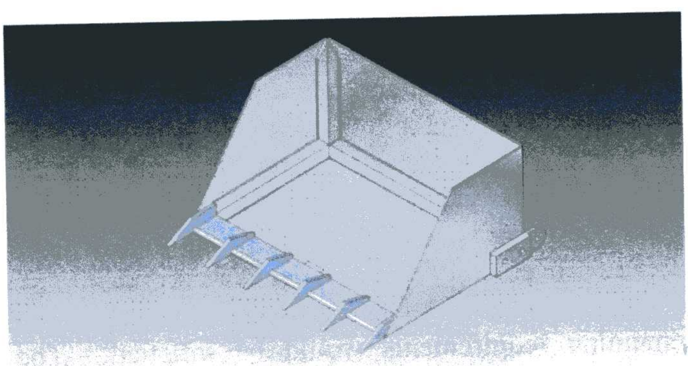

Figure 25: Bucket Design

The physical dimensions, weight, Digger Arm interface, and Pitch angle of the bucket design were verified using Solid Edge, and the actuator forces are in the process of being verified using Working Model. The Bill of Materials for the Bucket System can be found in Table D.3 of Appendix D.

Control Communication System:

The driving requirements for the electrical subsystem were:

- The CC subsystem shall interface with NASA's wireless network
- The excavator system shall be remotely controlled
- The CC subsystem shall provide enough power for at least 15 minutes

The product hierarchy, seen in Fig. 26, was developed after analyzing the requirements imposed on the CC subsystem.

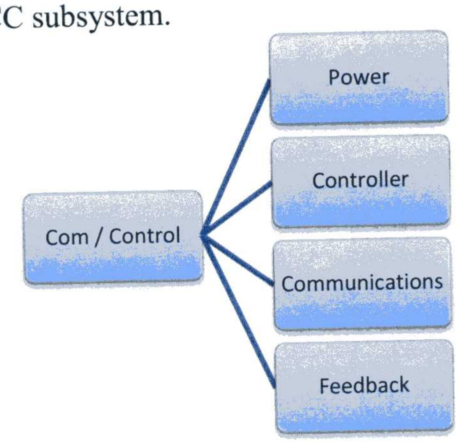

Figure 26: Control Communications Product Hierarchy

The electrical system is composed of two main subsystems: the base station and the teleoperated vehicle. The base station consists of a laptop with USB ports, a wireless modem, and a working installation of the Python programming environment. The vehicle's electrical system consists of a wireless transceiver board that passes messages between the base station and the vehicle's onboard microcontroller.

All messages between the base station and the microcontroller are simple serial commands. Once the microcontroller receives a serial command, it interprets and translates it into a command that is compatible with one of the three identical motor controllers. These motor controllers are responsible for providing power to the two linear actuators and four drive motors that accomplish the digging and driving design goals.

After extensive testing of the actuators and drive motors, it was determined that the actuators were capable of drawing 10A each at full load and the motors were capable of drawing up to 16A during high-torque turning operations. The motor controllers are able to continuously supply the actuators with the 120W that they occasionally require, but can only briefly supply the motors with the 360W that the worst-case turns will require. To protect the motor controllers, 40A fuses were added to the supply lines going to each motor controller and the vehicle operator is careful to only perform partial turns at a single time.

A wireless video camera is mounted on to the side of one of the digger arm support towers and is powered by a regulated 12V supply. Since the camera is able to connect to an external wireless network on its own, its signals are not passed through the wireless transceiver board. The orientation of the camera is fixed, so the teleoperator is unable to see what is immediately behind the vehicle. To account for this, a rear-facing infrared rangefinder is mounted on the vehicle and connected to the microcontroller. The microcontroller periodically polls this sensor and, if an obstacle is detected within the sensor's approximately 12 inch detection range, calculates the distance to any obstacles using the microcontroller's internal ADC. This distance is then sent to the base station, and the control software alerts the operator.

The electrical system implemented in the prototype lunar regolith excavator used a XBee wireless module to enable communication between the laptop base station and a specialized robot controller board. Relatively simple text control commands were interpreted by the robot controller and used to control one of the two actuators connected directly to the controller board or sent to the motor controller that provided power to the two drive motors.

While the prototype electrical system did allow for the remote operation and control of the excavator, several severe limitations soon surfaced during testing. The robot controller's two onboard power outputs while useful, were limited by the relatively low 12V, 2A limit imposed by the board's design. Since the actuators chosen by the mechanical team were rated for a maximum current draw of 2.9A during a full stall condition, this meant that the possibility of causing permanent damage to the electronics during regular operation was significant. Also, the analog ports on the robot controller were input-only. This design limitation forced the team to select a specific motor controller that was less than ideal, as no other way of communicating with an outside board could be found. The XBee wireless module was an extremely convenient means of communicating with the vehicle, but the XBee system is designed to function as an ad-hoc, point-to-point wireless network. The LMC rules state that all communication between vehicle and base station must pass through NASA's onsite wireless network. As there was no way of using the XBee modules on this network, major network design changes were required. But perhaps the strongest argument against the prototype electrical system was the software required to communicate with the robot controller board and thus the rest of the vehicle. The robot controller used in the prototype was not an open-source platform, and all programming had to be done with the use of Visual C++ and Microsoft Robotics Developer Studio software libraries provided by the manufacturer. As no team members were familiar with Visual C++, the Robotics Developer Studio libraries and thus development environment was used. However, the libraries had not been updated to function with the newest version of the development environment. This caused many problems with implementing features such as rear collision detection and automated arm control. The software was also found to respond somewhat erratically to gamepad joystick input, resulting in erratic and sometimes total loss of vehicle control.

The final excavator electrical system is similar in functionality to the prototype but features a much more versatile and reliable set of components. In place of the XBee wireless modules, a Lantronix WiPort evaluation board is used to connect the vehicle to an onsite wireless network and relay serial commands between base station and vehicle. Since the WiPort board also has several onboard general purpose digital pins, it is used to remotely trigger relays that control the power to the rest of the vehicle. This functionality allows for remote powering on and off of the vehicle, which is required in the 2010 LMC rules. Also capable of controlling vehicle power is a red emergency stop button mounted on the rear of the vehicle. The WiPort board passes all serial command signals to an Arduino Mega microcontroller. The Arduino Mega receives analog sensor data from a Sharp GP2D120 IR rangefinder and sends control commands to one of three Sabertooth 2x10 motor controllers. The IR rangefinder has a reliable proximity detection range of between 4cm and 22cm, which is enough to provide ample warning of a rear collision. Each Sabertooth motor controller is capable of providing up to 24V and 15A to two DC motors, which is enough to power the four drive motors and two linear actuators that are used in the vehicle. A Cisco wireless video camera provides the operator with a live video feed of the excavator's surroundings, enabling true remote operation. The motor controllers are powered by two 24V batteries wired in parallel, and the rest of the electronics are powered by a single 12V battery.

As per the rules given out by NASA, the excavator must be remotely controlled and receive start/stop signals through the NASA WiFi network. In order to accomplish this, the design process was implemented in the design of a software system for the excavator. The purpose of the software system is to provide control to, and feedback from the excavator remotely. To ensure that the software system provided these services while following the competition rules given by NASA, the design was based off a set of user requirements. After enumerating the requirements, the decision was made about what framework to use and how to layout the software system. A simple schematic of the system can be seen in Fig. 27.

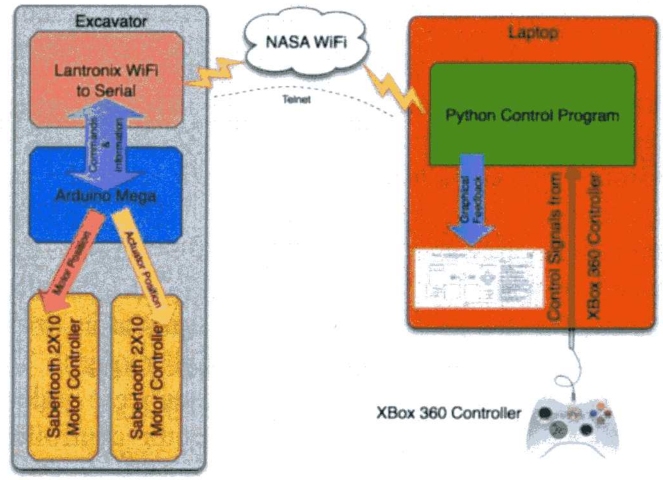

Figure 27: Software Schematic

The requirements that the software system adheres to is based on the rules given by NASA and by other requirements imposed by the team. These are the requirements that the software system adheres to:

- All communication shall travel over NASA's WiFi network
- All data communication shall not exceed 5Mbps
- The excavator shall be remotely started and killed
- The excavator shall be remotely controlled using a gamepad or joystick
- Information from the excavator shall be displayed (voltage, backup obstacle detection, etc...)

In order to facilitate serial communication over a WiFi network, the Lantronix WiPort device was selected as the gateway for communications to and from the Arduino Mega. The data transfer budget was rationed between the WiFi webcam and the connection to the Lantronix, but the communication between the computer and the Lantronix WiPort is negligible. The Lantronix board has some general purpose I/O ports that we will use to control the remote start and kill functions. The Input from the gamepad or joystick will be translated into a format that the Arduino Mega understands and sent from the Laptop to the Lantronix and ultimately the Arduino Mega from the Control Software. Any information collected from the Arduino Mega will be published to the Lantronix, which relays that information to the Control Software which then processes the information and displays it to the user.

The Lantronix WiPort board was selected to facilitate the communication of serial data over the NASA WiFi link. The Lantronix achieves this by connecting to a preconfigured WiFi access point and setting up a telnet server. Telnet is simple a legacy modem protocol, allowing us to easily send asynchronous serial data over a TCP socket. Basically the Lantronix board allows for transparent communication with the Arduino as if it were connected via USB. Conveniently the Lantronix will also allow us to enable/disable power to the excavator via the NASA WiFi as well. This is accomplished by sending a specially formatted UDP data packet to the Lantronix which instructs it to set certain Digital I/O pins to High or Low states. Using this feature we will set a pin High in order to enable a relay controlling power to the electronics, and conversely setting it Low to disable power flow to the excavator electronics.

Now that a solution had been found for WiFi connection the control software needed to be designed and implemented. The Control Software has several main functions:

- Manage connections to the Lantronix WiPort
- Send the enable/disable command to the Lantronix WiPort
- Translate Input from the gamepad or joystick into commands
- Send commands to the Arduino Mega via the Telnet server on the Lantronix WiPort
- Display any information the Arduino Mega sends back

In order to accomplish these functions the software framework needed to be able to fulfill these derived requirements:

- Connect to the Excavator via TCP/IP Telnet (Lantronix)
- Connect to the Excavator via USB (Serial via direct connection to the Arduino)
- Interface with gamepads and joysticks
- Operate under Graphical User Interface Environment
- Easy to use / Rapid Development (short development time)
- (optional) Cross-platform compatible (Windows, Mac OS X, Linux) development time)
- (optional) Display streaming video from the WiFi webcam

After reviewing the requirements the decision was made to use the Python (2.6.x) programming language to develop the Control Software due to the fact that it is easy to use, supports Telnet, supports Serial, supports Simple GUI's, supports interfacing with gamepads and joysticks, and is cross-platform compatible. Additionally the pygame library was chosen to facilitate the GUI and gamepad/joystick interfacing. In order to communicate through a Serial port the pySerial library is also required.

In testing, the redesigned electrical system performed exactly as expected. The two battery systems were more than capable of powering the onboard electronics for the necessary 15 minutes, and the WiPort board can be configured to connect to any wireless network. Once that connection was made, sending control commands to the Arduino Mega resulted in no unexpected behavior whatsoever. This was a significant improvement over the unreliable Serializer board and associated software used in the prototype vehicle. To see a full bill of materials for the electrical subsystem please refer to Table D.4 of Appendix D.

<u>Verification and Validation:</u>

The verification for the Team Pumpernickel's project began with the prototype excavator. It underwent frame and drive modification as well as Frame and Drive subsystem integration. The prototype excavator verification of system requirements as defined by the Lunabotics Mining Competition Rule Book took place on "E-Day" at Auburn University, and the results involved the design a new excavator based heavily on solving the problems experienced in the prototype's verification.

Solid Edge was used for the physical verification (weight, dimensions, etc.) of components and for the integration of components into subsystems. The subsystems were then assembled into a system and verified against the system requirements as defined by the Competition Rule Book. The resulting excavator system Solid Edge CAD assembly can be seen in Fig. 28.

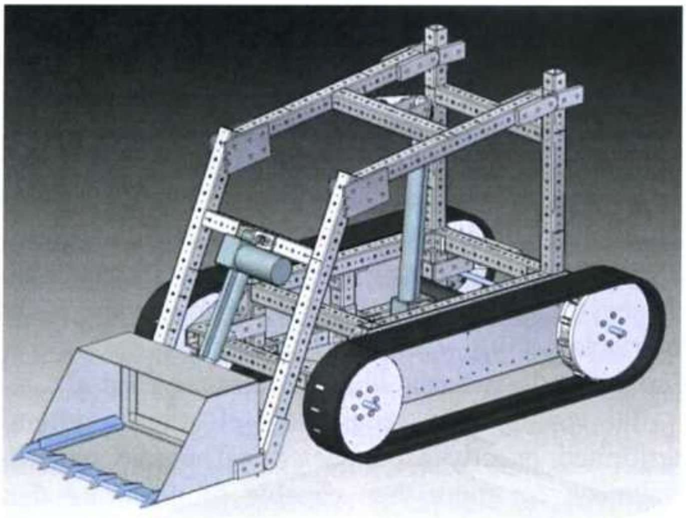

Figure 28: System Solid Edge Verification

FEMAP express, Working Model, and hand calculations were used to test the deflection and force/load requirements on each subsystem are met.

The excavator underwent extensive testing and system verification prior to the validation and launch of the lunar excavator. The excavator was taken to the USDA Soil Dynamics Lab in Auburn, AL and was tested against various environmental and operational conditions. A total of 2 visits were made. The first test at USDA involved verifying the Drive and Digger Arm subsystems. The excavator was driven on the hard packed soil in the covered facility and demonstrated full turning and driving capabilities. The soil was raked to remove large rocks, but the soil remained extremely compact. The treads were then taken off of the excavator to simulate possible risks during the competition after successful testing of the drive system with treads. The excavator was still able to turn and maneuver on the hard packed soil without treads because of the skid-steer capabilities of the 4 Motor Drive system. The Digger Arm subsystem was also tested in the hard packed soil. The excavator would stall if the bucket was engaging too much soil. The conclusion was to make multiple passes with the large bucket in order to collect a full scoop when the soil is hard packed. The excavator was actually able to dig easier without the treads because the exposed teeth on the wheel gave it more traction.

The second visit involved testing the excavator in extremely loose soil. The soil was tilled to a depth of 6 inches and was a fine talcum powder consistency. The excavator was still able to turn and maneuver with the treads in the soft soil, but was unable to turn when the treads were taken off. The narrow wheels would sink in and dig holes in the soil. The digger arm subsystem worked better, however, in the soft soil, collecting full scoops in single passes. The main concern that arose from the soft soil was the buildup of dirt on the inside of the tracks which would eventually stretch the treads. If stretched far enough the treads would derail from the wheels due to the short teeth on the wheels. The taught treads had the capability of bending the wheel shafts supporting the excavator.

The conclusion of the two tests that the excavator would be able to meet the system requirements in either case of soil conditions so long as the treads remained on. It was also concluded that proper tensioning of the treads would eliminate the risk of tread derailment. The USDA testing was recorded on video and can be found on the project drive.

The next step was to go to NASA and compete and therefore validate the system. During the testing time, team pumpernickel was known around the competition site for being one of the only teams to actually dump regolith in the dumping bin. Team pumpernickel was also widely complemented on the aesthetics and sturdiness of the design which was much different from the designs all the other teams. The robot was able to dump 10kgs with one scoop. It took the entire 15 minutes to dump the regolith because the control software would crash periodically and then would have to be rebooted.

After testing, problems arose which had to be fixed. The axles for the wheels were bent and the treads were stretched. To fix this problem, the axles were changed and found some cardboard boxes which the NASA administration gave to us. Using duck tape and the cardboard the idler wheels where increased in diameter and hence the treads were tightened. After the few modifications, team pumpernickel was able to rest for the competition the next day.

At the first day of competition, teams had to wait before their names were pulled out a hat for the competition run. Once team pumpernickel was called, the robot was weighed and place into the competition area. The robot functioned perfectly and the treads worked better than any test run but actuator which allowed the bucket to tilt was not working properly. It was a big disappointment. Because there were no teams to place, NASA allowed a second run for all the teams on the next competition day.

After the 1st competition the problem with the faulty actuator was found and solved. The wires to the actuator were loose from the board before the 1st competition run. Before the second competition run, the robot was weighed; the weight was 80kg which was the limit for the competition. Once the competition run commenced the robot was functioning perfectly. While dumping 6.66kg from the first scoop, the bucket became stuck pasted its critical position and would not retract to allow for more regolith excavation. During the remaining 12 minutes, the operator tried to maneuver the bucket to get it unstuck but failed.

The extra efforts of team pumpernickel were greatly rewarded. Team pumpernickel was second in overall regolith collection. The team also won the award for best systems engineering paper. The team was awarded their prizes in a museum where dinner was served under a retired spaceship. The team was awarded a total of $3000.

Resource Budgets:

One crucial part of any design is how the technical resources are distributed. This project had three designated technical resource budgets in weight, power, and data transfer rate. A technical resource budget was derived and can be seen in Table 4.

Table 4: Technical Resource Budget

SOURCE	COMPONENT	ALLOTTED	USED
Weight		80kg	
	Frame	30kg	
	Drive	20kg	
	Arm	20kg	
	Electrical	10kg	
Power		460 Watt-hrs	
24 V	Motor x4	300	264
	Actuator x2	154	139.2
	Motor Cntrl x3	3	1.08
	Relay x2	3	1.776
12 V		26.4 Watt-hrs	
	WiPort	5	2.31
	Camera	15	12
	Micro-Controller	5	1.25
Transfer Rate		5 Mbps	
	Camera	2.5Mbps	750kbps
	WiPort	2.5Mbps	45kbps

Risk Management:

The Excavator system that was created is a high risk system. The subsystems were designed around the basic necessities needed to fulfill requirements in an attempt to keep the overall weight and design time of the excavator to a minimum. Table E.2 of Appendix E shows examples of components that are not mission critical and the associated risk involved with each component as per *Chapter 2: Systems Engineering Risk Management guidelines* [3].

CONFIGURATION MANAGEMENT:

In today's engineering world computers are always involved in the design of systems and the solution of problems. One of the consequences of this is there are many computer files created during the design of a system such as a lunar excavator. One of the struggles is how to best organize and index all of these files so that all members are aware of their places. This is commonly referred to as configuration management and is a common problem in today's workplace, even outside of engineering. In order to keep all of the files created throughout this project several different techniques were used. There was a common drive provided by the school that all members had access to so this served as the main storage point for all files. Each member had an individual file on this drive where they would keep the work that they were currently working on; once the file was completed it was moved into a file corresponding to the subsystem it belonged to. Also once a new file was uploaded, if it was replacing an older version the older version was renamed and saved in an additional folder under that subsystem specifically for older designs. This was done so that in the event a new design did not work the old design could easily be reinstated. However since this drive was only accessible from a school computer a way to easily share current files needed to be found and implemented, the website dropbox.com provided this capability for Team Pumpernickel. This site was used for sharing files while members were away from campus. Through using both of these services and the explained organizational structure no problems with configuration management were experienced throughout the design process of the excavator.

PROJECT MANAGEMENT:

Management Structure:

The Management structure, seen in Fig. 29, for this project was similar to that of real world project in that there was a systems engineer who oversaw the whole project, then there where both mechanical and electrical engineering project leads followed by mechanical and electrical engineers.

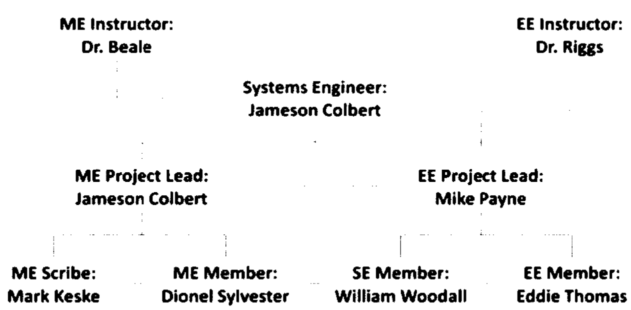

Figure 29: Management Structure Diagram

Schedule:

As is with every project, the excavator had a timeline for completion that must be met in order to complete the mission statement. This timeline was established by all of the members at the onset of this semester and has been altered to add new tasks when needed. Each subsystem had its own schedule for completion and an accompanying Gantt chart; those may be found in Appendix F. The Gantt chart for this semester may also be found in Appendix F.

Financial Budget:

With the economy in its current state money is something that is always important to keep a close eye on. This project is no different; the group was given a project budget at the beginning of the semester. One of the tasks assigned to the systems engineer was to ensure that the money was being spent properly and that the project stayed under budget. A copy of the budget can be found in Appendix G.

DELIVERABLES:

In order to ensure that each task is being completed and being done in accordance with the schedule each team member was required to provide a contract of deliverable (COD) at the onset of each process he began. The COD was then signed by the team member, the system engineer, and the instructor. These were graded assignments for each student so if the contract was not fulfilled then the student's grade would suffer from it. CODs were written for a wide variety of tasks from placing orders for parts to constructing the entire frame. CODs are attached in Appendix H to show how they were written and implemented into this project.

CONCLUSION:

Prototype Evaluation: The first task that was undertaken by the team was to evaluate the prototype and establish a baseline of performance so that it could be improved upon. The team used "E-Day" 2010 at Auburn University for verification purposes of the prototype and it was at such time that the team designated that the design was inadequate to complete the mission statement. For this purpose the design process was initiated for a new excavator design.

New Excavator Design:

As shown in the context of this paper the design process was instituted on a system, subsystem, and component level to best ensure that the team arrived at the optimal design that met all the requirements. After the process was followed the excavator was constructed and testing on each component began. One of the greatest accomplishments of Team Pumpernickel is that in the end the excavator was essentially designed, built, tested, and competed in only a two month span of time. This is a accomplishment that is to be accredited to the team and how well the members were able to work together to accomplish a common goal.

System Verification/Validation:

As discussed earlier, the excavator underwent strenuous testing throughout the entire process. As soon as any new part was installed it was immediately tested to ensure that it worked properly with the rest of its subsystem and the system as a whole. Thanks to the generosity of the people at USDA Team Pumpernickel was able to test the entire system in an environment similar to what was to be encountered at NASA. It is because of all of these combined efforts and resources that Team Pumpernickel was able to compete at the level it did and place as highly as it did.

Suggestions for Future Groups

As suggested, the team got together after the competition and compiled a list of suggestions should another team take on a similar project in the future so to better serve them and in hopes that they can avoid some of the same mistakes that caused trouble for Team Pumpernickel. Below you will find a list of suggestions in no particular order of importance:

- Control Software debugging (networking problems, unable to switch between competition and practice networks in order to verify excavator function prior to competition – being able to move the bucket, arm, treads before putting it in the competition box, time delays, commands backing up, software crashing, etc.)
- Secure electrical connections on control boards (solder, locktite, something that would prevent wires from being pulled out of the motor controllers)
- Dynamic Tread Tensioner
- Design way to limit dirt build up on the treads
- Limit switches/rubber bumper for bucket (the actuator was moved so it can't get stuck anymore, but it wouldn't hurt for something else).
- Extend notches on wheels so to better keep treads on track.
- While testing, make sure everything that could be a problem is solved. Don't assume you could work through even the smallest of problems.
- Finish the design and assembly early so lots of testing could be done.
- Take extra materials and tools are taken to competition in the case of something needs to be built during competition.

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APPENDIX A: Lunabotics Mining Competition Rules

Lunabotics Mining Competition Rules

May 25-28, 2010

Kennedy Space Center

Astronaut Hall of Fame

Introduction

NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations.

The competition will be conducted by NASA at Kennedy Space Center. The prize funding for the Lunabotics Student Mining Competition is provided by NASA. The teams that can use telerobotic or autonomous operation to excavate the most lunar regolith simulant within a 15-minute time limit will win the competition. The minimum excavation requirement is 10.0 kg, and the excavation hardware mass limit is 80.0 kg. Winners are eligible to receive first, second, or third prize of $5,000, $2,500, and $1,000, respectively.

Undergraduate and graduate student teams enrolled in a U.S. college or university are eligible to enter the Lunabotics Mining Competition. Design teams must include: at least one faculty or industry advisor with a college or university affiliation and two or more undergraduate or graduate students. Teams will compete in up to five categories including: on-site mining, systems engineering paper, outreach project, slide presentation (optional), and team spirit (optional). Additionally, collaboration between a majority and minority serving institutions, digital video footage, and multidisciplinary teams earn teams additional points toward the Joe Kosmo Award for Excellence.

Prizes include monetary scholarships, a school trophy or plaque, individual certificates, KSC VIP launch invitations, and up to $1,500 travel expenses for each team member and one faculty advisor to participate with the NASA Desert RATS as the winners of the Joe Kosmo Award for Excellence.

Scoring rubrics and prize details are available at www.nasa.gov/lunabotics.

Game Play Rules

1) These rules and specifications may be subject to future updates by NASA at its sole discretion.

2) Teams will be required to perform 1 official competition attempt using lunar regolith simulant, sandbox and collector provided by NASA. NASA will fill the sandbox with compacted lunar regolith simulant that matches as closely as possible to the lunar regolith described in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. NASA will randomly place 3 obstacles and create 2 craters on each side of the sandbox. Each competition attempt will occur with 2 teams competing at the same time in opposite directions, 1 on each side of the sandbox. After each competition attempt, the obstacles will be removed, the lunar regolith simulant will be returned to a compacted state, and the obstacles will be returned to the sandbox. See the Sandbox Diagrams on page 6.

3) In the official competition attempt, the teams that acquire (and deliver into the collector container) the first, second, and third most mass by excavating lunar regolith simulant over the minimum excavation requirement (10 kg) within the time limit (15 minutes) will respectively win first, second, and third place prizes. In the case of a tie, the teams will compete in a head-to-head round, where the team that acquires the most lunar regolith simulant in that round wins.

4) All excavated mass deposited in the collector during the official competition attempt will be weighed after completion of the competition attempt. Any obstacles deposited in the collector will be removed from the lunar regolith simulant collected.

5) The excavation hardware shall be placed in the randomly designated starting zones. The order of teams will be randomly chosen throughout the competition.

6) A team's excavation hardware shall only excavate lunar regolith simulant located in that team's respective mining zone at the opposite end of the sandbox from the team's starting zone. The team's exact starting point and transversal direction will be randomly selected immediately before the competition attempt.

7) The excavation hardware is required to move across the obstacle zone to the mining zone and then move back to the collector box to deliver the simulant into the collector box. See the Sandbox Diagrams on page 6.

8) Each team is responsible for placement and removal of their excavation hardware onto the lunar regolith simulant surface without the use of a ramp. There must be 1 person per 23 kg of mass of the excavation hardware, requiring 4 people to carry the maximum allowed mass. Assistance will be provided if needed.

9) Each team is allotted a maximum of 10 minutes to place the excavation hardware in its designated starting position within the sandbox and 5 minutes to remove the excavation hardware from the sandbox after the 15-minute competition attempt has concluded.

10) The excavation hardware operates during the 15-minute time limit of the competition attempt. The 15-minute time limit will be reduced if a team is not ready at the team's competition attempt start time. Time will start even if a team is still setting up their excavator after the 10 minute setup time period has elapsed. The competition attempt for both teams in the sandbox will end at the same time.

11) The excavation hardware will end operation immediately when the power-off command is sent, as instructed by the competition judges.

12) The excavation hardware cannot be anchored to the lunar regolith simulant surface prior to the beginning of the competition attempt.

13) Each team will be permitted to repair or otherwise modify the excavation hardware after the team's practice time. The excavation hardware will be inspected the evening before the competition takes place and quarantined until just before the team's competition attempt.

Field Rules

14) At the start of the competition attempt, the excavation hardware may not occupy any location outside the defined starting zone. At the start of each competition attempt the starting location and direction will be randomly determined.

15) The collector box top edge will be placed so that it is adjacent to the side walls of the sandbox without a gap and the height will be 1 meter from the top of the simulant surface directly below it. The collector top opening will be 1.65 meters long and .48 meters wide. See the Sandbox Diagrams in the Definitions. A target may be attached to the collector for navigation purposes only. This navigational aid must be attached during the setup time and removed afterwards during the removal time period. The mass of the navigational aid is included in the maximum excavation hardware mass limit of 80.0 kg and must be self-powered.

16) There will be 3 obstacles placed on top of the compressed lunar regolith simulant surface within the obstacle zone before the competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition attempt. No obstacles will be buried in the simulant. Each obstacle will have a diameter of approximately 20 to 30 cm and an approximate mass of 7 to 10 kg. Obstacles placed in the collector will not be counted as part of the excavated mass. There will be 2 craters of varying depth and width, being no wider or deeper than 30cm.

17) Excavation hardware must operate within the sandbox: it is not permitted to pass beyond the confines of the outside wall of the sandbox and the collector during the competition attempt. The regolith simulant must be collected in the mining zone allocated to each team and deposited in the collector. The team may only dig in its own mining zone. The simulant must be carried from the mining zone to the collector by any means. The excavator can separate intentionally, if desired, but all parts of the excavator must be under the team's control at all times. Any ramming of the wall may result in a safety disqualification at the discretion of the judges. A judge may disable the excavator by pushing the red emergency stop button at any time.

18) The excavation hardware must not push lunar regolith simulant up against the wall to accumulate lunar regolith simulant.

19) If the excavation hardware exposes the sandbox bottom due to excavation, touching the bottom is permitted, but contact with the sandbox bottom or walls cannot be used at any time as a required support to the excavation hardware. Teams should be prepared for airborne dust raised by either team during the competition attempt.

Technical Rules

20) During the competition attempt, excavation hardware is limited to autonomous and telerobotic operations only. No physical access to the excavation hardware will be allowed during the competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the excavation hardware. Visual and auditory isolation of the telerobotic operators from the excavation hardware in the Mission Control Room is required during the competition attempt. The Mission Control Room is approximately 60 meters from the sandbox. Telerobotic operators will be able to observe the sandbox through 2 fixed overhead cameras in 2 opposing corners of the sandbox through monitors that will be provided by NASA in the Mission Control Room. These monitors should be used for situational awareness only. The walls of the Mission Control Rooms are metal framed with 5/8" wall board on both sides of the framing. The sandbox will be outside the Astronaut Hall of Fame metal frame building in an enclosed tent.

21) Mass of the excavation hardware shall not exceed 80.0 kg. Subsystems on the excavator used to transmit commands/data and video to the telerobotic operators are counted towards the 80.0 kg mass limit. Equipment not on the excavator used to receive commands from and send commands to the excavation hardware for telerobotic operations is excluded from the 80.0 kg mass limit.

22) The excavation hardware must be equipped with an easily accessible red emergency stop button (kill switch) of minimum diameter 5 cm on the surface of the excavator requiring no steps to access. The emergency stop button must stop excavator motion and disable all power to the excavator with 1 push motion on the button.

23) The communications link used for telerobotic operations is required to have a total bandwidth of no more than 5.0 megabits/second. Teams will be required to demonstrate compliance prior to starting the competition attempt. Wi-Fi infrastructures will be provided and monitored by NASA: 1 for practice and 1 for the competition attempt. IP addresses will be provided and managed by NASA. Each team must request anticipated IP address requirements by March 15, 2010 by e-mailing Susan Sawyer at Susan.G.Sawyer@nasa.gov. IP address requests will be processed on January 15 and March 15, 2010. NASA anticipates a minimum of 2 IP addresses for each team. NASA technical experts will offer feedback on real-time networking performance during practice attempts. There will be no lunar latency time delay imposed on teams by NASA this year.

24) The excavation hardware must be contained within 1.5m width x .75m length x 2m height. The hardware may deploy beyond the 1.5 m x .75 m footprint after the start of the competition attempt, but may not exceed a 2 meter height. The excavation hardware may not pass beyond the confines of the outside wall of the sandbox and the collector during the competition attempt to avoid potential interference with the surrounding tent. The team must declare the orientation of length and width to the inspection judge. Because of actual lunar hardware requirements, no ramps of any kind will be provided or allowed.

25) To ensure that the excavation hardware is usable for an actual lunar mission, the excavation hardware cannot employ any fundamental physical processes (e.g., suction or water cooling in the open lunar environment), gases, fluids or consumables that would not work in the lunar environment. For example, any dust removal from a lens or sensor must employ a physical process that would be suitable for the lunar surface. Teams may use processes that require an Earth-like environment (e.g., oxygen, water) only if the system using the processes is designed to work in a lunar environment and if such resources used by the excavation hardware are included in the mass of the excavation hardware.

26) Components (i.e. electronic and mechanical) are not required to be space qualified for the lunar vacuum, electromagnetic, and thermal environments.

27) The excavation hardware may not use any process that causes the physical or chemical properties of the lunar regolith simulant to be changed or otherwise endangers the uniformity between competition attempts.

28) The excavation hardware may not penetrate the lunar regolith simulant surface with more force than the weight of the excavation hardware before the start of the competition attempt.

29) No ordnance, projectile, far-reaching mechanism, etc. may be used (excavator must move on the lunar regolith simulant).

30) No excavation hardware can intentionally harm another team's hardware. This includes radio jamming, denial of service to network, regolith simulant manipulation, ramming, flipping, pinning, conveyance of current, or other forms of damage as decided upon by the judges. Immediate disqualification will result if judges deem any maneuvers by a team as being offensive in nature. Erratic behavior or loss of control of the excavation hardware as determined by the judges will be cause for immediate disqualification.

31) Teams must submit documentation containing a description of the excavation hardware, its operation, potential safety hazards, a diagram, and basic parts list. Each team will deliver the team's written documentation in .pdf by April 15, 2010 to Susan.G.Sawyer@nasa.gov.

32) Teams must submit video documentation containing no less than 30 seconds of excavation hardware operation and at least 1 full cycle of operation. One full cycle of operations includes excavation and depositing material. Each team will deliver their video documentation by May 10, 2010 to Susan.G.Sawyer@nasa.gov. This video documentation is solely for technical evaluation of the team's excavation hardware. It is not for the video category in the overall Lunabotics Mining Competition. Video specifications:

Formats/Containers: .avi, .mpg, .mpeg, .ogg, .mp4, .mkv, .m2t, .mov; Codecs: MPEG-1, MPEG-2, MPEG-4 (including AVC/h.264), ogg theora; Minimum frame rate: 24 fps; Minimum resolution: 320 x 240 pixels

Definitions

Collector – A device provided by NASA for the competition attempt into which each team will deposit excavated regolith simulant. The collector will be large enough to accommodate each team's excavated regolith simulant. The collector will be stationary and located adjacent to the sandbox. Excavated regolith simulant mass will be measured after completion of the competition attempt. The collector mass will not be counted towards the excavated mass or the mass of the excavation hardware. The collector will be 1.65 meters long and .48 meters wide. The collector walls will rise to an elevation of 1 meter above the regolith simulant surface directly below the collector. See the Sandbox Diagrams on page 6.

Competition attempt – The operation of a team's excavation hardware intended to meet all the requirements for winning the competition by performing the functional task. The duration of the competition attempt is 15-minutes.

Excavated mass – Mass of the excavated lunar regolith simulant delivered to the collector by the team's excavation hardware during the competition attempt, measured in kilograms (kg) with official result recorded to the nearest one tenth of a kilogram (0.1 kg).

Excavation hardware – Mechanical and electrical equipment, including any batteries, gases, fluids and consumables delivered by a team to compete in the competition.

Functional task – The excavation of regolith simulant from the sandbox by the excavation hardware and deposit from the excavation hardware into the collector box.

Lunar regolith simulant – Specific lunar regolith simulant provided by NASA during the competition attempt is to be determined. The simulant will have a particle size and distribution similar to the lunar regolith as stated in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. Teams are encouraged to develop or procure simulants based on lunar type of minerals and lunar regolith particle size, shape, and distribution.

Minimum excavation requirement – 10.0 kg is the minimum excavated mass which must be met in order to qualify to win the competition.

Power – All power shall be provided by a system onboard the excavator. No facility power will be provided to the excavator. There are no power limitations except that the excavator must be self-powered and included in the maximum excavation hardware mass limit of 80.0 kg.

Practice time – Teams will be allowed to practice with their excavators in the sandbox on May 25 and 26, 2010. NASA technical experts will offer feedback on real-time networking performance during practice attempts.

Reference point – A fixed location on the excavation hardware that will serve to verify the starting location and traversal of the excavation hardware within the sandbox. An arrow on the reference point must mark the forward direction of the excavator in the starting position configuration. The judges will use this reference point and arrow to orient the excavator in the randomly selected direction and position.

Sandbox – An open-topped container (i.e., a box with a bottom and 4 side walls only), containing regolith simulant, within which the excavation hardware will perform the competition attempt. The inside dimensions of the each side of the sandbox will be 7.38 meters long and 3.88 meters wide, and 1 meter in depth. A dividing wall will be in the center of the sandbox. The sandbox for the official practice days and competition will be provided by NASA. See the Sandbox Diagrams on page 6.

Telerobotic – Communication with and control of the excavation hardware during the competition attempt must be performed solely through the provided communications link which is required to have a total bandwidth of no more than 5.0 megabits/second on all data and video sent to and received from the excavation hardware.

Time Limit – The amount of time within which the excavation hardware must perform the functional task, set at 15 minutes; set up excavation hardware, set at 10 minutes; and removal of excavation hardware, set at 5 minutes.

APPENDIX B: Preliminary Design Review

Corp_2 NASA Excavator

MECH 4210: Senior Design 1

March 29th, 2010

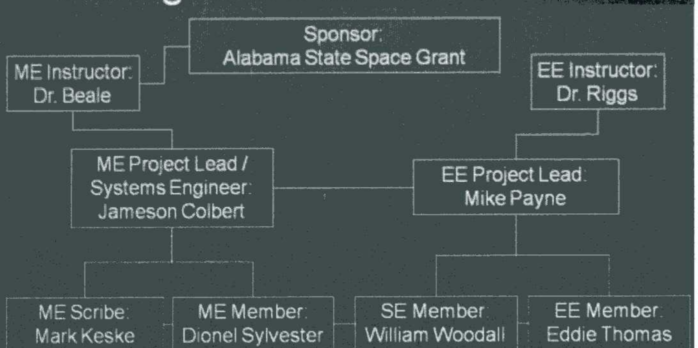
Jameson Colbert
Mark Keske
Dionel Sylvester
Mike Payne
Eddie Thomas
William Woodall

AUBURN UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

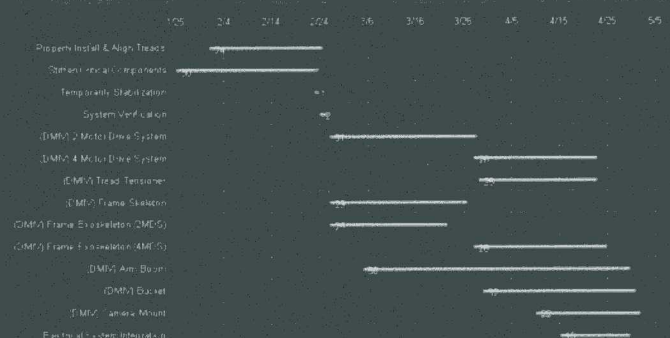
Outline

- Schedule / Budget
- Mission Statement and Environment
- Design Specifications
- Prototype Verification
- New Design
- Subsystems
- System Verification
- Future Milestones

Management Structure



Corp_2 Mechanical Schedule



Resource Budgets

SYSTEM	SEMESTER COST	VALUE OF RECOVERED PARTS
Drive	-$683.00	$826.23
Digger Arm	-$0.00	$309.98
Frame	-$542.24	$0.00
Electrical	-$308.81	$491.95
S&H	-$243.06	N/A
Total	-$1757.11	$1628.16
Total Budget	+$5000	
Remaining Budget	$3242.89	

Mission Statement

The mission of this group is to enhance the prototype Lunar Excavator built by the previous design group. The excavator is designed to compete in the NASA ESMD Lunar Regolith Excavator Competition. The competition calls for a telerobotic lunar regolith excavator to compete for fifteen minutes.

Mission Environment

The environment of operation for the excavator is theoretically the surface of the moon, however for competition purposes the environment will be a simulated lunar surface in a controlled climate on site at the Kennedy Space Station in Orlando, FL.

Design Requirements

MECHANICAL

- Must weigh under 80kg
- Must have an original footprint of less than .75m x 1.5m x 2m
- Components must be applicable to semi-lunar surfaces
- Must be able to dump soil into collection bin 1m above surface

ELECTRICAL

- Must be autonomous or telerobotic.
- Data limit of 5Mb/s
- Must have accessible emergency stop
- Does not have to be space rated

Mechanical Concepts of Operations

- Loader bucket designed to collect soil.
- Excavator will transport collected soil to a collection bin.
- Excavator will deposit collected soil in said collection bin.
- Excavator will be able to avoid and/or move obstacles in its path.

Electrical Concepts of Operations

- Batteries will provide power for 15mins of operation time
- Excavator will be controlled remotely via NASA's wireless network
- Operator will be able to independently control motors and actuators

Prototype

Prototype Frame Issues

- Thin wall carbon fiber tube frame deflections
  - Bending
  - Torsion
  - Compression
- Garolite (G-10) side panel deflections
  - Flat sheet bending

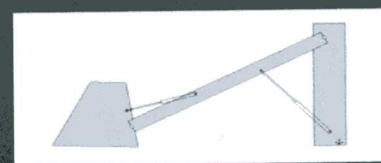
Tube frame deflecting under compression from bolts

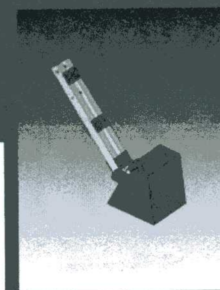
Prototype Drive Issues

- Motors directly mounted to side panel
- Motors directly mounted to wheels
- Tracks wouldn't stay on
- Bearing mount deflection
- Drive wheel mounting inadequate for proper power transmission

Prototype Arm Issues

Problems
- Slow
- Unstable





Prototype Electrical Issues

- Serializer
  - Produced erratic control
  - Software flexibility extremely limited
- AC inverter unnecessary for operation
- XBee not permitted per competition rules
- Devantech motor controller inadequate

Prototype Frame Alterations

- Replacement of 1/8" G-10 side panels with 1/8" 6061 aluminum sheet metal
- Additional aluminum front cross member
- Solid inserts for thin wall carbon fiber tube
- Temporary arm stabilization

Additional member and solid insert

Prototype Drive Alterations

- Motor mounts installed
- Side panel replaced
- Track tensioner installed
- Drive hubs installed

Prototype Validation (E-Day)

- Could only turn on slick surfaces
- Bucket arm TOO SLOW
- Bucket arm experiencing high deflections
- Frame fracture at bearing mounts
- Excavator was outside of competition dimensions
- Batteries did not provide cold cranking amps needed
- Serializer produced uncontrolled movement

Re-Design of Excavator

- Similar Architectural Design
  - Track drive system
  - Front-end loader design
- Salvaged Parts
  - Motors
  - Actuators
  - Lantronix WiPort board
  - E-Stop

Modified Derived Requirements

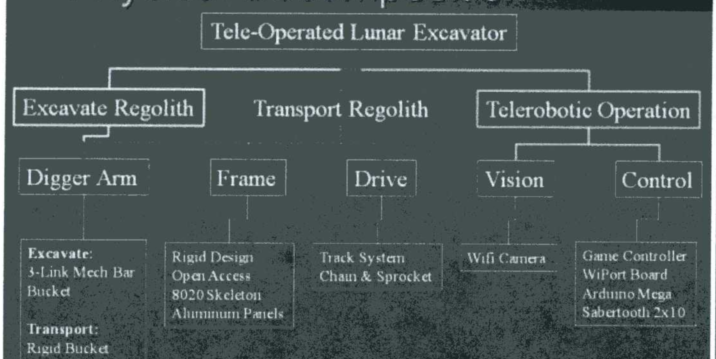
Mechanical

- Rigid Frame
- Increased turning torque
- Increase digger arm speed
- Increase rigidity of arm to frame interface
- Increase effectiveness of bucket

Electrical

- Control commands sent over wireless network
- More versatile onboard microcontroller

Physical Decomposition



Interfaces

INTERFACE	SOLUTION	INTERFACE	SOLUTION
Mech to Mech		**Elec to Mech/ Elec**	
Frame to Drive	Bearing Mounts	Controller to Motors	Sabertooth 2x10 MC
Frame to Digger Arm	Rigid Vertical Posts	Controller to Actuators	Sabertooth 2x10 MC
Mech to Mech/Elec		Elec to Elec	
Frame to Motors	Side Panel Mounts, Motor Mounts	Batteries to Electronics	Fuse Buss (in fabrication)
Frame to Actuator	Hinged Mount	Camera to Controller	Wireless Network
Drive to Motors	Chain & Sprocket System	Base Station to Excavator	WiPort Board
[illegible]	Hinged Mount	[illegible]	[illegible]
Mech to Elec		Network to Motor Controllers	Arduino Mega
[illegible]	Rigid Mount	[illegible]	[illegible]
Frame to Control Board	Rigid Mount		
Frame to Camera	[illegible] (to be manufactured)		

New Frame Design

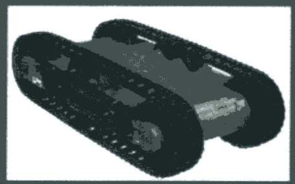
- Modified Derived Requirements
  - The new frame must be rigid
  - The new frame must account for maximum total system dimensions specified by the competition rules
  - The new frame must interface with the other Excavator subsystems

Design Decisions

Influencing Factors

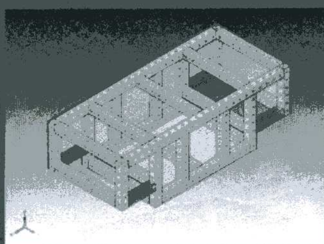
- Aluminum vs. Steel
  - Extra 8020
  - Ease of fabrication
- Interfacing between Drive and Arm system
  - 8020
- Past Prototype

Trade Studies

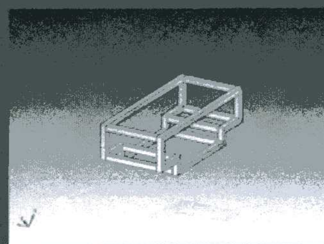


SuperDroidRobots HD2 Treaded Tank Robot

Possible Frame Designs



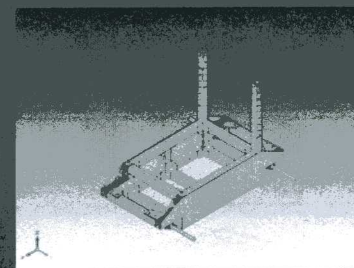
Full Box Frame



Welded Frame

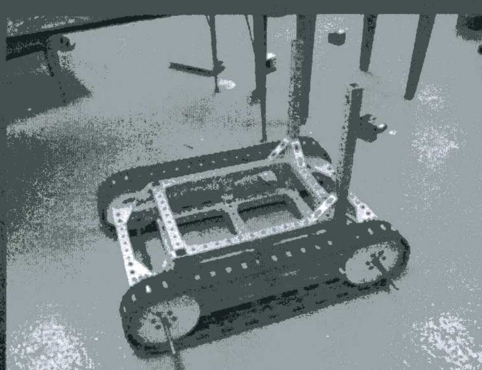
Frame Design

- Rigid frame
  - Drive and Digger Arm interface
- Able to support loads more than 80 kg
- Lighter than Full Box design
- Simpler Fabrication than Welded design



Frame Design

New Frame Verification



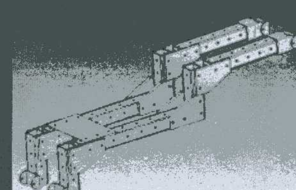
New Drive Design

- Mod Derived Requirements
  - Must be able to turn effectively in grass
  - Interface between drive and frame subsystems must be rigid
  - Treads must be capable of staying for 20 minutes of continuous use

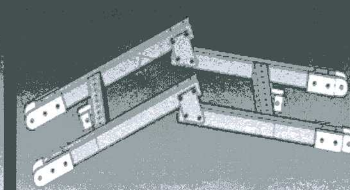
New Drive Design

- Turn Effectively
  - Chain drive w/ 3:1 reduction to increase torque
- Interface Rigidity
  - Motor mounts
  - Solid shafts
  - Split bearings
  - Sleeve bushings in wheels
- Treads remain in place
  - Correctly dimensioned center to center dimension
  - Tensioning system (in design)
    - Waiting for verification & evaluation of current system

New Arm Design Concepts



- Faster Speed
- More Parts
- Lower Dumping Height



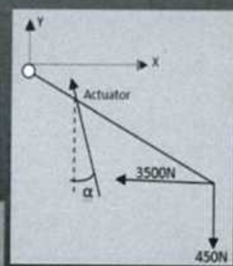
- Faster Speed
- Less Parts
- Taller Dumping Height

New Arm Specs

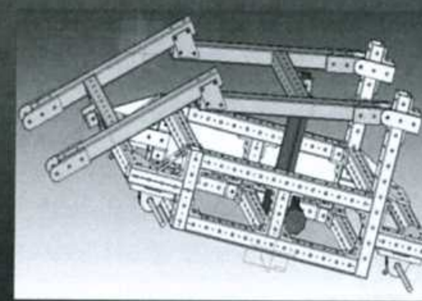
Velocity of New Concept Arm		
x(m) position from pivot	ω	Velocity(mm/s)
0.2	0.0400	31.48

Velocity of Original Arm		
x(m) position from pivot	ω	Velocity (mm/s)
0.42	0.0190	15.47
0.44	0.0182	14.76

Force Needed from Actuator for 80kg body carrying 100lbs in Bucket	
x(m) position from pivot	Force(N) at 0° angle
0.2	6021.04



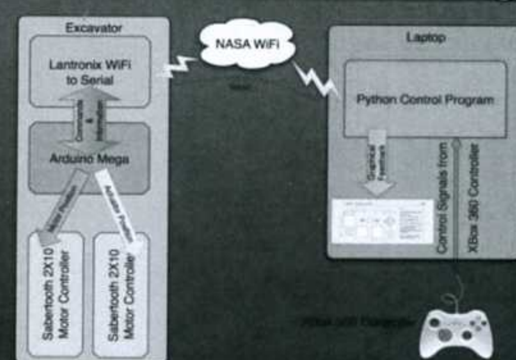
Proposed Arm Verification



New Electrical System Design

- WiPort Board
  - Receives control signals from base station
  - Provides remote start capability with relay control
- Arduino Mega
  - Converts control signals and passes them to Sabertooth motor controllers
  - Receives IR rangefinder signal and alerts operator of obstacles behind the excavator
- Sabertooth 2x10
  - Controls up to two 10A motors or actuators per board

New Software Control Design



Future Milestones

- Systems Engineering Documentation
- 4 Motor DMIV
- Arm MIV
- Bucket DMIV
- Vision System DMIV
- Electronic System Integration DMIV

APPENDIX C: Subsystem Interfaces

INTERFACE	SOLUTION	INTERFACE	SOLUTION
Mechanical to Mechanical		**Electrical to Mechatronic**	
Frame to Drive	Bearing Mounts	Controller to Motors	Sabertooth 2x10 MC
Frame to Digger Arm	Rigid Vertical Posts	Controller to Actuators	Sabertooth 2x10 MC
Mechanical to Mechatronic		**Electrical to Electrical**	
Frame to Motors	Side Panel Mounts, Motor Mounts	Batteries to Electronics	Fuse Buss
Frame to Actuator	Hinged Mount	Camera to Controller	Wireless Network
Drive to Motors	Chain & Sprocket	Base to Excavator	WiPort Board
Digger Arm to Actuator	Hinged Mount	Network to Motor Controllers	Arduino Mega
Mechanical to Electrical		Batteries to Relay	Emergency Stop
Frame to Batteries	Rigid Mount		
Frame to Control Board	Rigid Mount		
Frame to Camera	Custom Arm		

APPENDIX D: Bill of Materials

Table D.1: Frame Subsystem Bill of Materials Price

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	4302	2 Hole Standard Inside Corner Bracket	$2.95	42	$123.90	8020 Inc.
2	4306	3 Hole Joining Strip	$4.40	6	$26.40	8020 Inc.
3	4332	2 Hole Inside Corner Gusset	$4.30	6	$25.80	8020 Inc.
4	4350	4 Hole 90 Degree Joining Plate	$5.60	6	$33.60	8020 Inc.
5	8973K33	3003 AL .100" thick 24" x 36"	$44.29	3	$132.87	McMaster
6	90652A030	Nylon Insert Thin 5/16-18 Hex Lock Nut pack of 100	$10.30	2	$20.60	McMaster
7	91255A581	BHSCS 5/16-18, 3/4" pack of 50	$10.36	3	$31.08	McMaster
8	92949A594	18/8 SS BHSCS 5/16-18, 3" Pack of 5	$8.42	2	$16.84	McMaster
9	9701-145	1.5" Square Tube With Holes 145"Profile	$53.65	3	$160.95	8020 Inc.
10	97447A315	AL Rivets 1/8" Dia, 1/4" Grip, pack of 250	$9.42	2	$18.84	McMaster
			Grand Total		$590.88	

Table D.2: Drive Subsystem Bill of Materials

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	1139545	M5-0.8 x 12 12.9 Socket Head Cap Screws	$7.85	1	$7.85	Fastenal
2	1688K17	PTFE-Lubricated SAE 841 Bronze Sleeve Brng for 1/2" Shaft Diameter, 5/8" OD, 1" L	$0.98	8	$7.84	McMaster
3	2299K316	Machinable-Bore Flat Sprocket for #35 Chain, 3/8" Pitch, 30 Teeth, 1/2" min Bore	$9.45	4	$37.80	McMaster
4	6261K151	Standard ANSI Roller Chain, #35, Single Strand, 3/8" Pitch, Rollerless, .2" Diameter, 10' L	$28.80	1	$28.80	McMaster
5	6359K32	Cast Iron Base Mounted Babbitt-Lined Bearing Split, for 1/2" Shaft Diameter	$42.13	8	$337.04	McMaster
6	7321K1	ANSI Roller Chain Attachment, Connecting Link Style A-1 for #35 Chain	$1.67	4	$6.68	McMaster
7	9120K15	Galvanized Low-Carbon Steel Rod 1/2" Diameter, 3' Length	$9.67	4	$38.68	McMaster
8	9946K15	Aluminum Set Screw Shaft Collar 1/2" Bore, 1" O.D., 7/16" Width	$2.05	16	$32.80	McMaster

9	NC13770	Sprocket, 35B10, 12mm Bore	$44.48	4	$177.92	Parts Town
10	TD036290	IG52-02 24V DC 290 RPM Gear Motor w/encoder	$122.80	4	$491.20	Super Driod Robots
11	TD05200	4 in. tread set	$580.63	1	$580.63	Super Driod Robots
			Grand Total		$1,747.24	

Table D.3: Digger Arm Subsystem Bill of Materials

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	4330	6 Hole 30 Degree Joining Plate	$7.10	6	$42.60	8020 Inc.
2	4345	6 Hole 45 Degree Joining Plate	$7.10	4	$28.40	8020 Inc.
3	4376	3 Hole Inside Corner Bracket	$4.15	4	$16.60	8020 Inc.
4	4390	3 Hole Pivot Plate	$11.50	12	$138.00	8020 Inc.
5	125011	12V, 7 7/8" stroke linear actuator	$149.99	1	$149.99	Northern Tool
6	125012	12V, 11 13/16" stroke linear actuator	$159.99	1	$159.99	Northern Tool
7	8910K121	Low-Carbon Steel Rectangular Bar 1/8" Thick, 2" Width, 6' Length	$18.47	1	$18.47	McMaster
8	8982K21	Multipurpose Aluminum (Alloy 6061) 90 Deg Angle, 1/8" Thick, 1" X 1" Legs, 8' Length	$12.63	2	$25.26	McMaster
9	90652A030	Nylon-Insert Extra-Wide Thin Hex Locknut Zinc-Plated Grade 2 Steel, 5/16"-18 Thread Size, Packs of 100	$10.30	1	$ 10.30	McMaster
10	91255A581	Alloy Steel Button Head Socket Cap Screw 5/16"-18 Thread, 3/4" Length, Packs of 50	$10.36	1	$10.36	McMaster
11	91259A540	Alloy Steel Shoulder Screw 1/4" Shoulder Dia, 3/4" L Shoulder, 10-24 Thread	$1.03	4	$4.12	McMaster
12	91259A626	Alloy Steel Shoulder Screw 3/8" Shoulder Dia, 1-1/4" L Shoulder, 5/16"-18 Thrd	$1.50	3	$4.50	McMaster
13	97526A404	Choose-A-Color Blind Rivet Domed, 3/16" Dia, .126"-.250" Material Thk, Gray, Packs of 100	$7.00	2	$14.00	McMaster
14	98777A213	High-Strength Zinc-Plated Steel Blind Rivet Dome, 3/16" Dia, 0.251"-0.375" Material Thickness, Packs of 25	$8.64	1	$8.64	McMaster
			Grand Total		$631.23	

Table D.4: Com/Control Subsystem Bill of Material

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	231431	10 POS 15A Termial Strip	$3.39	2	$6.78	Jameco
2	282263	15A, 24V DC relay	$7.49	2	$14.98	Jameco
3	5183T11	Blade-Style Fuse Block for 6 Atc, AF, OR Ato/257 Fuses, 32 VDC	$41.44	1	$41.44	McMaster
4	653-A22E-L-02	DP Emergency Stop (manual)	$62.23	1	$62.23	Mouser Electronics
5	7243K116	Fully Insulated Quick-Disconnect Terminal Dbl Crimp Fem, 16-14 Awg,.187" W, .02" Thk Tab, 600V	$7.36	1	$7.36	McMaster
6	7587K461	Stranded Single-Conductor Wire, UL 1015, 14 Awg, 600 VAC, Red, 100' Length	$35.16	1	$35.16	McMaster
7	7587K65	Stranded Single-Conductor Wire UL 1015, 14 Awg, 600 VAC, Black, 100' Length	$35.16	1	$35.16	McMaster
8	7964K634	Solid Single-Conductor Wire UL 1015, 22 Awg, 600 VAC, White	$10.80	1	$10.80	McMaster
9	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Red, Packs of 5	$3.04	10	$30.40	McMaster
10	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Black, Packs of 5	$3.04	10	$30.40	McMaster
11	855-R30-3002502	3mm metal standoffs	$0.68	50	$34.00	Mouser Electronics
12	91280A102	3mx6m Hex Screw	$5.62	1	$5.62	McMaster
13	92005A116	Metri Pan Head Phillips Machine Screw, Zinc-Plated Steel, M3 Size, 6mm Length, .5mm Pitch, Packs of 100	$2.30	1	$2.30	McMaster
14	94150A325	Metric Type 316 Stainless Steel Hex Nut M3 Size, .5mm Pitch, 5.5mm Width, 2.4mm Height, packs of 50	$2.19	2	$4.38	McMaster
15	95225A315	3M washers	$8.35	1	$8.35	McMaster
16	TE-088-210	12V 2200 mAHr NiMH 2x5 Battery Pack	$23.90	1	$23.90	Super Driod Robots
17	TE-097-320	24V 10000 mAHr NiMH Battery Pack	$259.50	2	$519.00	Super Driod Robots
18	TE-106-018	Smart Charger for 9.6V - 18V	$28.95	1	$28.95	Super Driod Robots

		NiMH and NiCad				
19	TE-106-024	Smart Charger for 19.2V - 24V NiMH and NiCad	$29.95	2	$59.90	Super Driod Robots
20	WVC2300	Cisco Wireless-G Video Camera	$359.99	1	$359.99	Cisco
21		Lantronix WiPort	$300.00	1	$300.00	
22		Sabertooth 2x10 Motor Controler	$79.99	3	$239.97	Dimension Engineering
23		Arduino Mega	$64.77	1	$64.77	Robotshops.us
24		XBox 360 controller	$49.99	1	$49.99	
			Grand Total		$1,975.83	

APPENDIX E: Risk Management

Table E.1: Failure Classification [3]

Code	Name	Description
4	Mission Failure	If this error cannot be mitigated, the mission will be a failure – no communications to the ground station.
3	Reduced Lifetime	If this error cannot be mitigated, the mission is still a success, but further research is needed to extend mission lifetime in future missions.
2	Reduced Capability	If this error cannot be mitigated, the mission is still a success, but further research is needed to provide increased capability.
1	Non-Critical	If this error occurs, the primary mission could still be accomplished without additional need for redundancy.

Table E.2: Risk Management of Non-Mission Critical Components

Subsystem	Component	Failure/Result	Code	Mitigation
Frame				
	Nuts/Bolts	Loose Nuts/Bolts in components	2	Locking Nuts
	Side Panel Holes	Regolith entering cavity	2	Sealed Panels
	Non Critical Members	Frame deformations	3	Additional Support
	Side Panels	Crumpling / Deforming	3	Additional Support
	Bottom Panels	Crumpling / Deforming	3	Additional Support
	Battery Mount	Unrestrained batteries	2	Mount failsafe
	Controller Mount	Unrestrained controller components	2	Mount failsafe
	IR Mount	False position readings	1	Mount failsafe
	Antenna Mount	Improper signal connection	2	Mount failsafe
	Camera Mount	Lack of video feedback	3	Mount failsafe
Drive				
	Nuts/Bolts	Loose Nuts/Bolts in components	2	Locking Nuts
	Treads	Tread derails / tears	3	Four Driving Motors
	Chain for one motor	Drive chain derails	2	Chain Guard
	Drive Sprocket on one motor	Drive sprocket slips	2	Semi-Permanent Fastening
	Chain for two motors	Drive chain derails	3	Chain Guard
	Drive Sprocket for two motors	Drive sprocket slips	3	Semi-Permanent Fastening
	Motor on one side	Motor failure	3	Drive Slower
	Two Motors	Motor failure	3	Drive Slower
	Motor Mounts	Unsupported drive motors	2	Mount failsafe
Digger				

	Nuts/Bolts	Loose Nuts/Bolts in components	2	Locking Nuts
	Bucket Teeth	Tooth breaks	2	Sharp Cutting Blade
	Bucket Top	Top of bucket fractures	1	Secondary Reinforcement
Electrical				
	IR Sensor	False position reading	1	Filter
	One Battery	Limited power	3	Cells in Parallel
	Camera Battery	No video feedback	3	Cells in Parallel
	Actuators / Motors simultaneously drawing current	Limited power / Operational time	3	Individual Actuator / Motor Cells

APPENDIX F: System Schedule

Table F.1: Excavator System Schedule

System

Task	Start Date	Duration	End Date
Properly Install & Align Treads	2/1/2010	24	2/25/2010
Stiffen Critical Components	1/25/2010	30	2/24/2010
Temporarily Stabilization	2/23/2010	1	2/24/2010
System Verification	2/24/2010	2	2/26/2010
(DMIV) 2 Motor Drive System	2/26/2010	31	3/29/2010
(DMIV) 4 Motor Drive System	3/28/2010	26	4/23/2010
(DMIV) Tread Tensioner	3/29/2010	25	4/23/2010
(DMIV) Frame Skeleton	2/26/2010	29	3/27/2010
(DMIV) Frame Exoskeleton (2MDS)	2/26/2010	25	3/23/2010
(DMIV) Frame Exoskeleton (4MDS)	3/28/2010	28	4/25/2010
(DMIV) Arm Boom	3/5/2010	56	4/30/2010
(DMIV) Bucket	3/30/2010	32	5/1/2010
Electrical System Integration	4/10/2010	22	5/2/2010
System Verification	5/1/2010	20	5/21/2010

KEY
Jamie
Mark
Ray
All (See Designated Tab)

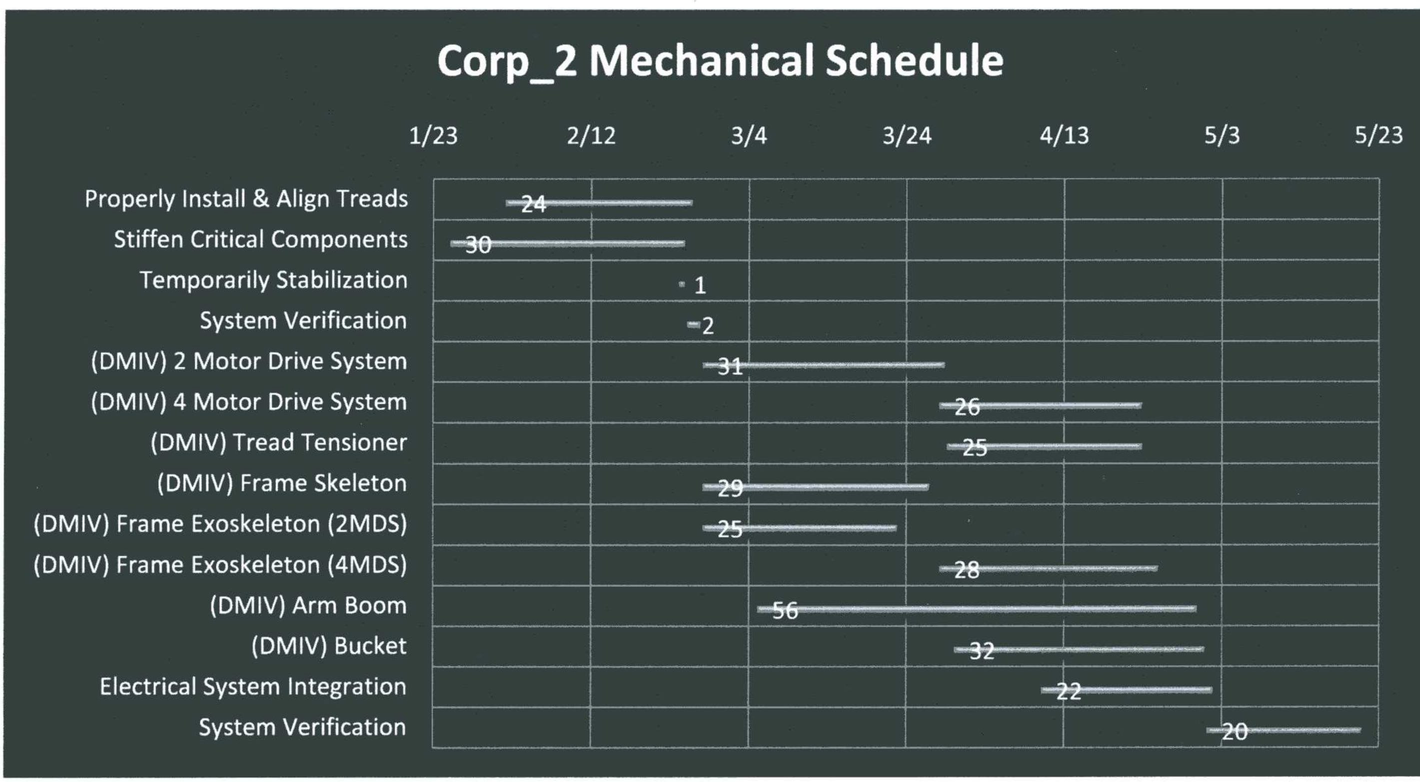


Figure F.1: Excavator System Mechanical Engineering Gantt Chart

Table F.2: Prototype Schedule

Prototype

Task	Start Date	Duration	End Date
Drive			
Properly Install & Align Treads	**2/1/2010**	**24**	**2/25/2010**
(DMI) Power Transmission Solution	2/1/2010	23	2/24/2010
(DMI) Motor Mounts	2/8/2010	7	2/15/2010
(DMI) Tensioning Apparatus	2/18/2010	5	2/23/2010
Subsystem Verification	2/15/2010	10	2/25/2010
Frame			
Stiffen Critical Components	**1/25/2010**	**30**	**2/24/2010**
(MI) Aluminum Side Panels	1/25/2010	14	2/8/2010
(MI) Inner Bracing	2/20/2010	4	2/24/2010
(DMI) Tube Frame Inserts	2/19/2010	3	2/22/2010
(MI) Additional Cross Member	2/23/2010	1	2/24/2010
Subsystem Verification	2/10/2010	14	2/24/2010
Arm			
Temporarily Stabilization	**2/23/2010**	**1**	**2/24/2010**
(DMI) Rope & Knot System	2/23/2010	1	2/24/2010
Subsystem Verification	2/23/2010	1	2/24/2010
System			
System Verification	2/24/2010	2	2/26/2010

KEY
Jamie
Mark
Ray
All

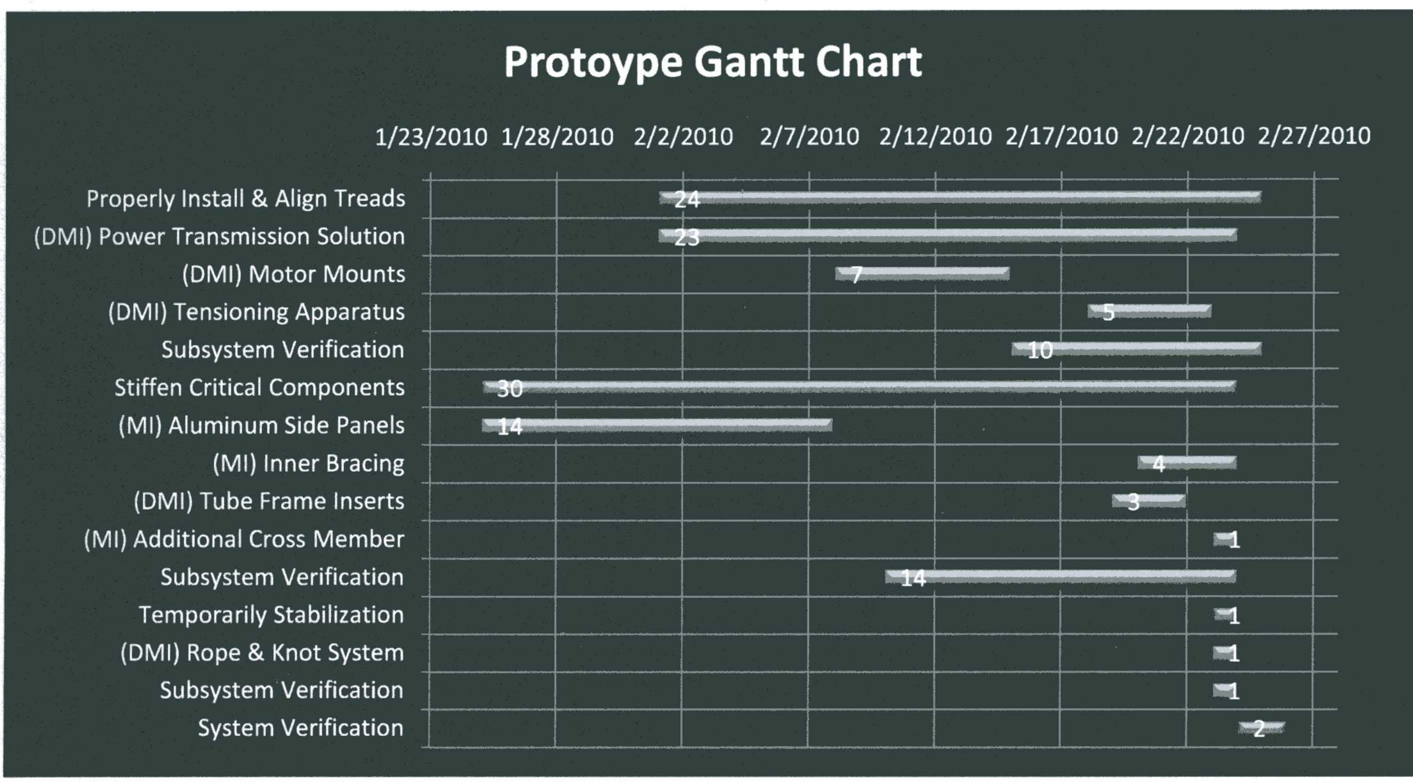


Figure F.2: Prototype Gantt Chart

Table F.3: Excavator Drive Subsystem Schedule

New Excavator Drive

Task	Start Date	Duration	End Date
(DMIV) 2 Motor Drive System	**2/26/2010**	**31**	**3/29/2010**
Design 2MDS	2/26/2010	3	3/1/2010
Manufacture 2MDS	3/15/2010	3	3/18/2010
Install 2MDS	3/17/2010	6	3/23/2010
Verify 2MDS	3/26/2010	2	3/28/2010
(DMIV) 4 Motor Drive System	**3/28/2010**	**26**	**4/23/2010**
Design 4MDS	3/28/2010	2	3/30/2010
Manufacture 4MDS	4/15/2010	7	4/22/2010
Install 4MDS	4/18/2010	6	4/24/2010
Verify 4MDS	4/24/2010	7	5/1/2010
(DMIV) Tread Tensioner	**3/29/2010**	**25**	**4/23/2010**
Design TT	3/29/2010	14	4/12/2010
Manufacture TT	4/16/2010	5	4/21/2010
Install TT	4/20/2010	2	4/22/2010

KEY
Jamie
Mark
Ray
All (See Designated Tab)

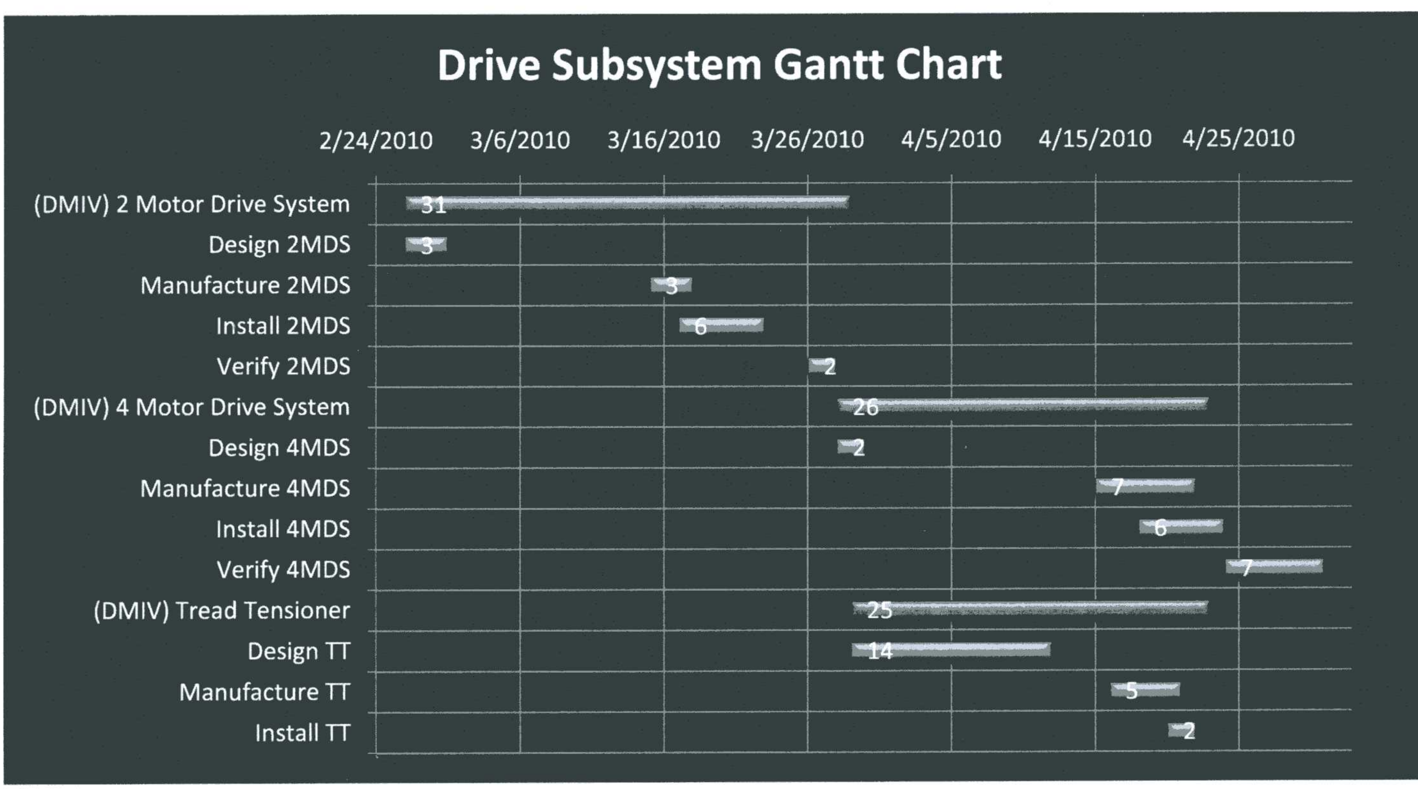


Figure F.3: Excavator Drive Subsystem Gantt Chart

Table F.3: Excavator Frame Subsystem Schedule

Frame

Task	Start Date	Duration	End Date
(DMIV) Frame Skeleton	**2/26/2010**	**29**	**3/27/2010**
Design FS	2/26/2010	12	3/10/2010
Manufacture FS	3/12/2010	3	3/15/2010
Install FS	3/14/2010	3	3/17/2010
Verify FS	3/17/2010	10	3/27/2010
(DMIV) Frame Exoskeleton (2MDS)	**2/26/2010**	**25**	**3/23/2010**
Design FE	2/26/2010	12	3/10/2010
Manufacture FE	3/11/2010	2	3/13/2010
Install FE	3/19/2010	3	3/22/2010
Verify FE	3/22/2010	1	3/23/2010
(DMIV) Frame Exoskeleton (4MDS)	**3/28/2010**	**28**	**4/25/2010**
Design FE	3/28/2010	2	3/30/2010
Manufacture FE	4/15/2010	2	4/17/2010
Install FE	4/16/2010	1	4/17/2010
Verify FE	4/24/2010	1	4/25/2010

KEY
Jamie
Mark
Ray
All (See Designated Tab)

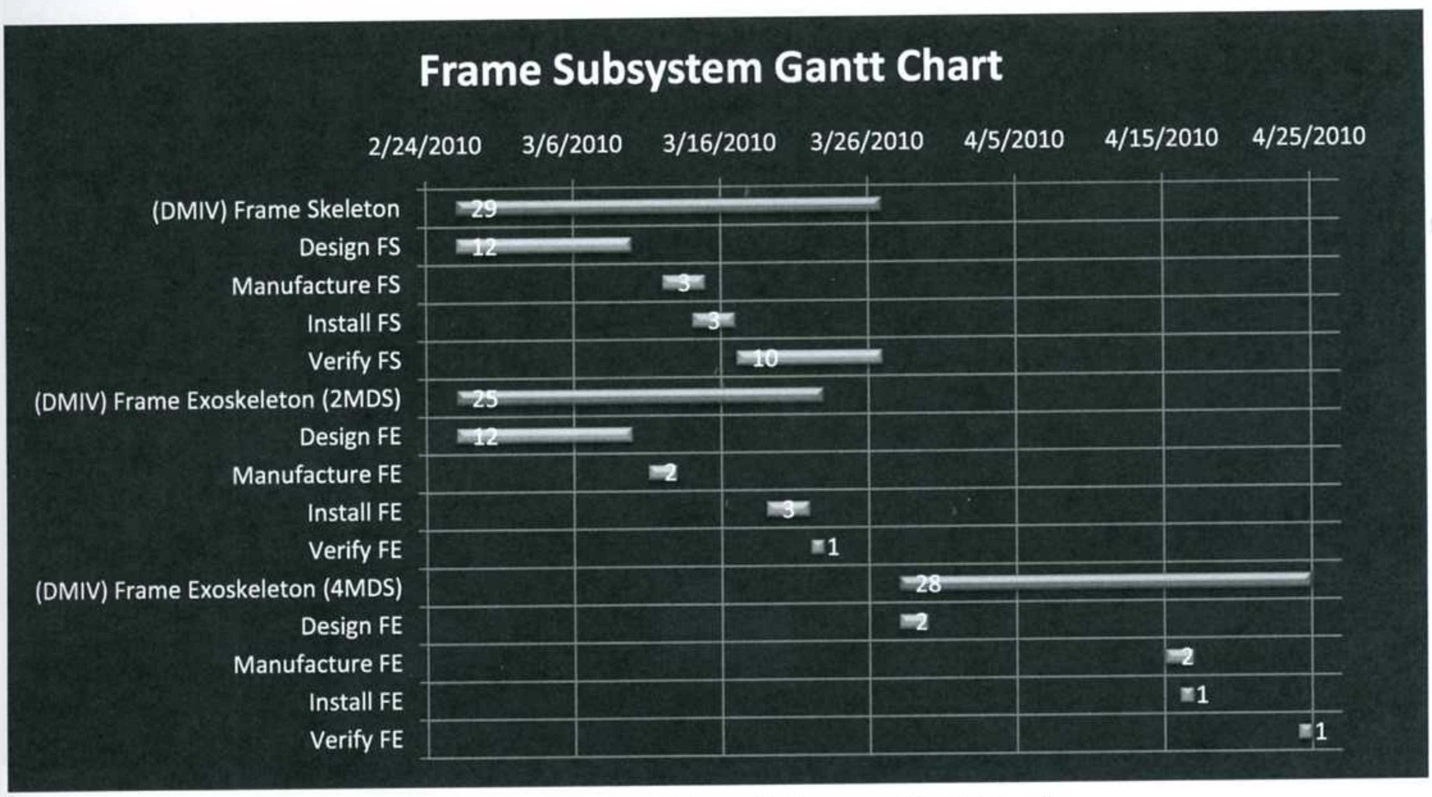


Figure F.4: Excavator Frame Subsystem Gantt Chart

Table F.3: Excavator Digger Arm Subsystem Schedule

Digger Arm

Task	Start Date	Duration	End Date	
(DMIV) Arm Boom	**3/5/2010**	**56**	**4/30/2010**	KEY
Design AB	3/5/2010	40	4/14/2010	Jamie
Manufacture AB	4/16/2010	4	4/20/2010	Mark
Install AB	4/18/2010	6	4/24/2010	Ray
Verify AB	4/25/2010	5	4/30/2010	All (See Designated Tab)
(DMIV) Bucket	**3/30/2010**	**32**	**5/1/2010**	
Design B	3/30/2010	14	4/13/2010	
Manufacture B	4/16/2010	6	4/22/2010	
Install B	4/22/2010	3	4/25/2010	
Verify B	4/25/2010	6	5/1/2010	

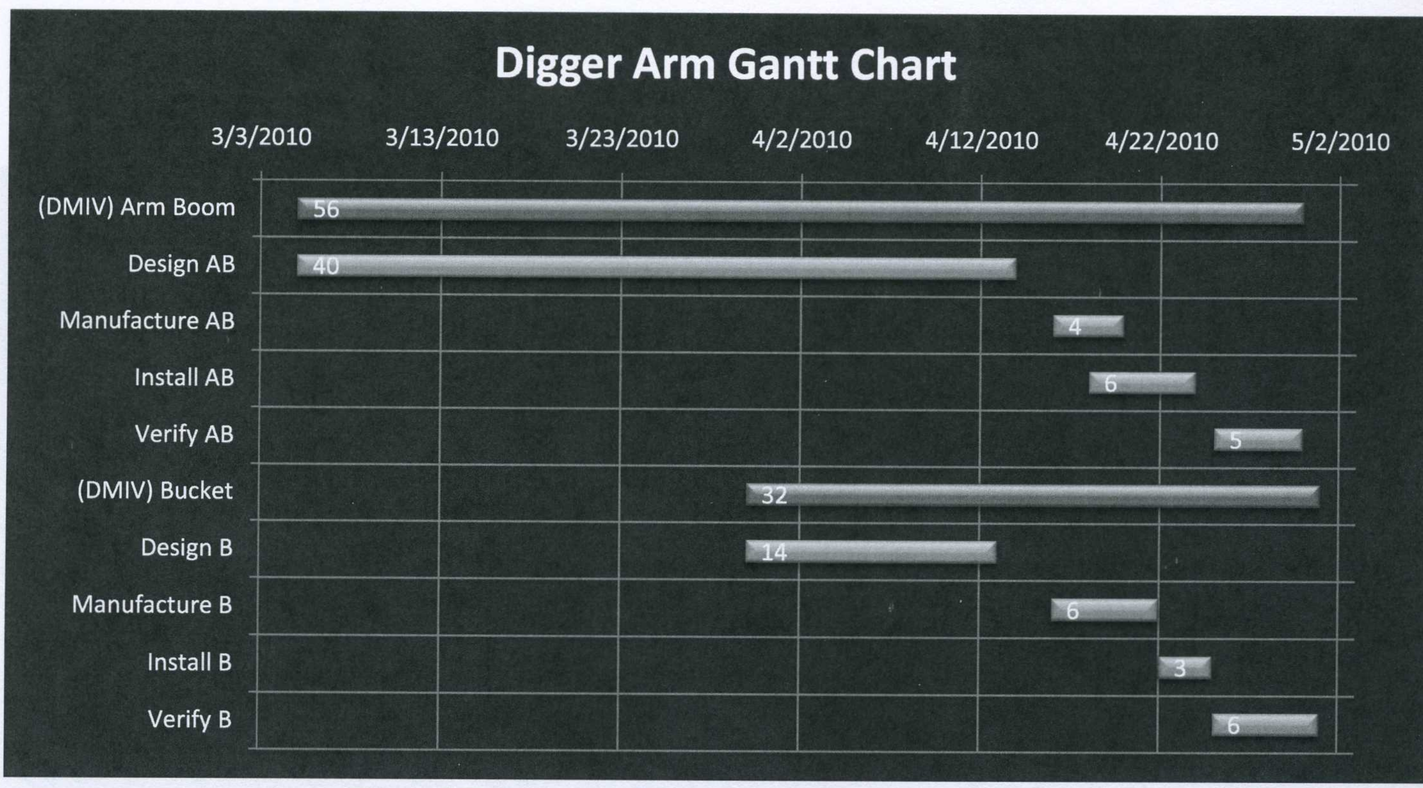


Figure F.5: Excavator Digger Arm Subsystem Gantt Chart

Table F.4: Excavator Electrical Subsystem Schedule

Electrical Subsystem

Task	Start Date	Duration	End Date	
ELECTRICAL SYSTEM				KEY
Component Selection	2/26/2010	17	3/15/2010	Mike
Power Distribution	3/3/2010	6	3/9/2010	Eddie
Component Integration	3/10/2010	15	3/25/2010	William
Complete System Testing	3/15/2010	37	4/21/2010	All Team Members
Power System Wiring	3/28/2010	14	4/11/2010	
Control System Wiring	4/10/2010	5	4/15/2010	
Base Station Software	3/29/2010	18	4/16/2010	
Arduino Programming	4/13/2010	8	4/21/2010	
Control Refinements	4/20/2010	5	4/25/2010	

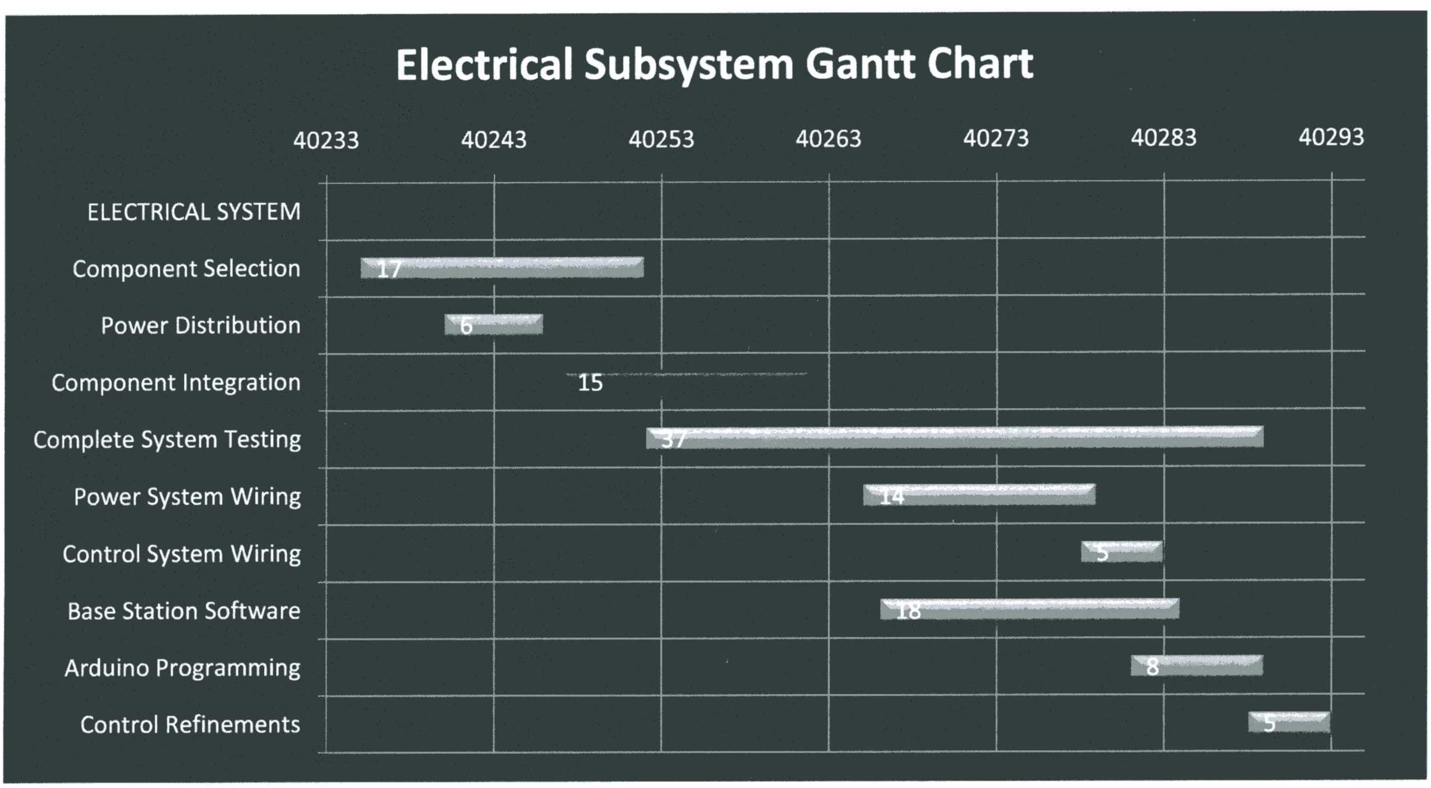


Figure F.6: Excavator Electrical Subsystem Gantt Chart

APPENDIX G: Budget

Table G.1: System Budget

#	Part #	Description	UC	Q	EC	Source
1	2469K4	Metric One-Piece Clamp-on Shaft Coupling Steel	$29.39	4	$117.56	McMaster
2	7321K1	ANSI Roller Chain Attachment, Connecting Link Style A-1 for #35 Chain	$1.67	4	$6.68	McMaster
3	6261K151	Standard ANSI Roller Chain, #35, Single Strand, 3/8" Pitch, Rollerless, .2" Diameter, 10' L	$28.80	1	$28.80	McMaster
4	2299K316	Machinable-Bore Flat Sprocket for #35 Chain, 3/8" Pitch, 30 Teeth, 1/2" min Bore	$9.45	4	$37.80	McMaster
5	O-HUB21235	Die Cast Hub, 3-3/4" x 1/2" bore	$8.99	4	$35.96	Robotmarketplace.com
6	4302	2 Hole Standard Inside Corner Bracket	$2.95	42	$123.90	8020 Inc.
7	4332	2 Hole Inside Corner Gusset	$4.30	6	$25.80	8020 Inc.
8	4306	3 Hole Joining Strip	$4.40	6	$26.40	8020 Inc.
9	4350	4 Hole 90 Degree Joining Plate	$5.60	6	$33.60	8020 Inc.
10	4330	6 Hole 30 Degree Joining Plate	$7.10	6	$42.60	8020 Inc.
11	4390	3 Hole Pivot Plate	$11.50	6	$69.00	8020 Inc.
12	2315T518	Phenolic Wheel 4" x 2", 1/2" & 3/4" Axle, Roller Beraing, 800 Lb Cap	$8.44	4	$33.76	McMaster
13	1688K17	PTFE-Lubricated SAE 841 Bronze Sleeve Brng for 1/2" Shaft Diameter, 5/8" OD, 1" L	$0.98	8	$7.84	McMaster
14	94150A325	Metric Type 316 Stainless Steel Hex Nut M3 Size, .5mm Pitch, 5.5mm Width, 2.4mm Height, packs of 50	$2.19	2	$4.38	McMaster
15	8670T7	Shell Grease Lithiium, Alvania EP, 14.1-oz Grease Gun Cartrige	$3.12	1	$3.12	McMaster
16	8947A224	118 Degree Point HSS Short Length Drill Bit B/O, 39/64", 4-1/4" L Overall	$22.31	1	$22.31	McMaster
17	3087A59	Chucking Reemer HSS, Undersize, .6240" Diameter, .5620" Shank Dia.	$32.36	1	$32.36	McMaster
18	92949A594	18/8 SS BHSCS 5/16-18, 3" Pack of 5	$8.42	2	$16.84	McMaster
19	90652A030	Nylon Insert Thin 5/16-18 Hex Lock Nut pack of 100	$10.30	2	$20.60	McMaster
20	91255A581	BHSCS 5/16-18, 3/4" pack of 50	$10.36	3	$31.08	McMaster
21	8973K33	3003 AL .100" thick 24" x 36"	$44.29	2	$88.58	McMaster
22	97447A315	AL Rivets 1/8" Dia, 1/4" Grip, pack of 250	$9.42	2	$18.84	McMaster
23	6359K32	Cast Iron Base Mounted Babbitt-Lined Bearing Split, for 1/2" Shaft Diameter	$42.13	4	$168.52	McMaster
24	9120K15	Galvanized Low-Carbon Steel Rod 1/2" Diameter, 3' Length	$9.67	4	$38.68	McMaster
25	9946K15	Aluminum Set Screw Shaft Collar 1/2" Bore, 1" O.D., 7/16" Width	$2.05	16	$32.80	McMaster

26	NC13770	Sprocket, 35B10, 12mm Bore	$44.48	2	$88.96	Parts Town
27		Various Items from Lowes	$45.00	1	$45.00	Lowes Home Improvement
28	1139545	M5-0.8 x 12 12.9 SCHS	$7.85	1	$7.85	Fastenal
29	LA-12V26Ah (D)	Sealed Lead Acid Battery 12V 26AH for Wheel Chair	$59.95	2	$119.90	Batteryspace.com
30		Sabertooth 2x10 Motor Controler	$79.99	2	$159.98	Dimension Engineering
31		14Ga Wire	$4.69	2	$9.38	Home Depot
32		Alligator Clips	$3.49	1	$3.49	Home Depot
33		14Ga Terminal Disconnects	$2.99	1	$ 2.99	Home Depot
34		14Ga Terminal Ring Connectors	$6.78	1	$6.78	Home Depot
35		4" Zip Ties	$1.91	1	$1.91	Home Depot
36	NC13770	Sprocket, 35B10, 12mm Bore	$ 44.48	2	$88.96	Parts Town
37	TE-097-320	24V 10000 mAHr NiMH Battery Pack	$259.50	2	$519.00	Super Driod Robots
38	TE-088-210	12V 2200 mAHr NiMH 2x5 Battery Pack	$23.90	1	$23.90	Super Driod Robots
39	TE-106-024	Smart Charger for 19.2V - 24V NiMH and NiCad	$29.95	2	$59.90	Super Driod Robots
40	TE-106-018	Smart Charger for 9.6V - 18V NiMH and NiCad	$28.95	1	$28.95	Super Driod Robots
41	92005A116	Metri Pan Head Phillips Machine Screw, Zinc-Plated Steel, M3 Size, 6mm Length, .5mm Pitch, Packs of 100	$2.30	1	$2.30	McMaster
42	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Red, Packs of 5	$3.04	10	$30.40	McMaster
43	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Black, Packs of 5	$3.04	10	$30.40	McMaster
44	7587K461	Stranded Single-Conductor Wire, UL 1015, 14 Awg, 600 VAC, Red, 100' Length	$35.16	1	$35.16	McMaster
45	7587K65	Stranded Single-Conductor Wire UL 1015, 14 Awg, 600 VAC, Black, 100' Length	$35.16	1	$35.16	McMaster
46	7964K634	Solid Single-Conductor Wire UL 1015, 22 Awg, 600 VAC, White	$10.80	1	$10.80	McMaster
47	7243K116	Fully Insulated Quick-Disconnect Terminal Dbl Crimp Fem, 16-14 Awg,.187" W, .02" Thk Tab, 600V	$7.36	1	$7.36	McMaster
48	8973K33	3003 AL .100" thick 24" x 36"	$44.29	3	$132.87	McMaster
49	8982K21	Multipurpose Aluminum (Alloy 6061) 90 Deg Angle, 1/8" Thick, 1" X 1" Legs, 8' Length	$12.63	2	$25.26	McMaster
50	8910K121	Low-Carbon Steel Rectangular Bar 1/8" Thick, 2" Width, 6' Length	$18.47	1	$18.47	McMaster
51	97526A404	Choose-A-Color Blind Rivet Domed, 3/16" Dia, .126"-.250" Material Thk, Gray, Packs of 100	$7.00	2	$14.00	McMaster

52	98777A213	High-Strength Zinc-Plated Steel Blind Rivet Dome, 3/16" Dia, 0.251"-0.375" Material Thickness, Packs of 25	$8.64	1	$8.64	McMaster
53	91255A581	Alloy Steel Button Head Socket Cap Screw 5/16"-18 Thread, 3/4" Length, Packs of 50	$10.36	1	$10.36	McMaster
54	90652A030	Nylon-Insert Extra-Wide Thin Hex Locknut Zinc-Plated Grade 2 Steel, 5/16"-18 Thread Size, Packs of 100	$10.30	1	$ 10.30	McMaster
55	91259A540	Alloy Steel Shoulder Screw 1/4" Shoulder Dia, 3/4" L Shoulder, 10-24 Thread	$1.03	4	$4.12	McMaster
56	91259A626	Alloy Steel Shoulder Screw 3/8" Shoulder Dia, 1-1/4" L Shoulder, 5/16"-18 Thrd	$1.50	3	$4.50	McMaster
57	5183T11	Blade-Style Fuse Block for 6 Atc, AF, OR Ato/257 Fuses, 32 VDC	$41.44	1	$41.44	McMaster
58	60225K14	Belt and Roller Chain Tensioner Horizontal-Mount, 3/8" Idler Bore, Manually Adjust	$51.78	2	$103.56	McMaster
59	6231K12	Flat-Belt Pulley Finished Bore, 1-1/2" Belt Width, 2" OD, 2" Width	$56.49	2	$112.98	McMaster
60	91309A730	Znc-Pltd Stl Low-Strength Hex Head Cap Screw 1/2"-13 Thread, 4-1/2" Length, Fully Threaded	$7.48	1	$7.48	McMaster
61	98026A033	Zinc & Yellow Grade 8 Steel USS Flat Washer 1/2" Screw Size, 1-3/8" OD, .09"-.18" Thick	$7.14	1	$7.14	McMaster
62	97135A250	Grade 8 Steel Nylon-Insert Hex Locknut Znc-Yellow Pltd, 1/2"-13 Thrd Sz, 3/4" W, 19/32" H	$3.28	1	$3.28	McMaster
63	4345	6 Hole 45 Degree Joining Plate	$7.10	4	$28.40	8020 Inc.
64	4390	3 Hole Pivot Plate	$11.50	6	$69.00	8020 Inc.
65	4376	3 Hole Inside Corner Bracket	$4.15	4	$16.60	8020 Inc.
66	RB-Ard-13	Arduino Mega	$64.77	1	$64.77	Robotshops.us
72	98320A004	Zinc-Plated Steel Ring-Grip Quick-Release Pin 3/16" Diameter, 0.4" Usable Length	$1.30	10	$13.00	McMaster
76	SDA11.3-.98	1010 lbs. Thrust Linear Actuator	$399.99	1	$399.99	ServoCity.Com
77	8880T35	Extended Length Steel U-Bolt, 3/8"-16 Thread, for 2" O.D. 1090#WII, pack of 5	$8.34	1	$8.34	McMaster
78	3042T14	Clampling U-Bolt Steel, 3/8"-16 Thread, for 2"O.D.	$2.07	3	$6.21	McMaster
79	8982K62	Multipurpose Aluminum (6061) 90 Deg Angle, 1/4" Thick, 3"x3" Legs, 4' Length	$32.59	1	$32.59	McMaster
81	PRT-08812	3" Proto Board	$4.50	2	$9.00	SparkFun.com
82	PRT-08076	5-pin Spring Terminals	$1.50	4	$6.00	SparkFun.com
84	Sabertooth 2x10	Sabertooth 2x10A Motor Controller	$79.99	1	$79.99	Dimension Engineering
85	PicoPSU-80-WI-32V	12-32V input DC-DC ATX power supply unit (PSU)	$55.95	1	$55.95	mini-box.com

86		20 Pin ATX Extension Cable	$5.95	1	$5.95	mini-box.com
87	TD-036-136	IG52-04 24VDC 136 RPM Gear Motor	$123.12	4	$492.48	Super Droid Robots
			Total		$3,779.02	

APPENDIX H: Contracts of Deliverables Examples

Contract of Deliverable

Contract Title: Prototype Motor Mount
Contract Number: MPK001
Team: Corp_2 NASA ESMD Lunabotics Mining Competition
Student Name: Mark P. Keske
Date: 18 February 2010

Task: Design, manufacture, install, and verify an internal motor mount for the prototype drive subsystem in preparation for the E-Day system verification. The motors are expected to still experience deflections large enough to cause tread derailing after the installation of an aluminum side panel (COD-C1).

The design solutions are as follows:

- Install a rigid motor mount that will be placed in between the end of the motor located inside the prototype and the inside bottom panel of the prototype. The design will consist of a u-bolt with clamping mount plate on top of a balsa wood spacer.

The manufacturing processes are as follows:

- The u-bolts and necessary hardware will be purchased. The balsa spacers will be manufactured using a cutting knife and hand operated power tools. Holes will be drilled in the bottom panel of the prototype according to desired u-bolt placement.

The installation processes are as follows:

- The motor mounts will be installed after the motors have been installed into the side panels.

The verification processes are as follows:

- The motor mount will be verified through physical deflection tests and tread alignment

The deliverables for this contract include:

- Motor Mount DMIV

Interfacing Plan: The prototype drive motor mount will be designed in accordance with the prototype frame design. The motor mount bolt holes will be placed according to the specified location of the side panel motor mount hole (COD C1). The verification of the motor mounts is dependent upon the completion of the Prototype Frame Modifications (COD C1).

Delivery Date: 26 February 2010

Student's Signature	Manager's Signature	____Optional______ Instructor's Signature

Figure H.1: Contract MPK001, Prototype Motor Mount

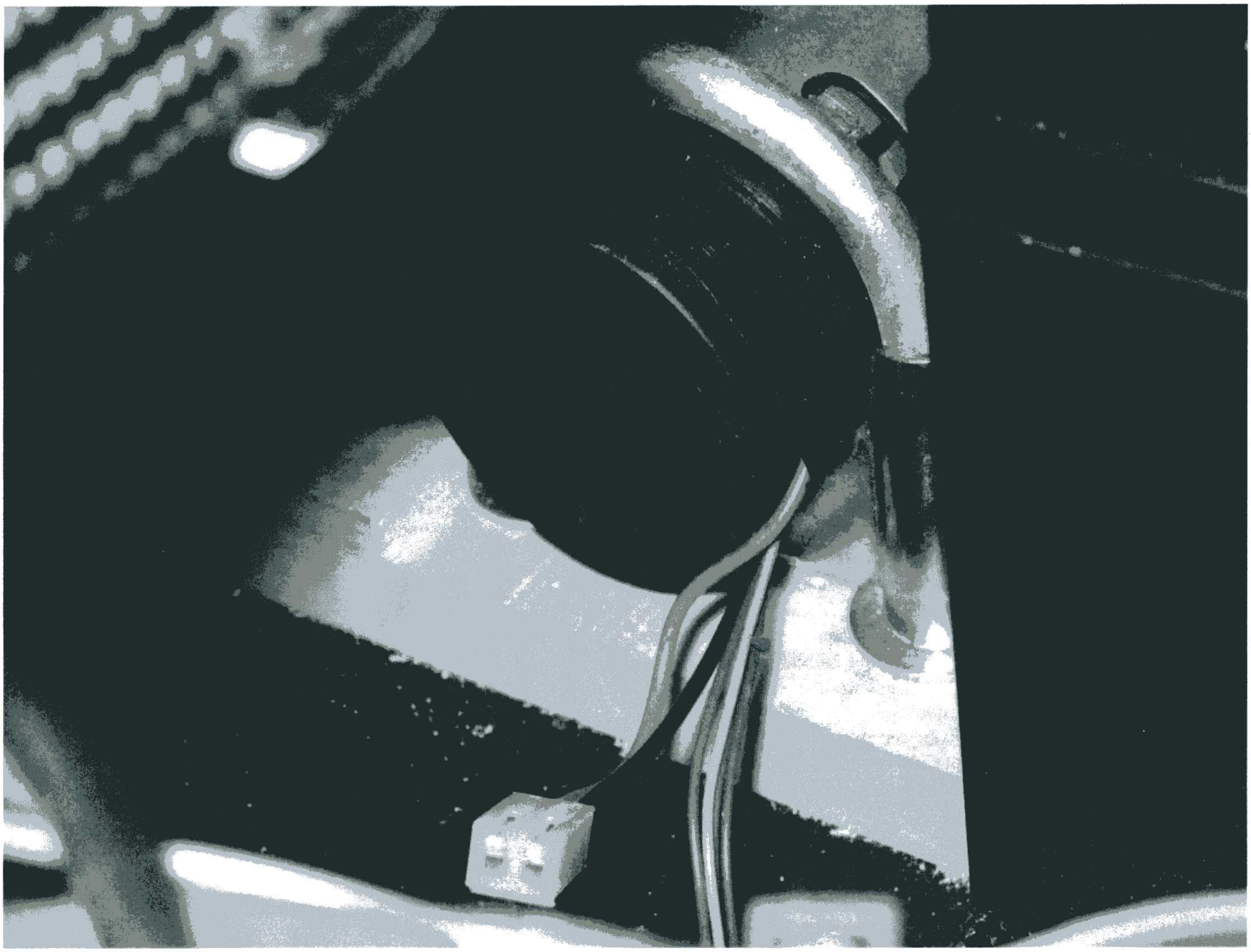


Figure H.2: Contract MPK001, Prototype Motor Mount Deliverable

Contract of Deliverable

Contract Title: Collaborative Prototype Frame Modification
Contract Number: C1
Team: Corp_2 NASA ESMD Lunabotics Mining Competition
Student Name: Jameson Colbert and Mark P. Keske
Date: 02 February 2010

Task: Design, manufacture, install, and verify prototype excavator frame modifications in preparation for the E-Day system verification. The prototype excavator frame subsystem experiences high deflections under loading from the prototype drive subsystem interface. Areas of significant importance include the G-10 Garolite side panel to which the drive motor and drive wheel are directly mounted, the hollow carbon fiber tubes to which the front wheel shafts are mounted, and the hollow carbon fiber tubes which support the tension in the treads. The location of internal cross members is also an area of importance due to drive subsystem motor mount bolt pattern (COD-MPK001).

The design solutions are as follows:

- The G-10 side panels will be replaced with 1/8" 6061 aluminum side panels in order to reduce the deflections experienced from flat plate bending.
- The hollow tube carbon fiber front members will be reinforced with internal bracing made of balsa wood in order to increase compression and torsional rigidity of the members.
- A 90 degree aluminum reinforcement member will be installed between the front left and front right members in order to provide greater bending rigidity.
- Translate internal carbon fiber cross members such that the motor mount u-bolt can be installed

The manufacturing processes are as follows:

- The aluminum side panels will be manufactured from oversized aluminum sheet metal. The overall dimensions of the side panels will be machined using the DML, and the rivet holes and motor mount hole locations will be transferred from the G-10 side panel. The holes will then be drilled to size.
- The balsa inserts will be manufactured using previous prototype mock-up material which already has the correct outer dimensions. Radii will be cut into the corners of the balsa inserts using a knife blade, and through holes will be drilled for the wheel shaft mount bolts. Channels will also be cut along the sides to provide clearance for the rivets along the inside of the frame.
- The aluminum cross member will be cut to the proper length dimension, and holes will be drilled for mounting at the wheel shaft mount.
- The internal carbon fiber cross member rivets will be drilled out. The members will then be translated, and the rivet hole locations transferred from the cross members to the bottom panel of the excavator body. The bottom panel will then be drilled to hole specification.

The installation process for the proposed design solutions are as follows:

Figure H.3.A: Contract C1, Collaborative Prototype Frame Modification

- The G-10 side panels will be removed, and the aluminum side panels will be riveted in place.
- The front wheel shaft mounts will be unbolted and removed, and the balsa inserts will be slid into place from the front of the carbon fiber tube. The wheel shafts will then be reinstalled with the bolts going through the balsa insert.
- One nut from each front wheel shaft mount will be removed, and the aluminum cross member will be mounted onto the front wheel shaft mount bolts. The nut will then be reinstalled.
- The cross members will be re-riveted in place after translation.

The verification procedure for the design solutions include:

- Side Panel verification will include FEMAP analysis of flat plate bending in aluminum vs. G-10, and physical deflection tests
- Balsa insert verification will include physical deflection tests
- Aluminum cross member verification will include physical deflection tests
- The translated cross members will be verified through mating / fitment of the drive motor mounts

The deliverables for this contract include:

- Side Panel DMIV
- Balsa Insert DMIV
- Aluminum cross member DMIV
- Translated carbon fiber V
- Frame rigidity verification through tread subsystem verification

Interfacing Plan:

The prototype frame modifications will be made in collaboration with Jameson Colbert and the prototype drive modifications. The location of the rivet and mount holes in the side panels will not be changed in order to maintain previously verified tread tension. The holes in the balsa wood inserts will be dimensioned according to the hole dimensions of the front wheel shaft mount in the drive subsystem. The holes in the aluminum cross member will be dimensioned according to the wheel shaft mount location on the frame subsystem. The location of the translated internal carbon fiber mounts will be driven by the location of the motor mount bolt holes (COD-MPK001). The side panel shall accommodate for the belt tensioner subsystem (COD-C2). The verification of the prototype frame modifications is dependent upon the completion of the drive subsystem modifications and verification.

Delivery Date: 26 February 2010

MARK P. KESR | [signature] | Optional
Student's Signature | Manager's Signature | Instructor's Signature

Figure H.3.B: Contract C1, Collaborative Prototype Frame Modification Cont.

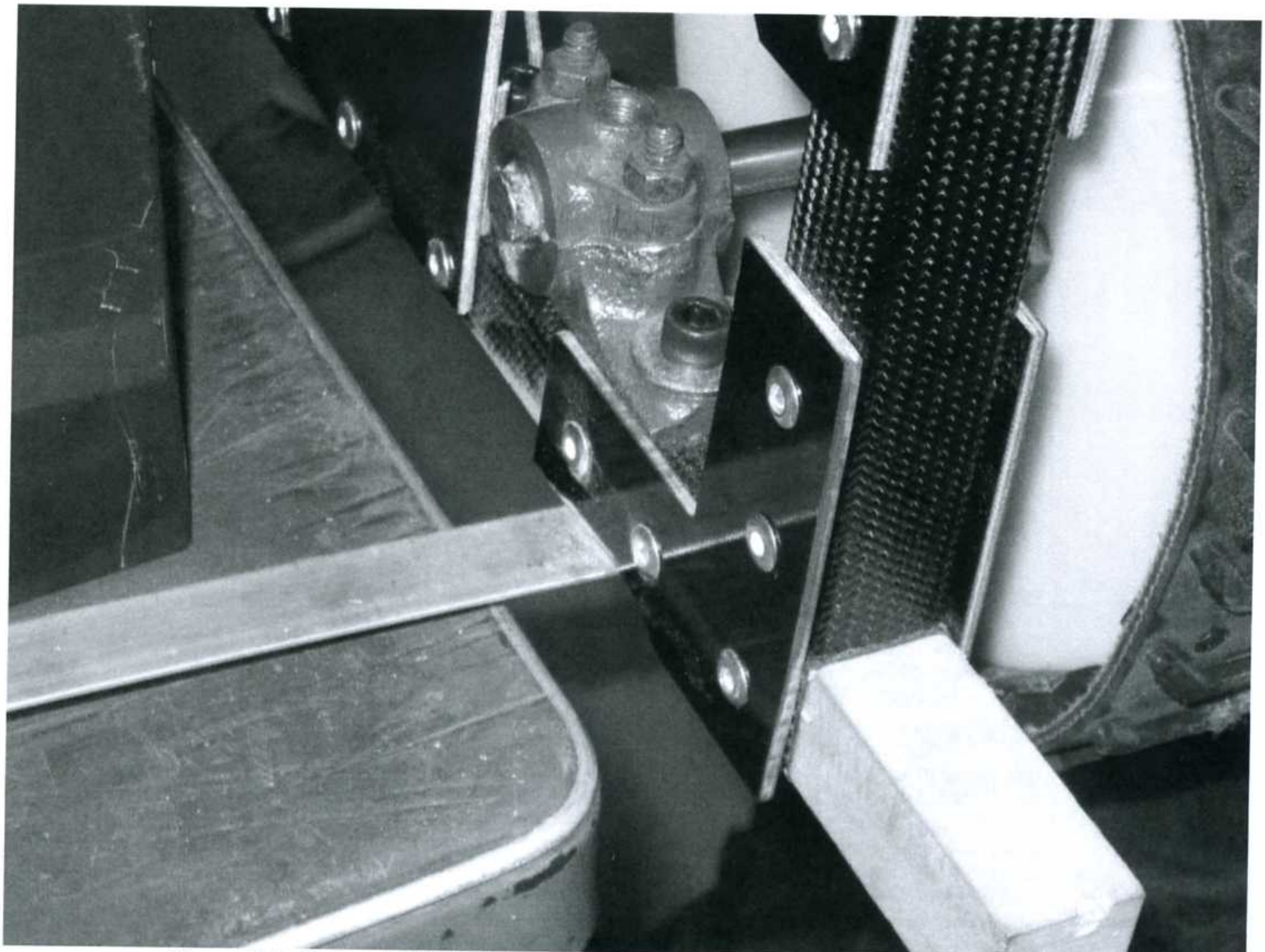


Figure H.4: Contract C1, Collaborative Prototype Frame Modification Deliverable

Contract of Deliverable

Contract Title: Collaborative Prototype Drive Component Modification
Contract Number: C2
Team: Corp_2 NASA ESMD Lunabotics Mining Competition
Student Name: Jameson Colbert and Mark P. Keske
Date: 02 February 2010

Task: Design, manufacture, install, and verify a tread tensioner and a custom motor shaft wheel hub for the prototype drive subsystem in preparation for the E-Day system verification. The prototype power transmission system failed during preliminary verification. The failure occurred in that the motor drive shaft spun freely in the drive wheel. The treads on the prototype drive subsystem were improperly tensioned causing the treads to derail.

The design solutions are as follows:

- Install a solid linkage in the form of a bolt on wheel hub between the motor drive shafts and drive wheels. The design will consist of a 12mm shaft collar welded to a flat plat with the wheel assembly bolt pattern
- Install a static idler pulley system inside the tread loop such that the idler pulley pushes up on the treads. The design will consist of a solid shaft to which the idler pulleys will be mounted. The shaft will be supported by shaft ball bearings at each end. The shaft will be mounted through the body of the excavator such that the bearings will be mounted in the hanging position from the top frame member.

The manufacturing processes are as follows:

- The 12mm shaft collars will be purchased. The square flat plate will be cut out of steel using an abrasive saw and the surface will be prepared for welding. The center of the plate will be marked and the 12mm shaft collar will be welded to the plate. The dead center of the plate is not completely necessary since the bolt pattern will be added to the flat plate after the collar is attached. The collar will be welded piecewise in order to reduce heat expansion and contraction deflections. The bolt pattern will be placed by rotating the shaft / plate on the axle of the wheel, thus scribing the bolt pattern diameter (BPD). The bolt location will be transferred onto the BDP using white out, and the holes will be drilled.
- A ½" shaft will be purchased, salvaged bearings, and salvaged idler pulleys in the form of plastic lawnmower wheels will be used. A hole will be drilled in the side panel to allow for the passing of the shaft, and two bolt holes will be drilled in the upper carbon fiber frame member for bearing mounting. The treads of the lawnmower wheels will be removed in order to obtain the desired O.D. of the idler pulley.

The installation processes are as follows:

- The wheel hubs will be first mounted onto the motor drive shafts, and then the wheels will be bolted to the wheel hubs.
- The wheel bearings will be mounted loosely in place, and the shaft will then be slid into place. Once in place, the bearings and shaft will be secured. The idler pulleys will then be slid onto the shaft and secured in place with shaft collars.

The verification processes are as follows:

Figure H.5.A: Contract C2, Collaborative Prototype Drive Modification

- The wheels hubs will be verified through visual inspection of the rotation of the wheel and tread alignment
- The belt tensioner will be verified through visual inspection of the rotation of the wheel and tread alignment

The deliverables for this contract include:
- Custom Wheel Hub DMIV
- Tensioner DMIV

Interfacing Plan: The collaborative prototype drive modifications will be made in accordance with the prototype frame design. The motor mount bolt holes will be placed according to the specified location of the side panel motor mount hole (COD-MPK001). The verification of the custom wheel Hubs and motor mounts is dependent upon the completion of the Prototype Frame Modifications (COD-C1)

Delivery Date: 26 February 2010

Student's Signature	Manager's Signature	Optional Instructor's Signature

Figure H.5.A: Contract C2, Collaborative Prototype Drive Modification Cont..

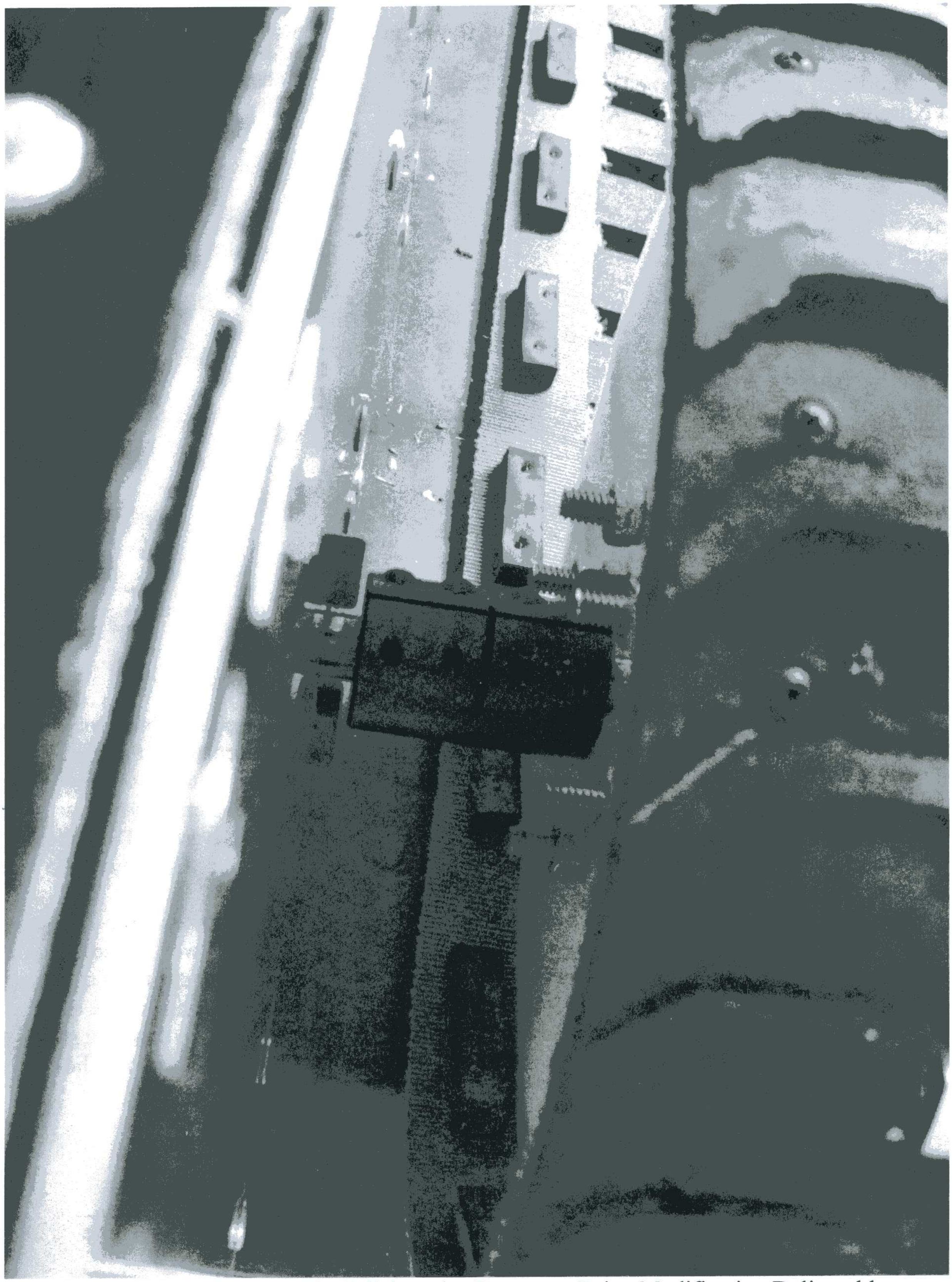


Figure H.5.A: Contract C2, Collaborative Prototype Drive Modification Deliverable

Contract of Deliverable

Contract Title: Lunar Excavator Frame Design
Contract Number: MPK001
Team: Corp_2 NASA ESMD LMC
Student Name: Mark P. Keske
Date: 26 February 2010

Task: Design a frame subsystem for the lunar excavator. The frame design shall be

- Rigid (derived from prototype testing)
- No more than 19.5 inches wide (derived from prototype testing and overall width restrictions as per Rule 24 of the Lunabotics Mining Competition Rulebook)
- Less than 30kg overall mass (derived from system mass requirements as per Rule 21 of the Lunabotics Mining Competition Rulebook)
- Easily fabricated
- Composed of salvaged parts
- Able to provide multiple subsystem interfaces, i.e. motor holes in side panels and motor mount holes in bottom panels

Deliverables: The frame shall be modeled in Solid Edge and verified against physical requirements such as rigidity, overall width, and subsystem weight prior to fabrication.

Interfacing Plan:

The frame's detailed design is driven by the interface requirements of the other subsystems. The center to center distance between wheels on the drive subsystem drives the length requirement of the frame, and the tread width drives the overall width of the frame. These and other interface issues with the drive system with be addressed with Jameson Colbert. The minimum lift height of the digger arm subsystem drives how tall the frame needs to be. This and other digger arm issues will be addressed with Ray Sylvester. The battery size and location also drives the overall length/width of the frame and will be addressed with Mike Payne and Jamie Colbert.

Conversely, the design of the other excavator subsystems cannot be completed until the design of the frame is completed and finalized. The frame, however, shall need to be adaptable as well. Other subsystems are liable to undergo addition to, or modification of their designs, and the frame will need to be able to adapt.

The placement of the motor holes and motor mount holes depends upon the design of the drive subsystem. These features cannot be dimensioned in the frame design until finalized in the drive subsystem, but the frame can be modified after assembly to accommodate for the motor holes and motor mount holes.

Delivery Dates: 10 March 2010

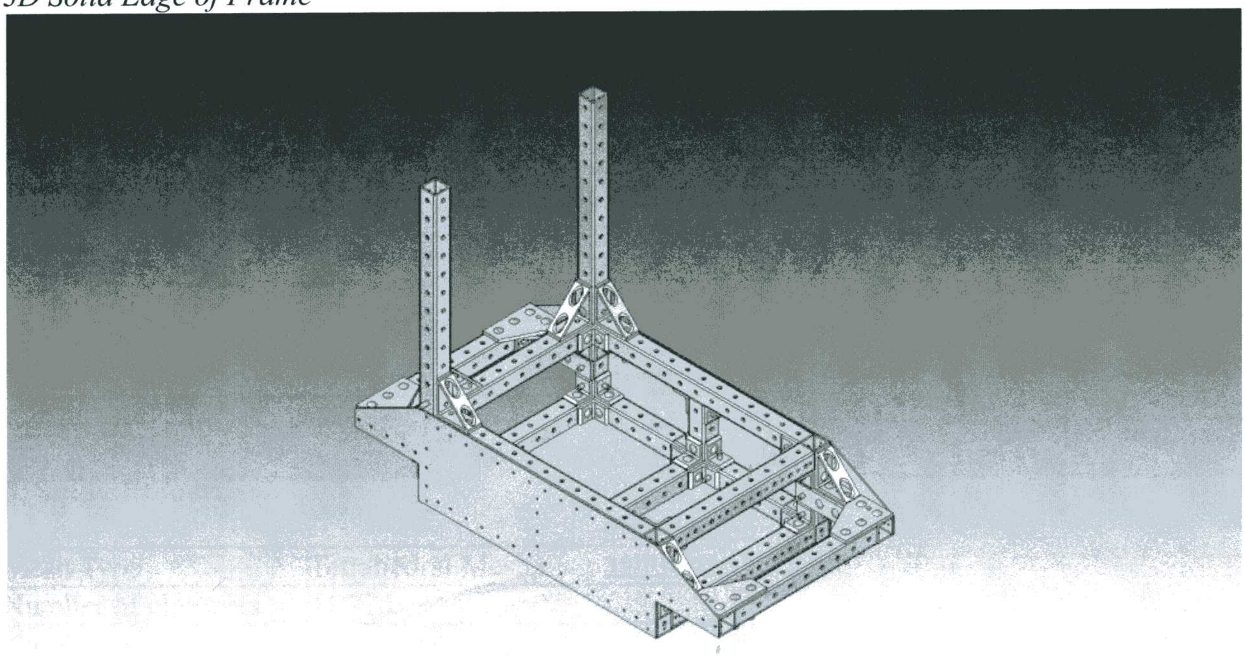
Student's Signature	Manager's Signature	Instructor's Signature

Deliverables

Detailed Drawings:

See "Frame Detailed Drawings" in Report

3D Solid Edge of Frame



FEA of 8020 Components

Corp_2

Mark P. Keske

Table of Contents

1. Introduction

2. Part Properties

Part Name	Bearing Mount Piece Draft.par
Mass	0.377 lbm
Volume	3.846 in^3
Weight	0.377 lbf

3. Material Properties

Material Name	Aluminum, 6061-T6
Mass Density	0.098 lbm/in^3
Young's Modulus	10000.000 ksi
Poisson's Ratio	0.330
Thermal Expansion Coefficient	0.0000 /F
Thermal Conductivity	104.002 BTU/hr-ft-F
Yield Strength	40.000 ksi
Ultimate Strength	45.000 ksi

4. Load and Constraint Information

Load Set

Load Set Name	Load 1
Load Type	Force
Number of Load Elements	1
Load value	50.000 lbf

Constraints

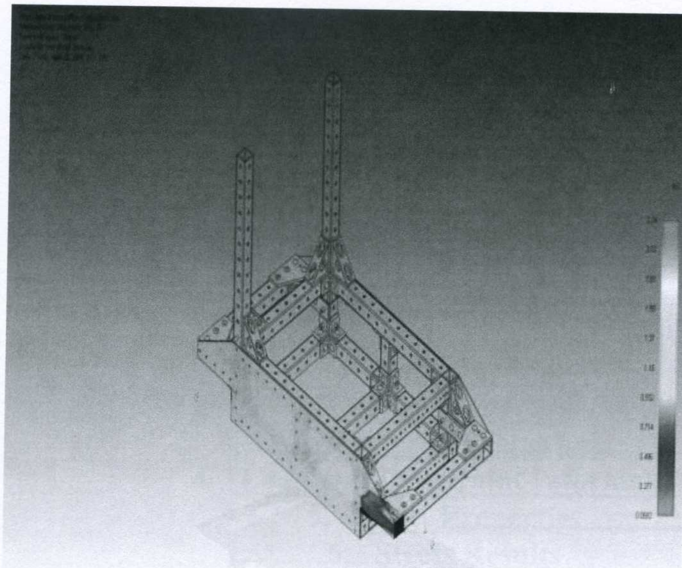
Number of Constrained Faces	1

5. Study Properties

Mesh Type	Tetrahedral Mesh
Number of elements	11,724
Number of nodes	24,141
Solver Type	Nastran

6. Stress Results

Type	Extent	Value	X	Y	Z
Von Mises Stress	Minimum	5.916e-002 ksi	-1.836 in	0.043 in	0.625 in
	Maximum	2.242e+000 ksi	2.250 in	-0.164 in	-0.750 in



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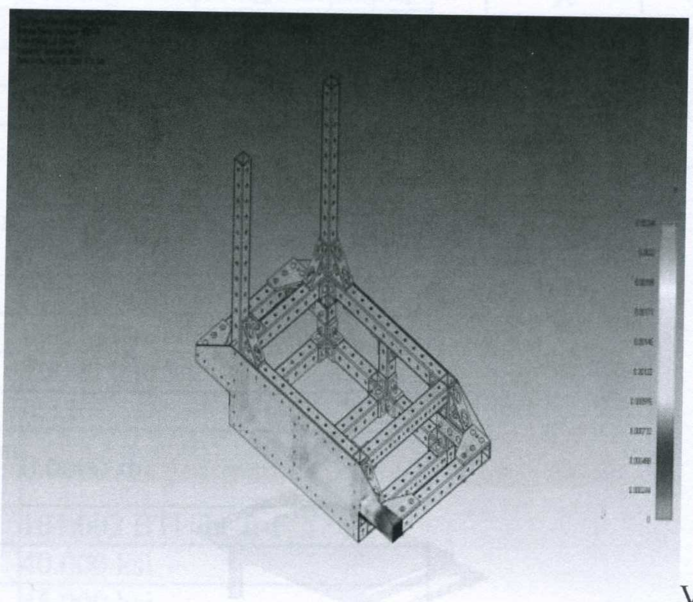
7. Displacement Results

Type	Extent	Value	X	Y	Z
Resultant Displacement	Minimum	0.000e+000 in	3.000 in	0.625 in	0.562 in
	Maximum	2.441e-003 in	-3.000 in	0.069 in	-0.750 in



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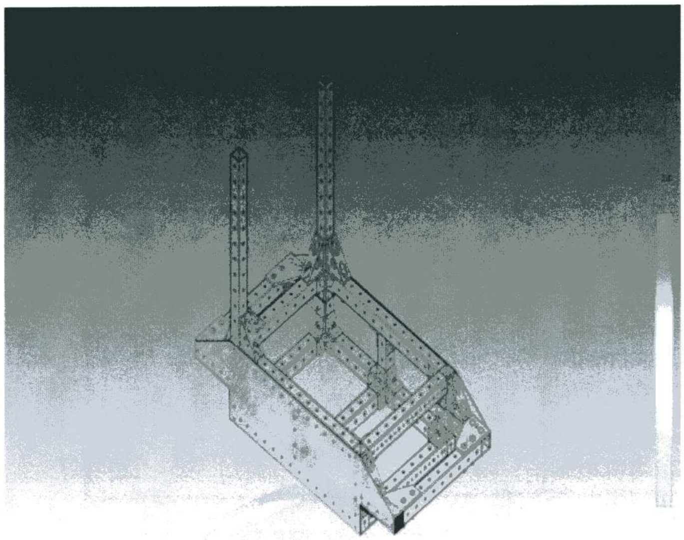
8. Factor of Safety

Factor of Safety Value	17.842



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9. Conclusion

10. Disclaimer

Important Information

This report should not be used to solely judge a design idea's suitability to a given set of environmental conditions. Siemens makes every effort to ensure that its products provide as much guidance and help as possible. However this does not replace good engineering judgment, which is always the responsibility of our users. A qualitative approach to engineering should ensure that the results of this evaluation are evaluated in conjunction with the practical experience of design engineers and analysts, and ultimately experimental test data. The results contained within this report are believed to be reliable but should not be construed as providing any sort of warranty for fitness of purpose.

Weight Inspection
Physical Properties Report

Volume= 341.740 in^3
Mass= 35.964 lbm

With respect to the Global Coordinate System.

Center Of Mass:
X= 1.022 in
Y= -7.507 in
Z= -3.558 in

Center Of Volume:
X= 1.022 in
Y= -7.503 in
Z= -3.574 in

Mass Moments Of Inertia:
Ixx= 4733.98 lbm-in^2
Iyy= 4693.91 lbm-in^2
Izz= 7216.08 lbm-in^2

Ixy= -278.21 lbm-in^2
Ixz= -475.68 lbm-in^2
Iyz= 961.08 lbm-in^2

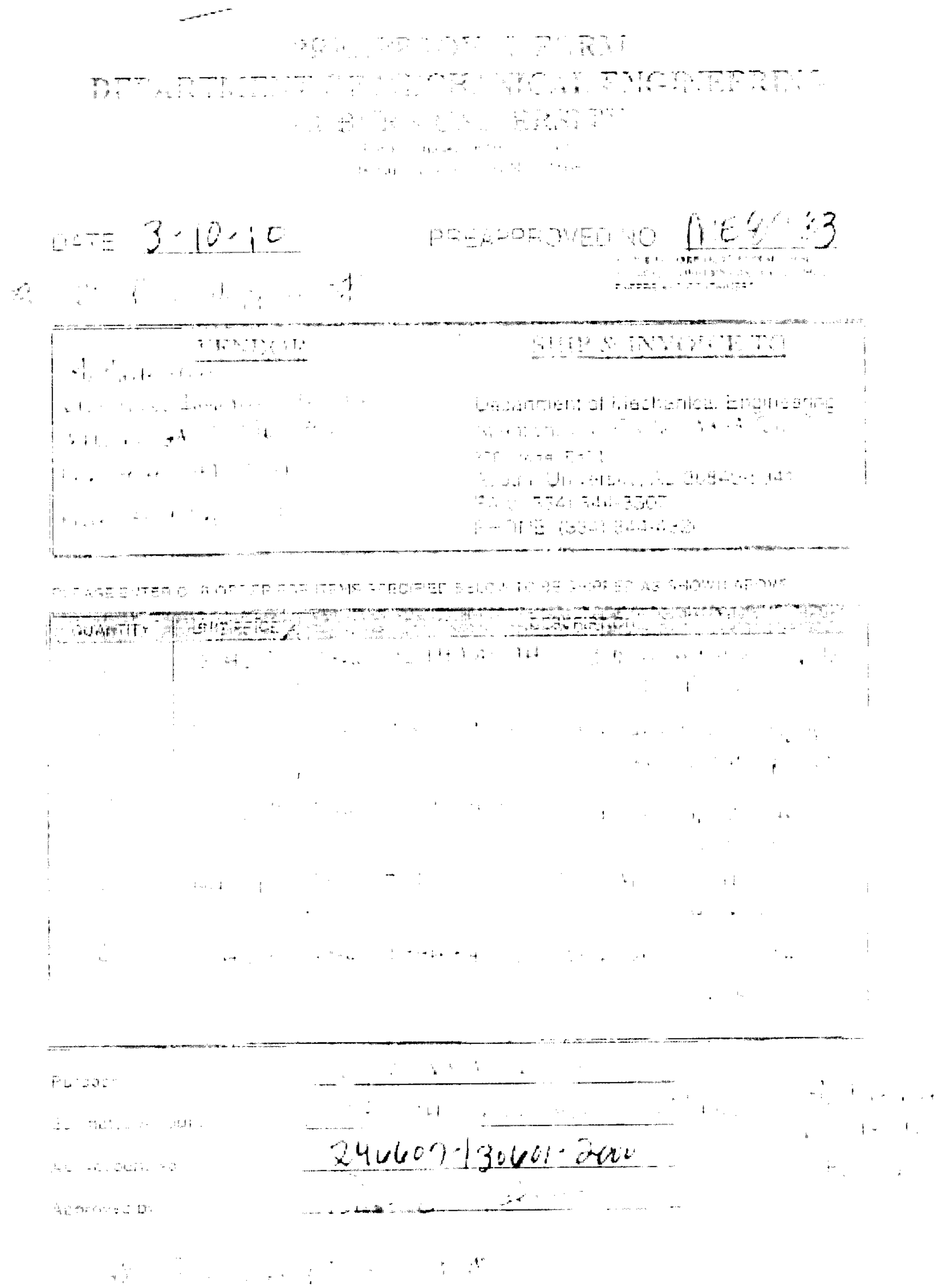
Principal Axes Orientation:

1= 0.117	0.000	0.993
2= 0.001	1.000	0.000
3= -0.993	0.001	0.117

With respect to the Principal Axes

Principle Moments Of Inertia:
I1= 5192.22 lbm-in^2
I2= 4201.20 lbm-in^2
I3= 2211.50 lbm-in^2

Radii Of Gyration :
K1= 12.015 in
K2= 10.808 in
K3= 7.842 in



DATE 3-10-10

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Department of Mechanical Engineering

QUANTITY

24060?-130601-2000

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NAME : MECHANICAL ENG.
FAX : 3348443387
TEL : 3348444820

DATE,TIME	03/10 00:35
FAX NO./NAME	*76255545[illegible]14843499091
DURATION	00:00:45
PAGE(S)	02
RESULT	OK
MODE	STANDARD

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2nd Day Ship

PLEASE ENTER OUR ORDER FOR ITEMS SPECIFIED BELOW TO BE SHIPPED AS SHOWN ABOVE.

QUANTITY	UNIT PRICE	DESCRIPTION
42	2.95	Part #. 4302 ✓ 2 Hole Standard Inside Corner Bracket
6	4.30	Part # 4332 ✓ 2 Hole Inside Corner Gusset
6	4.40	Part # 4366 ✓ 3 Hole Joining Strip
6	5.60	Part # 4350 ✓ 4 Hole 90° Joining Plate
6	7.10	Part # 4330 ✓ 6 Hole 30° Joining Plate
6	11.50	Part # 4390 ✓ 3 Hole Pivot Plate

Purpose: Corp 2 NASA Excavator

Estimated Amount: 321.30 ~~[illegible]~~ (plus shipping 2nd Day)

Must receive no later than Friday

AU Account No: 24667-130601-2000

Approved by: [signature]

★ Tax Exempt Account ★

TRANSMISSION VERIFICATION REPORT

TIME : 03/10/2010 00:44
NAME : MECHANICAL ENG.
FAX : 3348443307
TEL : 3348444020

DATE,TIME	03/10 00:44
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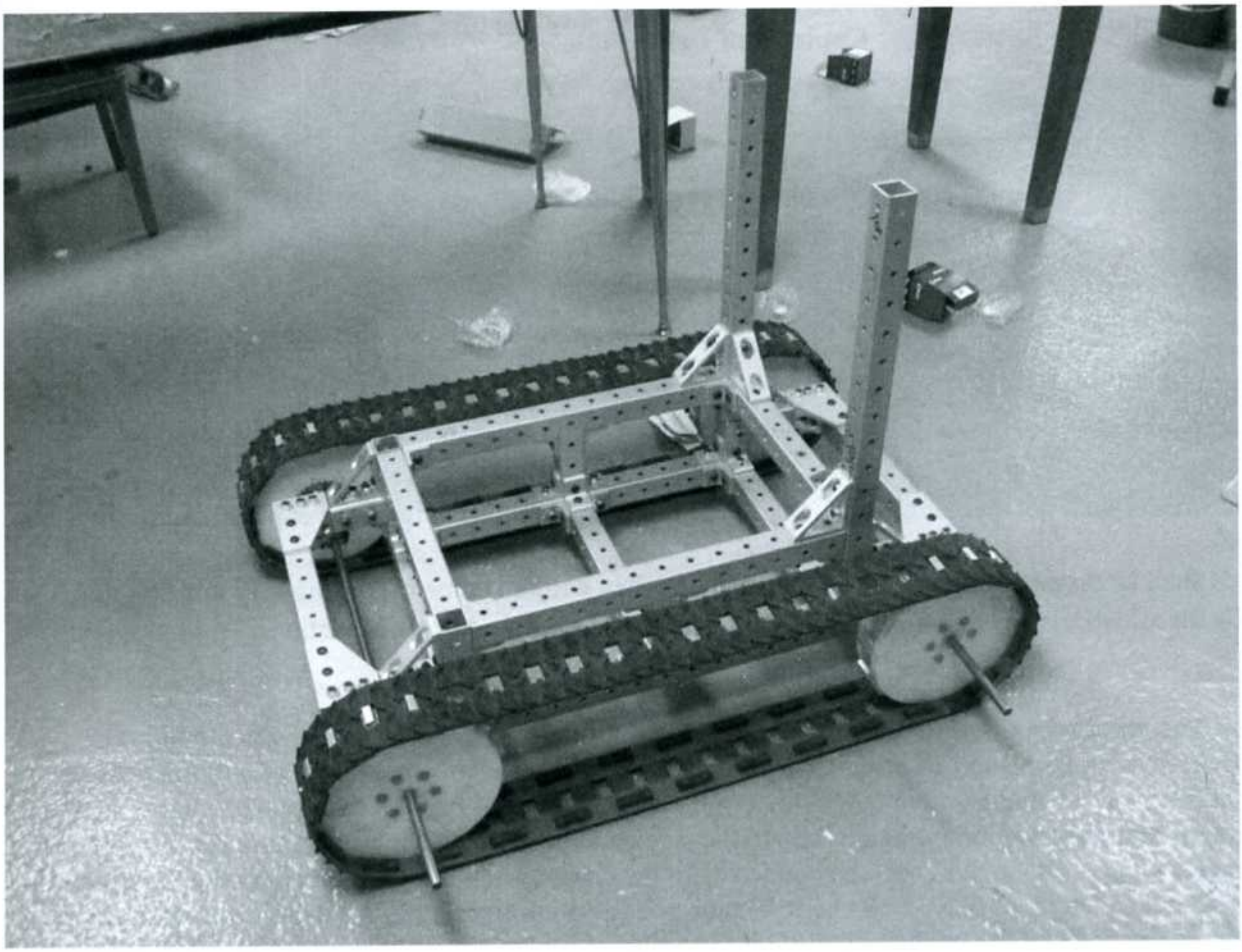


Contract of Deliverable

Contract Title: Drive System Design
Contract Number: JAC001
Team: Corp_2 NASA ESMD LMC
Student Name: Jameson Colbert
Date: 30 March 2010

Task: Design A 2 motor drive subsystem for the motion of the excavator. The drive subsystem must be able to meet the following requirements.

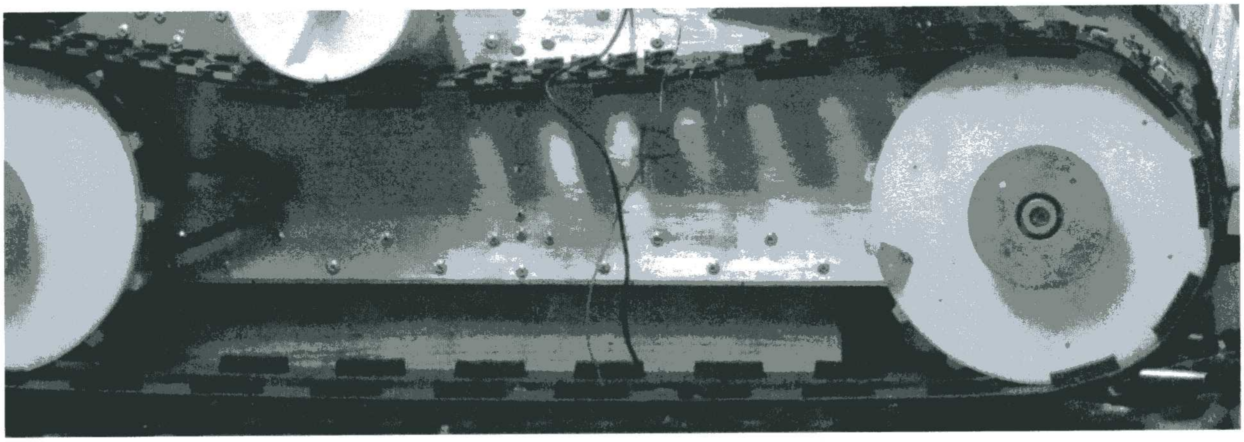
- Combined weight of all component may not exceed 20kg
- Must enable the excavator to turn "effortlessly" in grass both unloaded and with various collections of regolith. (collections will not exceed 30kg)
- The drive wheels shall not be mounted directly to the motors. (to reduce deflections experienced in the prototype)
- The treads shall be properly aligned & tensioned so that they will not come off during a 30 min test run.
- The shafts for all wheels shall be mounted such that they experience minimal deflections.

Interfacing Plan: The drive subsystem shall interface with both the frame subsystem and also the ground. The interface with the drive subsystem shall be achieved by the use of solid steel shafts that the drive and free wheels will "ride" on. The steel shafts shall be mounted to the frame by use of modified split bearings. The motors shall be mounted to the frame subsystem by mounting directly to the side panels and shall also be supported at the opposite end by use of a motor mount. The motors shall be connected to the drive wheels by use of a ten tooth spur gear, a thirty tooth sprocket, and a length of #35 ASNI chain. The drive subsystem shall interface with the ground by use of treaded tracks. The tracks shall be the same ones used by the previous design groups in the construction of the prototype.

Delivery Date: 29 March 2010

________________	________________	____Optional_____
Student's Signature	Manager's Signature	Instructor's Signature

Deliverables: Completed design 2 motor drive system.



Contract of Deliverable

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Contract Number: JAC001
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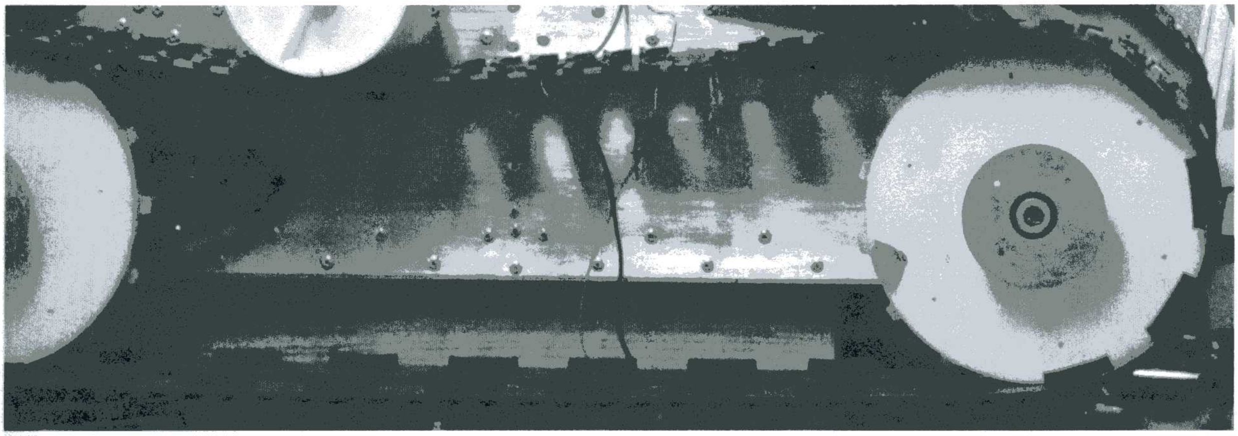
- The treads shall be properly aligned & tensioned so that they will not come off during a 30 min test run.
- The shafts for all wheels shall be mounted such that they experience minimal deflections.

Interfacing Plan: The drive subsystem shall interface with both the frame subsystem and also the ground. The interface with the drive subsystem shall be achieved by the use of solid steel shafts that the drive and free wheels will "ride" on. The steel shafts shall be mounted to the frame by use of modified split bearings. The motors shall be mounted to the frame subsystem by mounting directly to the side panels and shall also be supported at the opposite end by use of a motor mount. The motors shall be connected to the drive wheels by use of a ten tooth spur gear, a thirty tooth sprocket, and a length of #35 ASNI chain. The drive subsystem shall interface with the ground by use of treaded tracks. The tracks shall be the same ones used by the previous design groups in the construction of the prototype.

Delivery Date: 29 March 2010

________________	________________	____Optional______
Student's Signature	Manager's Signature	Instructor's Signature

Deliverables: Completed design 2 motor drive system.



Contract of Deliverable

Contract Title: Drive System Altered Design
Contract Number: JAC002
Team: Corp_2 NASA ESMD LMC
Student Name: Jameson Colbert
Date: 30 March 2010

Task: Revisit the design of the drive subsystem and add two more motors to bring the total to four. Each wheel will be drive by an independent motor. The new drive system bust still adhere to all of the previous design requirements listed below in italics, as well as the new design requirements that are not italic.

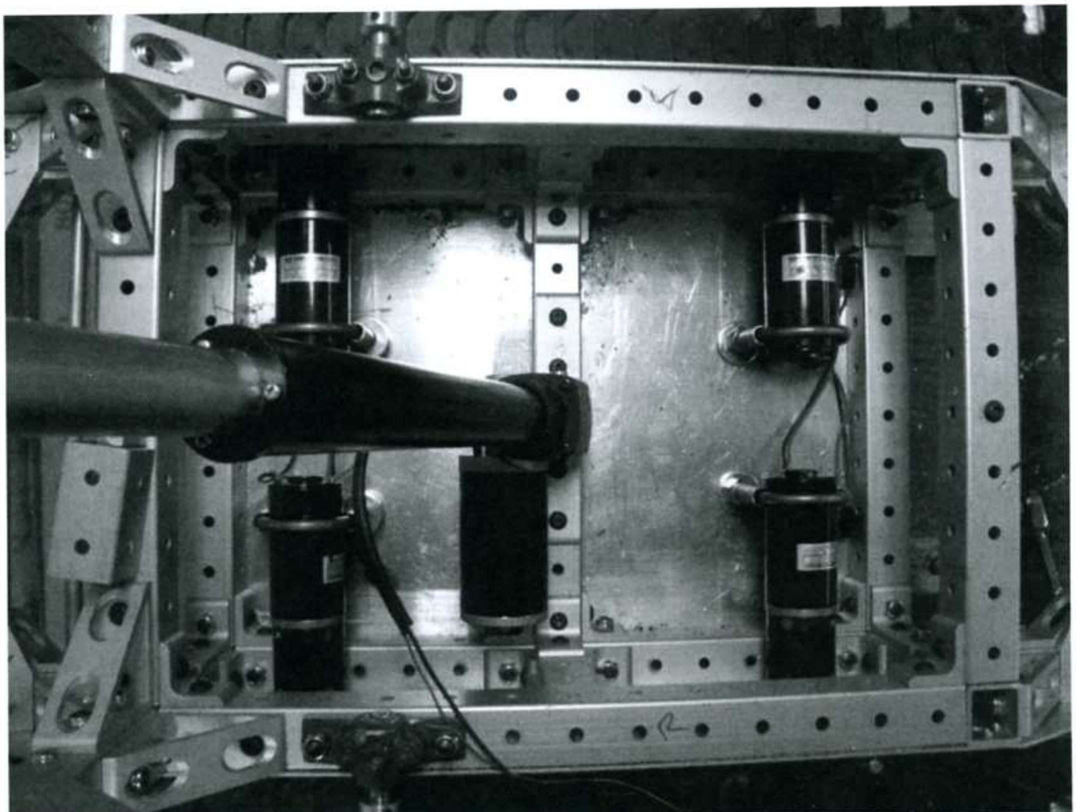
- The additional motors shall be mounted in the same fashion as the previous two.
- The length of chain for the new motors shall be of the same length for the previous two.
- *Combined weight of all component may not exceed 20kg*
- *Must enable the excavator to turn "effortlessly" in grass both unloaded and with various collections of regolith. (collections will not exceed 30kg)*
- *The drive wheels shall not be mounted directly to the motors. (to reduce deflections experienced in the prototype)*
- *The treads shall be properly aligned & tensioned so that they will not come off during a 30 min test run.*
- *The shafts for all wheels shall be mounted such that they experience minimal deflections.*

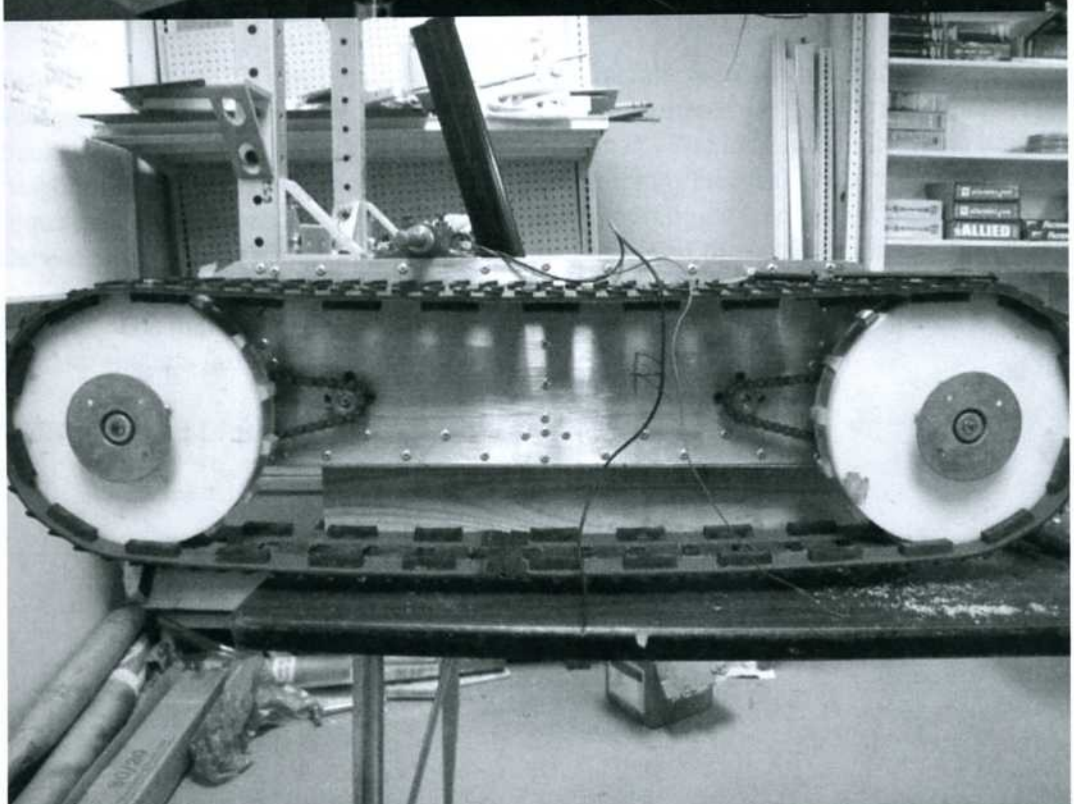
Interfacing Plan: The drive subsystem shall interface with both the frame subsystem and also the ground. The interface with the drive subsystem shall be achieved by the use of solid steel shafts that the drive wheels will "ride" on. The steel shafts shall be mounted to the frame by use of modified split bearings. The motors shall be mounted to the frame subsystem by mounting directly to the side panels and shall also be supported at the opposite end by use of a motor mount. The motors shall be connected to the drive wheels by use of a ten tooth spur gear, a thirty tooth sprocket, and a length of #35 ASNI chain.

Delivery Date: 29 April 2010

_______________	_______________	____Optional_____
Student's Signature	Manager's Signature	Instructor's Signature

Deliverables: Completed design 4 motor drive system.





Contract of Deliverable

Contract Title: Bucket Design for Digger Arm subsystem
Contract Number: MPK006
Team: Corp_2 NASA ESMD LMC
Student Name: Mark P. Keske
Date: 30 March 2010

Task: Design bucket components for the digger arm subsystem of the excavator. Two buckets shall be designed: one large wide bucket for scraping, and one narrow bucket for deep digging. The bucket design shall

- Be rigid and robust (derived from prototype testing)
- Interface in a quick-detach manner within the digger arm subsystem (various arm designs)
- Be no more than 15 inches long (derived from prototype testing and overall width restrictions as per Rule 24 of the Lunabotics Mining Competition Rulebook)
- of the Lunabotics Mining Competition Rulebook and Technical Resource Budget)
- Be able to pitch 145 degrees from the horizontal (derived from the arm component angle change)
- Digging pressure at tip of bucket (derived from Technical Paper)
- Be able to collect 10 kg of simulant in one scoop (derived from minimum collection)

Deliverables: Completed design of the bucket components.

Interfacing Plan: The bucket components must be interfaced with the arm components to make the Digger Arm subsystem. The bucket shall mate with the arm components using 8020 pivot plates. The detailed design of the bucket depends on the design of the arm components. The maximum allowable length of the bucket is determined based remaining distance between the arm – bucket interface (8020 pivot plates) and the overall system length requirement (59.5 inches). The interfacing and integrating of the bucket into the digger arm subsystem also involves the usage of a linear actuator to control the pitch angle of the bucket. The bucket shall mate with the actuator such that the actuator does not interfere with the pitching of the bucket (tip of the actuator shall not hit the back of the bucket). The mating between the actuator and the bucket with either compatible 8020 components or custom actuator mounts (angle iron).

Delivery Date: 14 April 2010

________________	________________	____Optional______
Student's Signature	Manager's Signature	Instructor's Signature

Deliverables:

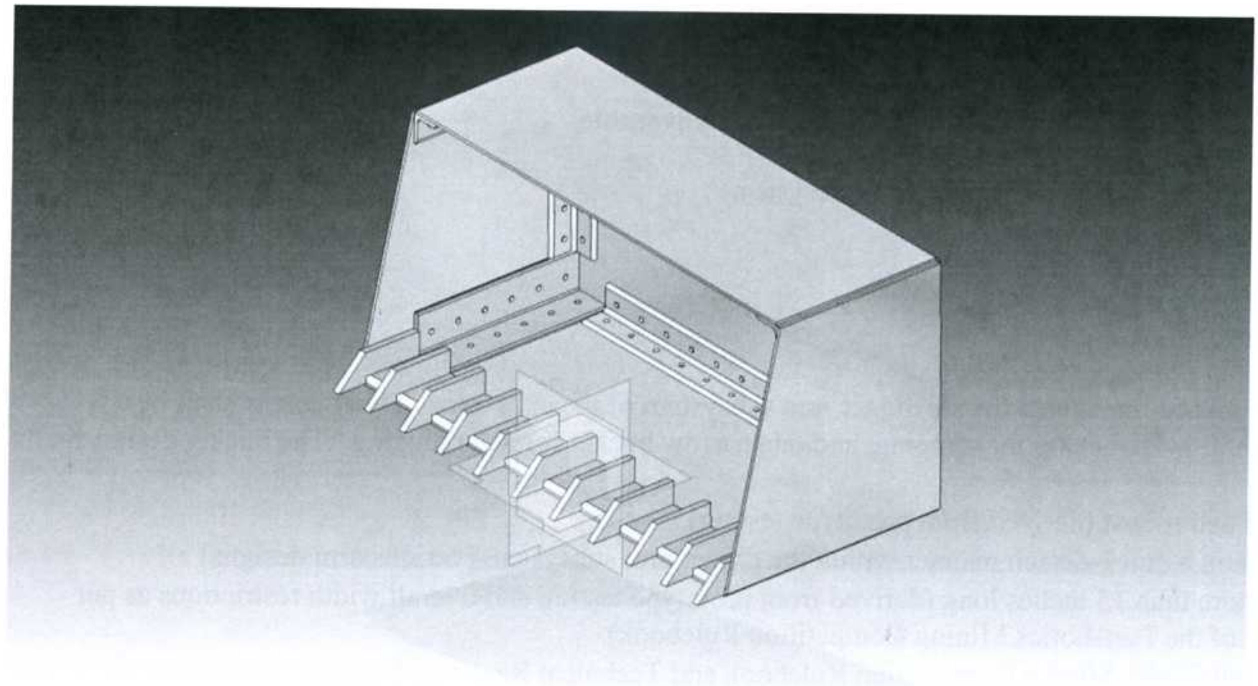


Figure 30: Small Bucket

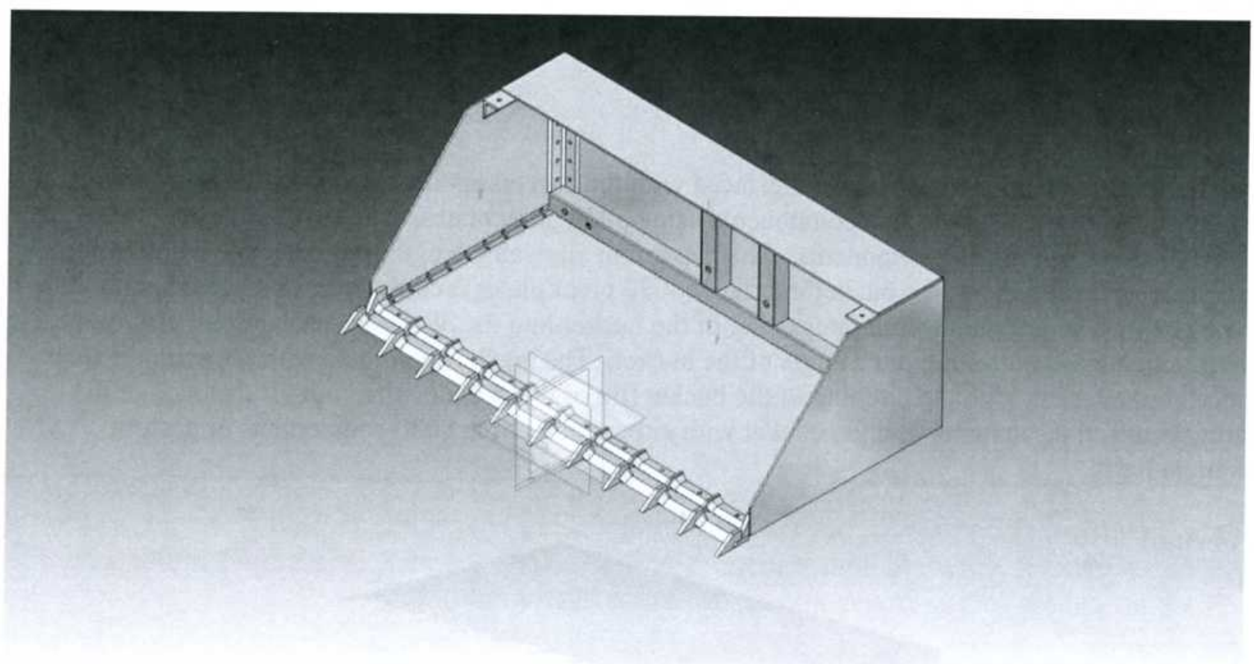
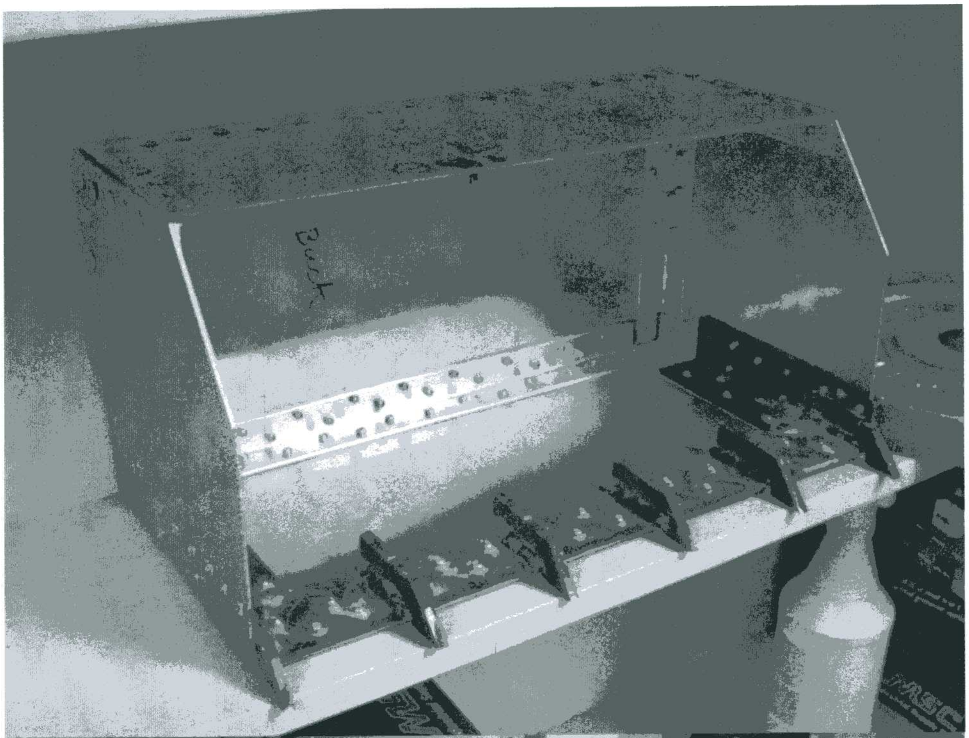
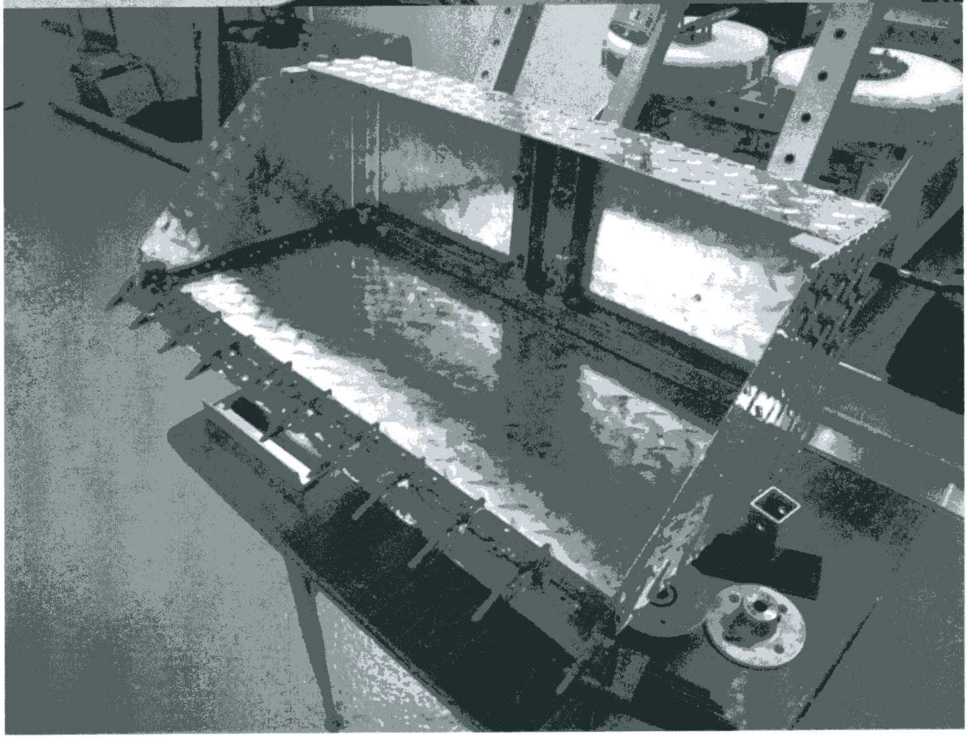


Figure 31: Large Bucket

Detailed Drawings: See "Bucket Detailed Drawings" in Report

Buckets





Contract of Deliverable

Contract Title: Digger Arm Concept
Contract Number: 1
Team: Corp 2
Student Name: Dionel Sylvester
Date: 4/27/2010

Task:

1) Main Task: - Design an Excavator (Digger) mechanism that requires minimum energy to excavate maximum regolith. The design will be influenced by the old design but will differ from it as far as the maximum reachable height, speed reaching maximum height, and the weight of the bucket. The system will be fabricated using mostly parts which we already have in the shop.

   Deliverables:
   a. CAD drawings of the system
   b. Picture of Arm Assembly

Interfacing Plan: The Excavator system will have two main interfaces that will "mate" with the rest of the vehicle. The arms that carry the bucket will be hinged to the frame with pins and the base of the actuator will be also hinged to the frame. The dimensions of this system will be communicated and correlated with those of the frame system.

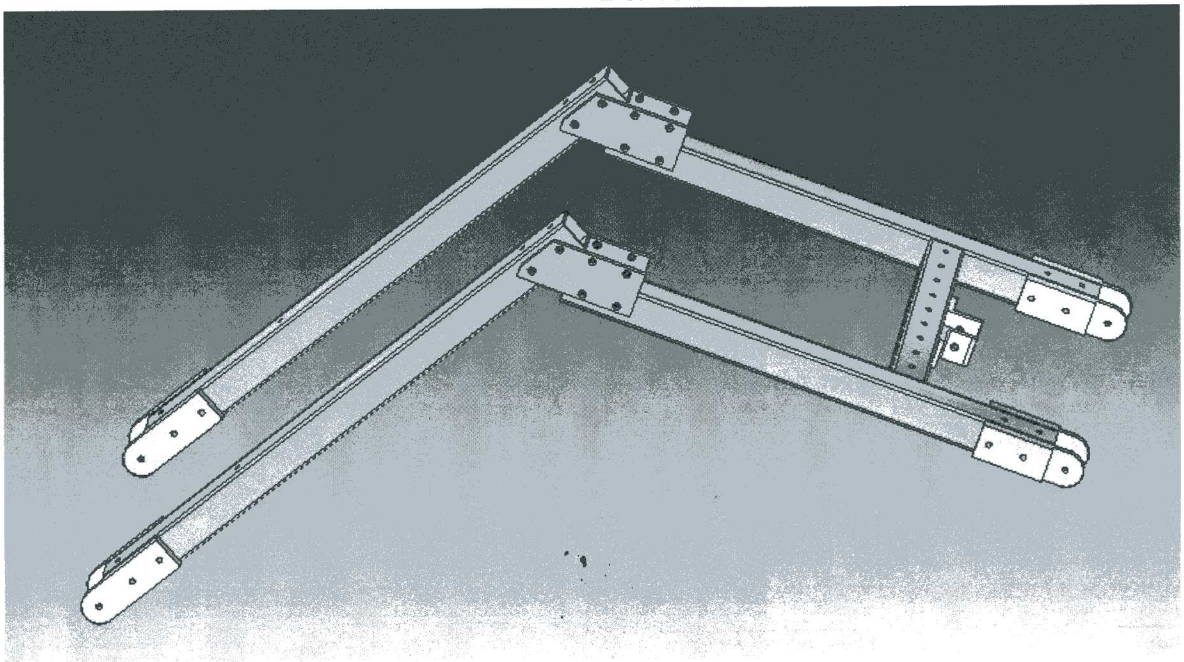
Delivery Date: 03/30/2010

Student's Signature ______________

Manager's Signature ______________

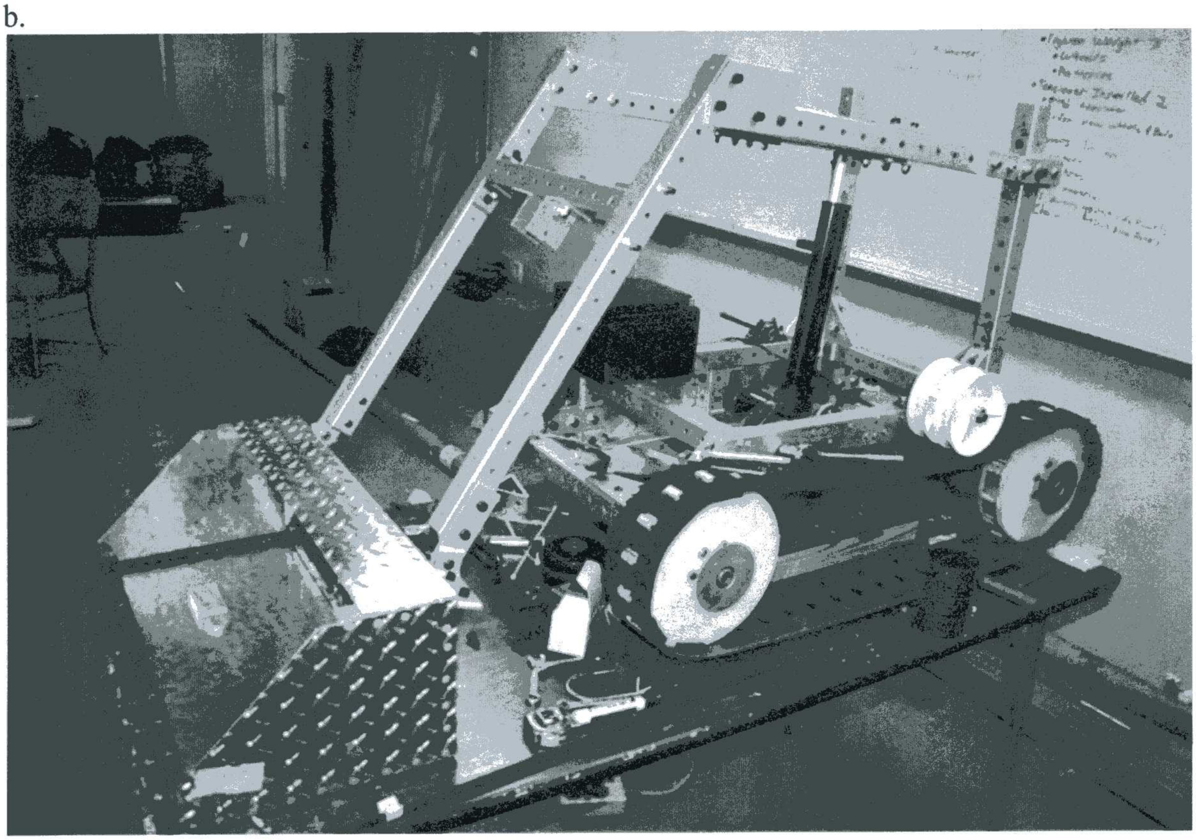
Instructor's Signature ______________

Deliverables



a.

b.



Contract of Deliverable

Contract Title: Digger Force Analysis
Contract Number: 3
Team: Corp 2
Student Name: Dionel Sylvester
Date:

Delivery Date: 03/30/2010

Task: Conduct a force-analysis of the digger subsystem.

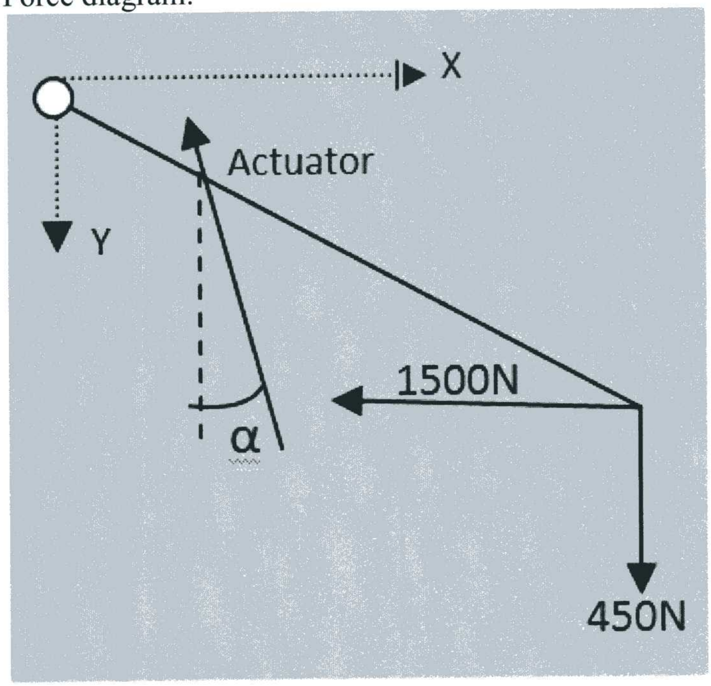
The purpose of this analysis is to get an understanding of the behavior of various forces acting on this subsystem. The deliverables will be Hand calculations, Excel tables and graphs.

Student's Signature

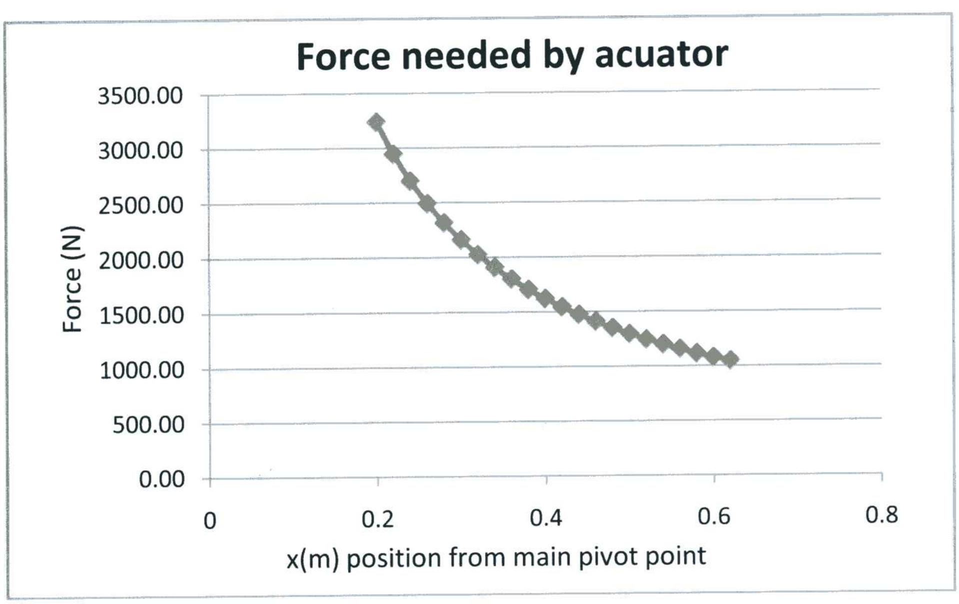
Manager's Signature

Instructor's Signature

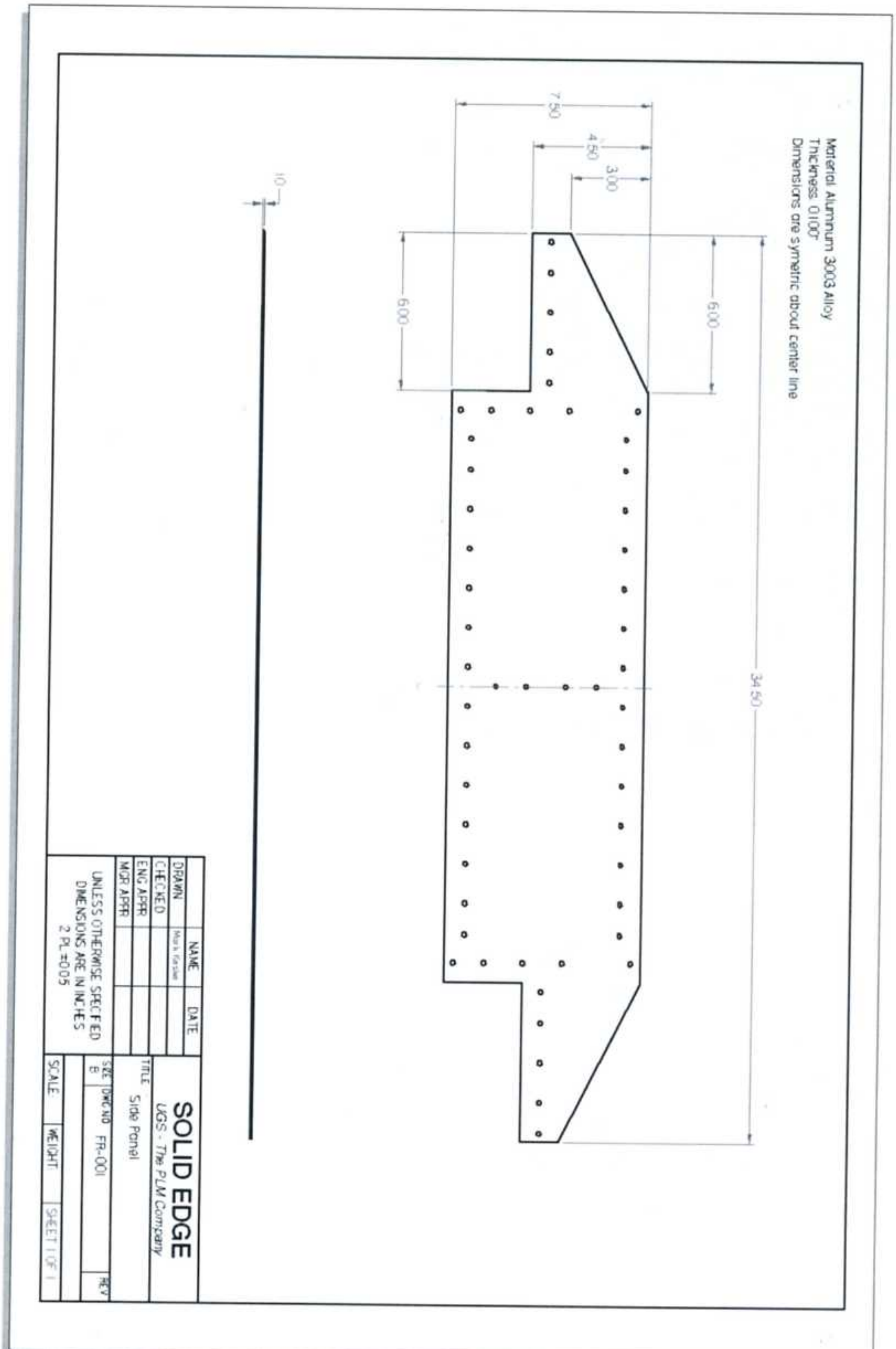
1. Force diagram:

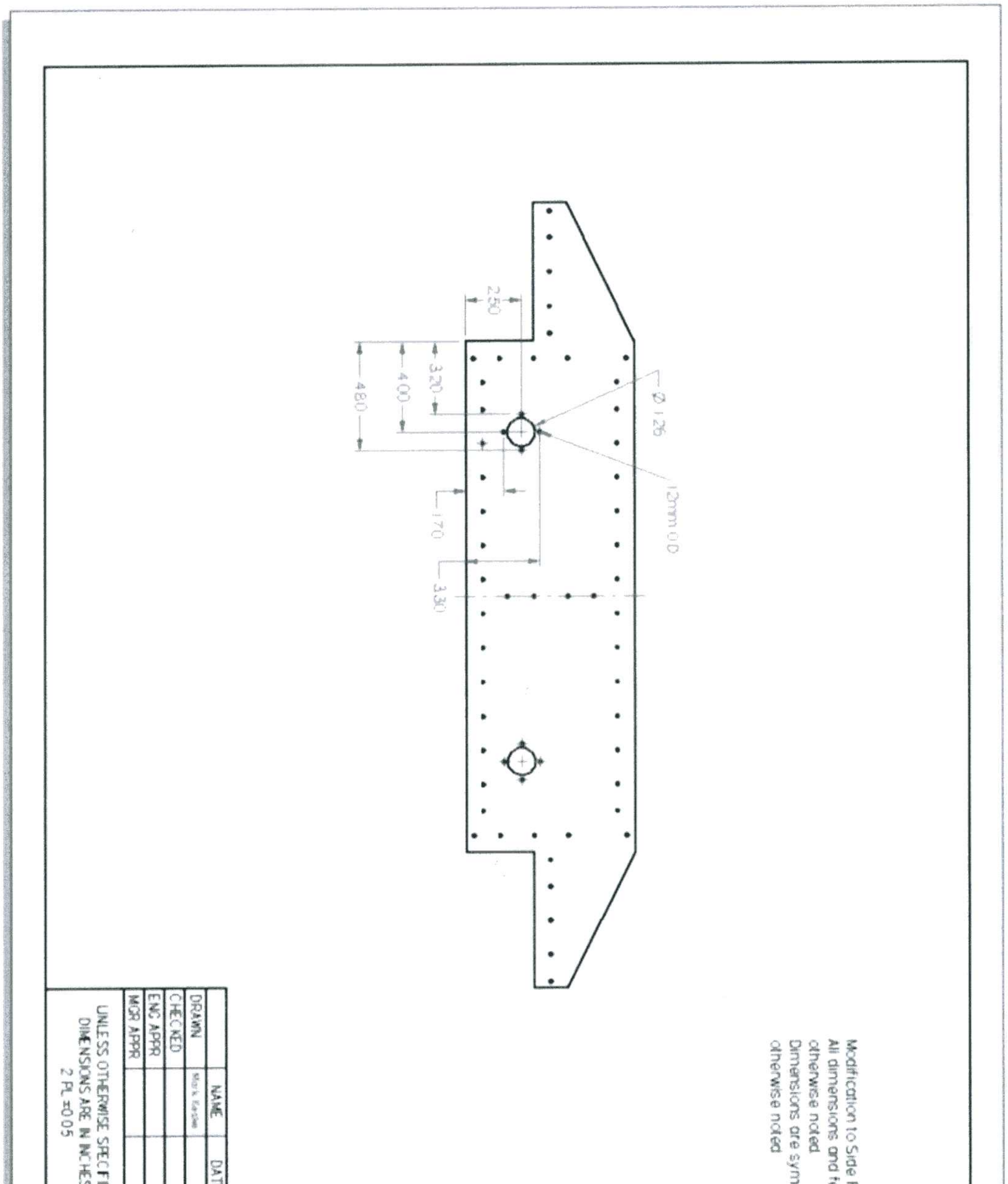


2.

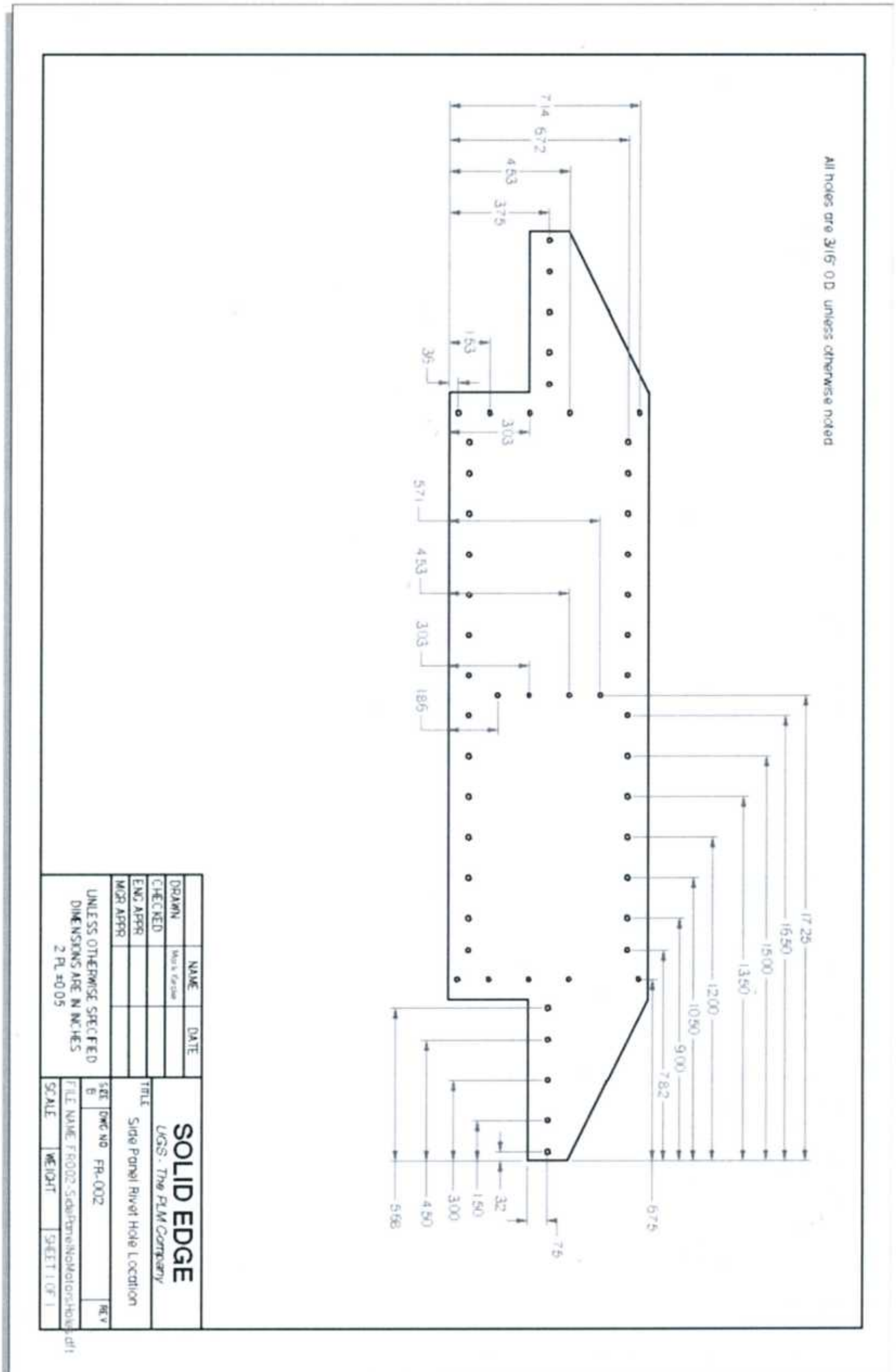


APPENDIX I: Frame Detailed Drawings

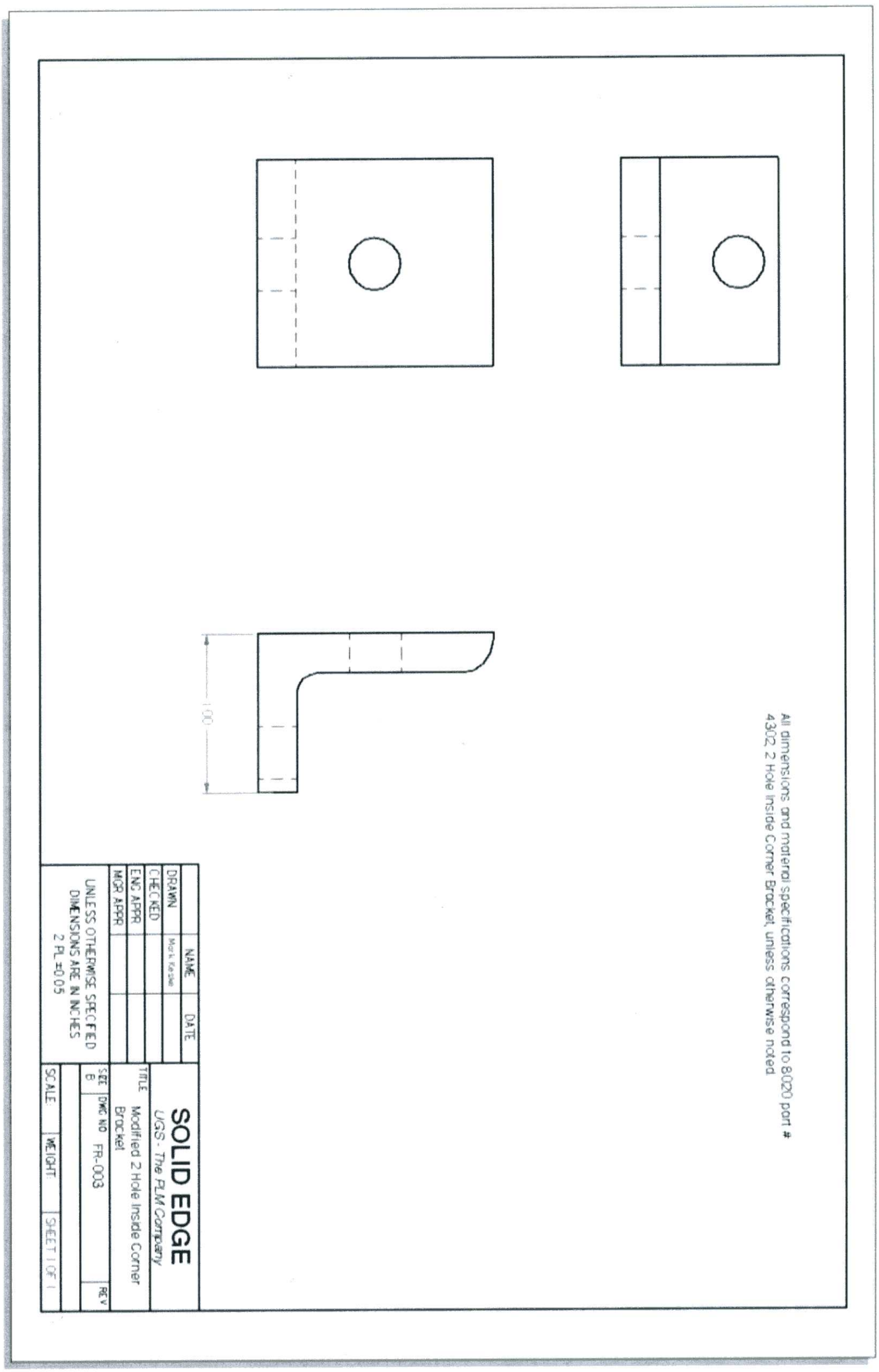


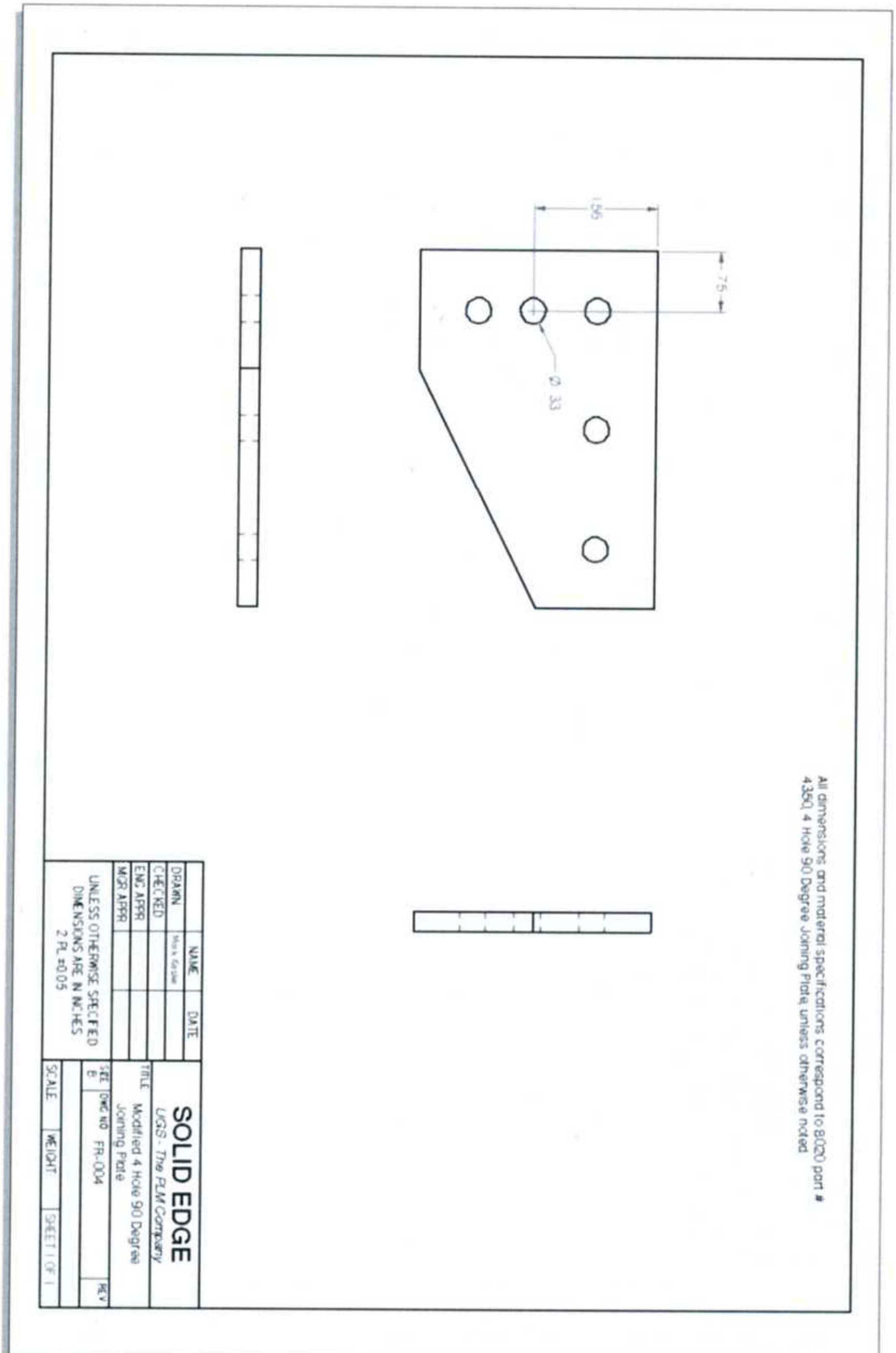


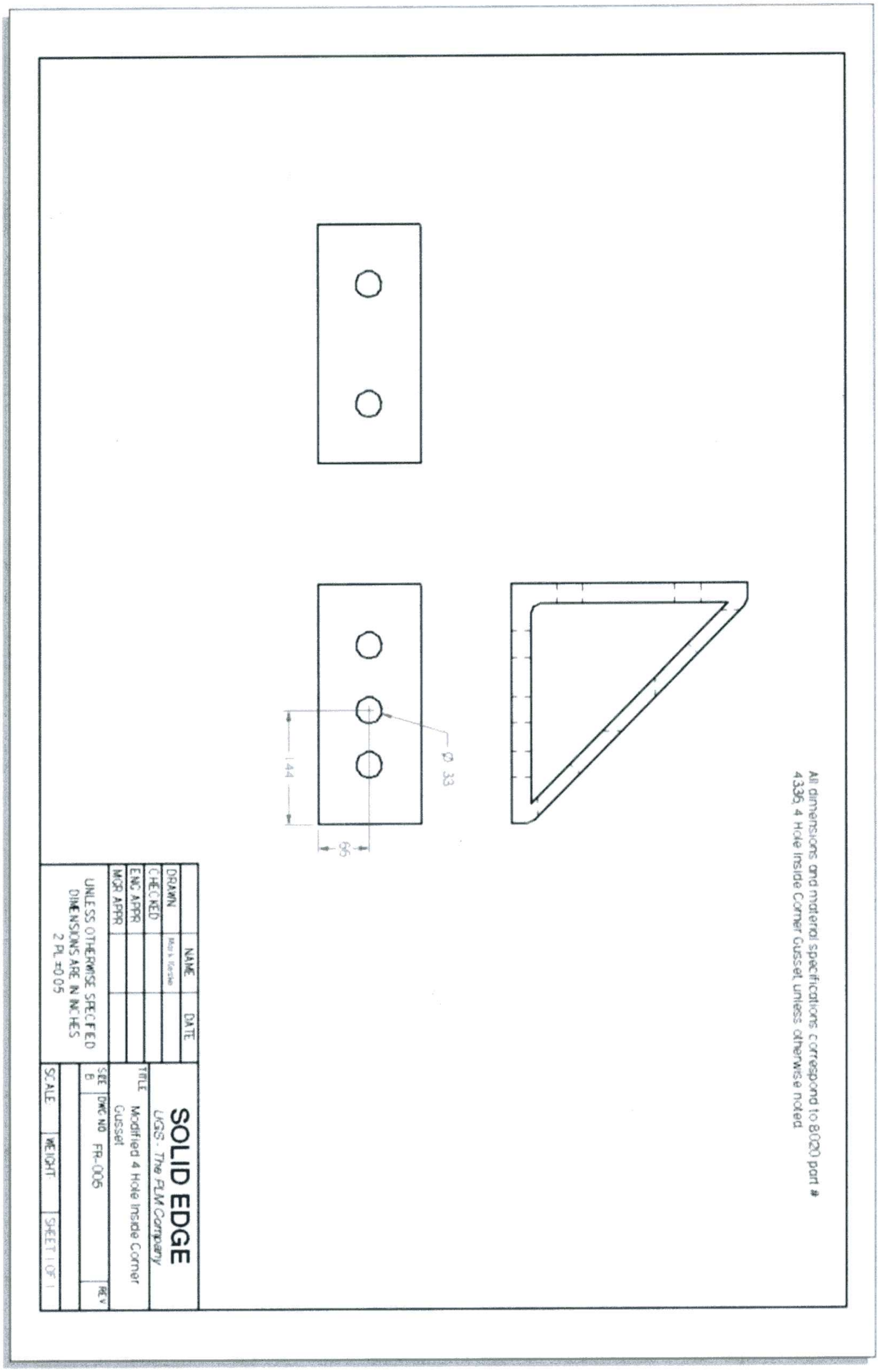
.250
.320
.400
.480
Ø.126
12mm OD
.170
.330
Modification to Side Panel, part # FR00I
All dimensions and features remain the same, unless otherwise noted
Dimensions are symetric about centerline unless otherwise noted
SOLID EDGE
UGS - The PLM Company
TITLE
Side Panel
SIZE B
DWG NO FR-001-A
REV
SCALE
WEIGHT
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

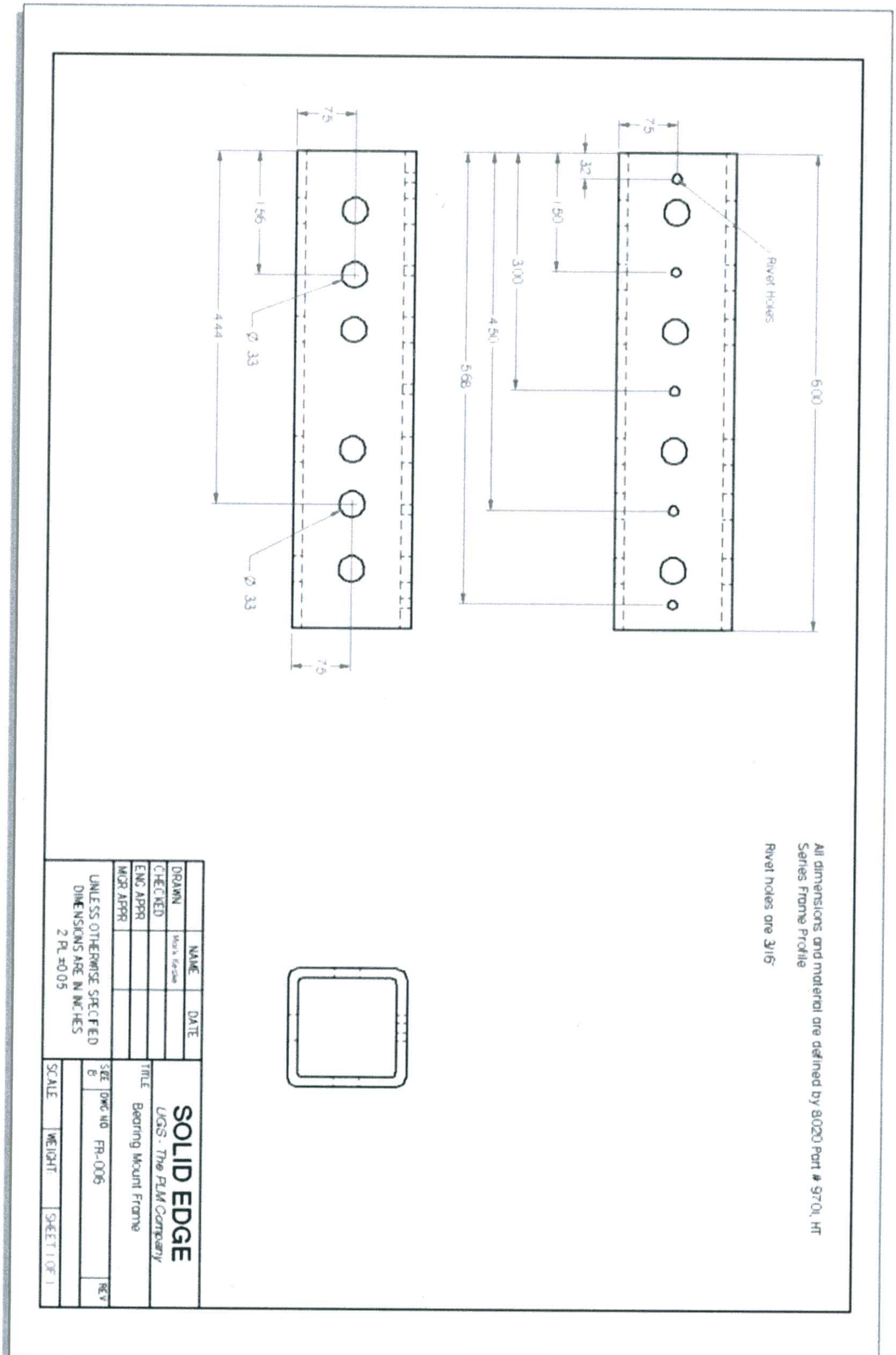


All holes are 3/16" O.D. unless otherwise noted
SOLID EDGE
UGS. The PLM Company
TITLE
Side Panel Rivet Hole Location
SIZE
B
DWG NO
FR-002
REV
FILE NAME: FR002-SidePanelNoMotorsHoles.dft
SCALE
WEIGHT
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

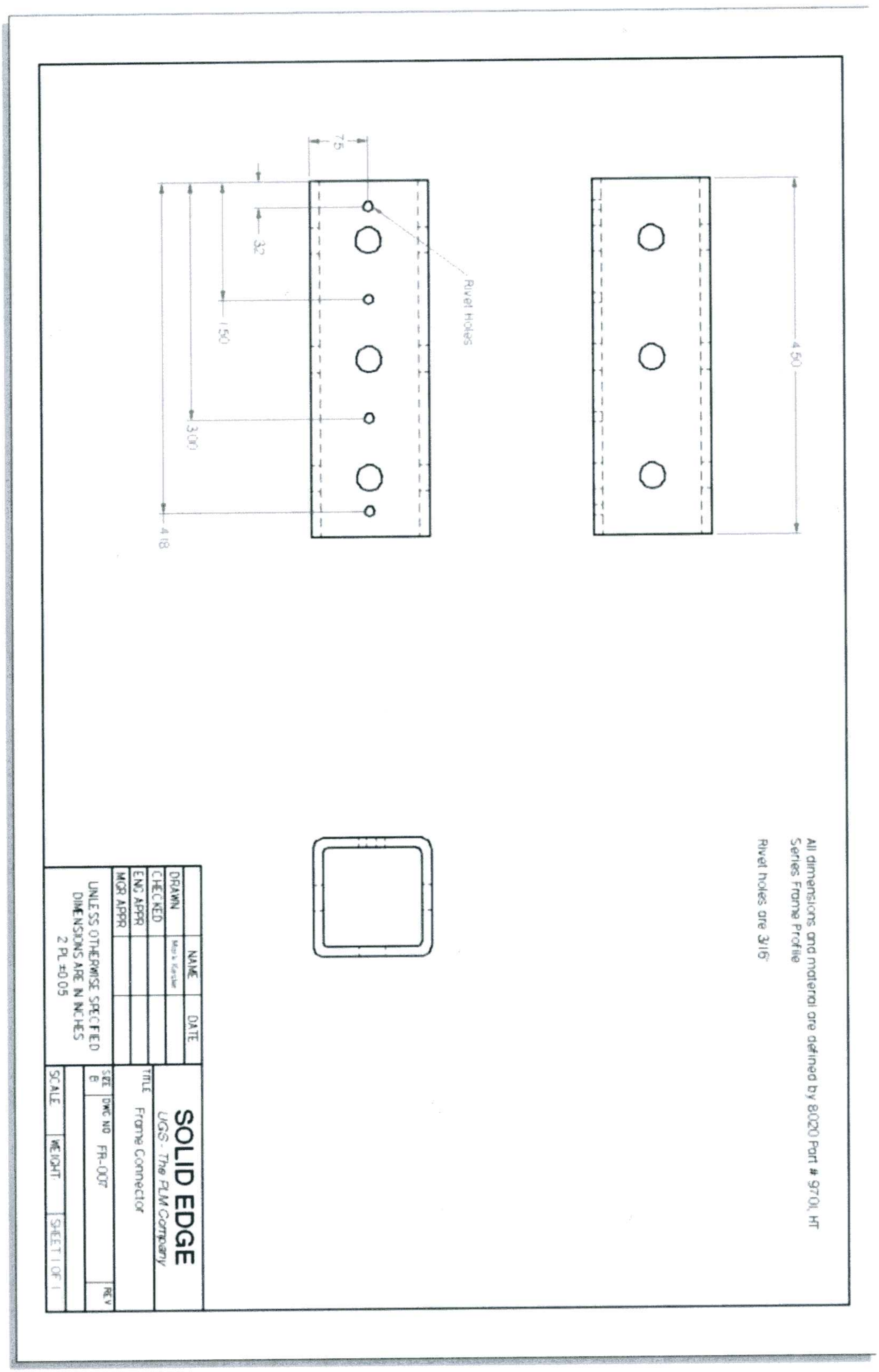

All dimensions and material specifications correspond to 8020 part # 4302, 2 Hole Inside Corner Bracket, unless otherwise noted.
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
SOLID EDGE
UGS - The PLM Company
TITLE
Modified 2 Hole Inside Corner Bracket
SIZE
B
DWG NO
FR-003
REV
SCALE
WEIGHT
SHEET 1 OF 1

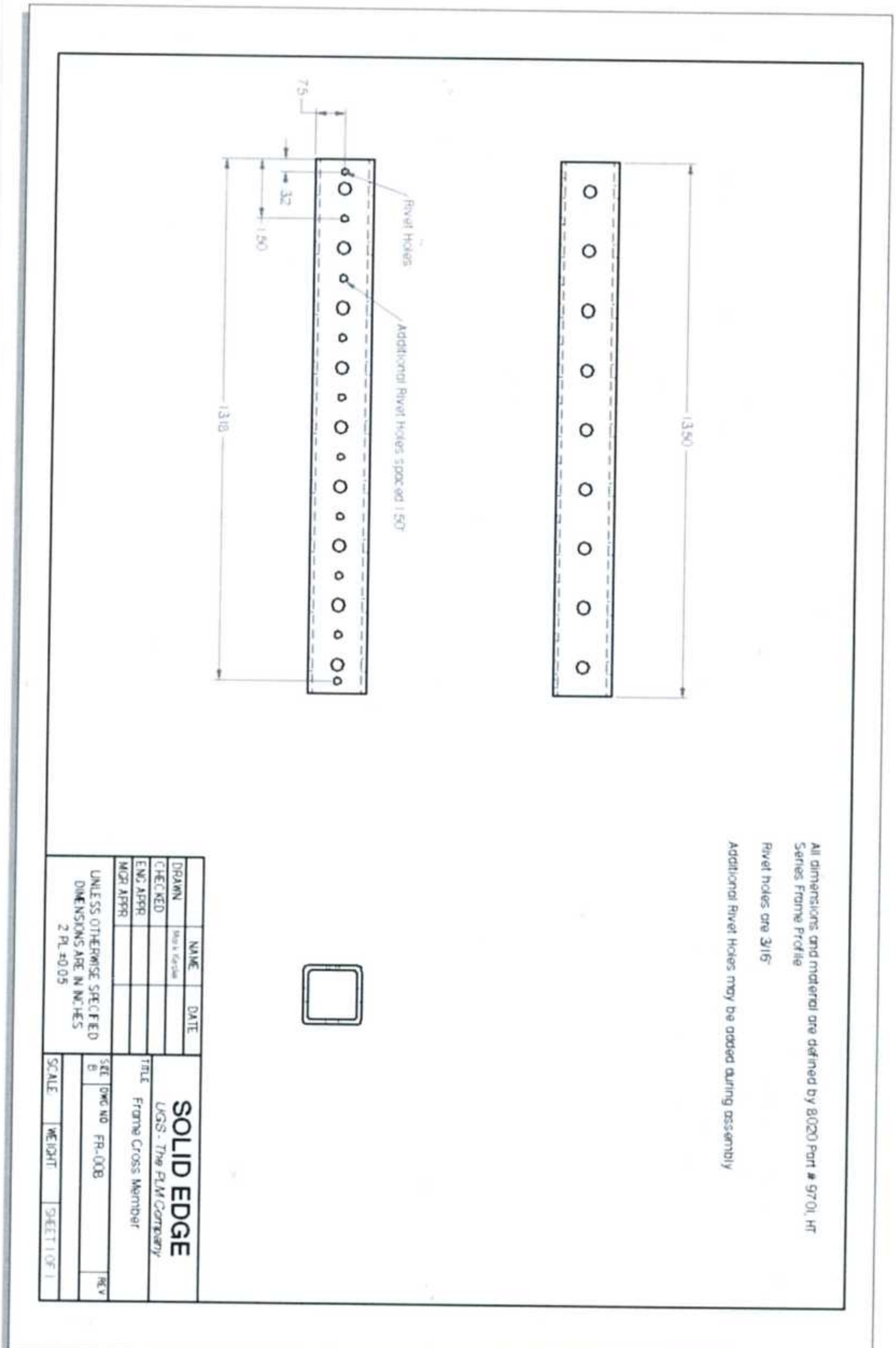

1.56
.75
Ø .33
All dimensions and material specifications correspond to 8020 part # 4350, 4 Hole 90 Degree Joining Plate, unless otherwise noted.
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Modified 4 Hole 90 Degree Joining Plate
SIZE B
DWG NO FR-004
REV
SCALE
WEIGHT
SHEET 1 OF 1


All dimensions and material specifications correspond to 8020 part # 4336, 4 Hole Inside Corner Gusset unless otherwise noted
SOLID EDGE
UGS - The PLM Company
TITLE Modified 4 Hole Inside Corner Gusset
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SIZE B
DWG NO FR-005
REV
SCALE
WEIGHT
SHEET 1 OF 1

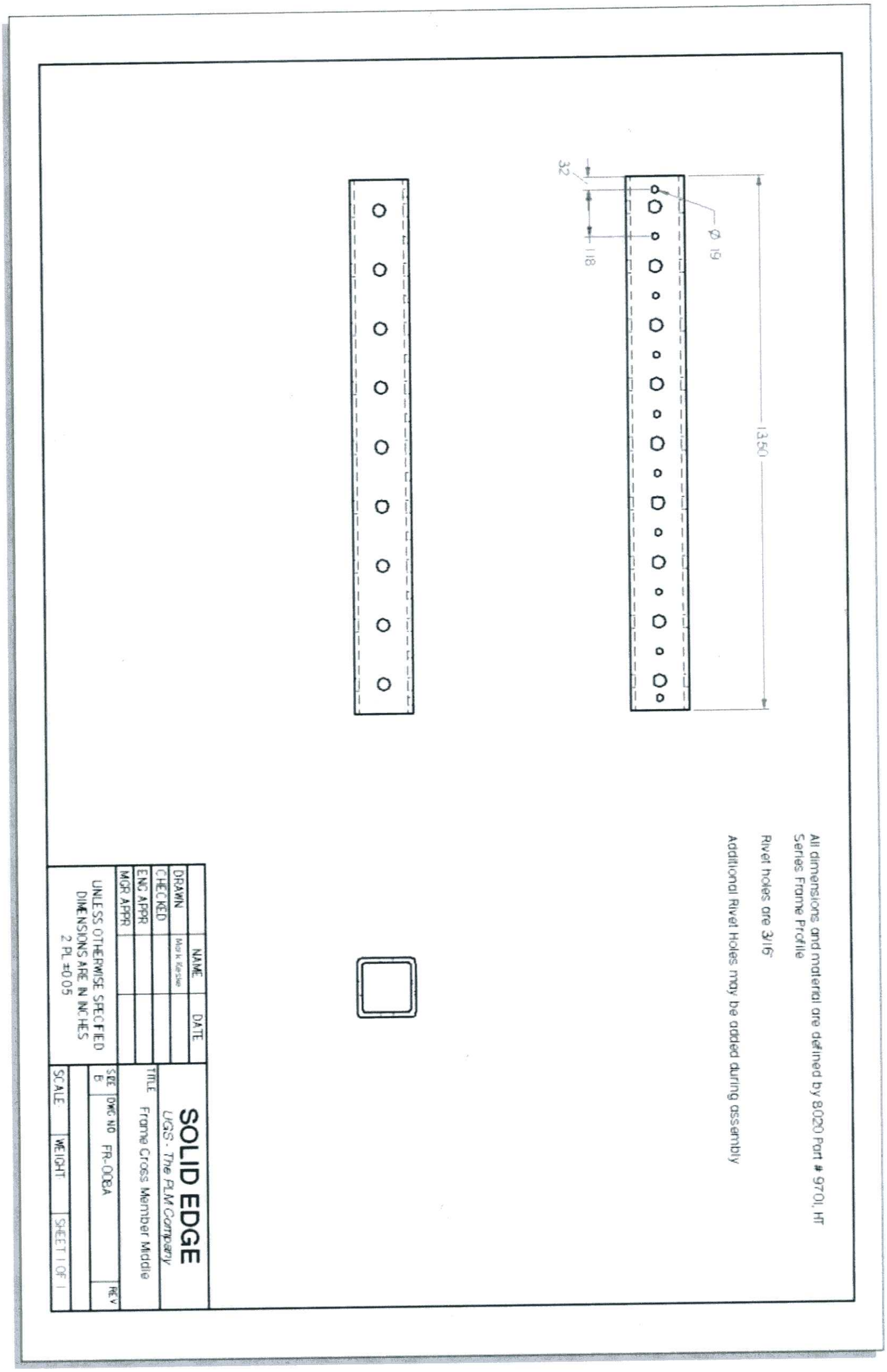


All dimensions and material are defined by 8020 Part # 9701, HT Series Frame Profile
Rivet holes are 3/16"
Rivet Holes
.75
.32
1.50
3.00
4.50
5.68
6.00
1.56
4.44
Ø .33
SOLID EDGE
UGS - The PLM Company
TITLE
Bearing Mount Frame
SIZE B
DWG NO FR-006
REV
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SCALE
WEIGHT
SHEET 1 OF 1


.75
.32
1.50
3.00
4.18
Rivet Holes
4.50
All dimensions and material are defined by 8020 Part # 970L HT Series Frame Profile
Rivet holes are 3/16"
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Connector
SIZE
B
DWG NO
FR-007
REV
SCALE
WEIGHT
SHEET 1 OF 1



All dimensions and material are defined by 8020 Part # 9701, HT Series Frame Profile
Rivet holes are 3/16"
Additional Rivet Holes may be added during assembly
Rivet Holes
Additional Rivet Holes spaced 1.50"
.75
.32
1.50
13.18
13.50
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Cross Member
SIZE B
DWG NO FR-008
REV
SCALE
WEIGHT
SHEET 1 OF 1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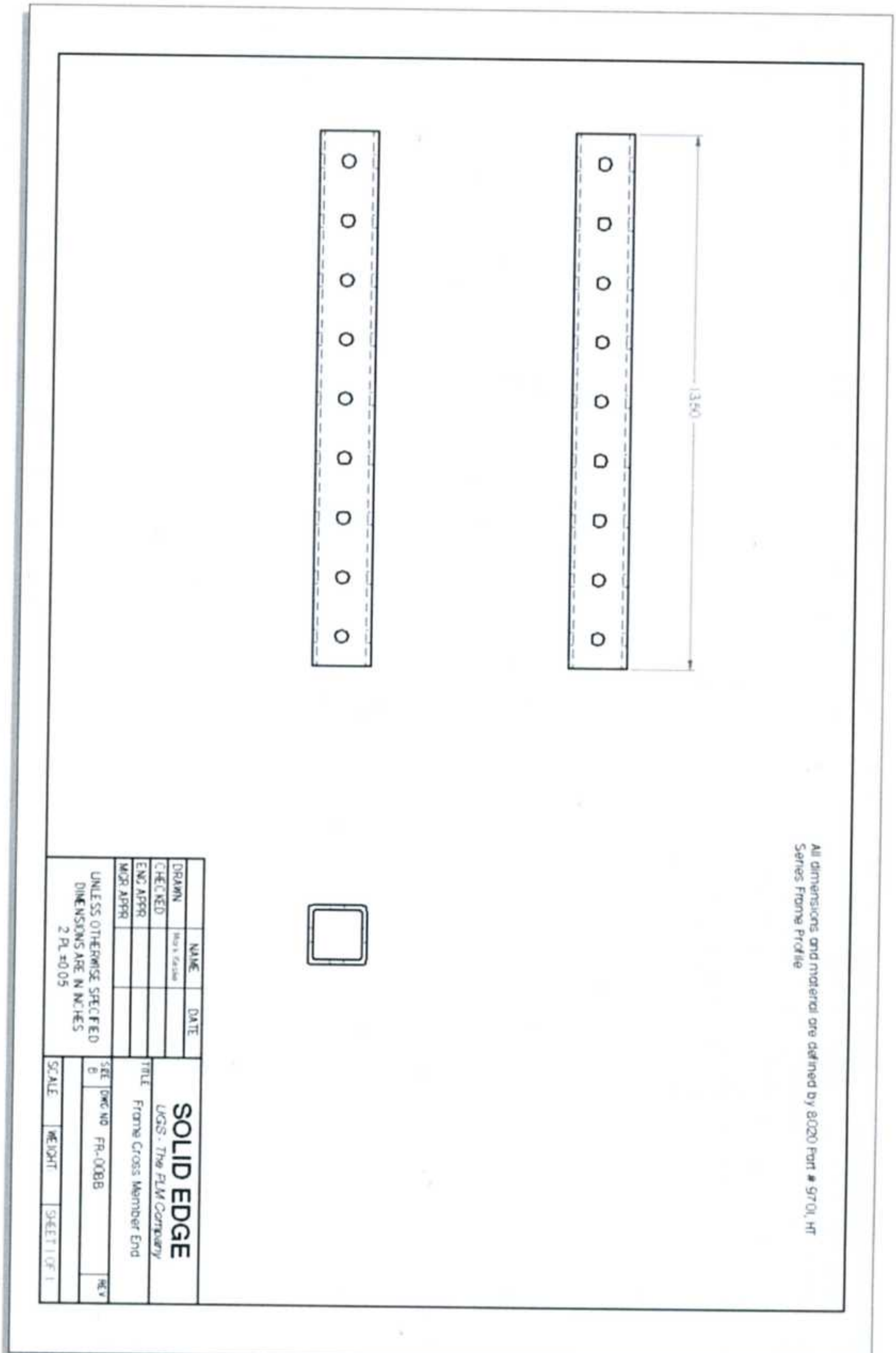
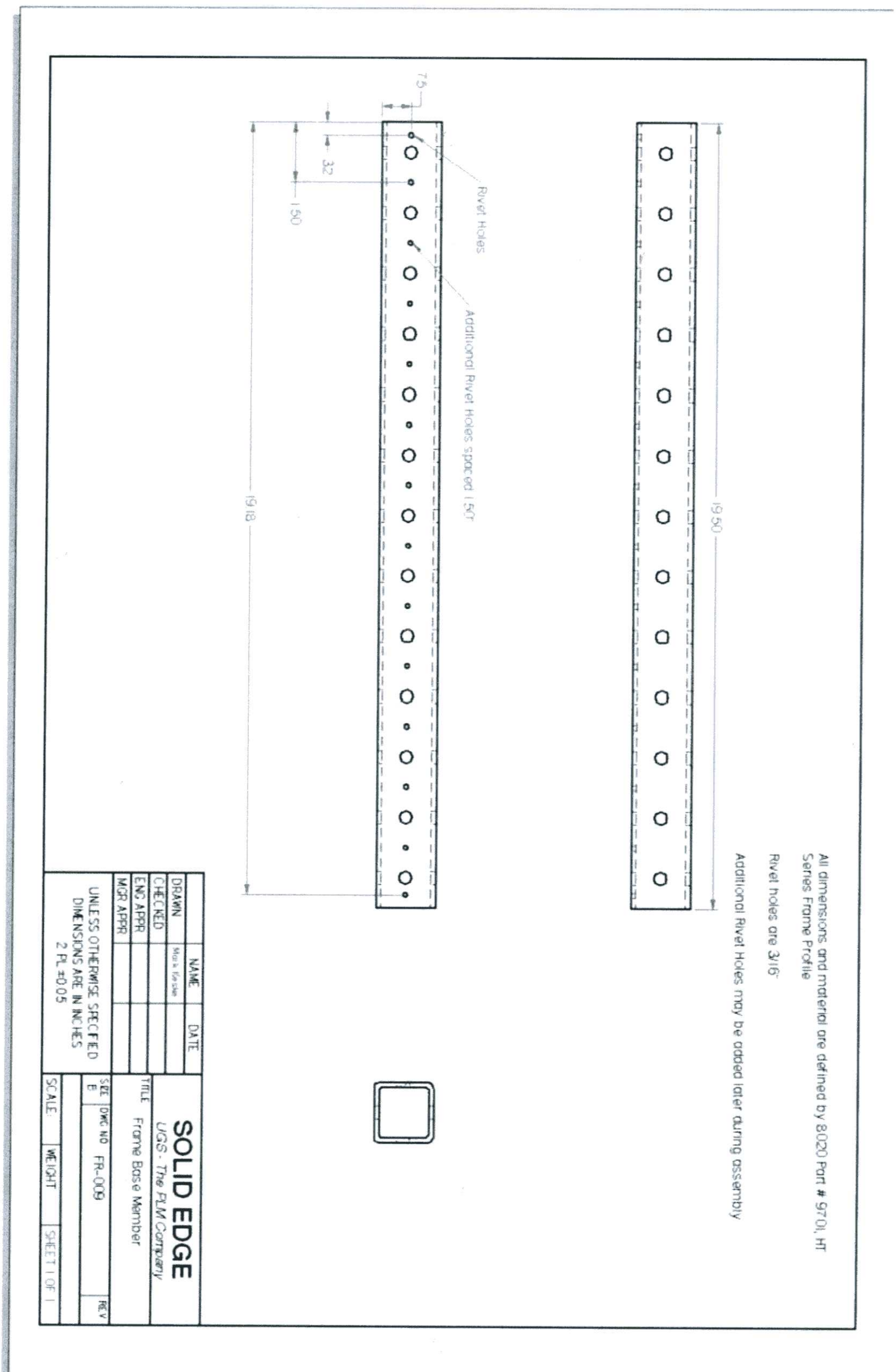
Rivet holes are 3/16"
Additional Rivet Holes may be added during assembly
.32
.18
Ø .19
13.50
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Cross Member Middle
SIZE B
DWG NO FR-008A
REV
SCALE
WEIGHT
SHEET 1 OF 1


13.50
All dimensions and material are defined by 8020 Part # 9701, HT Series Frame Profile
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Cross Member End
SIZE B
DWG NO FR-008B
REV
SCALE
WEIGHT
SHEET 1 OF 1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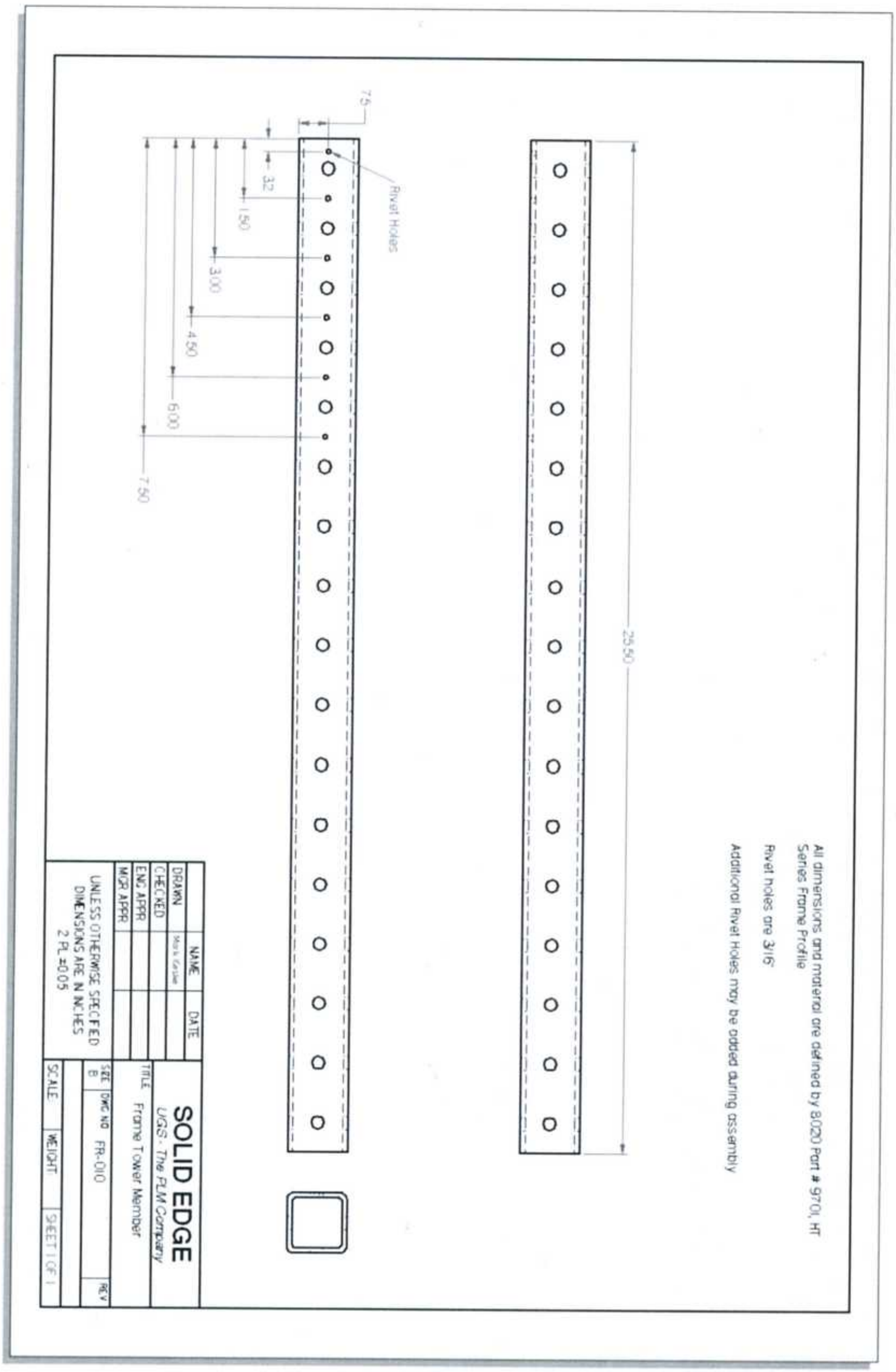
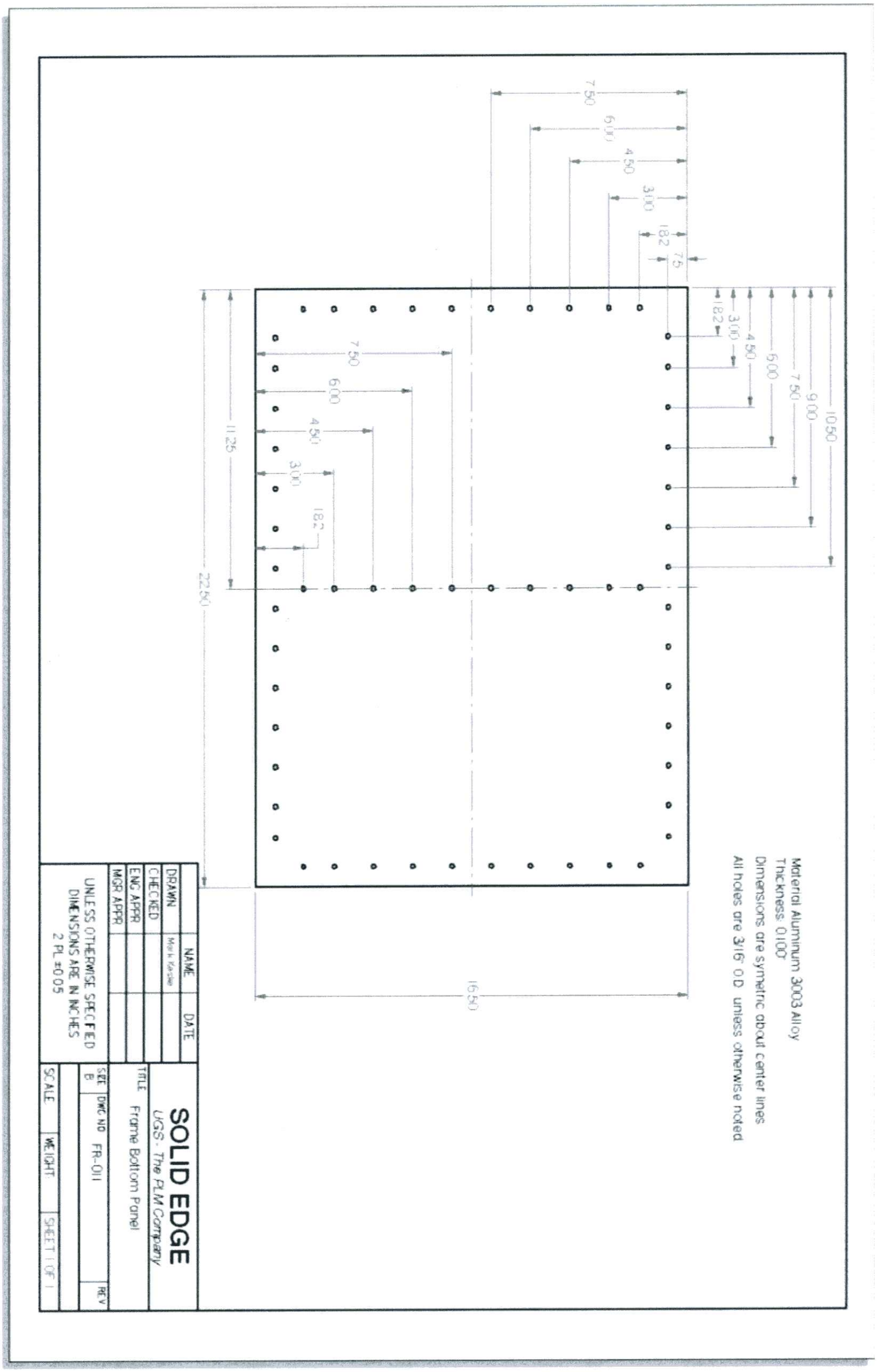
Rivet holes are 3/16"
Additional Rivet Holes may be added later during assembly
.75
.32
1.50
Rivet Holes
Additional Rivet Holes spaced 1.50"
19.18
19.50
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Base Member
SIZE
B
DWG NO
FR-009
REV
SCALE
WEIGHT
SHEET 1 OF 1



.75
.32
1.50
3.00
4.50
6.00
7.50
Rivet Holes
29.50
All dimensions and material are defined by 8020 Part # 9701, HT Series Frame Profile
Rivet holes are 3/16"
Additional Rivet Holes may be added during assembly
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Tower Member
SIZE
B
DWG NO
FR-010
REV
SCALE
WEIGHT
SHEET 1 OF 1


Material Aluminum 3003 Alloy
Thickness .0100"
Dimensions are symetric about center lines
All holes are 3/16" O.D. unless otherwise noted
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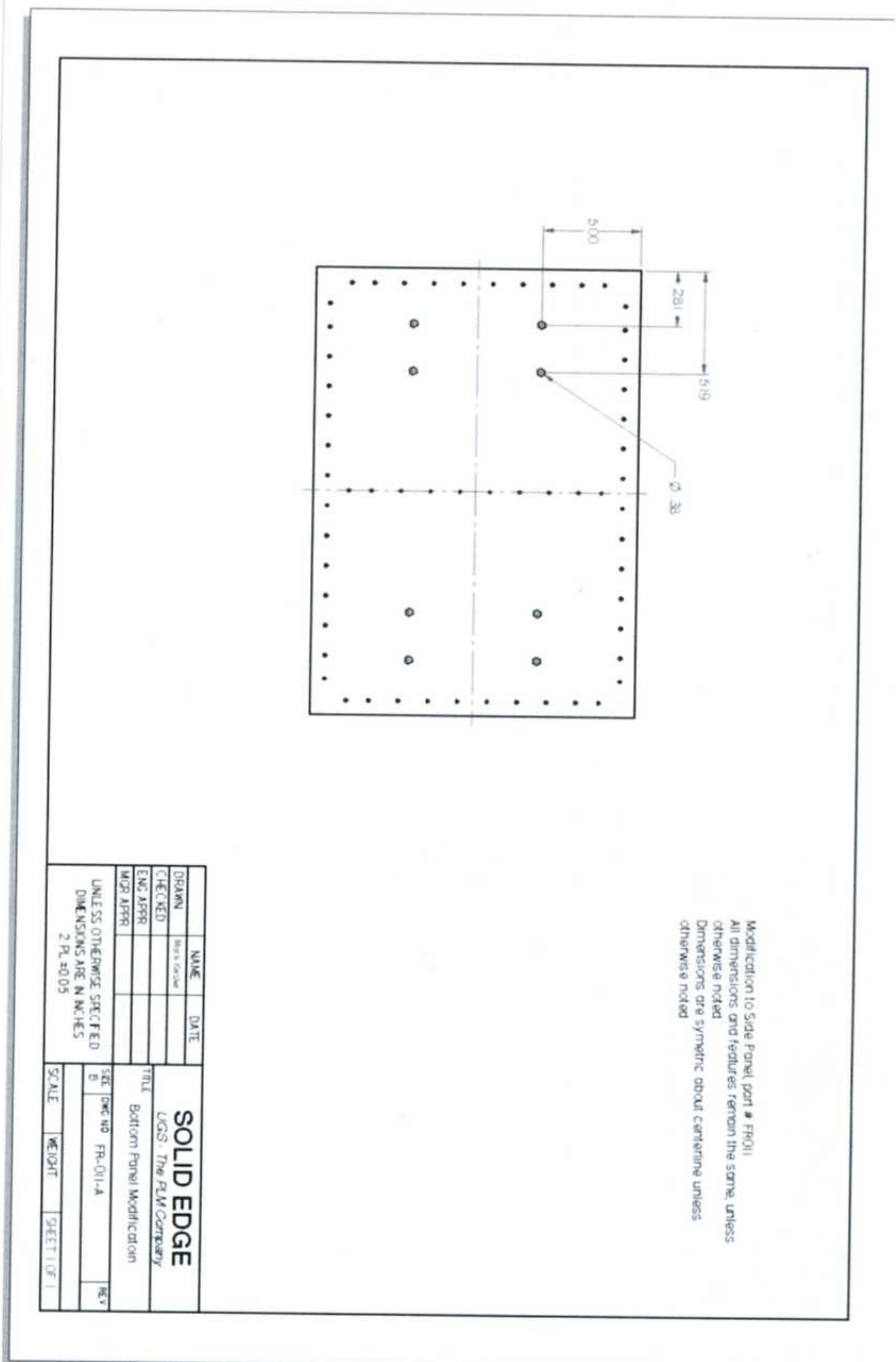
6.00
4.50
3.00
1.82
.75
9.00
10.50
11.25
22.50
16.50
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±.005
SOLID EDGE
UGS - The PLM Company
TITLE
Frame Bottom Panel
SIZE
B
DWG NO
FR-011
REV
SCALE
WEIGHT
SHEET 1 OF 1


.500
.281
.519
Ø.38
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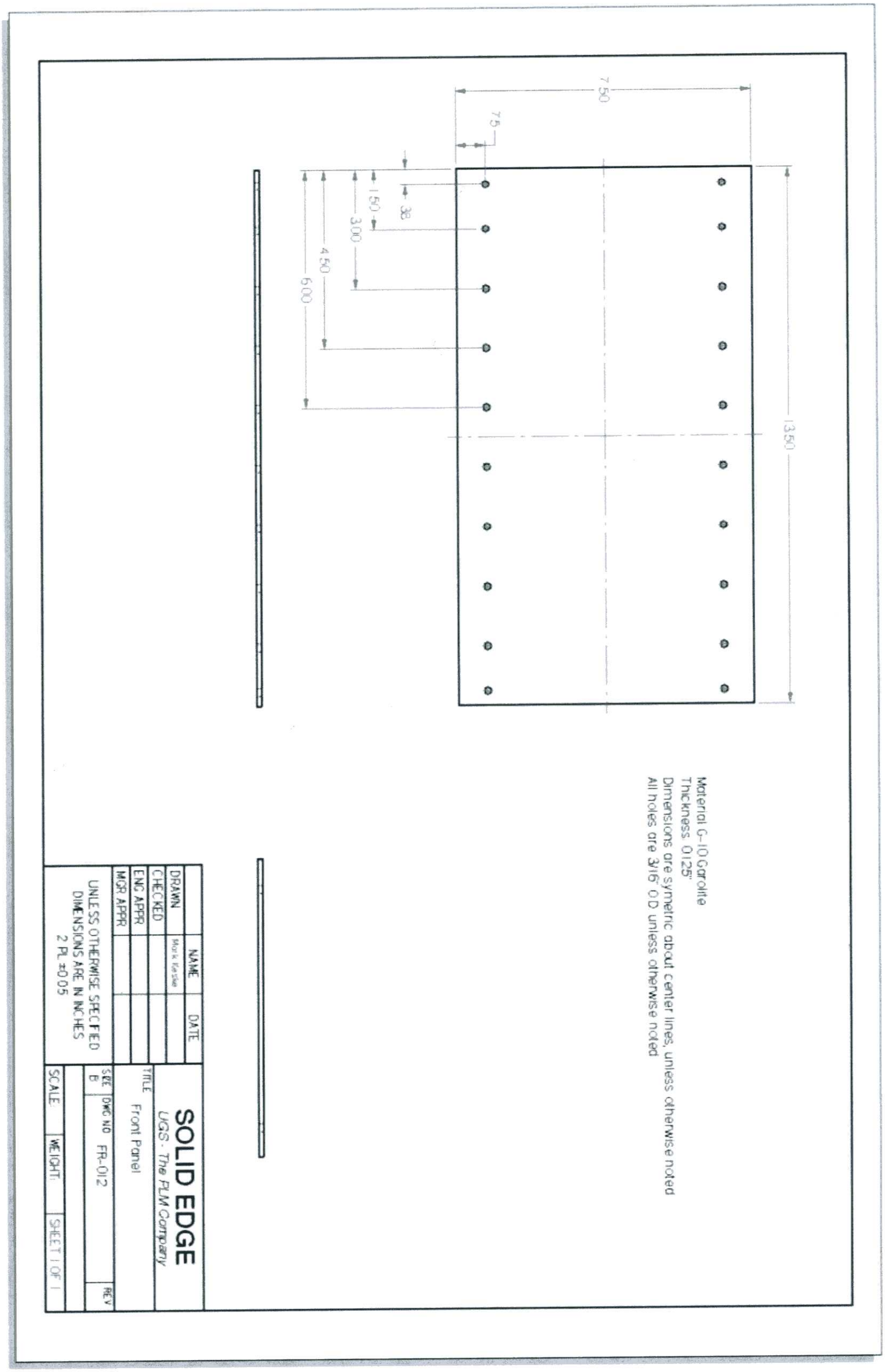
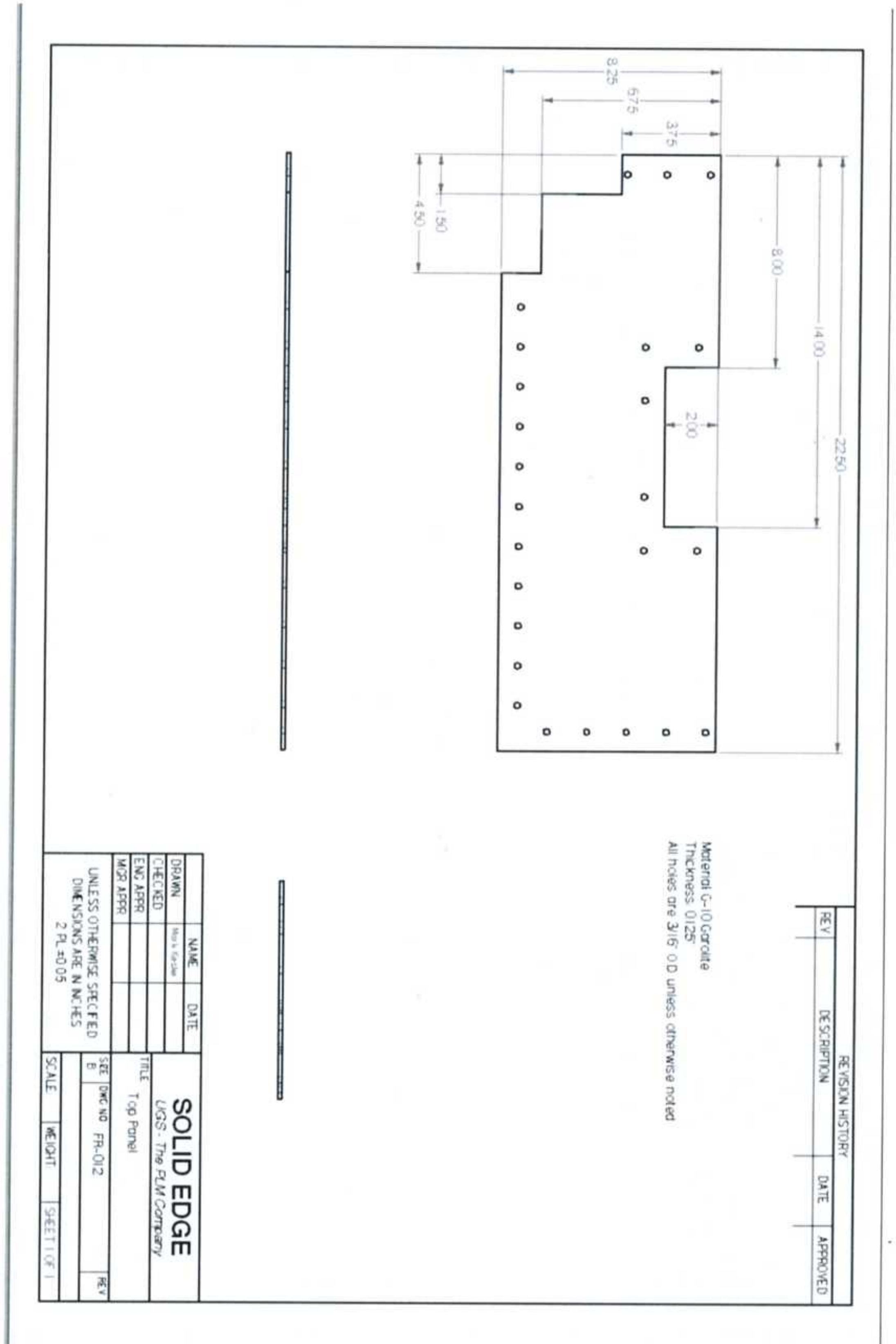
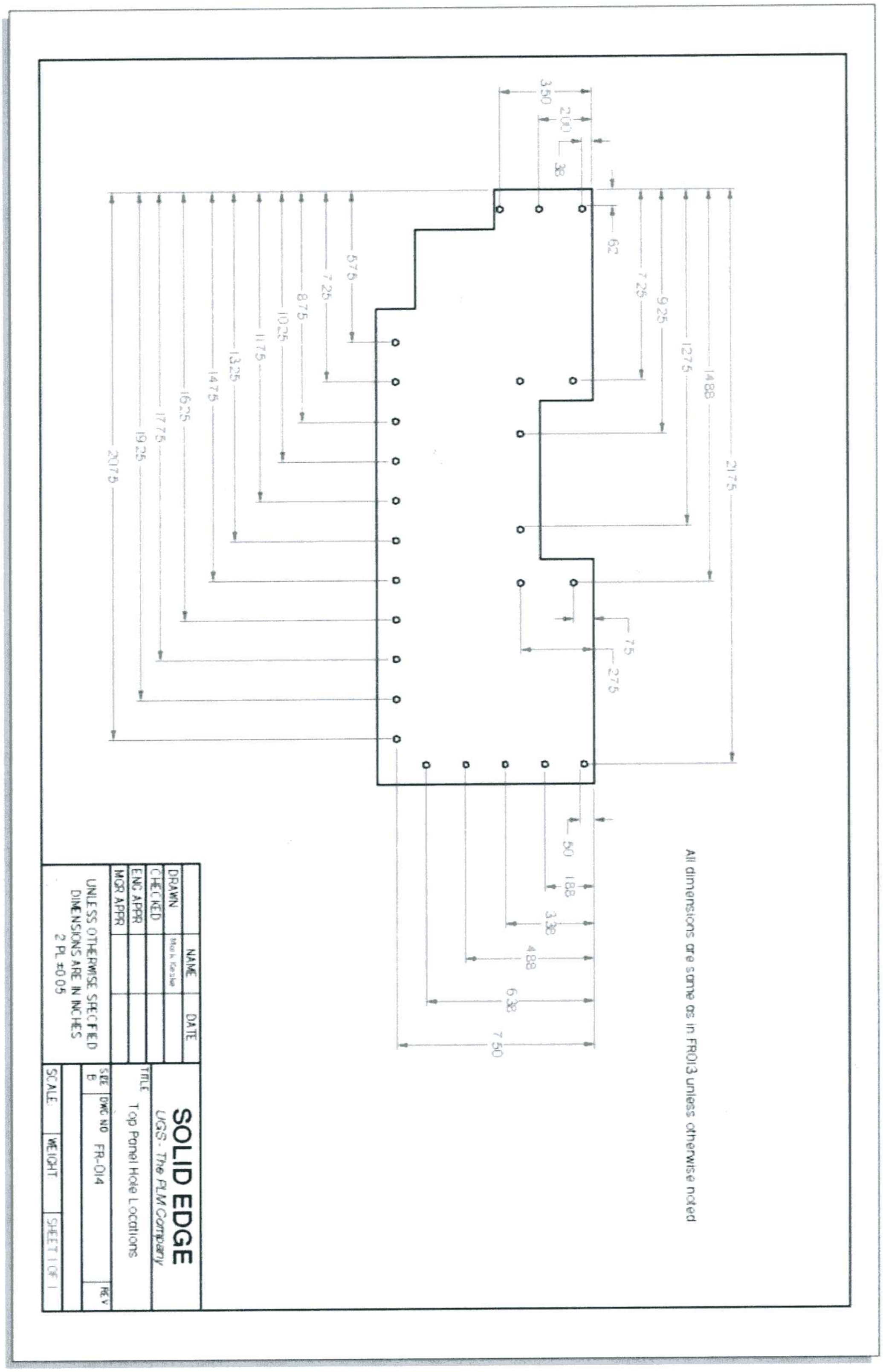
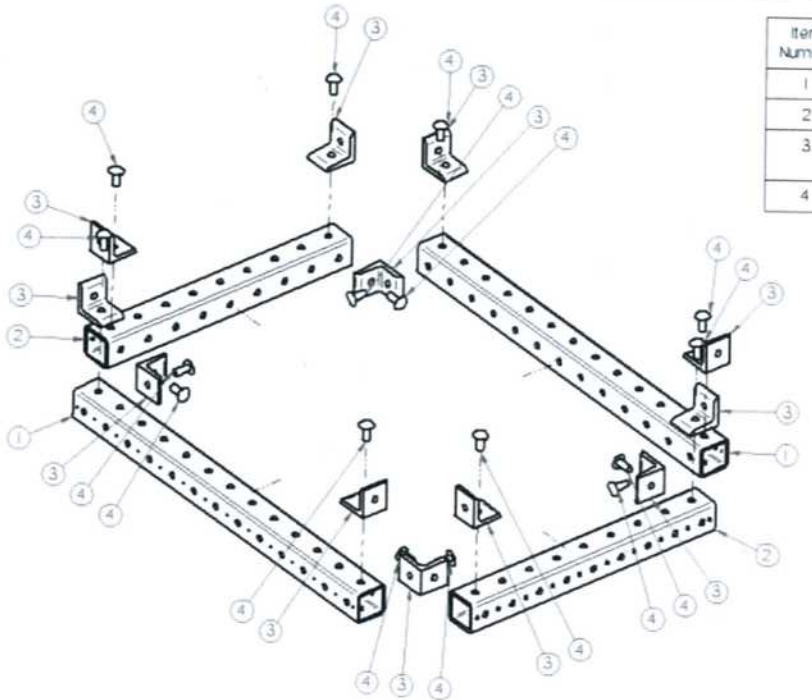
Dimensions are symetric about centerline unless otherwise noted
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Bottom Panel Modification
SIZE
B
DWG NO
FR-011-A
REV
SCALE
WEIGHT
SHEET 1 OF 1


Material G-10 Garolite
Thickness .0125"
Dimensions are symetric about center lines, unless otherwise noted
All holes are 3/16" O.D unless otherwise noted
7.50
.75
.38
1.50
3.00
4.50
6.00
13.50
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Front Panel
SIZE
B
DWG NO
FR-012
REV
SCALE
WEIGHT
SHEET 1 OF 1


8.25
6.75
3.75
1.50
4.50
8.00
14.00
22.50
2.00
Material G-10 Garolite
Thickness .0125"
All holes are 3/16" O.D. unless otherwise noted
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Top Panel
SIZE
B
DWG NO
FR-012
REV
SCALE
WEIGHT
SHEET 1 OF 1


All dimensions are same as in FR013 unless otherwise noted
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Top Panel Hole Locations
SIZE
B
DWG NO
FR-014
REV
SCALE
WEIGHT
SHEET 1 OF 1



Item Number	Revision	Document Number	Title	Quantity
1	FR009	9107	Frame Base	2
2	FR008	9107	Cross Member	2
3		4302	2 Hole Standard Inside Corner Bracket	12
4		91255A581	5/16-3/4 SHCS	16

STEPS
1 Assemble Inner Corner Bracket First
2 All Bolts Heads on outside
3 Ensure Squareness
4 Tighten Nuts

*Note: Will Need Two Sub Frame Step A

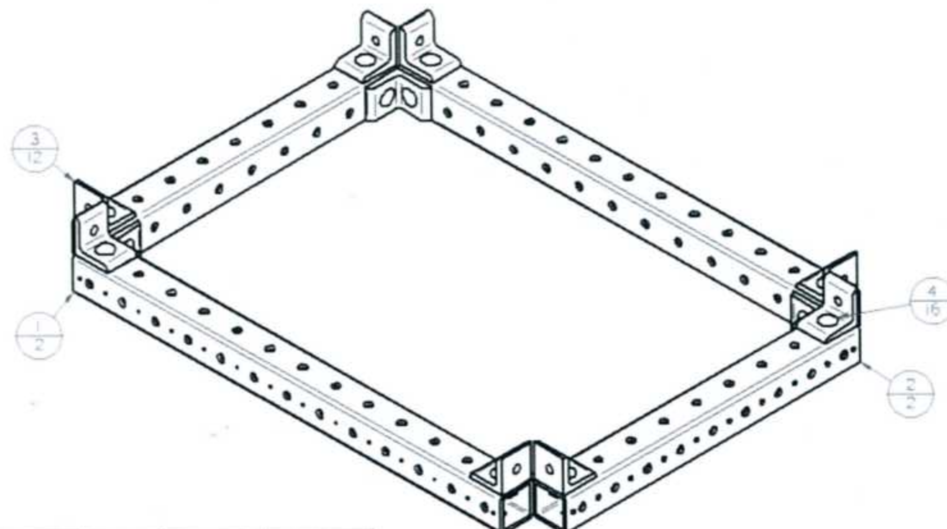
	NAME	DATE
DRAWN	Mark Kessler	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05

SOLID EDGE
UGS - The PLM Company
TITLE Sub Frame Step A
SIZE B DWG NO AFR-00A REV
SCALE WEIGHT SHEET 2 OF 2

NOTE All bolts require 5/16-18 Self Locking Nut

Nuts were not included due to computer memory capabilities!



Item Number	Revision	Document Number	Title	Quantity	Company	Category
1	FR009	9107	Frame Base	2	8020 Inc	In House Modified
2	FR008	9107	Cross Member	2	In House Modification (8020 Inc)	8020 Components
3		4302	2 Hole Standard Inside Corner Bracket	12	8020 Inc	8020 Components
4		91255A581	5/16-3/4 SHCS	16	McMaster	hardware

	NAME	DATE
DRAWN	Mark Karpe	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05

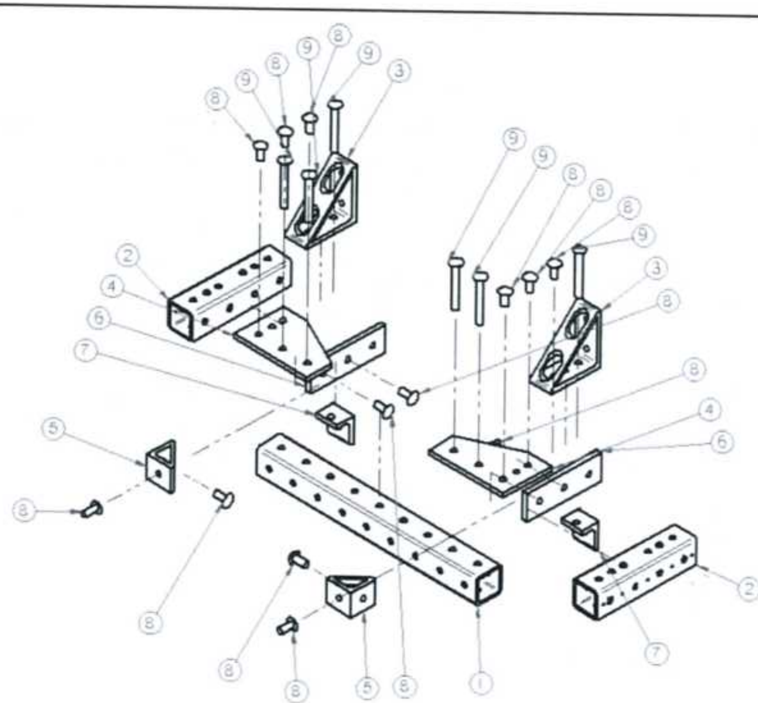
SOLID EDGE

UGS - The PLM Company

TITLE Sub Frame Step A

SIZE B | DWG NO AFR-00A | REV

SCALE | WEIGHT | SHEET 1 OF 2



Item Number	Revision	Document Number	Title	Quantity
1	FR008B	9107	End Cross Member	1
2	FR006	9107	Frame - Bearing Mount Piece	2
3	FR005	4336	Modified 4 Hole Inside Corner Gusset	2
4	FR004	4350	Modified 4 Hole 90 Degree Joining Plate	2
5		4332	2 Hole Inside Corner Gusset	2
6		4306	3 Hole Joining Strip	2
7	FR003	4302	Modified 2 Hole Inside Bracket	2
8		91255A581	5/16-3/4 SHCS	14
9		92949A594	5/16- 2 and 1/2 SHCS	6

NOTE All bolts require 5/16-18 Self Locking Nut

!Nuts were not included due to computer memory capabilities!

	NAME	DATE
DRAWN	Mark Kesler	
CHECKED		
ENG APPR		
MGR APPR		

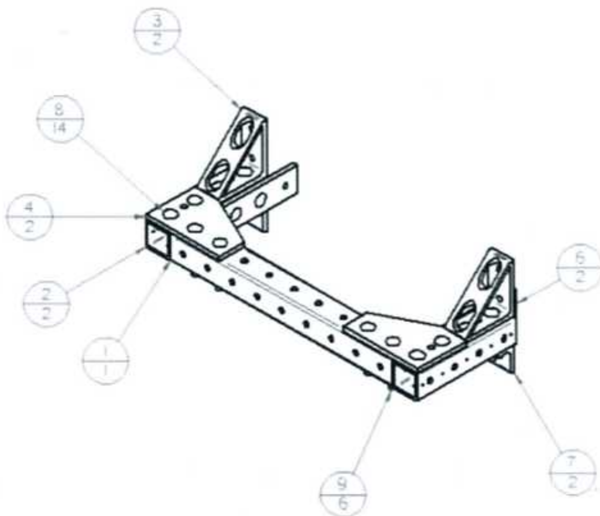
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE AFR00B Subframe_B

SIZE A | DWG NO AFR00B Subframe_B | REV

SCALE | WEIGHT | SHEET 2 OF 2



Item Number	Revision	Document Number	Title	Quantity	Company	Category
1	FR008B	9107	End Cross Member	1	In House Modification (8020 Inc)	8020 Components
2	FR006	9107	Frame - Bearing Mount Piece	2	8020 Inc	In House Modification
3	FR005	4336	Modified 4 Hole Inside Corner Gusset	2	In House Modification (8020 Inc)	8020 Components
4	FR004	4350	Modified 4 Hole 90 Degree Joining Plate	2	In House Modification (8020 Inc)	8020 Components
5'		4332	2 Hole Inside Corner Gusset	2	8020 Inc	8020 Components
6		4306	3 Hole Joining Strip	2	8020 Inc	8020 Components
7	FR003	4302	Modified 2 Hole Inside Bracket	2	In House Modification (8020 Inc)	8020 Components
8		91255A581	5/16-3/4 SHCS	14	McMaster	Hardware
9		92949A594	5/16- 2 and 1/2 SHCS	6	McMaster	Hardware

NOTE: All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities!

	NAME	DATE
DRAWN	Mark Kersler	
CHECKED		
ENG APPR		
MGR APPR		

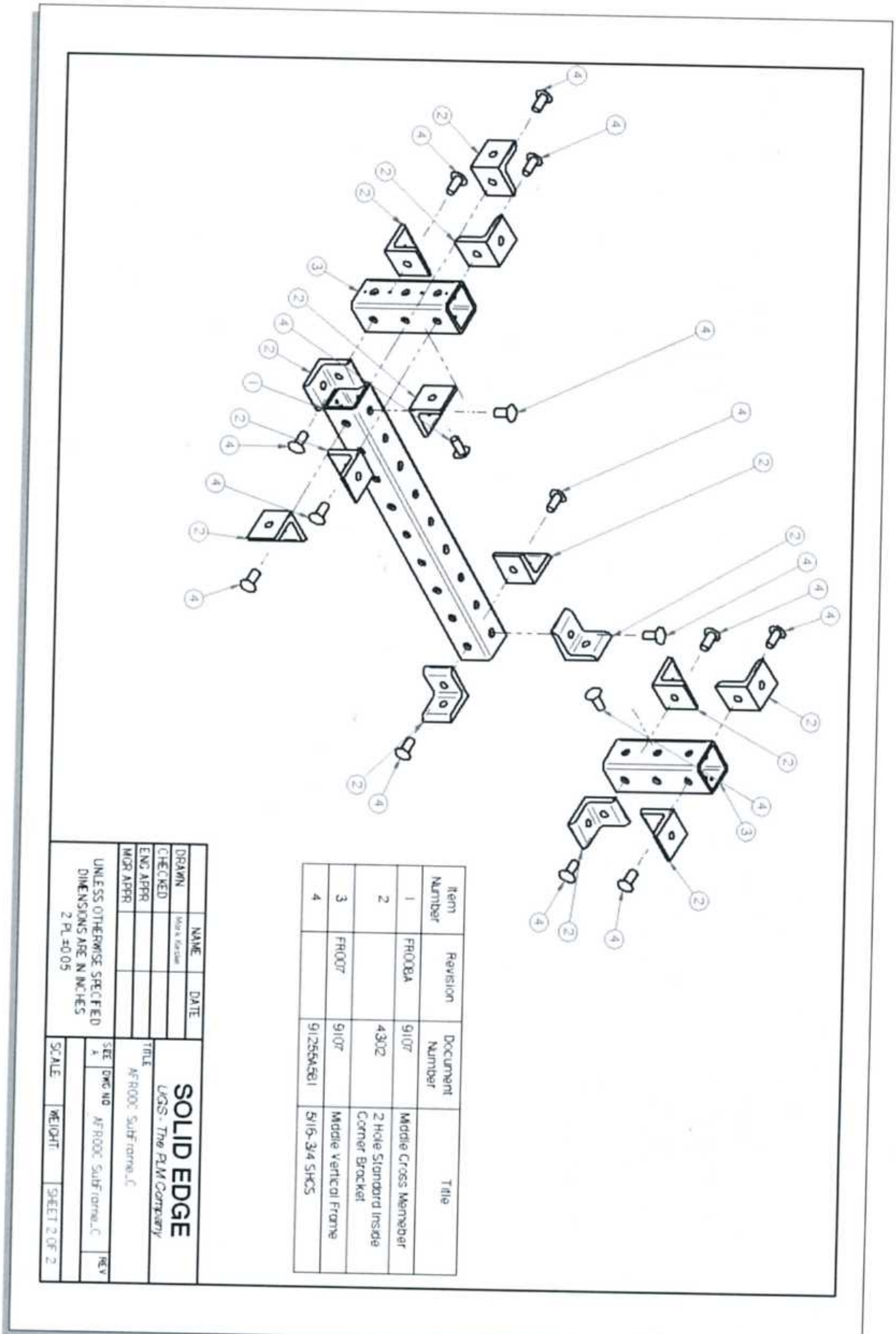
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

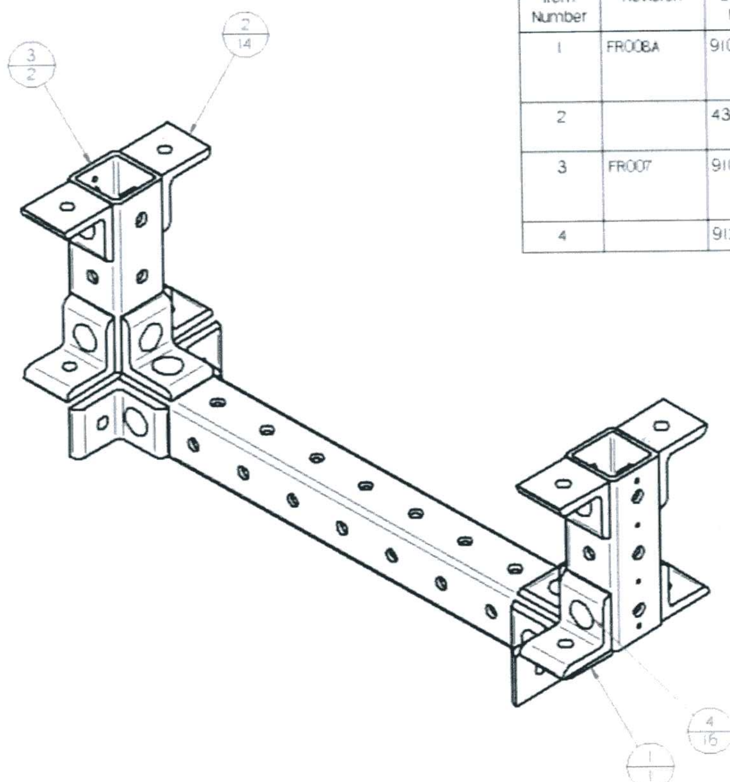
TITLE AFR00B Subframe_B

SIZE A | DWG NO AFR00B Subframe_B | REV

SCALE | WEIGHT | SHEET 1 OF 2



Item Number	Revision	Document Number	Title
1	FR008A	9107	Middle Cross Memeber
2		4302	2 Hole Standard Inside Corner Bracket
3	FR007	9107	Middle Vertical Frame
4		91255A581	5/16-3/4 SHCS



Item Number	Revision	Document Number	Title	Quantity	Category	Company
1	FR008A	9107	Middle Cross Memeber	1	8020 Components	In House Fabrication (8020 Inc)
2		4302	2 Hole Standard Inside Corner Bracket	14	8020 Components	8020 Inc.
3	FR007	9107	Middle Vertical Frame	2	8020 Components	In House Modification (8020 Inc)
4		91255A581	5/16-3/4 SHCS	16	Hardware	McMaster

	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

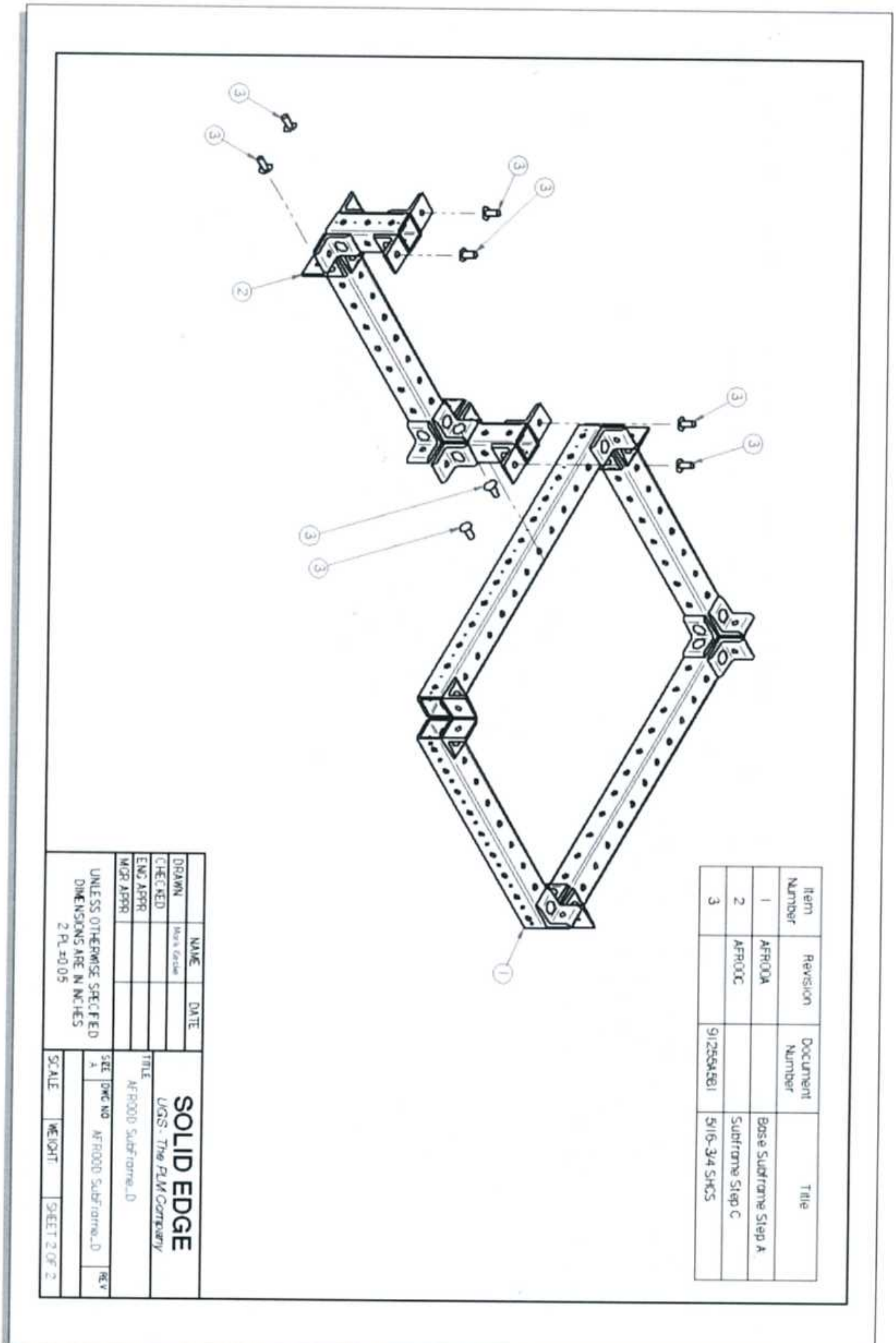
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

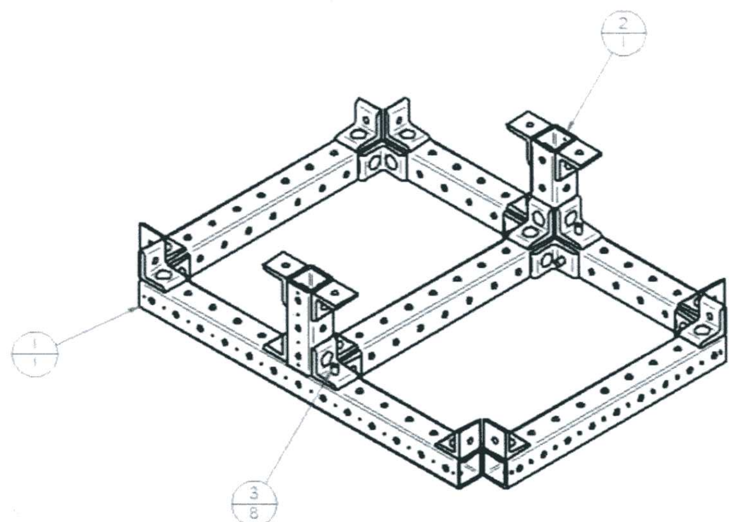
TITLE AFROOC SubFrame_C

SIZE A | DWG NO AFROOC SubFrame_C | REV

SCALE | WEIGHT | SHEET 1 OF 2


Item Number
Revision
Document Number
Title
1
AFR00A
Base Subframe Step A
2
AFR00C
Subframe Step C
3
91255A581
5/16-3/4 SHCS
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
AFR00D Subframe_D
SIZE
A
DWG NO
AFR00D Subframe_D
REV
SCALE
WEIGHT
SHEET 2 OF 2

Item Number	Revision	Document Number	Title	Quantity	Company	Category
1	AFR00A		Base Subframe Step A	1		
2	AFR00C		Subframe Step C	1		
3		91255A581	5/16-3/4 SHCS	8	McMaster	Hardware



	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE AFR00D SubFrame_D

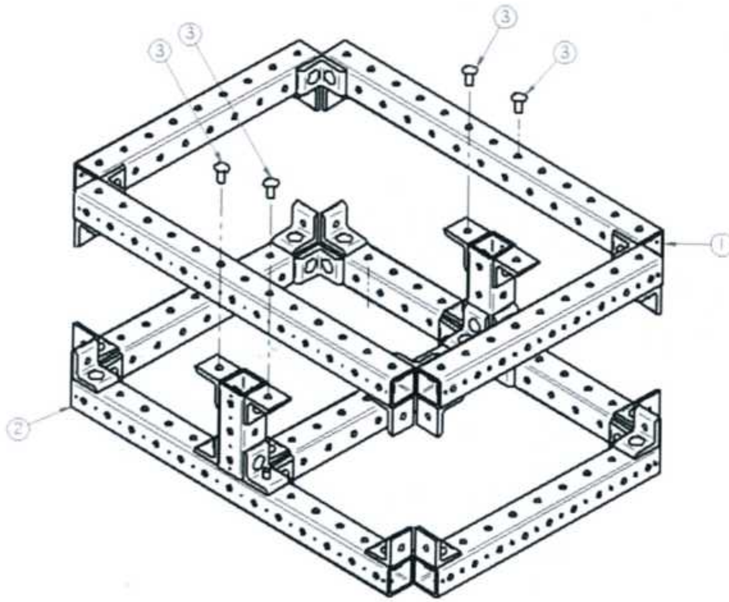
SIZE A | DWG NO AFR00D SubFrame_D | REV

SCALE | WEIGHT | SHEET 1 OF 2

NOTE: All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities)

Item Number	Revision	Document Number	Title	Quantity
1	AFR00A		Base Subframe Step A	1
2	AFR00D		Subframe Step D	1
3		91255A581	5/16-3/4 SHCS	4



	NAME	DATE
DRAWN	Mark Kerske	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE: AFR00E SubFrame_E

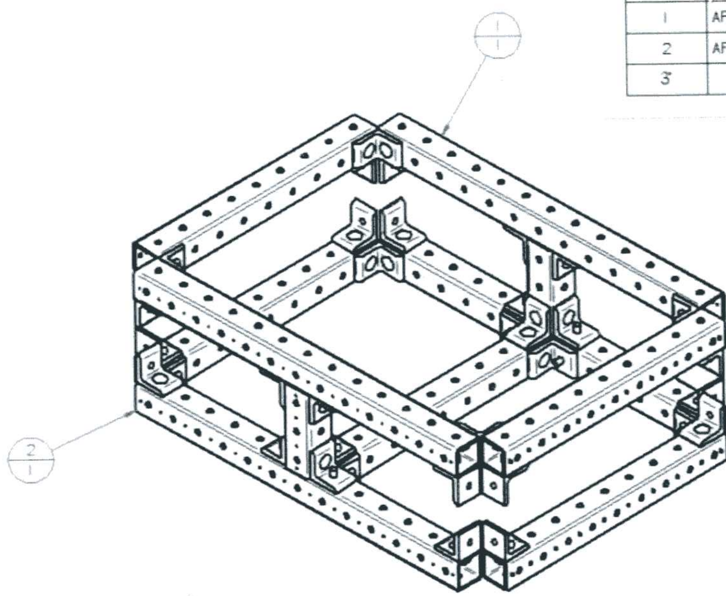
SIZE: A | DWG NO: AFR00E SubFrame_E | REV

SCALE | WEIGHT | SHEET 2 OF 2

NOTE: All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities)

Item Number	Revision	Document Number	Title	Quantity	Category	Company
1	AFROOA		Base Subframe Step A	1		
2	AFROOD		Subframe Step D	1		
3		91255A581	5/16-3/4 SHCS	4	Hardware	McMaster



	NAME	DATE
DRAWN	Mark Kessler	
CHECKED		
ENG APPR		
MGR APPR		

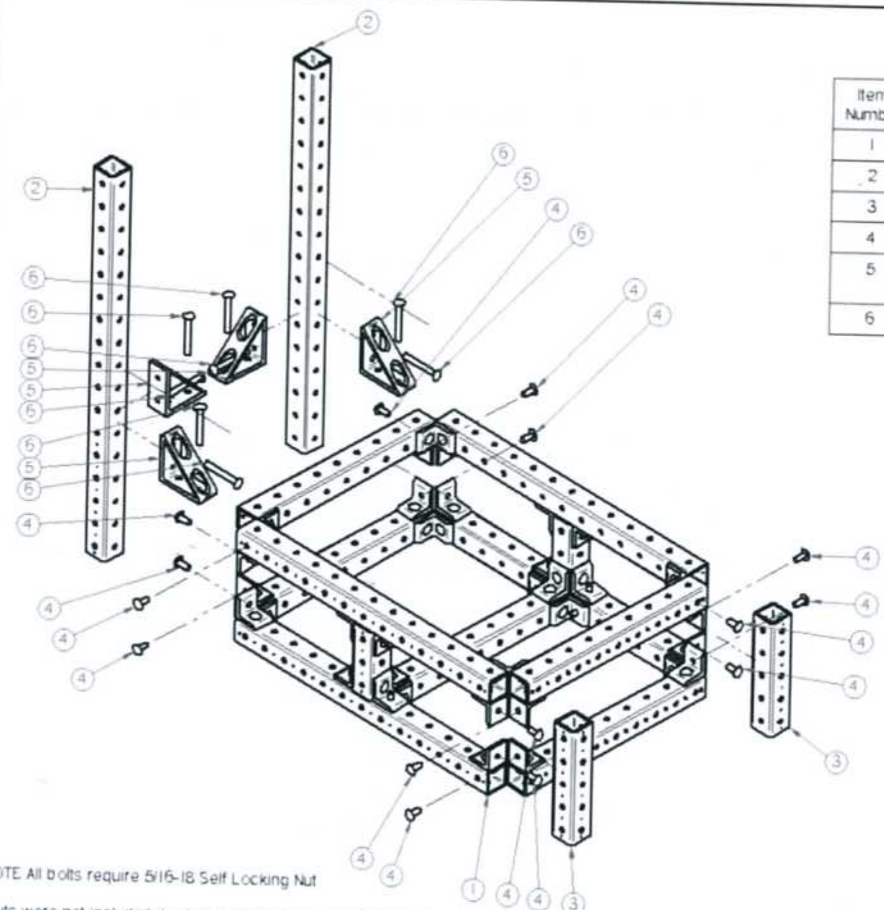
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE: AFROOE SubFrame_E

SIZE: A | DWG NO: AFROOE SubFrame_E | REV:

SCALE: | WEIGHT: | SHEET 1 OF 2



Item Number	Revision	Document Number	Title	Quantity
1	AFROOE		Subframe Step E	1
2	FR010	9107	Rear Tower	2
3	FR015	9107	Frame End	2
4		91255A581	5/16-3/4 SHCS	16
5		4336	4 Hole Inside Corner Gusset	4
6		92949A594	5/16- 2 and 1/2 SHCS	8

NOTE: All bolts require 5/16-18 Self Locking Nut

Nuts were not included due to computer memory capabilities!

	NAME	DATE
DRAWN	Mark Kerske	
CHECKED		
ENG APPR		
MGR APPR		

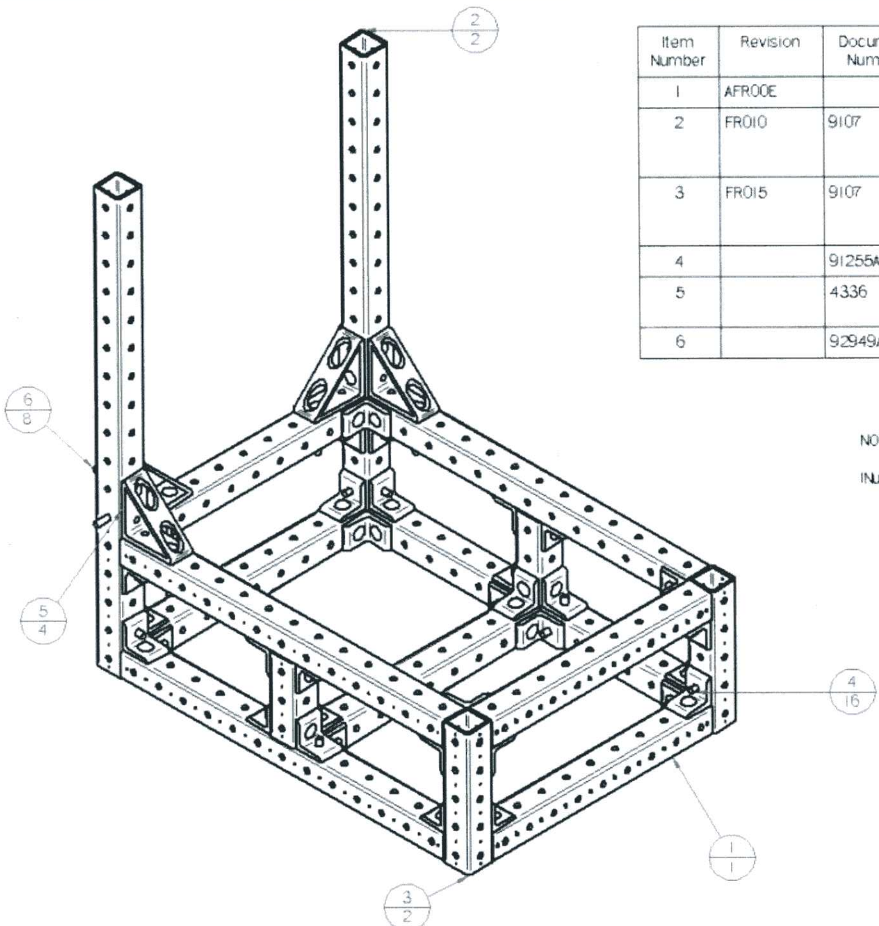
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE: AFROOF SubFrame_F

SIZE: A | DWG NO: AFROOF SubFrame_F | REV:

SCALE: | WEIGHT: | SHEET 2 OF 2



Item Number	Revision	Document Number	Title	Quantity	Category	Company
1	AFROOE		Subframe Step E	1		
2	FR010	9107	Rear Tower	2	8020 Components	In House Modification (8020 Inc)
3	FR015	9107	Frame End	2	8020 Components	In House Modification (8020 Inc)
4		91255A581	5/16-3/4 SHCS	16	Hardware	McMaster
5		4336	4 Hole Inside Corner Gusset	4	8020 Components	8020 Inc.
6		92949A594	5/16- 2 and 1/2 SHCS	8	Hardware	McMaster

NOTE: All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities)

	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

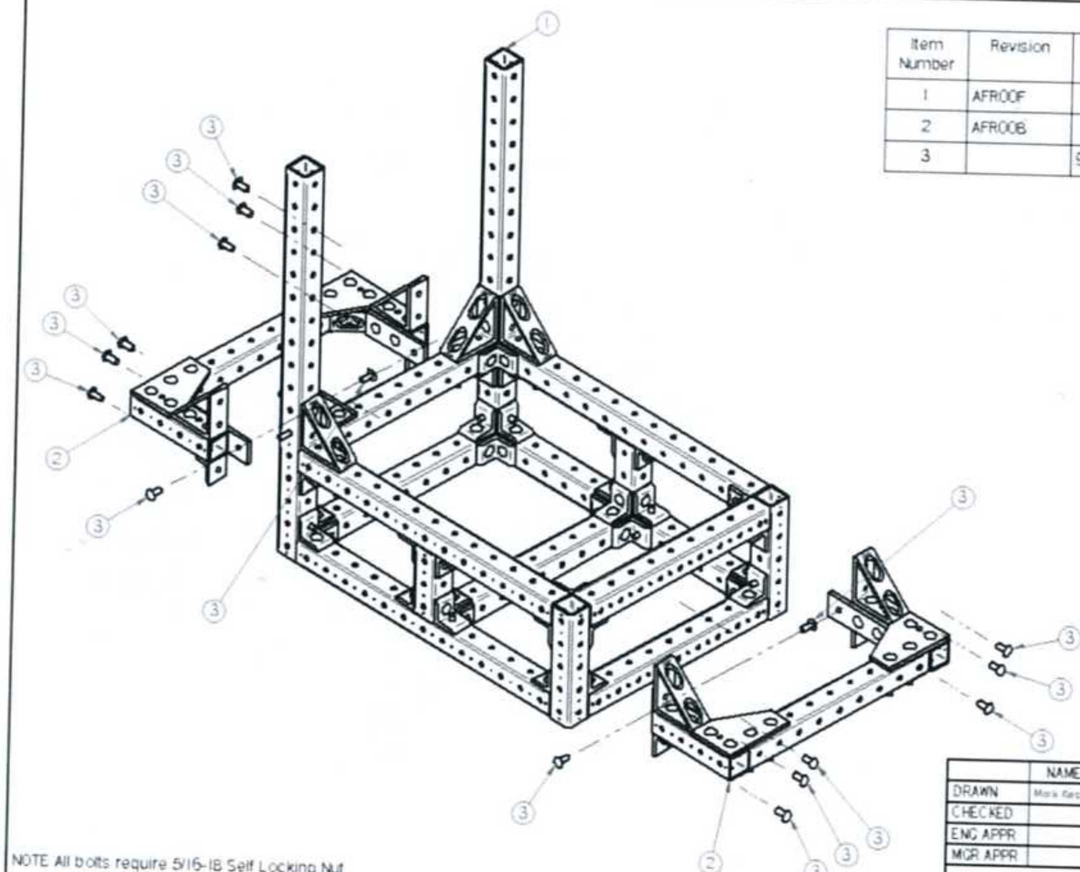
SOLID EDGE
UGS - The PLM Company

TITLE: AFROOF SubFrame_F

SIZE: A | DWG NO: AFROOF SubFrame_F | REV:

SCALE: | WEIGHT: | SHEET 1 OF 2

Item Number	Revision	Document Number	Title	Quantity
1	AFROOF		Subframe Step F	1
2	AFROOB		Subframe Step B	2
3		91255A581	5/16-3/4 SHCS	16



NOTE All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities)

	NAME	DATE
DRAWN	Mark Kerbe	
CHECKED		
ENG APPR		
MGR APPR		

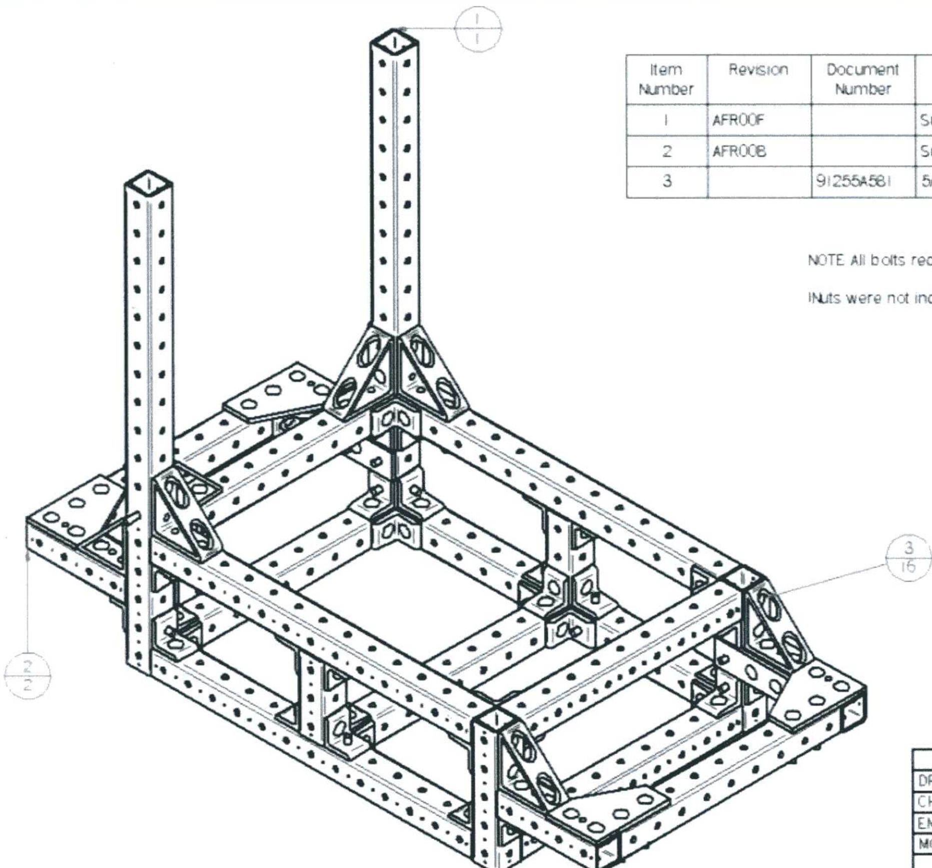
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE AFR00C SubFrame_C

SIZE A DWG NO AFR00C SubFrame_C REV

SCALE WEIGHT SHEET 2 OF 2



Item Number	Revision	Document Number	Title	Quantity	Category	Company
1	AFR00F		Subframe Step F	1		
2	AFR00B		Subframe Step B	2		
3		91255A581	5/16-3/4 SHCS	16	Hardware	McMaster

NOTE All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities)

	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE AFR00G SubFrame_G

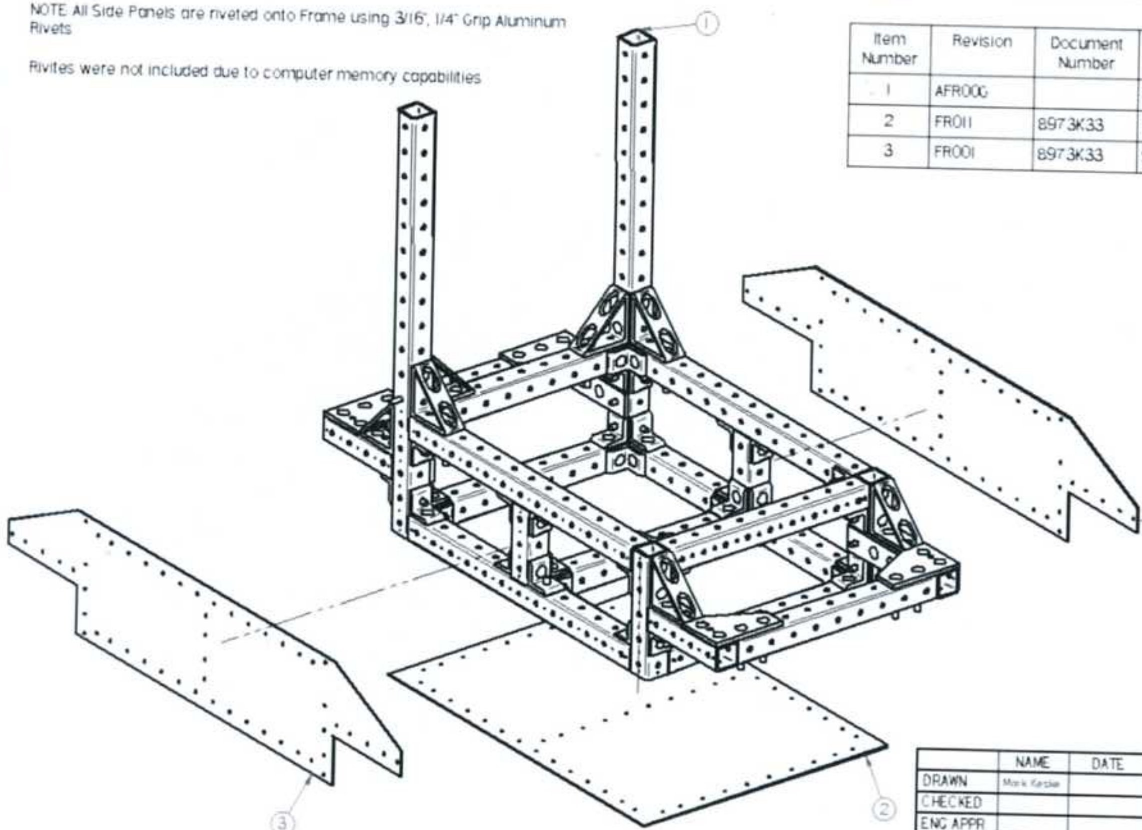
SIZE A | DWG NO AFR00G SubFrame_G | REV

SCALE | WEIGHT | SHEET 1 OF 2

NOTE: All Side Panels are riveted onto Frame using 3/16", 1/4" Grip Aluminum Rivets

Rivites were not included due to computer memory capabilities

Item Number	Revision	Document Number	Title	Quantity
1	AFR00G		Subframe Step G	1
2	FR011	8973K33	Bottom Panel (No Motors)	1
3	FR001	8973K33	Side Panel (No Motors)	2



	NAME	DATE
DRAWN	Mark Kerske	
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE: AFR2

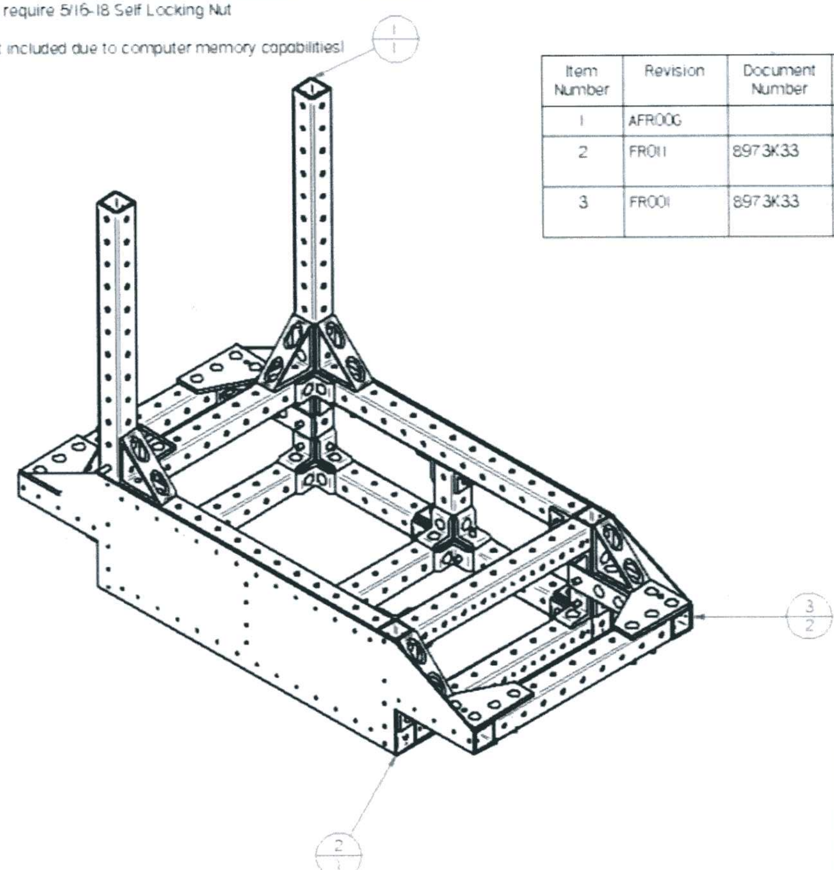
SIZE: A | DWG NO: AFR2 | REV

SCALE | WEIGHT | SHEET 2 OF 2

NOTE All bolts require 5/16-18 Self Locking Nut

(Nuts were not included due to computer memory capabilities)

Item Number	Revision	Document Number	Title	Quantity	Category	Company
1	AFR00G		Subframe Step G	1		
2	FR011	8973K33	Bottom Panel (No Motors)	1	In House Modification	McMaster
3	FR001	8973K33	Side Panel (No Motors)	2	In House Modification	McMaster



	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

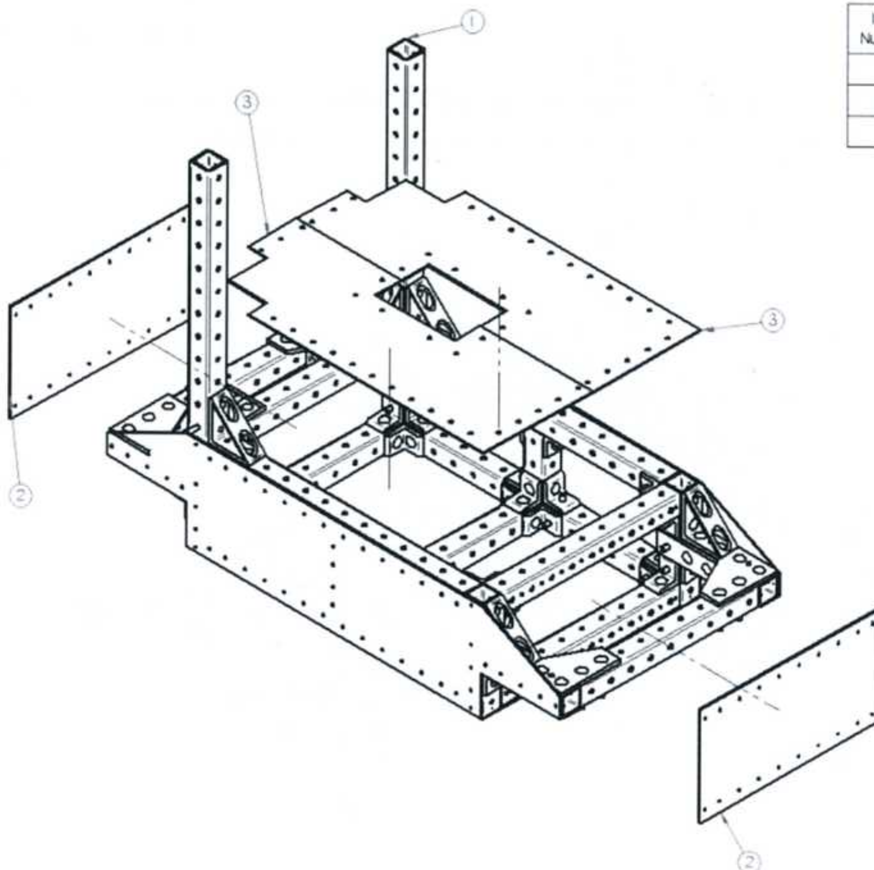
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE AFR Frame

SIZE A | DWG NO AFR Frame | REV

SCALE | WEIGHT | SHEET 1 OF 2



Item Number	Revision	Document Number	Title	Quantity
1	AFR		AFR Frame	1
2	FR012	Garolite G-10	Front and Rear Pannel	2
3	FR013	Garolite G-10	Top Panel Half	2

	NAME	DATE
DRAWN	Mark Kerske	
CHECKED		
ENG APPR		
MGR APPR		

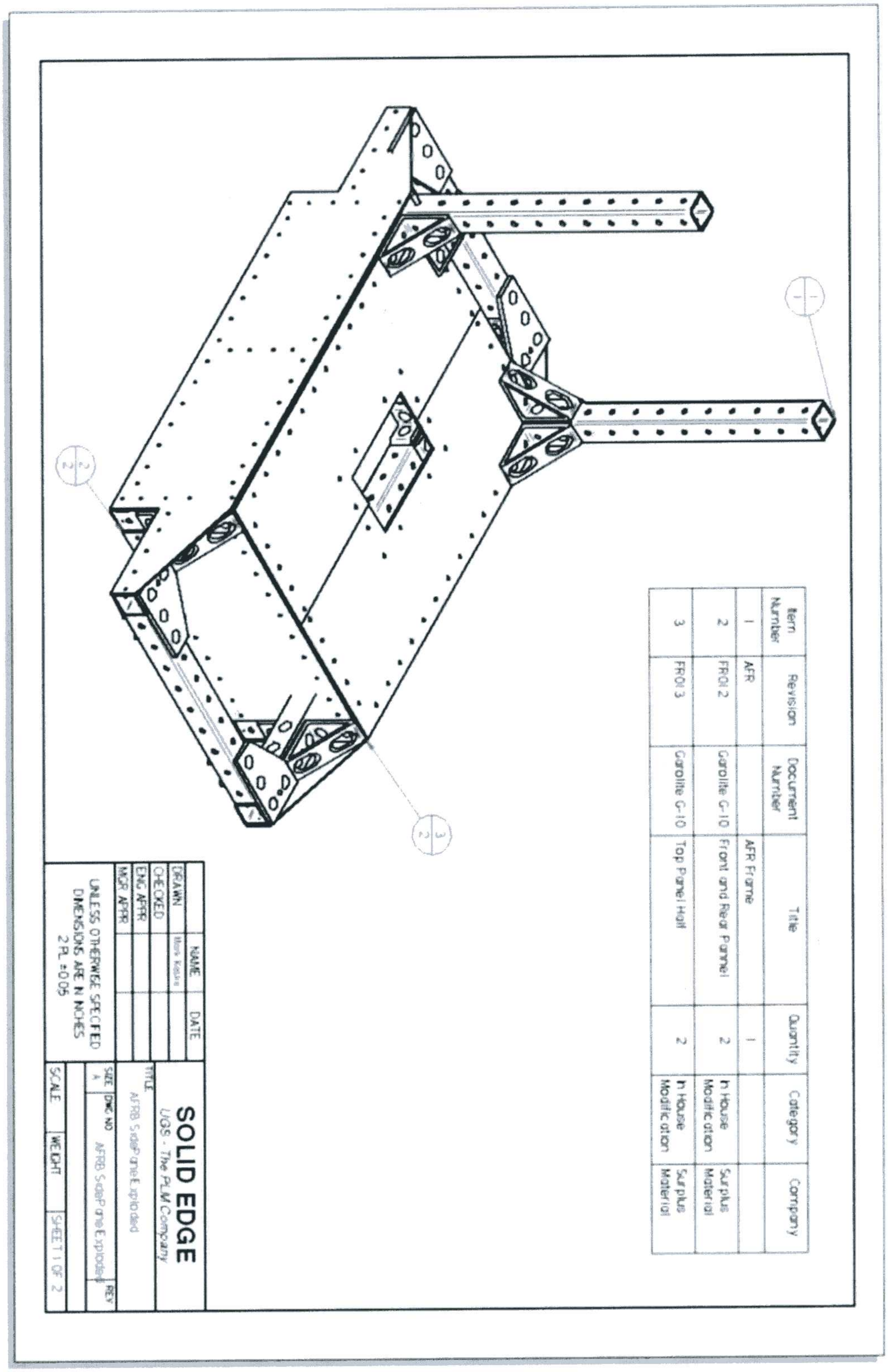
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE
AFRB SidePane Exploded

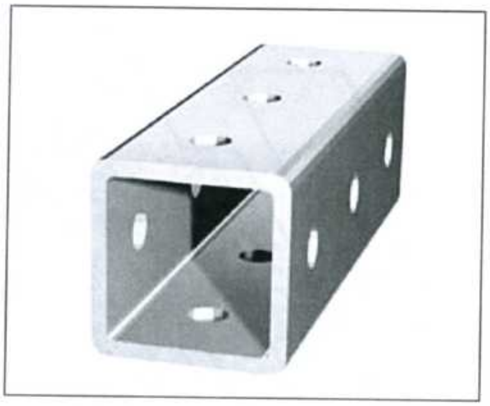
SIZE	DWG NO	REV
A	AFRB SidePane Exploded	

SCALE	WEIGHT	SHEET 2 OF 2



Item Number	Revision	Document Number	Title	Quantity	Category	Company
1	AFR		AFR Frame	1		
2	FR01 2	Garolite G-10	Front and Rear Pannel	2	In House Modification	Surplus Material
3	FR01 3	Garolite G-10	Top Panel Half	2	In House Modification	Surplus Material

APPENDIX M: Frame Component Spec Sheets

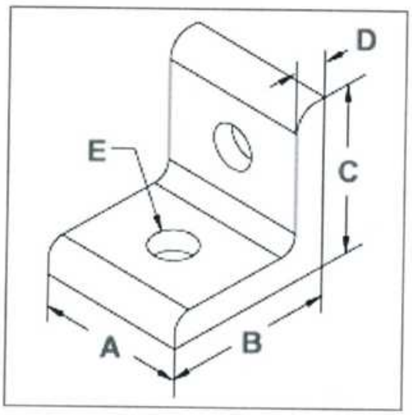


9701 is a 1.5" x 1.5" HT Series™ aluminum profile made from 6105-T5 aluminum. This profile has pre-fabricated holes and no flanges. 9701 works with most HT Series™ accessories and fasteners.

Part No.	Finish	lbs. / Ft.	Stock Length	Area
9701	Clear Anodized	.7886	145" or 242"	.6775 Sq./In.

80/20 Inc. **9701 Square Tube Profile**

2 Hole Inside Corner Bracket



Most HT Series™ AND 15 Series flat joining plates, strips, and inside corner brackets & gussets are made of .25" thick 6105-T5 clear anodized aluminum with .328" diameter holes on 1.50" centerlines except where noted.

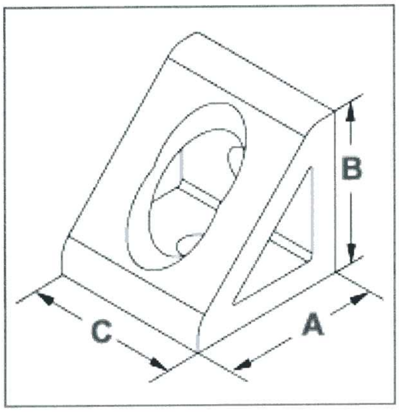
Joining plates are also a great way to transition to and from 15 Series T-slotted profiles.

Part No.	A	B	C	D	E	lbs.
4302	1.310	1.500	1.500	.250	Ø .328	.085

Recommended Fractional & Metric Bolt Assemblies

Part No.	Description	Quantity
3961	5/16-18 x 2" Button Head w/ Washer and Hex Nut	2
	Or Use	
3964	M8 x 50mm Button Head w/ Washer and Hex Nut	2

2 Hole Inside Corner Gusset



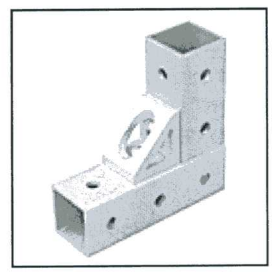
Most HT Series™ AND 15 Series flat joining plates, strips, and inside corner brackets & gussets are made of .25" thick 6105-T5 clear anodized aluminum with .328" diameter holes on 1.50" centerlines except where noted.

Joining plates are also a great way to transition to and from 15 Series T-slotted profiles.

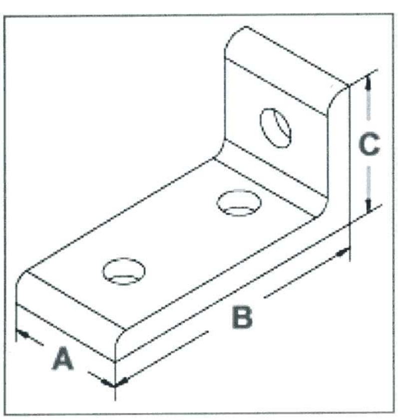
Part No.	A	B	C	lbs.
4332	1.500	1.500	1.310	.125

Recommended Fractional & Metric Bolt Assemblies

Part No.	Description	Quantity
3961	5/16-18 x 2" Button Head w/ Washer and Hex Nut	2
	Or Use	
3964	M8 x 50mm Button Head w/ Washer and Hex Nut	2



3 Hole Inside Corner Bracket



Most HT Series™ AND 15 Series flat joining plates, strips, and inside corner brackets & gussets are made of .25" thick 6105-T5 clear anodized aluminum with .328" diameter holes on 1.50" centerlines except where noted.

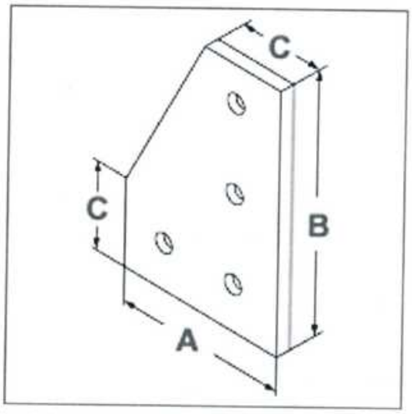
Joining plates are also a great way to transition to and from 15 Series T-slotted profiles.

Part No.	A	B	C	lbs.
4376	1.310	3.000	1.500	.130

Recommended Fractional & Metric Bolt Assemblies

Part No.	Description	Quantity
3961	5/16-18 x 2" Button Head w/ Washer and Hex Nut	3
	Or Use	
3964	M8 x 50mm Button Head w/ Washer and Hex Nut	3

4 Hole 90° Joining Plate



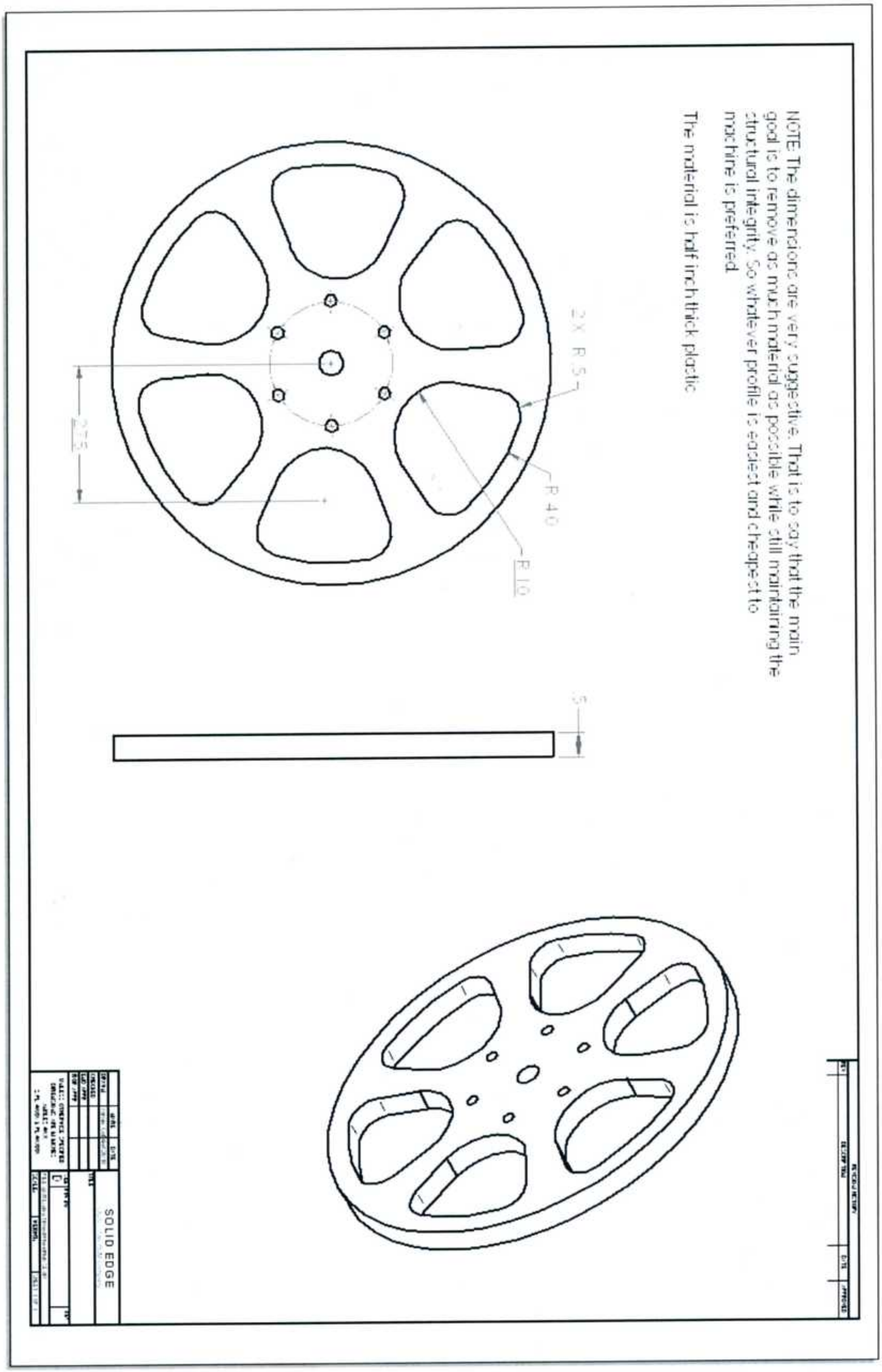
Most HT Series™ AND 15 Series flat joining plates, strips, and inside corner brackets & gussets are made of .25" thick 6105-T5 clear anodized aluminum with .328" diameter holes on 1.50" centerlines except where noted.

Joining plates are also a great way to transition to and from 15 Series T-slotted profiles.

Part No.	A	B	C	lbs.
4350	3.000	4.500	1.500	.260

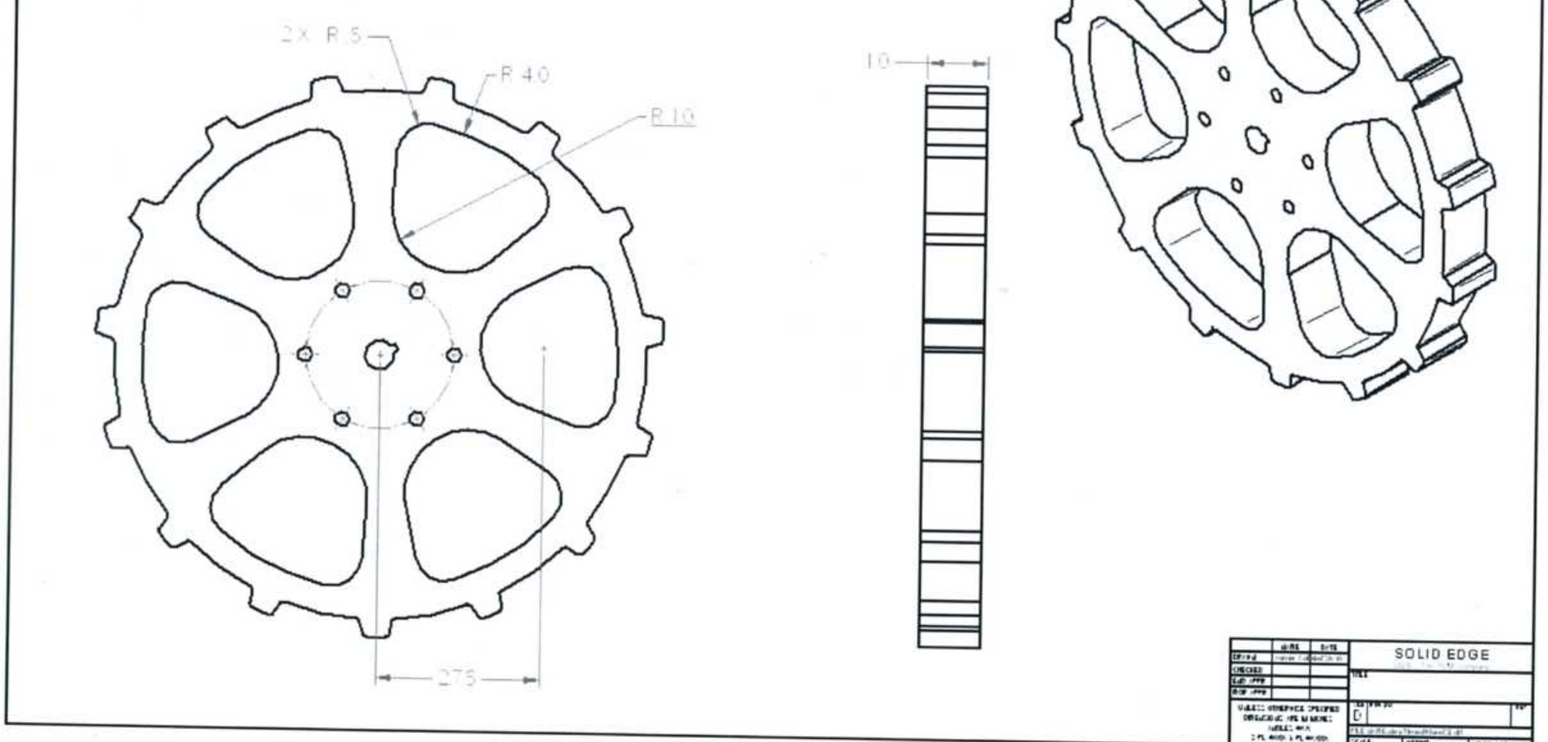
Part No.	Description	Quantity
3960	5/16-18 x 2" Flanged Hex Bolt w/ Hex Nut	4
	Or Use	
3963	M8 x 50mm Flanged Hex Bolt w/ Hex Nut	4

APPENDIX K: Drive Detailed Drawings



NOTE: The dimensions are very suggestive. That is to say that the main goal is to remove as much material as possible while still maintaining the structural integrity. So whatever profile is easiest and cheapest to machine is preferred.

The material in one inch thick aluminum.



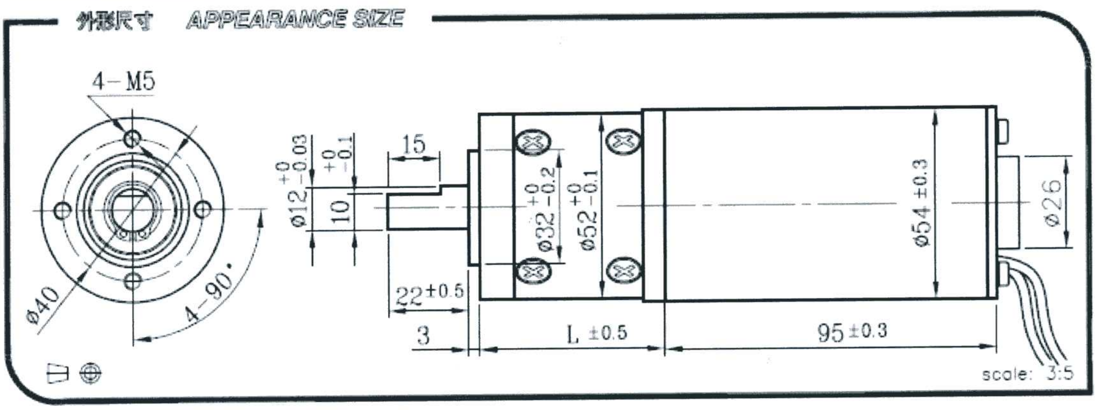
直流馬達 (DC Carbon-brush motors)

IG-52 GEARHEAD SERIES

IG-52GM

03&04 TYPE

REDUCTION RATIO	L	REDUCTION RATIO	L
1/3~1/4	53.0	1/150~1/936	99.5
1/12~1/26	68.5		
1/43~1/113	84.0		



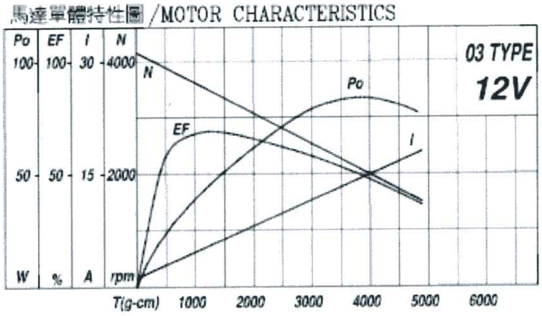
GEARED MOTOR TORQUE/SPEED

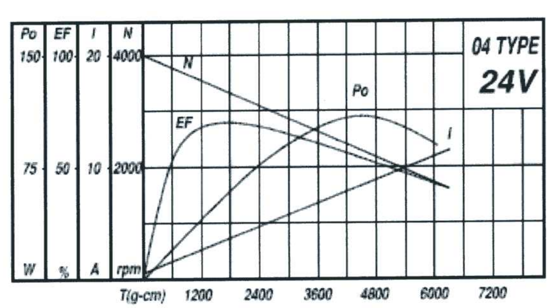
	減速比 Reduction ratio	1/3	1/4	1/12	1/15	1/19	1/26	1/43	1/53	1/66	1/81	1/100	1/113	1/150	1/230	1/285	1/353	1/488	1/546	1/676	1/936
12V	定格扭力(Kg-cm) Rated torque	2.5	3.1	7.7	9.5	11.8	16	23	28	35	44	54	60	67	100	100	100	100	100	100	100
	定格回轉數(rpm) Rated speed	1030	835	295	238	192	139	84	68	55	44	36	32	24	15.5	12.8	10.4	7.6	6.7	5.6	4.0
24V	定格扭力(Kg-cm) Rated torque	3.6	4.5	11	13.5	17	23	33	41	51	62	78	88	97	100	100	100	100	100	100	100
	定格回轉數(rpm) Rated speed	1000	815	285	230	185	136	82	67	54	44	35	31	23.5	15.6	12.9	10.5	7.7	6.8	5.7	4.1

馬達單體型式 /MOTOR DATTA

定格電壓 Rated volt (V)	定格扭力 Rated torque (g-cm)	定格回轉數 Rated speed (rpm)	定格電流 Rated current (mA)	無負荷回轉數 No load speed (rpm)	無負荷電流 No load current (mA)	定格出力 Rated output (W)	重量 Weight (g)
12	900	3620	≤ 4100	4000	≤ 1200	33.5	920
24	1300	3550	≤ 2850	4000	≤ 700	48.6	920

馬達單體特性圖 /MOTOR CHARACTERISTICS





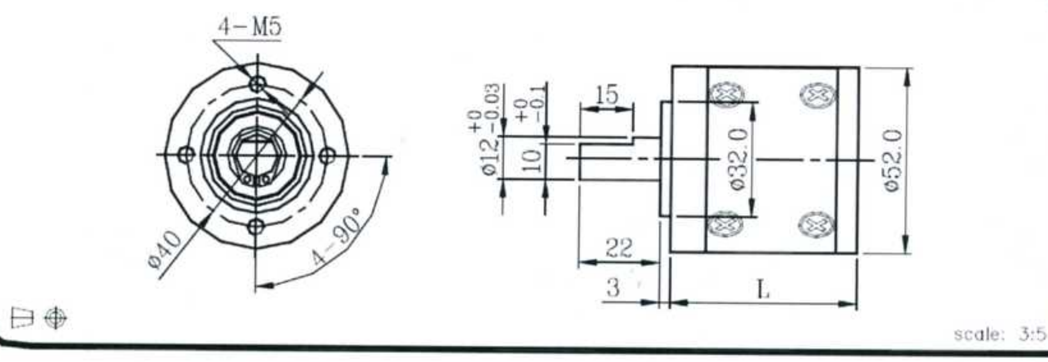
IG-52

● 滾珠軸承型式
Gearbox with ball bearings

★使用相對溼度：20%~85%RH
Operating relative humidity

★使用溫度範圍：-10℃~+60℃
Operating temperature range

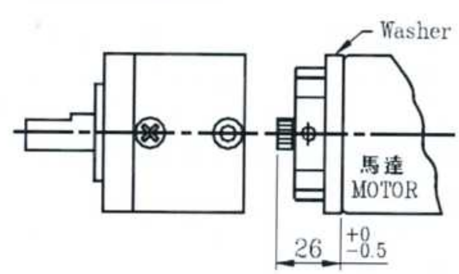
外形尺寸 APPEARANCE SIZE



馬達齒輪型式 PINION SPECIFICATIONS

模數 Module	1.0		
齒數 No. of teeth	8	12	16
壓力角 Pressure angle	20		
孔徑 Hole diameter	Ø3.98	Ø5.98	
減速比 Reduction ratio	1/21, 1/26, 1/126 1/156, 1/488, 1/546 1/676, 1/756, 1/936	1/4, 1/15 1/53, 1/66 1/81, 1/230 1/285, 1/353	1/3 1/12 1/43

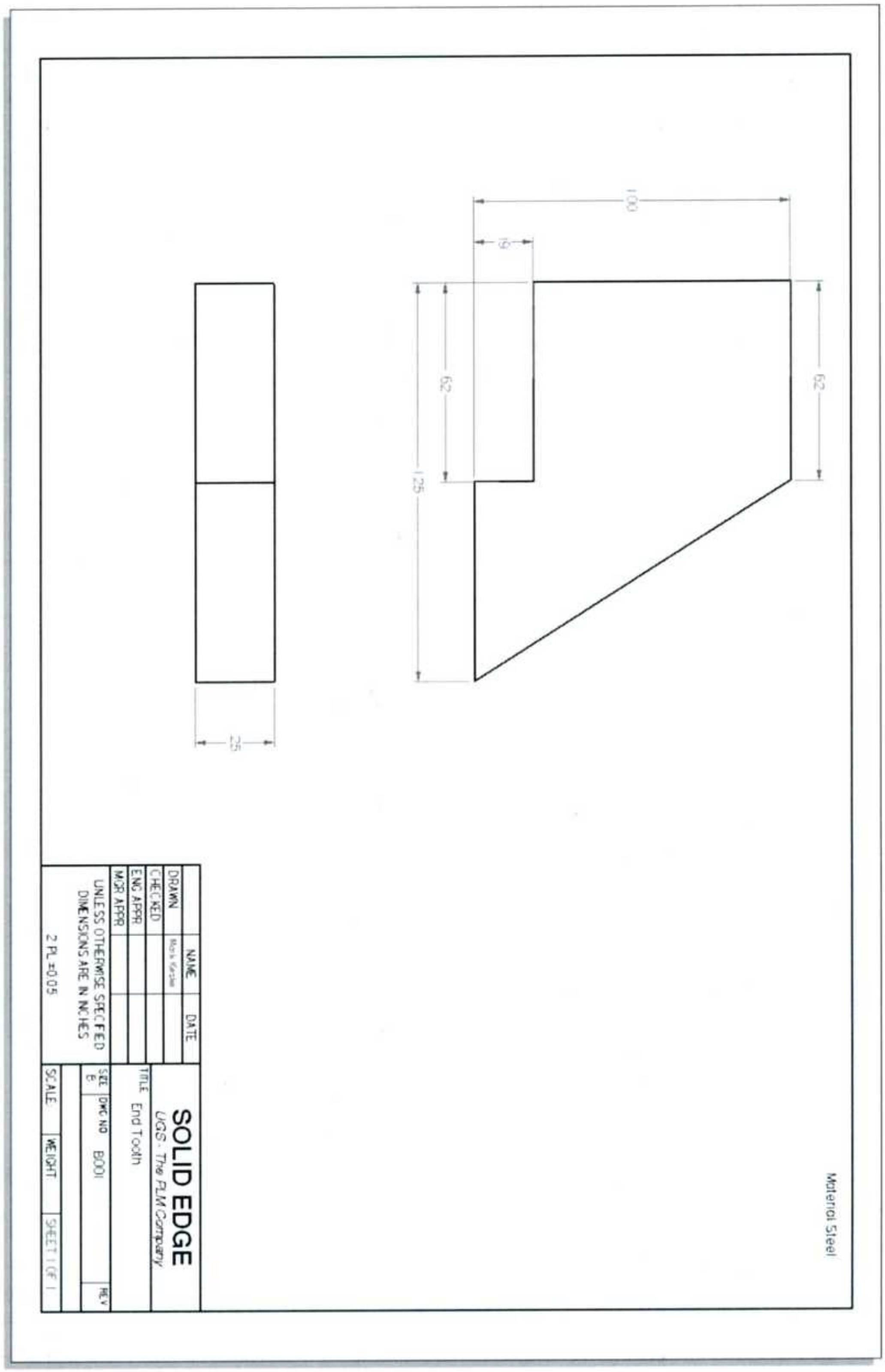
馬達裝卸方法 MOTOR INSTALLATION

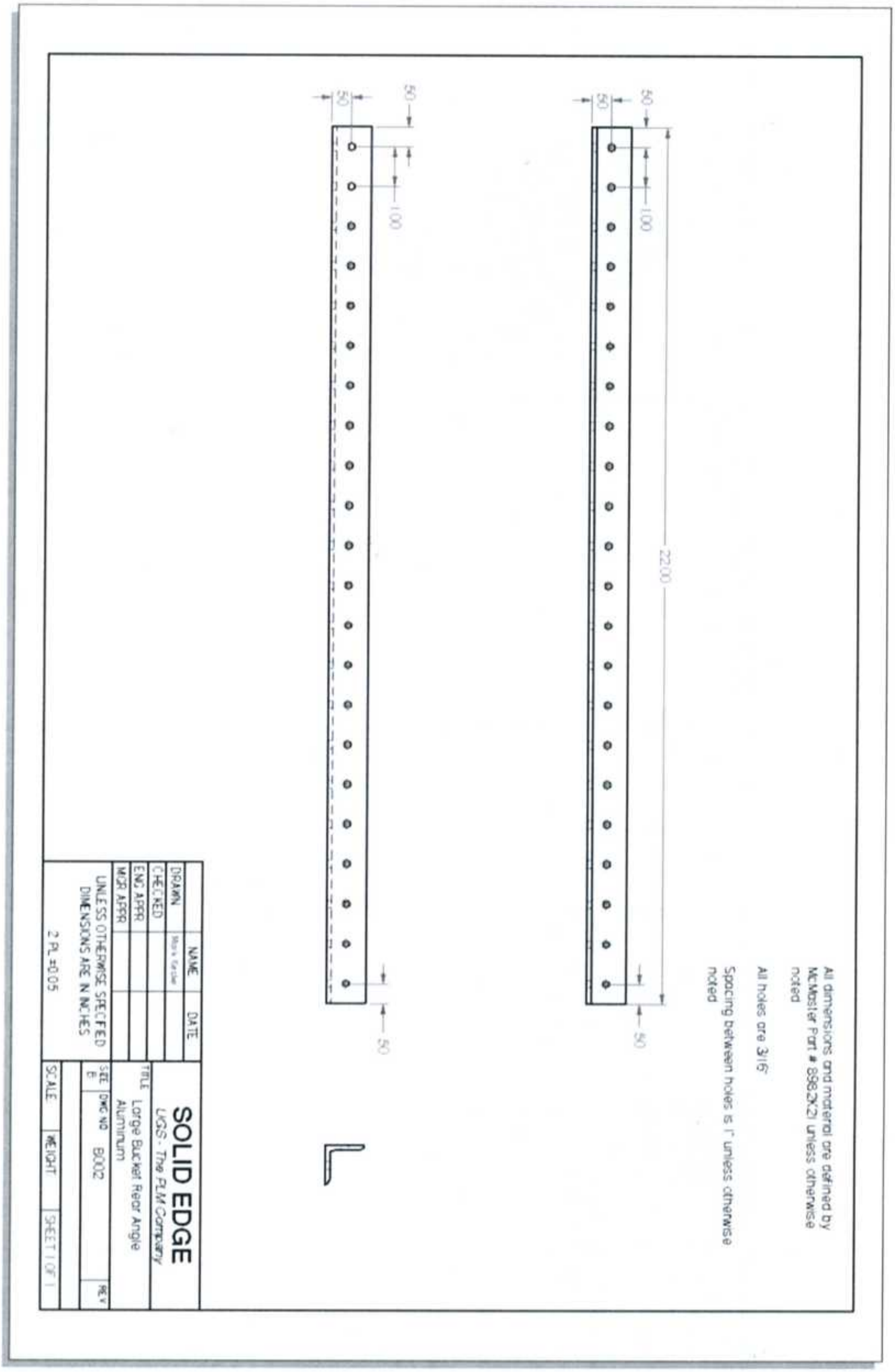


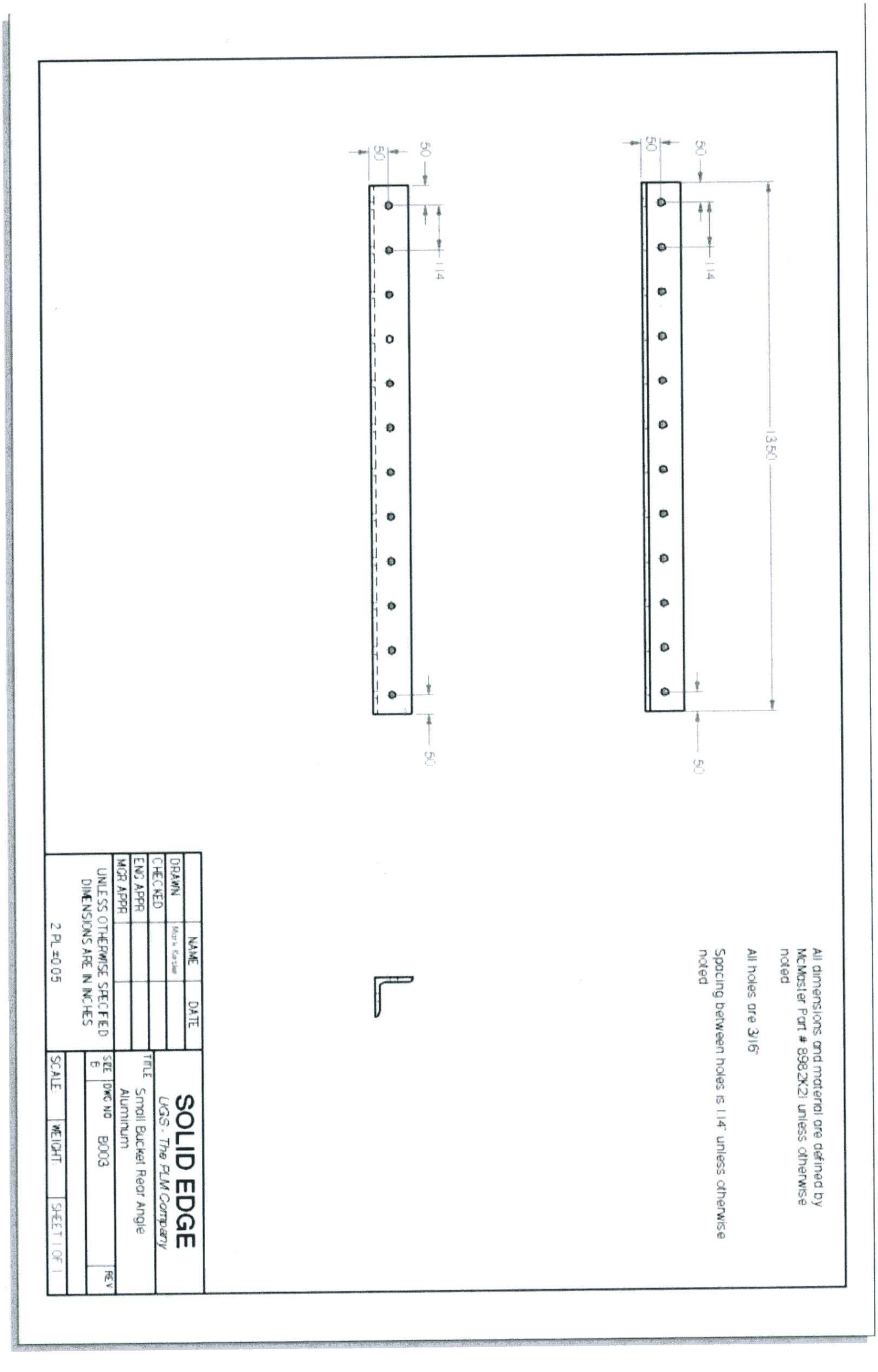
標準減速比型式 GEARBOXES SPECIFICATIONS

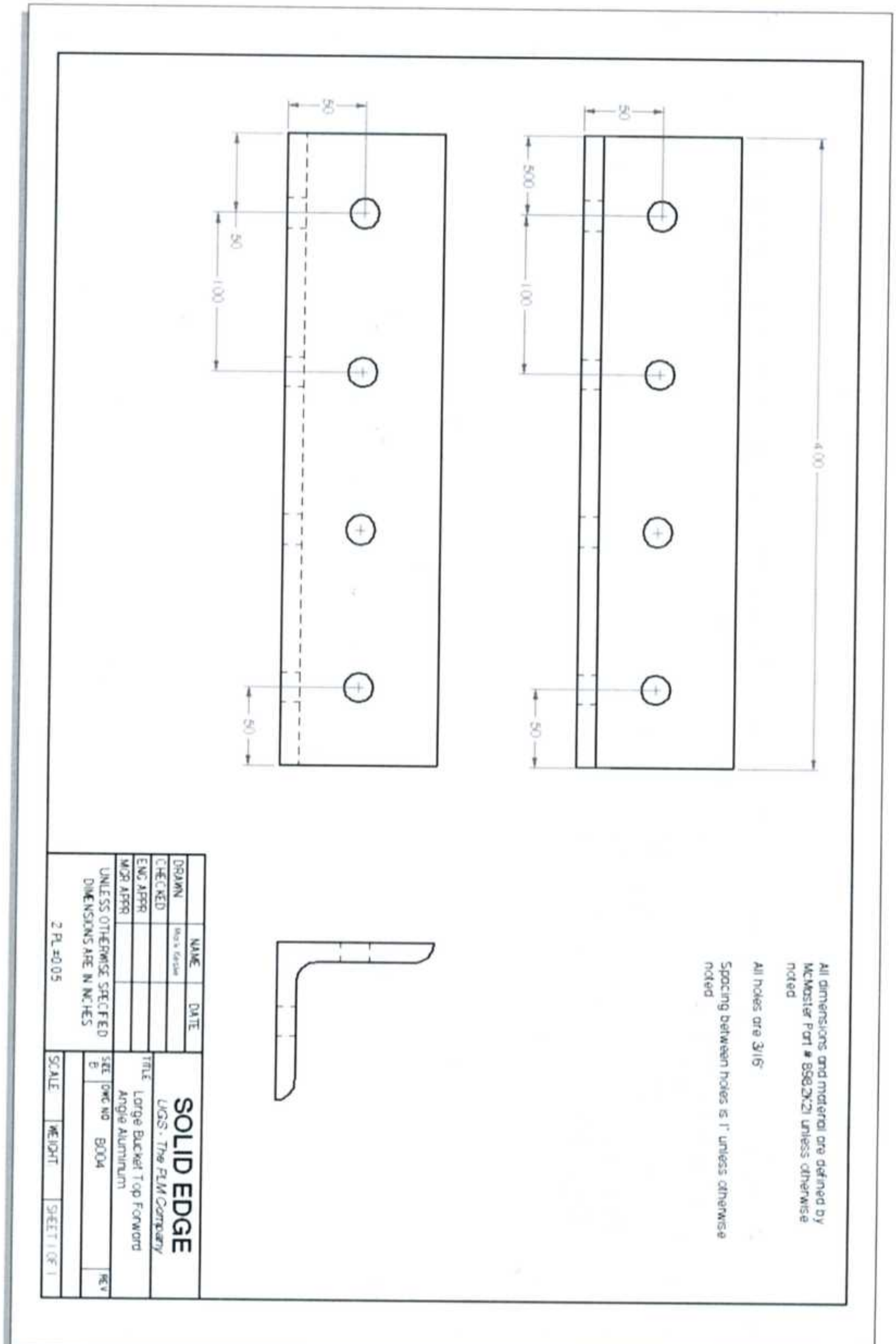
減速比 Reduction ratio	精確減速比 Exact reduction ratio	定格容許扭力 Rated tolerance torque	最大瞬間容許扭力 Max momentary Tolerance torque	效率 Efficiency	軸之徑向公差 Radial play Of shaft	軸之軸向公差 Thrusts play of shaft	L
1/3, 1/4	3 1/2 , 4 1/3	15kgf－cm Max	45 kgf - cm	80%	≦ 0.05mm	≦ 0.3mm	53.0
1/12, 1/15	12 1/4 , 15 1/6	50kgf－cm Max	150 kgf - cm	70%	↑	↑	68.5
1/21, 1/26	21 , 26	50kgf－cm Max	150 kgf - cm	70%	↑	↑	68.5
1/43, 1/53, 1/66	42 7/8 , 53 1/12 , 65 13/18	100kgf－cm Max	300 kgf - cm	60%	↑	↑	84.0
1/81, 1/100	81 10/27 , 100 2/7	100kgf－cm Max	300 kgf - cm	60%	↑	↑	84.0
1/126, 1/156	126 , 156	100kgf－cm Max	300 kgf - cm	60%	↑	↑	84.0
1/230, 1/285	230 1/36 , 284 43/54	100kgf－cm Max	300 kgf - cm	50%	↑	↑	99.5
1/353, 1/488	352 49/81 , 488 2/9	100kgf－cm Max	300 kgf - cm	50%	↑	↑	99.5
1/546, 1/676	546 , 676	100kgf－cm Max	300 kgf - cm	50%	↑	↑	99.5
1/756, 1/936	756 , 936	100kgf－cm Max	300 kgf - cm	50%	↑	↑	99.5

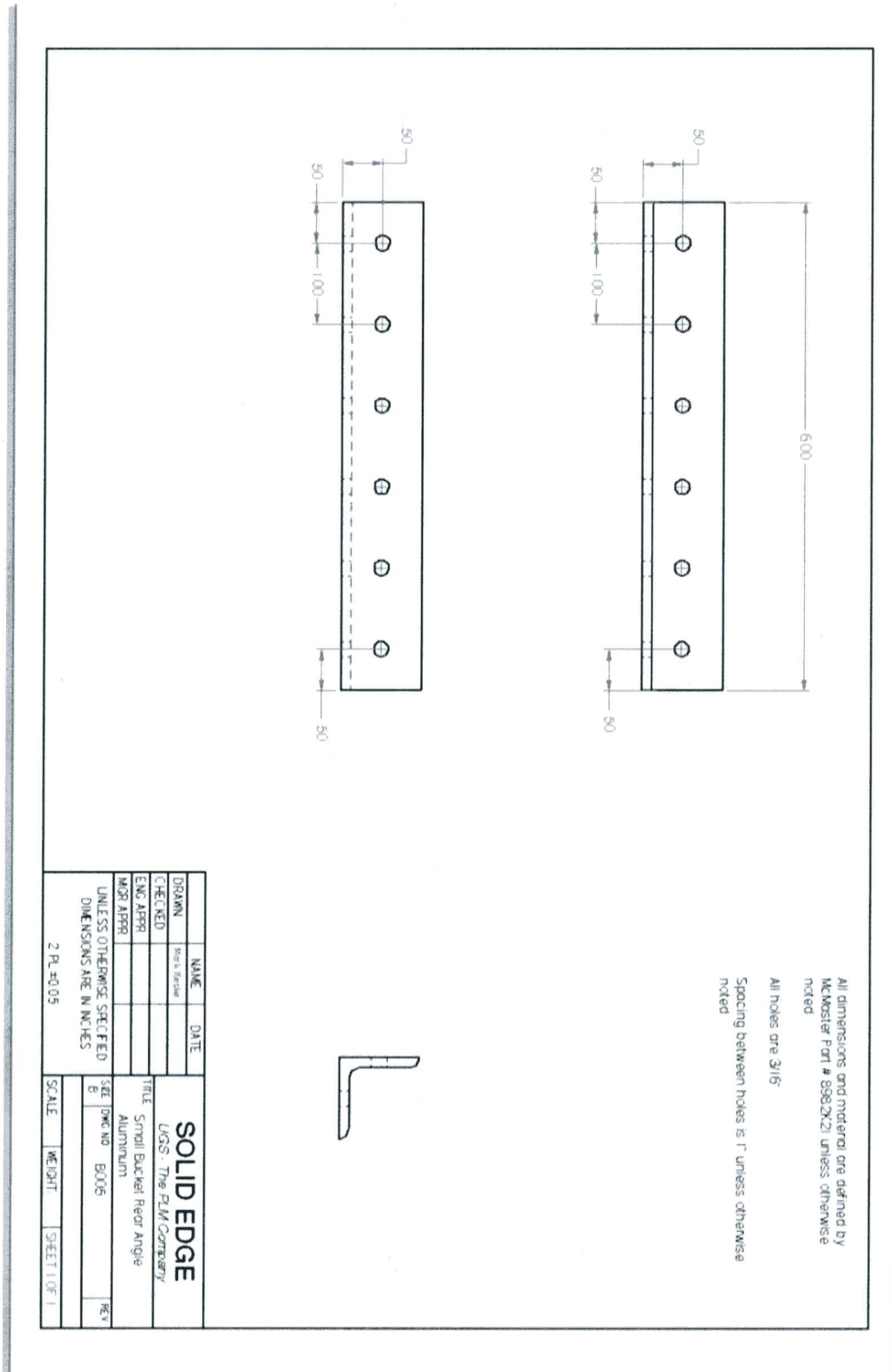
APPENDIX M: Bucket Technical Drawings

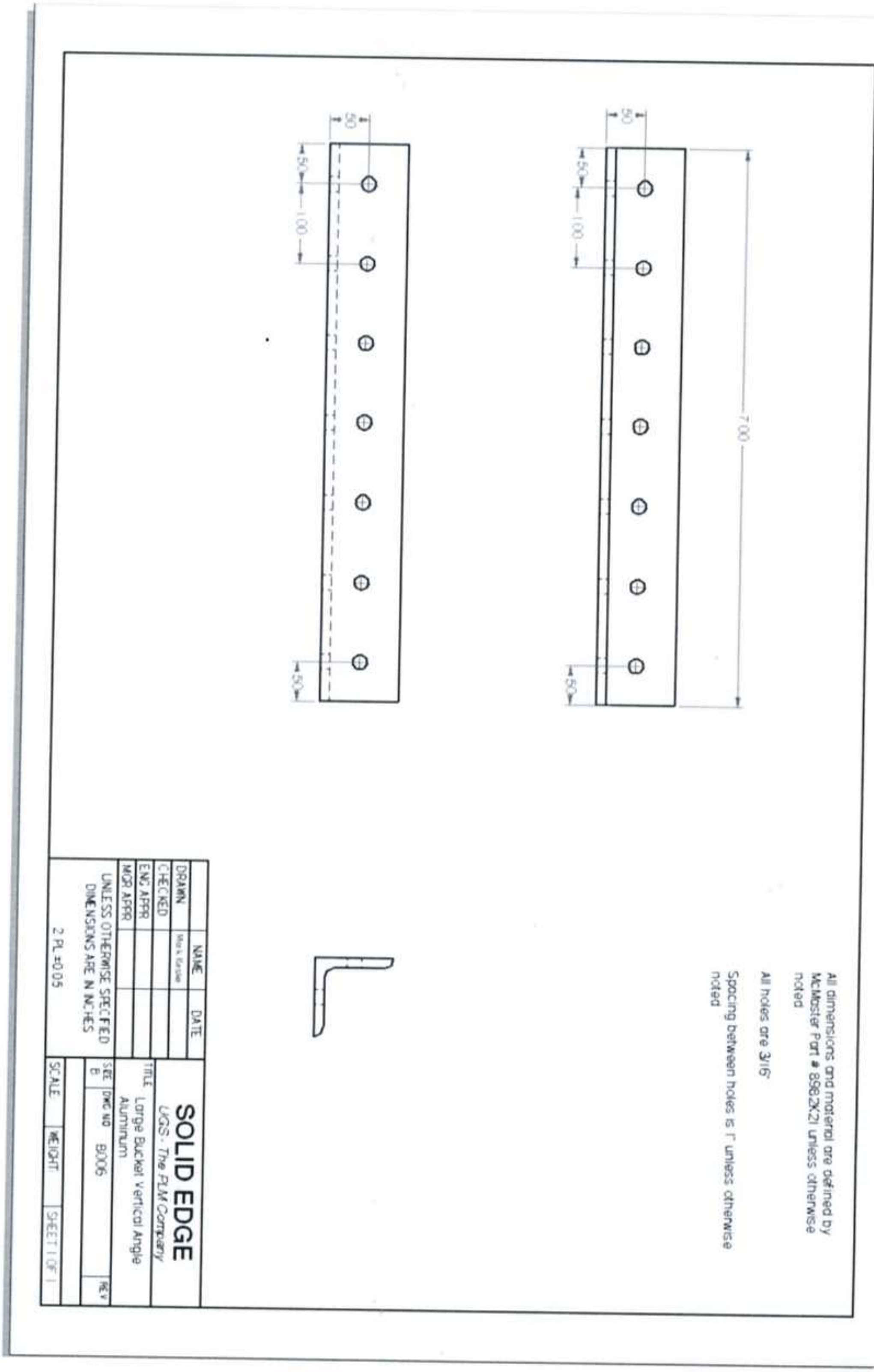


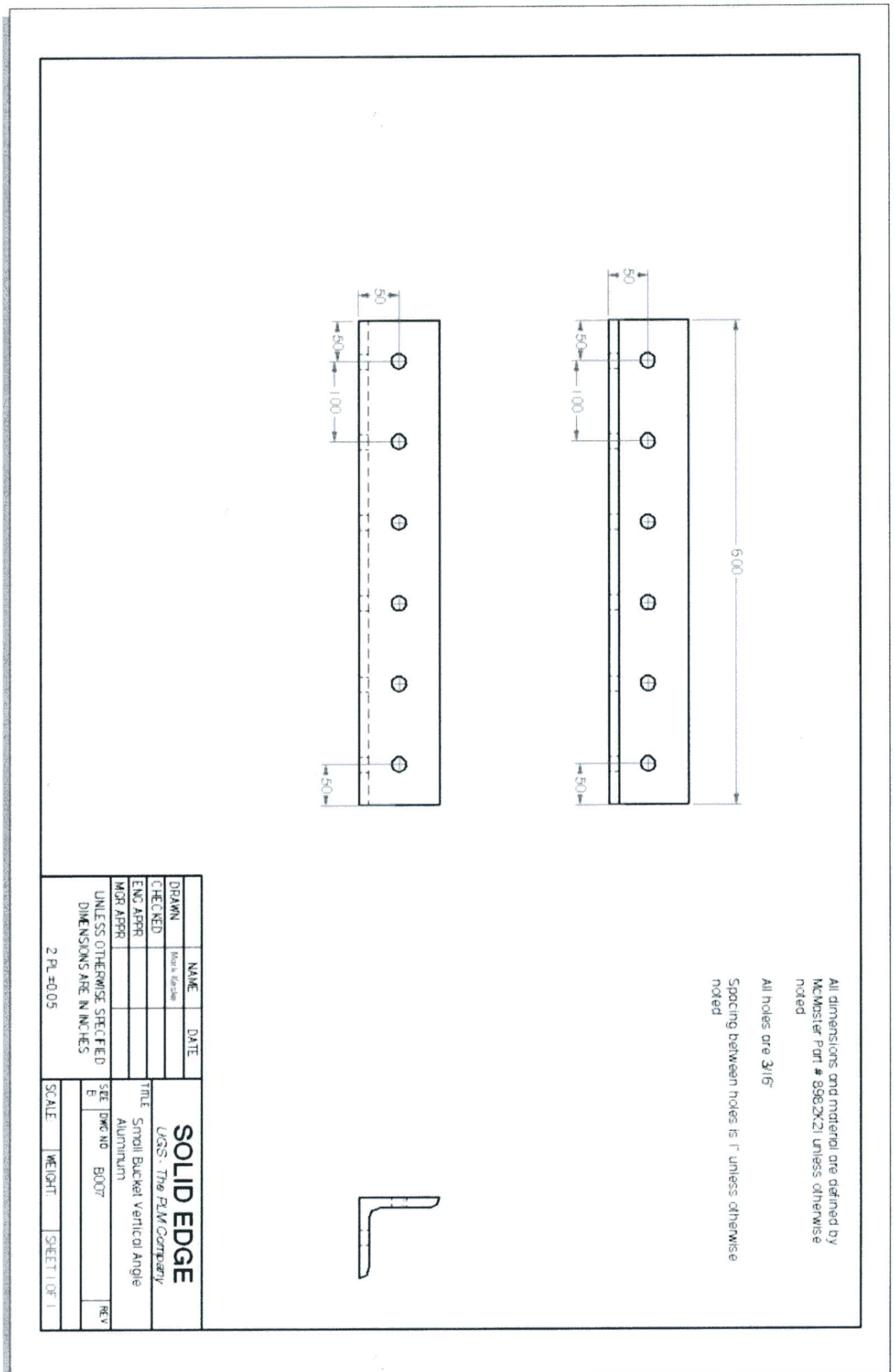

All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
All holes are 3/16"
Spacing between holes is 1" unless otherwise noted
.50
1.00
22.00
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Rear Angle
Aluminum
SIZE
B
DWG NO
B002
REV
SCALE
WEIGHT
SHEET 1 OF 1

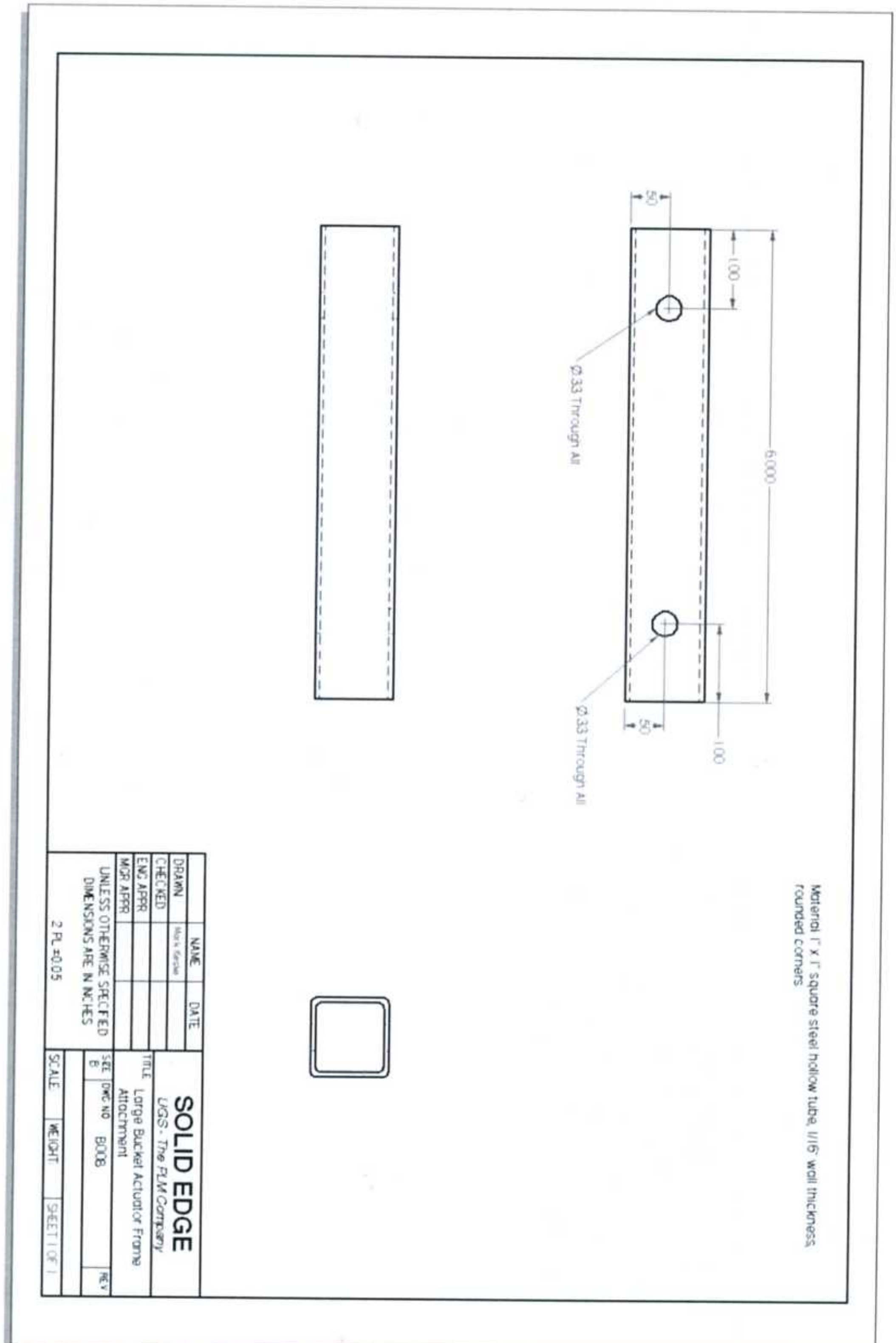

All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
All holes are 3/16"
Spacing between holes is 1.14" unless otherwise noted
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Rear Angle
Aluminum
SIZE
B
DWG NO
B003
REV
SCALE
WEIGHT
SHEET 1 OF 1

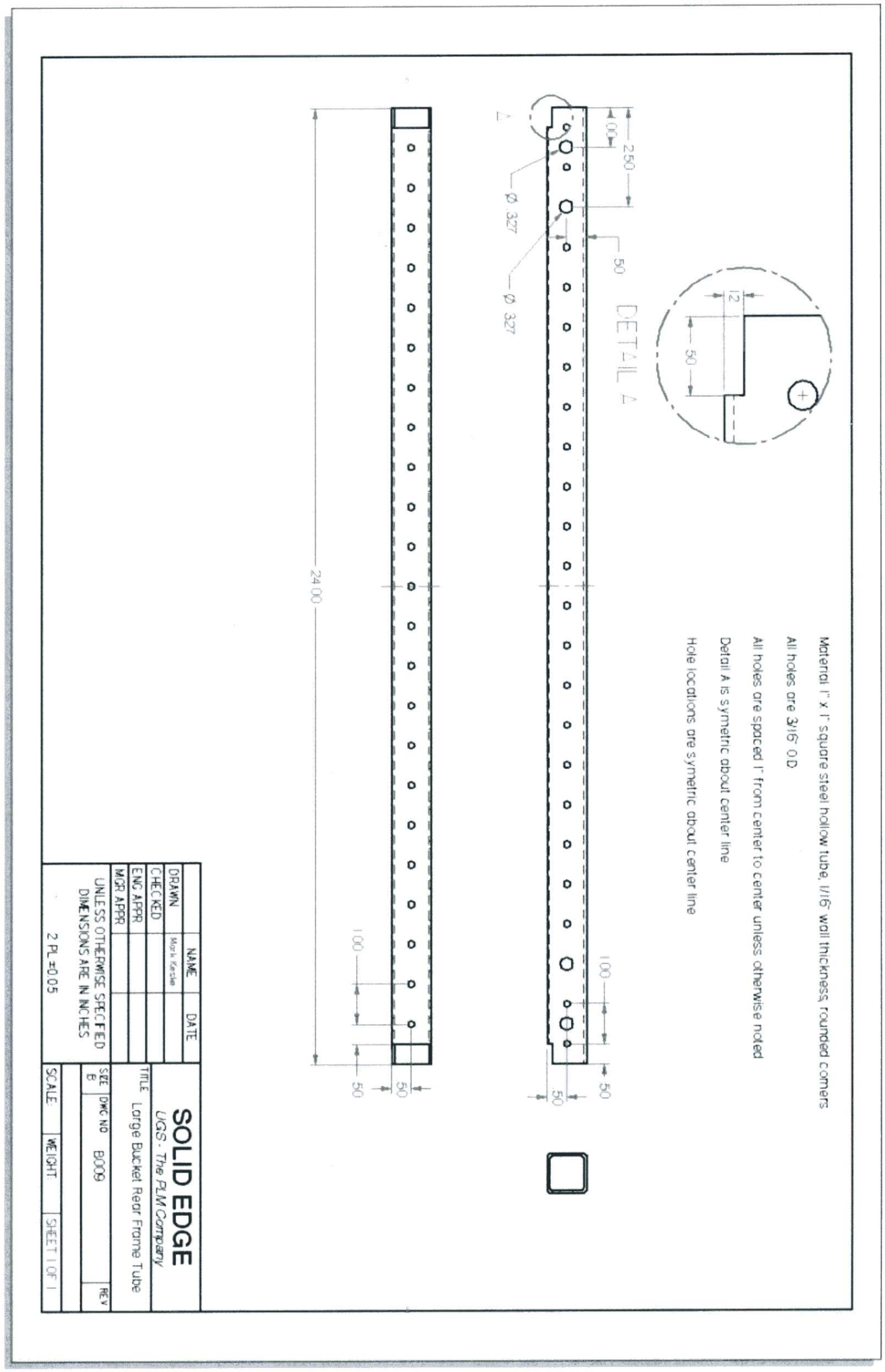

.50
.500
.50
1.00
4.00
All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
All holes are 3/16"
Spacing between holes is 1" unless otherwise noted
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE Large Bucket Top Forward Angle Aluminum
SIZE B
DWG NO B004
REV
SCALE
WEIGHT
SHEET 1 OF 1


All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
All holes are 3/16"
Spacing between holes is 1" unless otherwise noted
.50
1.00
6.00
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Rear Angle
Aluminum
SIZE B
DWG NO B005
REV
SCALE
WEIGHT
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05

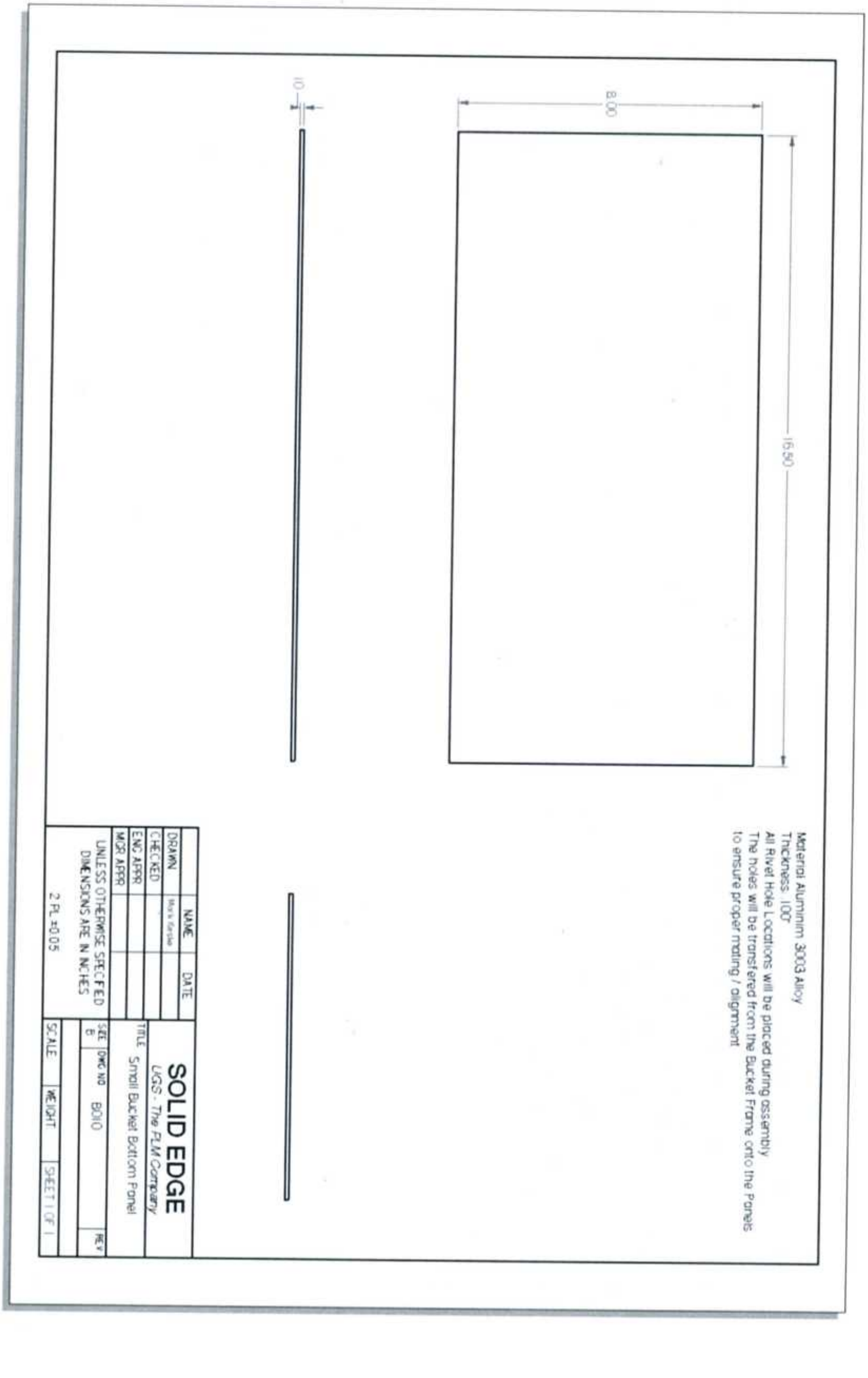

All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
All holes are 3/16"
Spacing between holes is 1" unless otherwise noted
7.00
.50
.50
1.00
.50
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Vertical Angle
Aluminum
SIZE
B
DWG NO
B006
REV
SCALE
WEIGHT
SHEET 1 OF 1


All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
All holes are 3/16"
Spacing between holes is 1" unless otherwise noted
.50
1.00
6.00
SOLID EDGE
UGS - The PLM Company
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
TITLE Small Bucket Vertical Angle Aluminum
SIZE B
DWG NO B007
REV
SCALE
WEIGHT
SHEET 1 OF 1

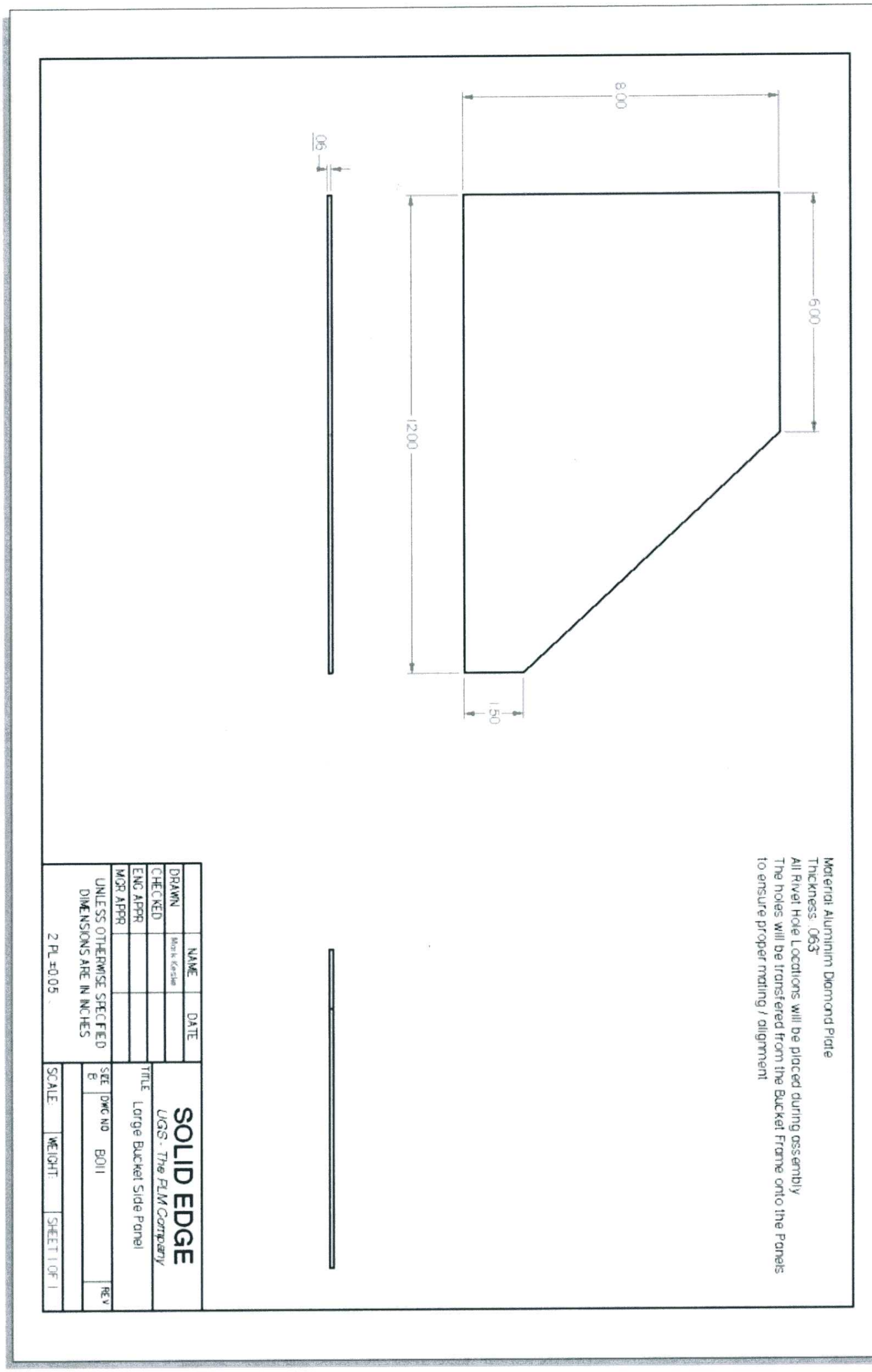

Material 1" x 1" square steel hollow tube, 1/16" wall thickness
rounded corners
Ø.33 Through All
Ø.33 Through All
6.000
1.00
1.00
.50
.50
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Actuator Frame Attachment
DWG NO
B008
REV
SIZE
B
SCALE
WEIGHT
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

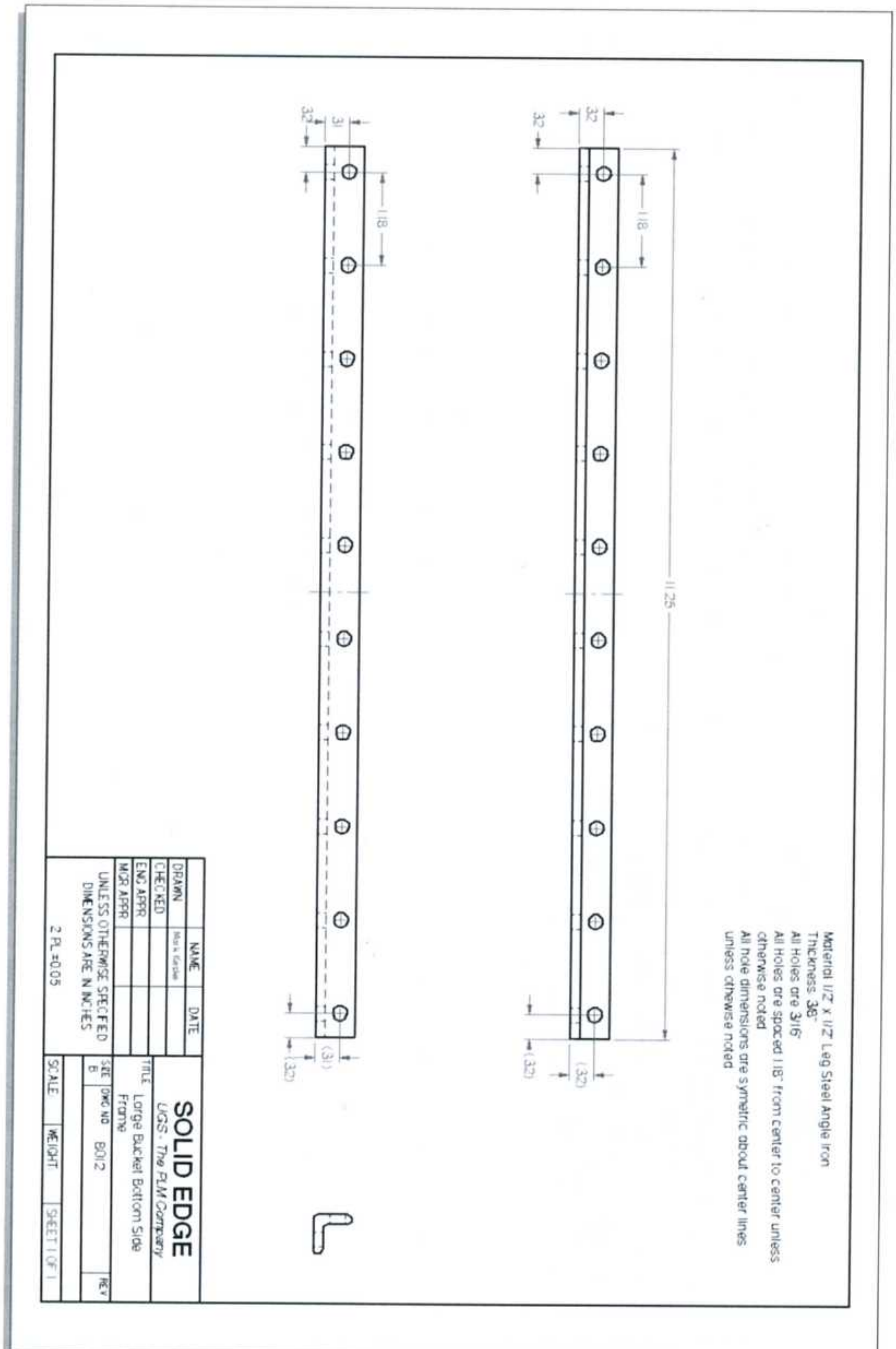


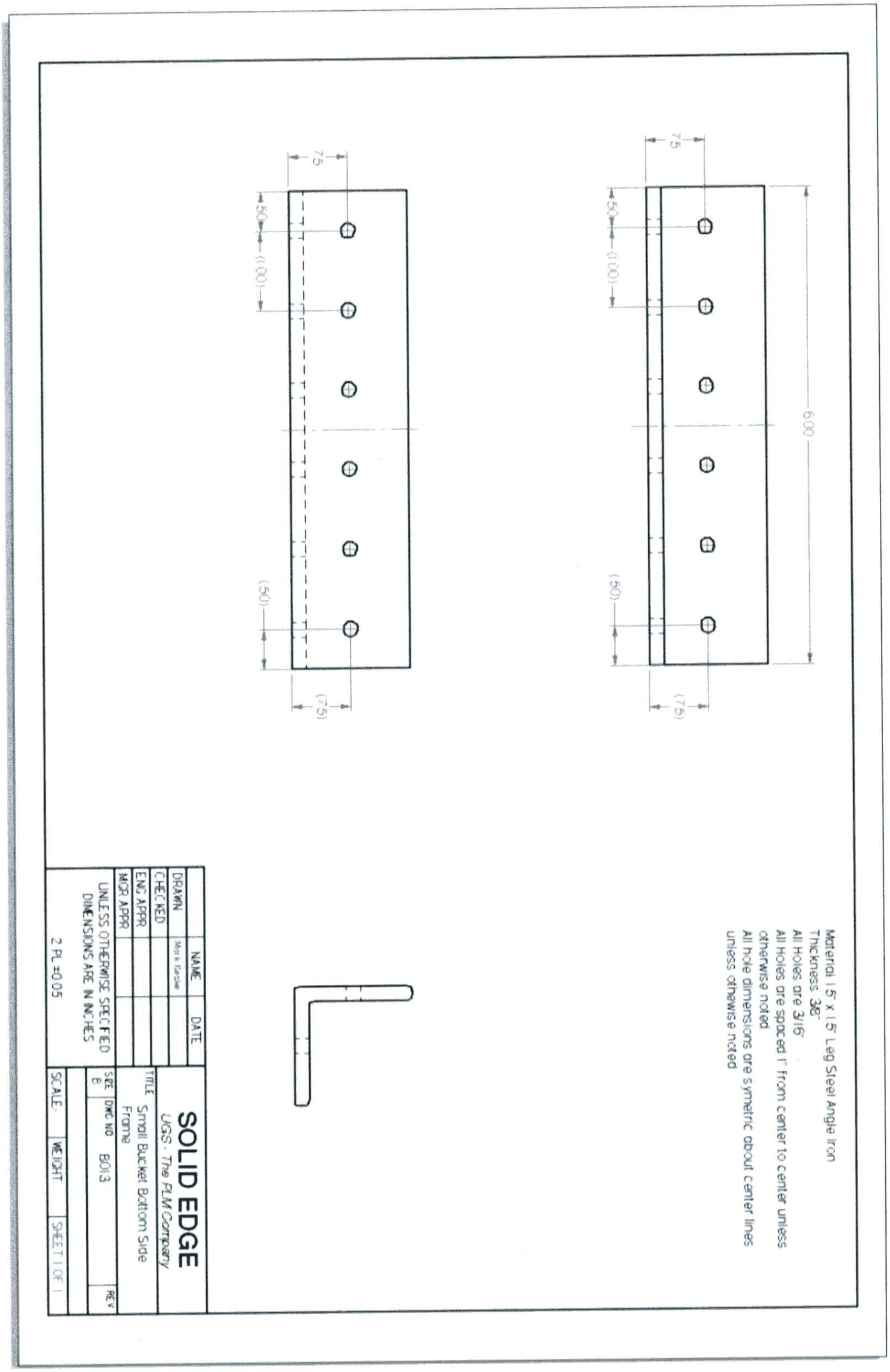
Material 1" x 1" square steel hollow tube, 1/16" wall thickness rounded corners
All holes are 3/16" O.D.
All holes are spaced 1" from center to center unless otherwise noted
Detail A is symetric about center line
Hole locations are symetric about center line
DETAIL A
Ø .327
24.00
SOLID EDGE
UGS - The PLM Company
TITLE Large Bucket Rear Frame Tube
DRAWN Mark Kerske
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SIZE B
DWG NO B009
REV
SCALE
WEIGHT
SHEET 1 OF 1



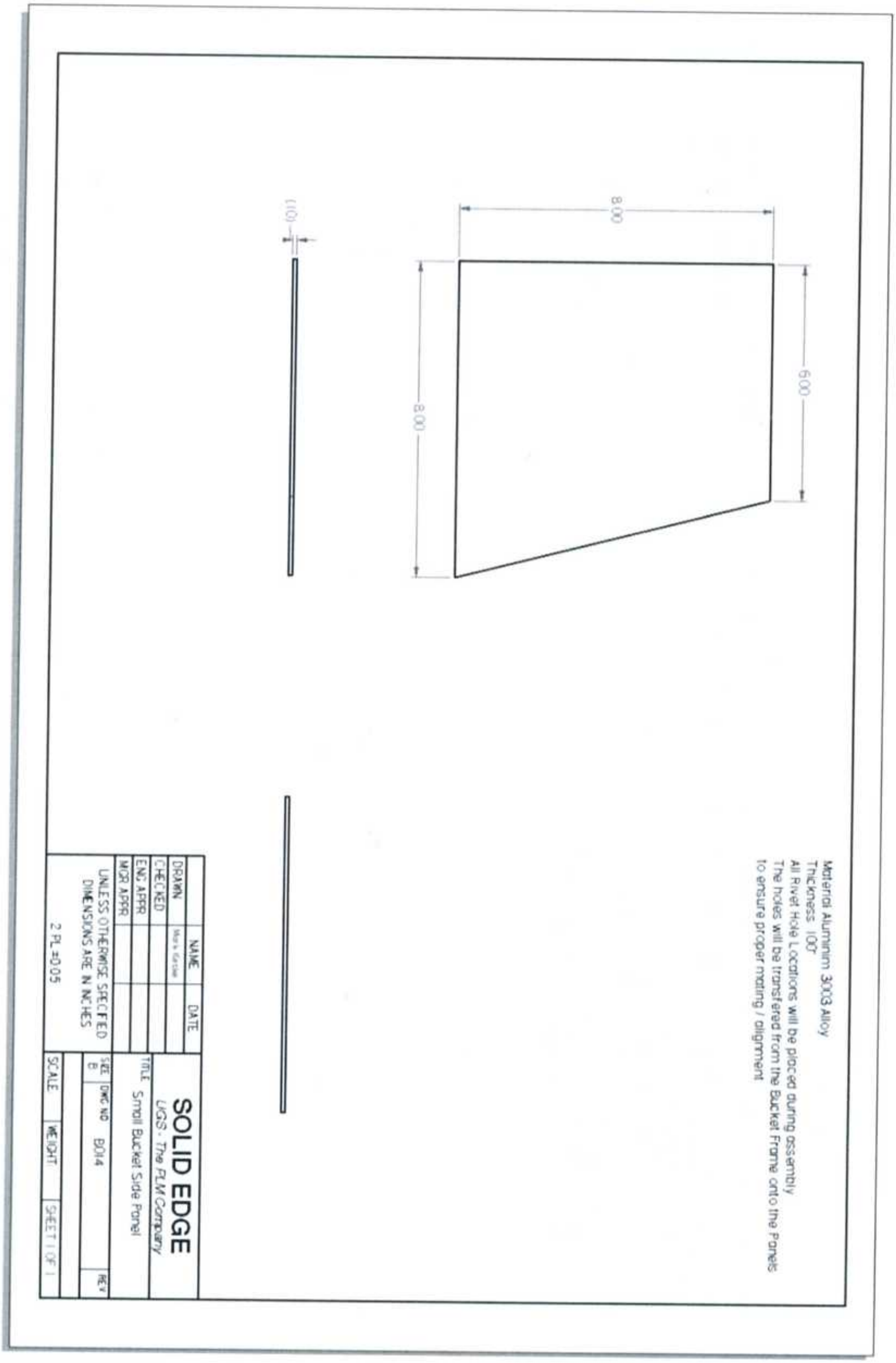
8.00
16.50
.10
Material Aluminim 3003 Alloy
Thickness .100"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Bottom Panel
SIZE
B
DWG NO
B010
REV
SCALE
WEIGHT
SHEET 1 OF 1

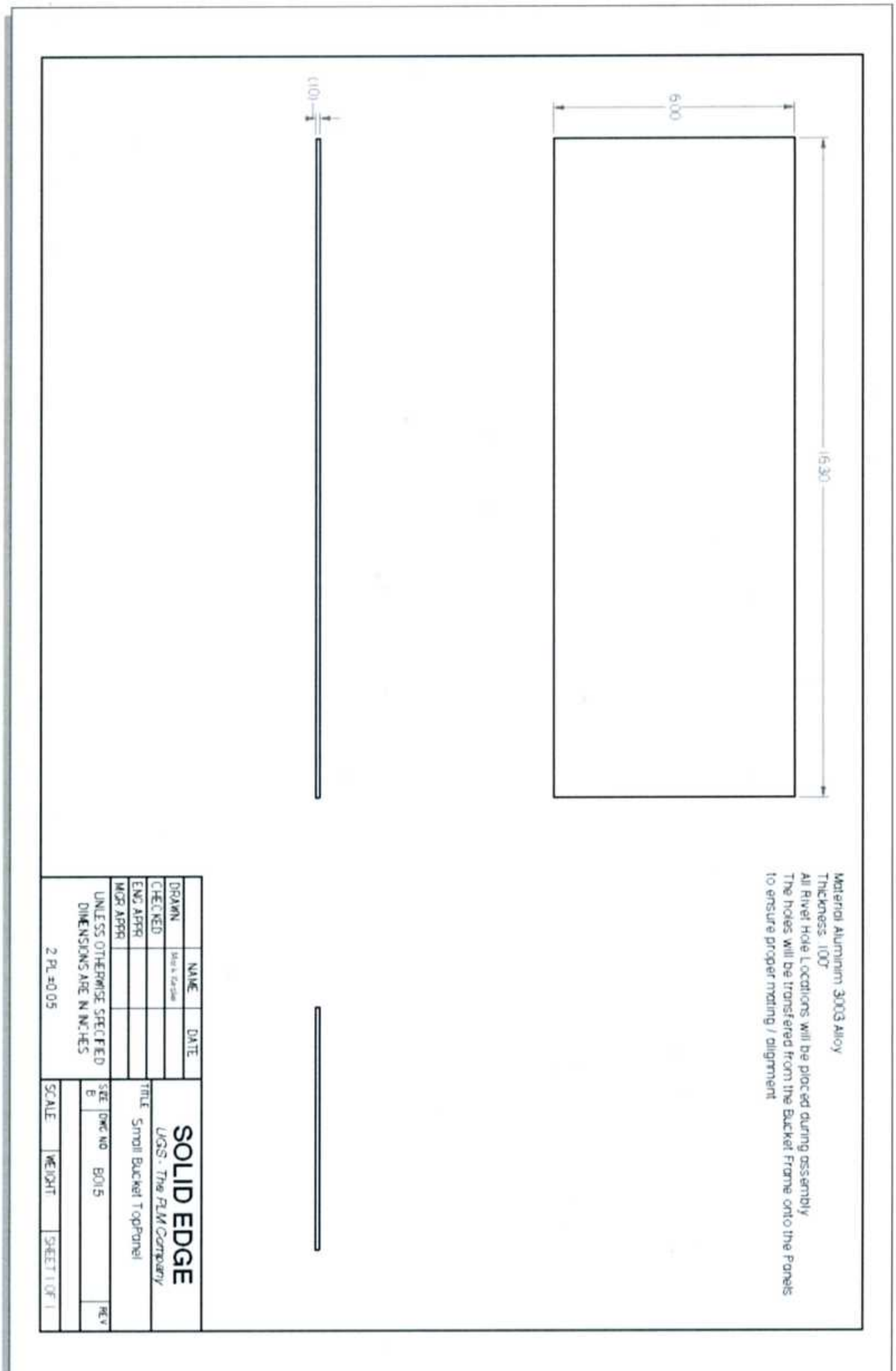

Material: Aluminim Diamond Plate
Thickness: .063"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
6.00
8.00
1.50
12.00
.06
NAME
DATE
DRAWN
Mark Keske
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Side Panel
SIZE
B
DWG NO
B011
REV
SCALE:
WEIGHT:
SHEET 1 OF 1

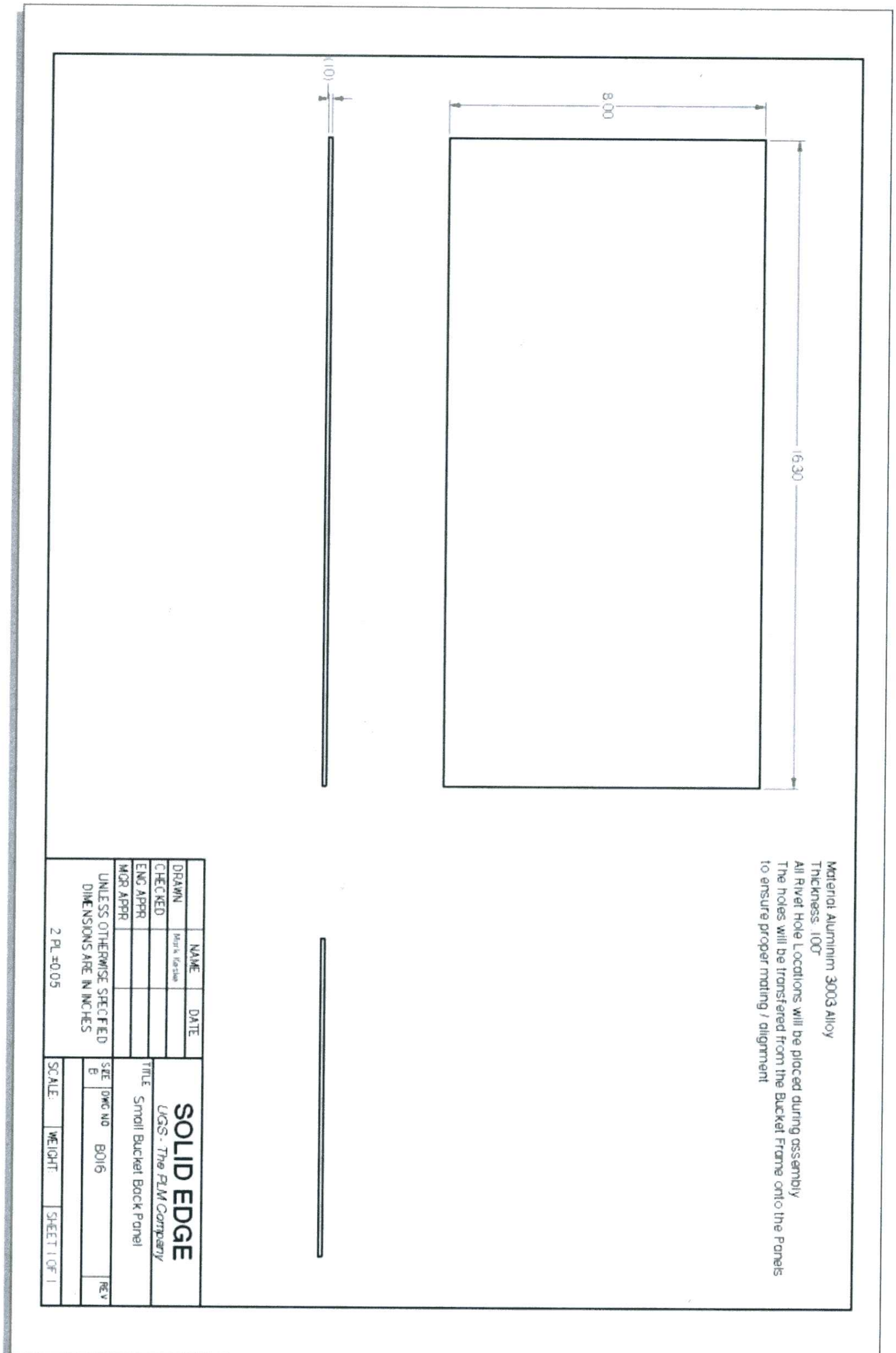

Material 1/2" x 1/2" Leg Steel Angle Iron
Thickness .38"
All Holes are 3/16"
All Holes are spaced 1.18" from center to center unless otherwise noted
All hole dimensions are symetric about center lines unless otherwise noted
.32
.31
.32
1.18
11.25
(.31)
(.32)
SOLID EDGE
UGS - The PLM Company
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
TITLE
Large Bucket Bottom Side Frame
SIZE
B
DWG NO
B012
REV
SCALE
WEIGHT
SHEET 1 OF 1



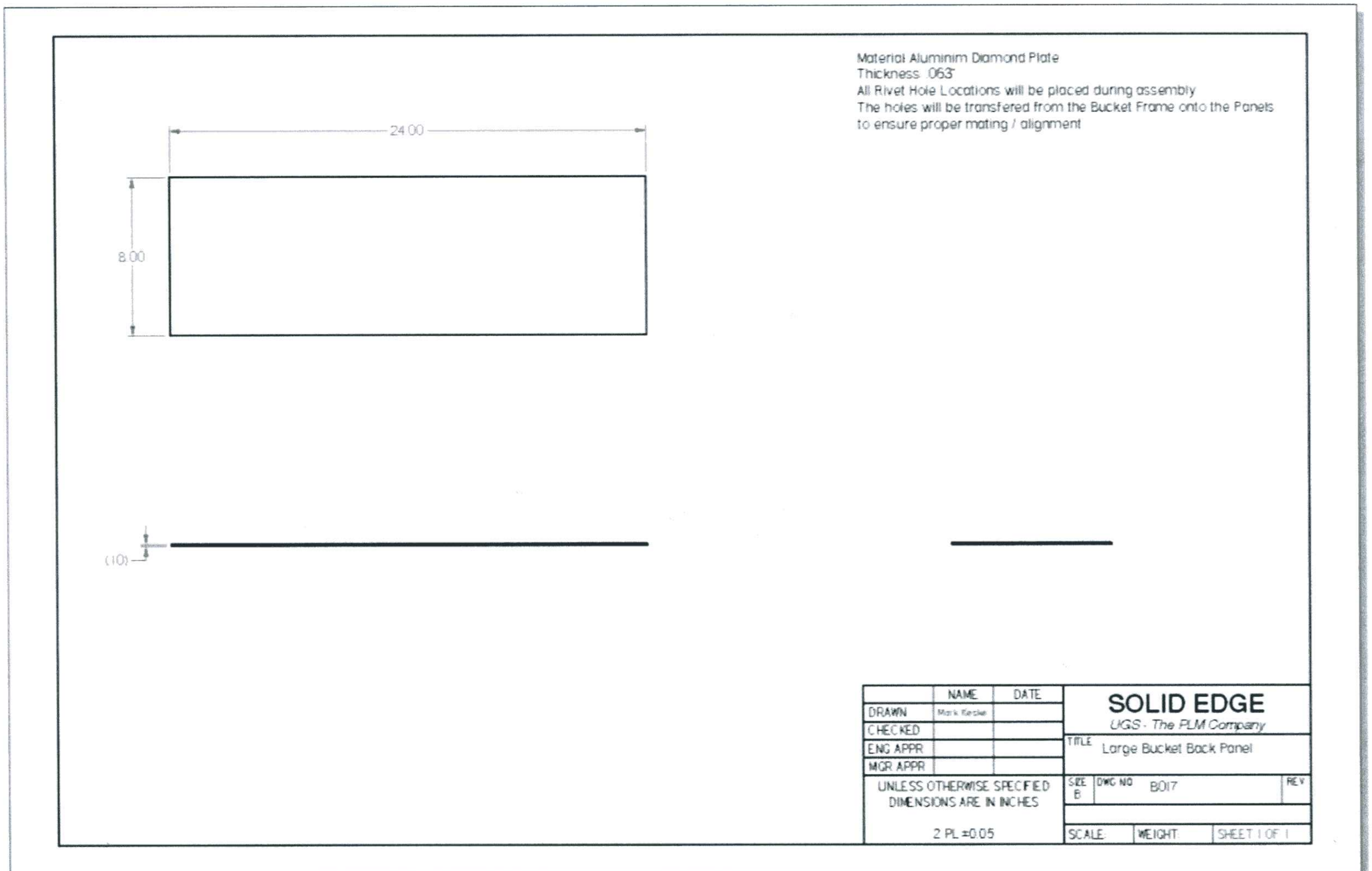
Material 1.5" x 1.5" Leg Steel Angle Iron
Thickness .38"
All Holes are 3/16"
All Holes are spaced 1" from center to center unless otherwise noted
All hole dimensions are symetric about center lines unless otherwise noted
.75
.50
(1.00)
(.50)
(.75)
6.00
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Bottom Side Frame
SIZE
B
DWG NO
B013
REV
SCALE
WEIGHT
SHEET 1 OF 1

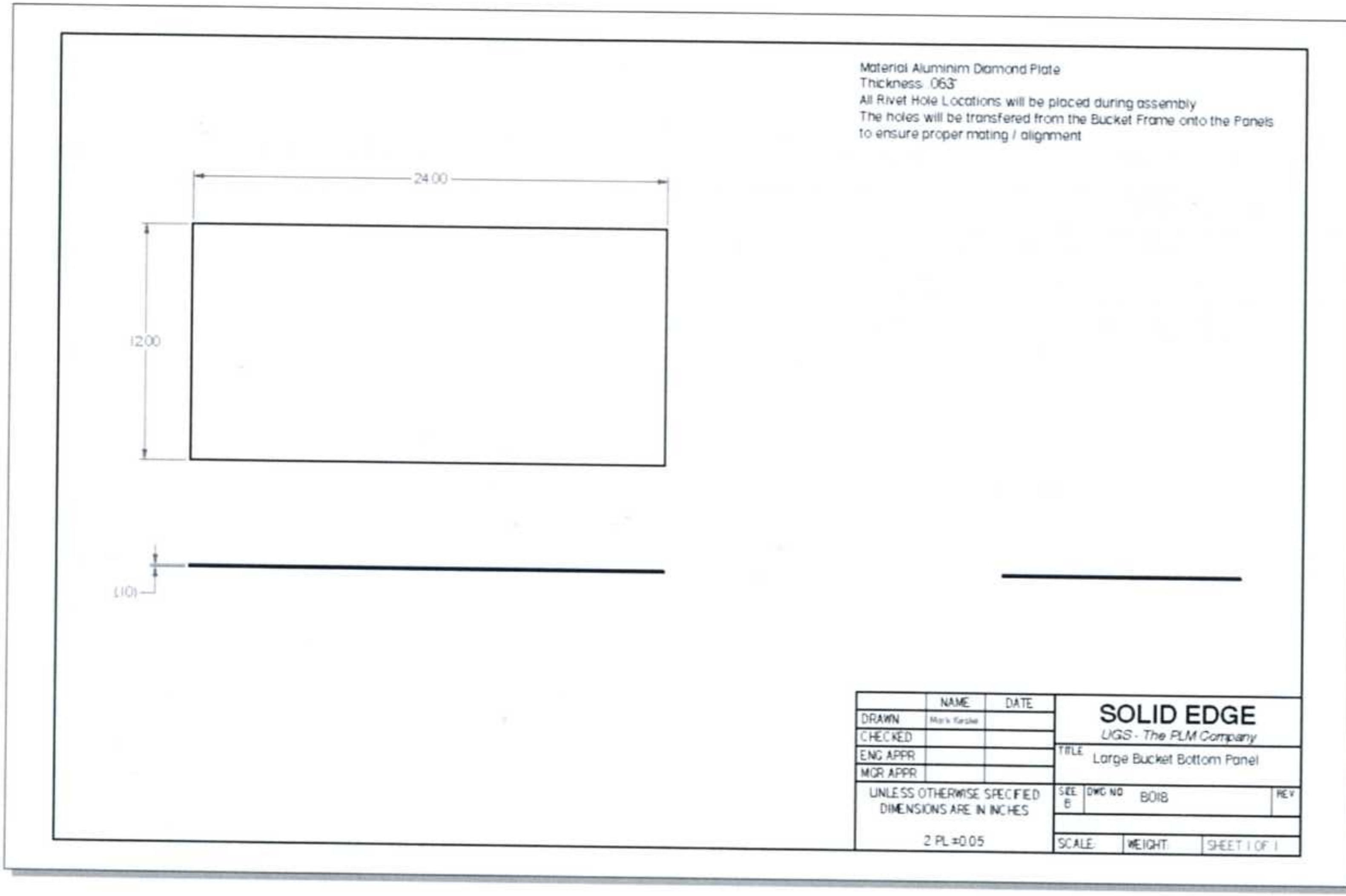

Material Aluminim 3003 Alloy
Thickness .100"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
6.00
8.00
8.00
(.10)
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Side Panel
SIZE
B
DWG NO
B014
REV
SCALE
WEIGHT
SHEET 1 OF 1

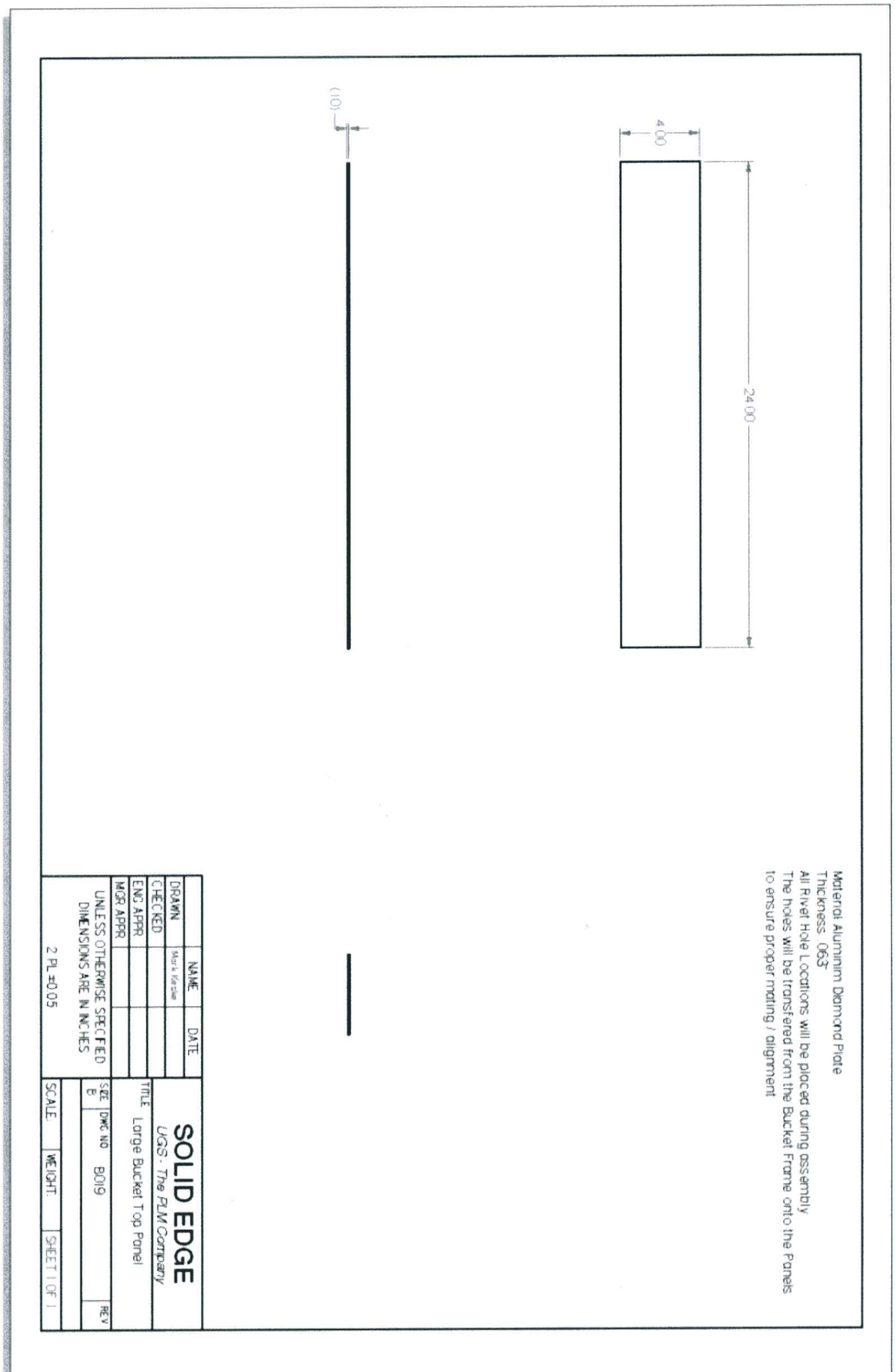

Material Aluminim 3003 Alloy
Thickness .100"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
16.30
6.00
(.10)
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket TopPanel
SIZE
B
DWG NO
B015
REV
SCALE
WEIGHT
SHEET 1 OF 1

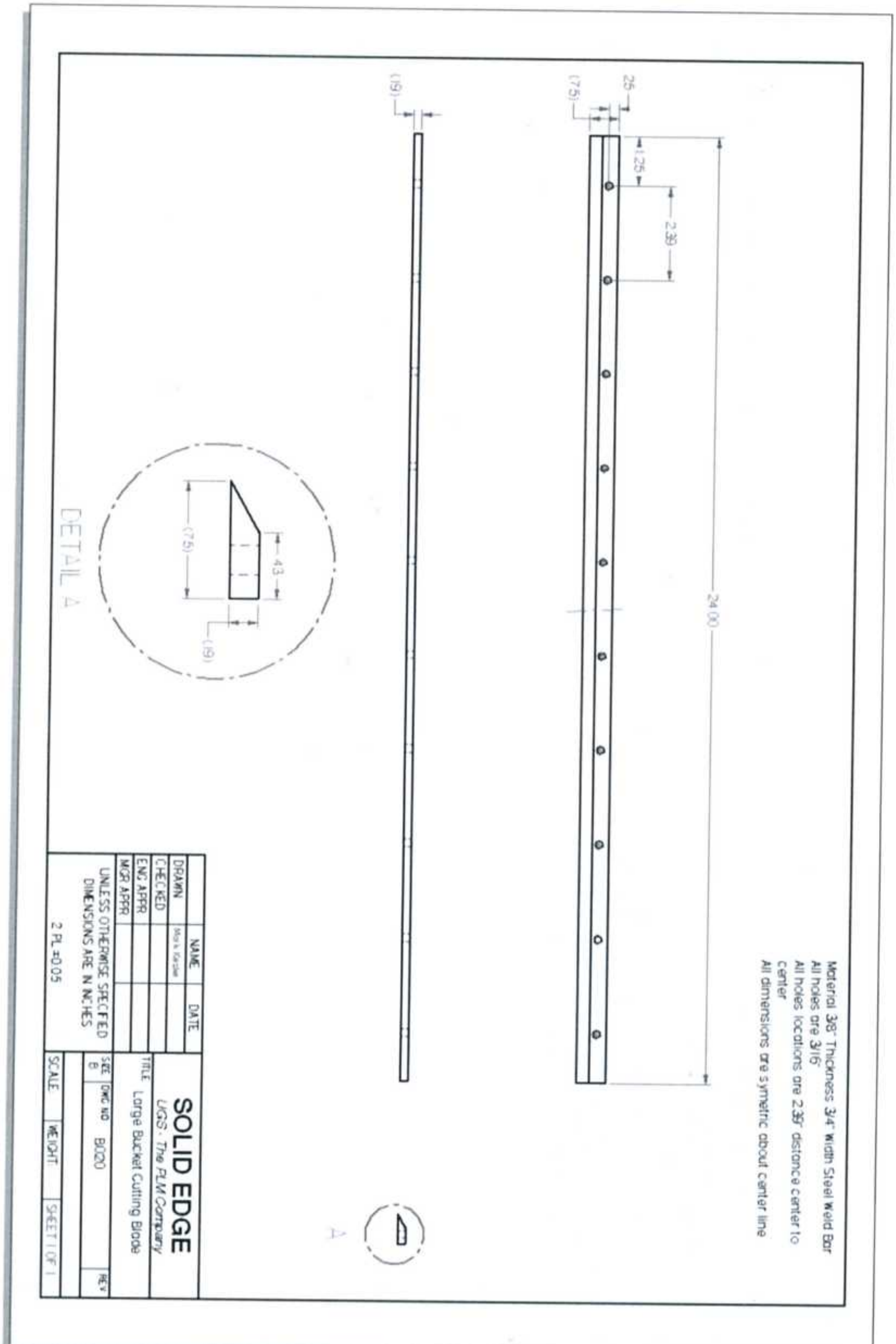


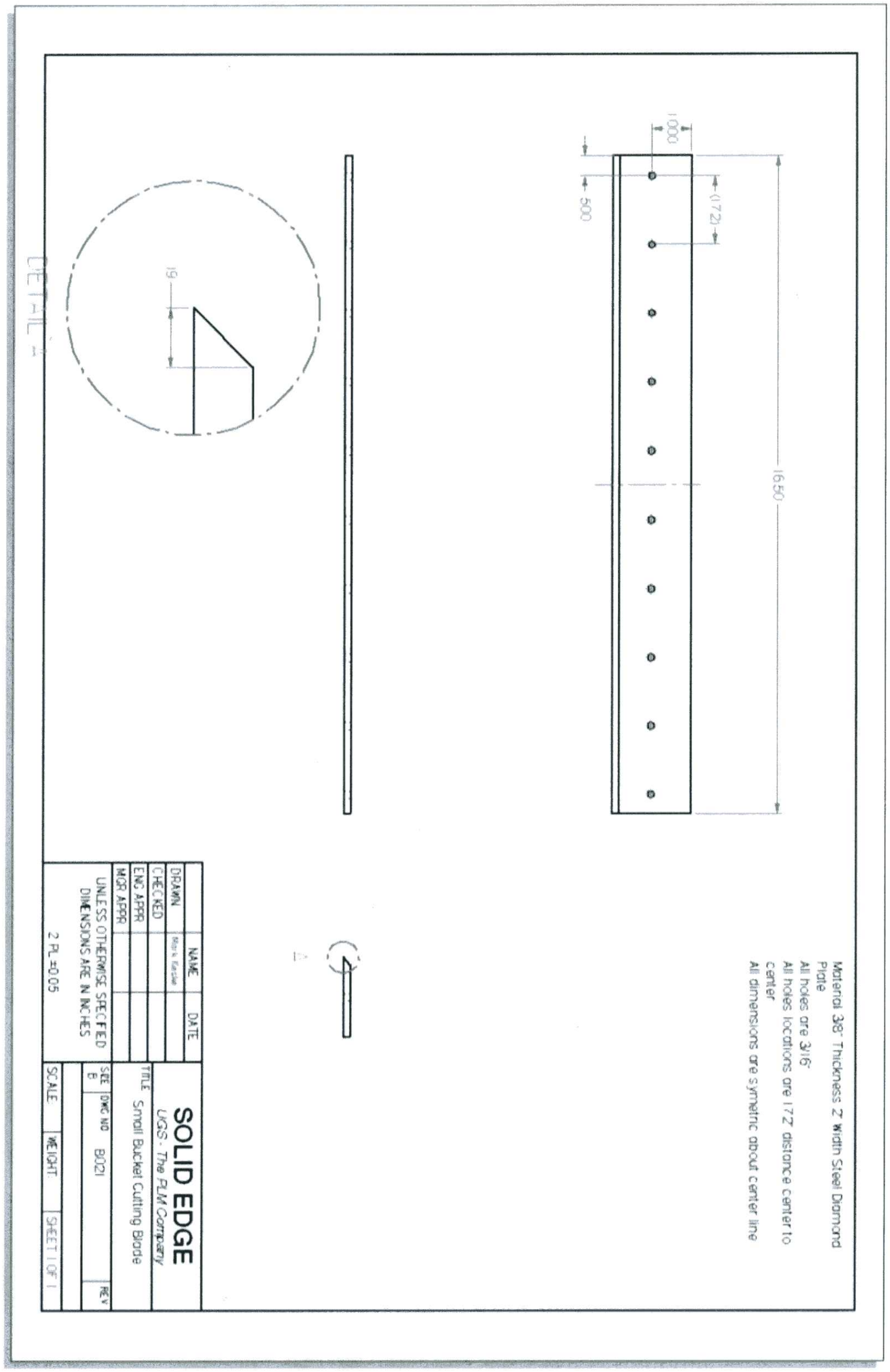
16.30
8.00
(.10)
Material: Aluminim 3003 Alloy
Thickness: .100"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
NAME
DATE
DRAWN
Mark Keske
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Back Panel
SIZE
B
DWG NO
B016
REV
SCALE:
WEIGHT:
SHEET 1 OF 1

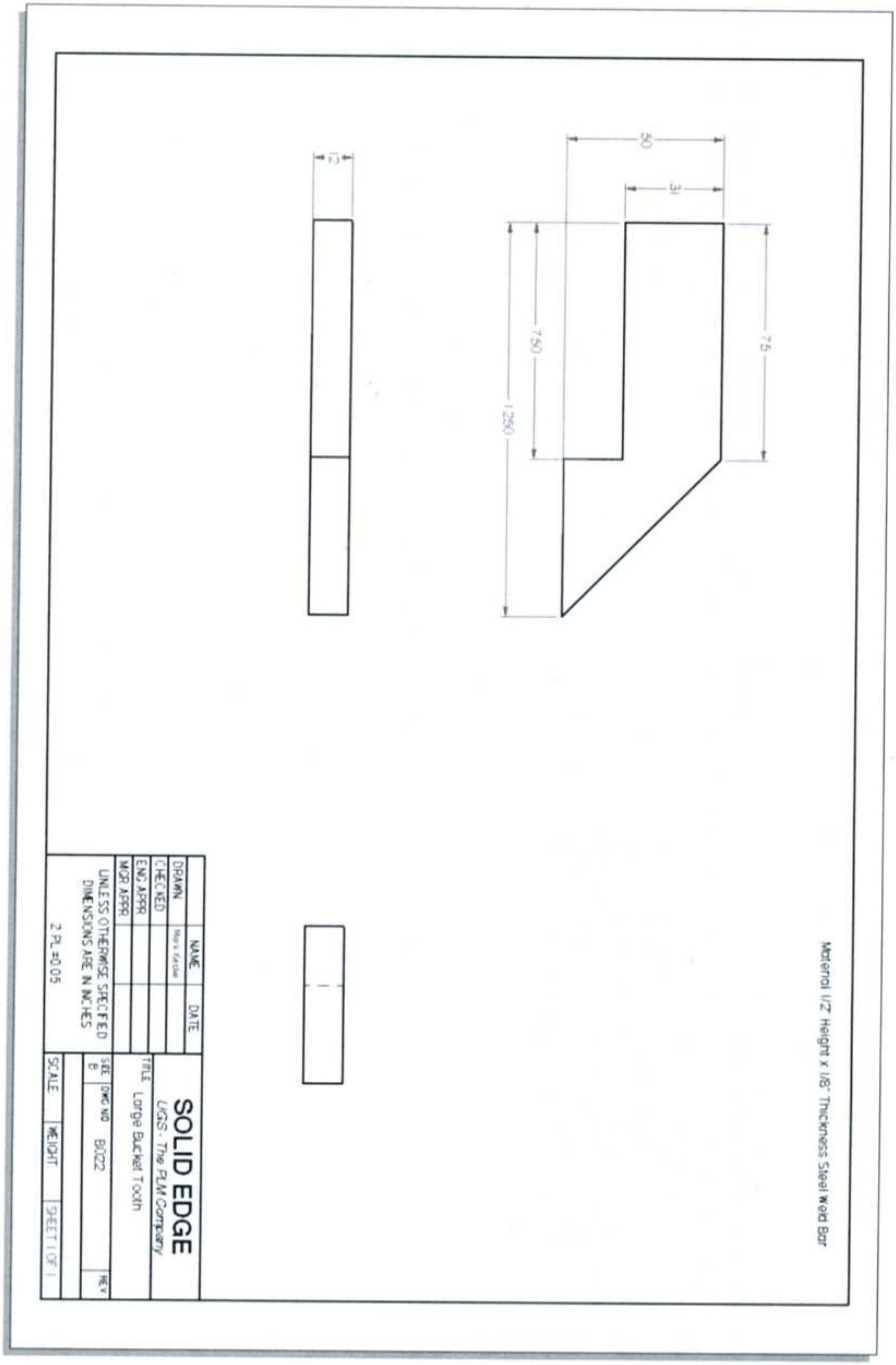

Material Aluminim Diamond Plate
Thickness .063"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
24.00
8.00
(.10)
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Back Panel
SIZE
B
DWG NO
B017
REV
SCALE
WEIGHT
SHEET 1 OF 1

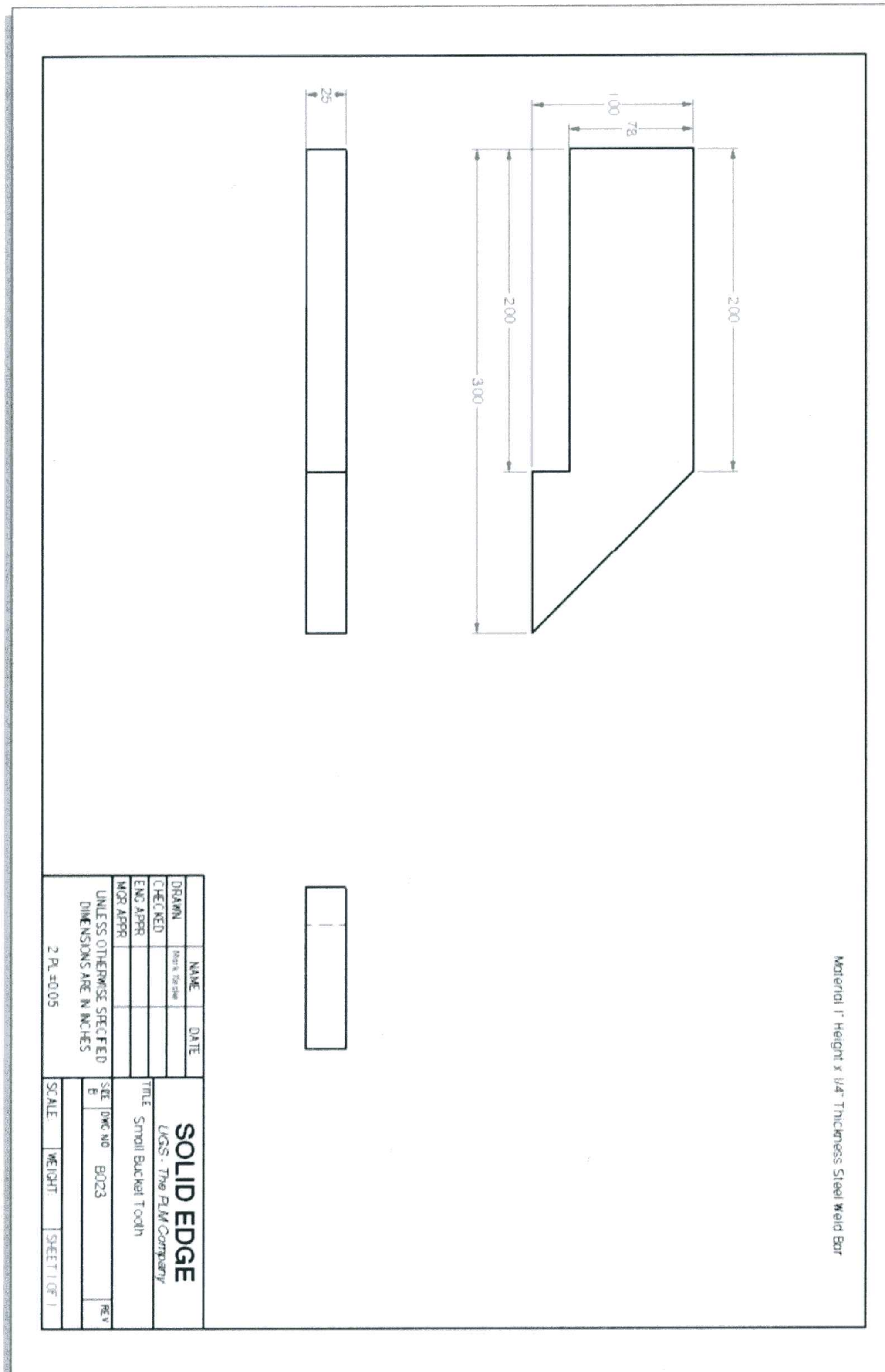

Material Aluminim Diamond Plate
Thickness .063"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
24.00
12.00
(.10)
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Bottom Panel
SIZE
B
DWG NO
B018
REV
SCALE
WEIGHT
SHEET 1 OF 1

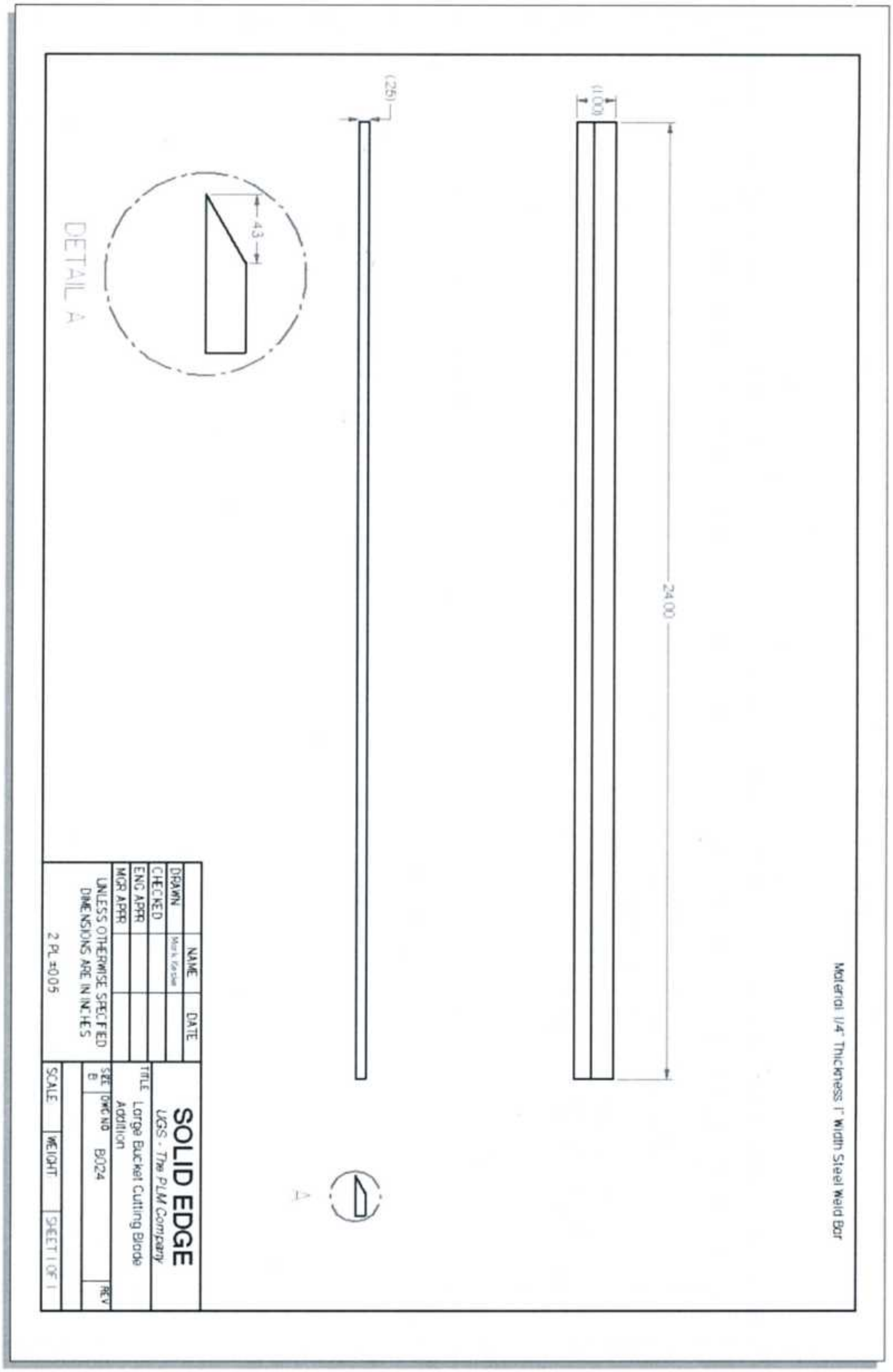

Material Aluminum Diamond Plate
Thickness .063"
All Rivet Hole Locations will be placed during assembly
The holes will be transfered from the Bucket Frame onto the Panels
to ensure proper mating / alignment
4.00
24.00
(.10)
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Top Panel
SIZE
B
DWG NO
B019
REV
SCALE
WEIGHT
SHEET 1 OF 1

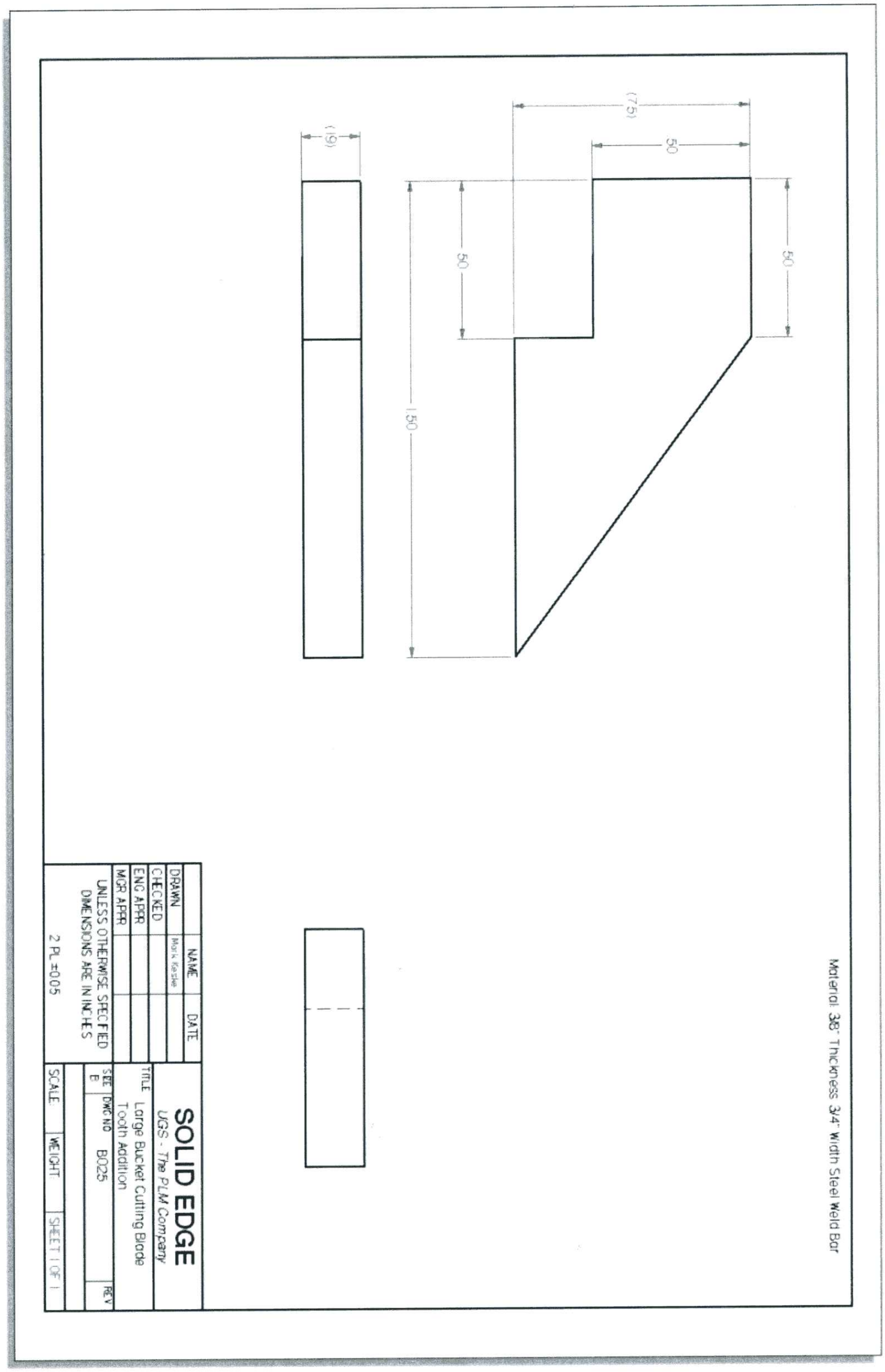

Material 3/8" Thickness 3/4" Width Steel Weld Bar
All holes are 3/16"
All holes locations are 2.39" distance center to center
All dimensions are symetric about center line
24.00
2.39
1.25
.25
(.75)
(.19)
.43
DETAIL A
A
SOLID EDGE
UGS - The PLM Company
TITLE Large Bucket Cutting Blade
SIZE B
DWG NO B020
REV
SCALE
WEIGHT
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

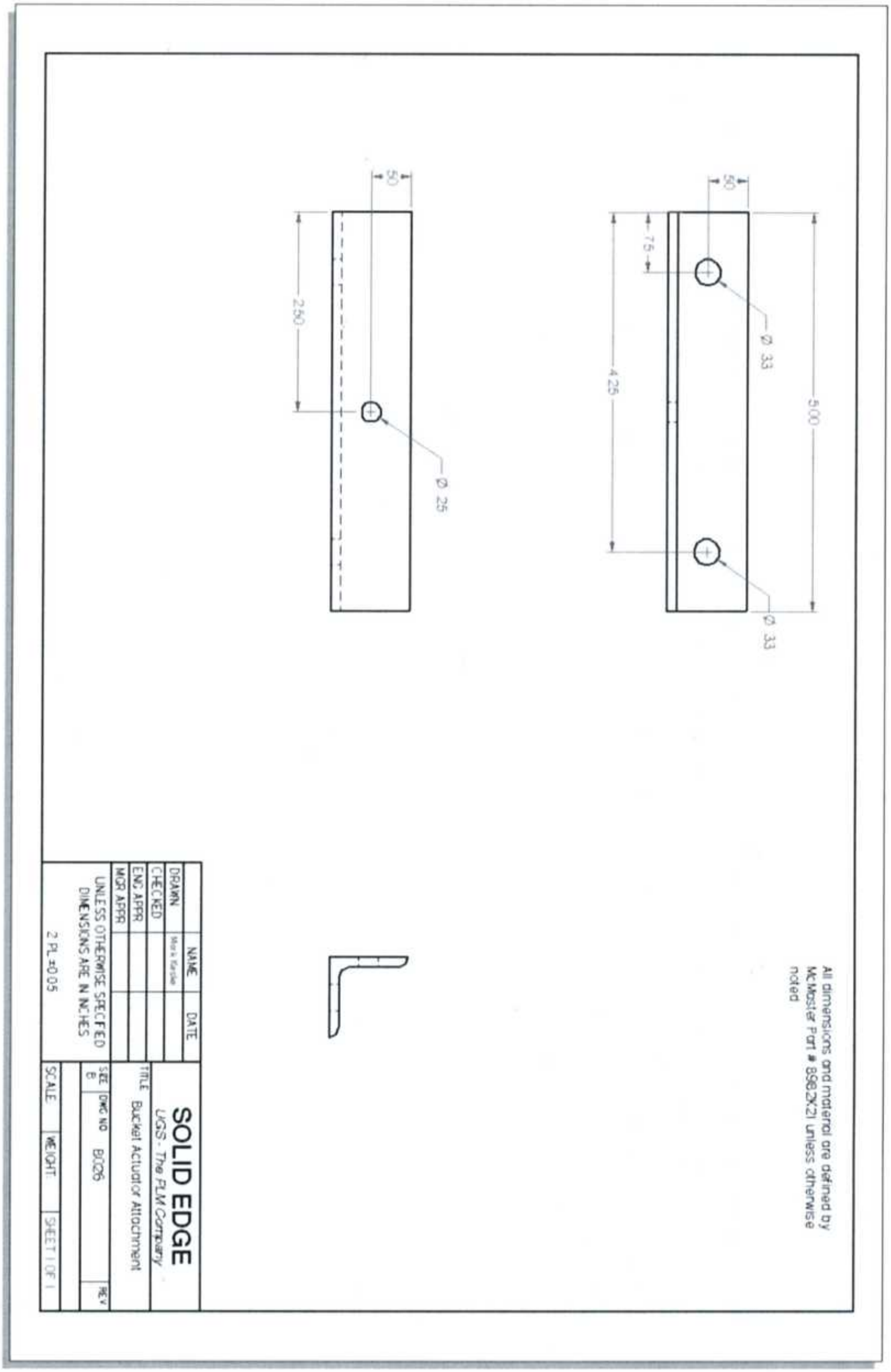

Material 3/8" Thickness 2" Width Steel Diamond Plate
All holes are 3/16"
All holes locations are 1.72 distance center to center
All dimensions are symetric about center line
1.000
.500
(1.72)
16.50
19
DETAIL A
A
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Cutting Blade
SIZE
B
DWG NO
B021
REV
SCALE
WEIGHT
SHEET 1 OF 1


Material 1/2" Height x 1/8" Thickness Steel Weld Bar
.50
.31
.750
1.250
.75
.12
SOLID EDGE
UGS - The PLM Company
TITLE Large Bucket Tooth
SIZE B
DWG NO B022
REV
SCALE
WEIGHT
SHEET 1 OF 1
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

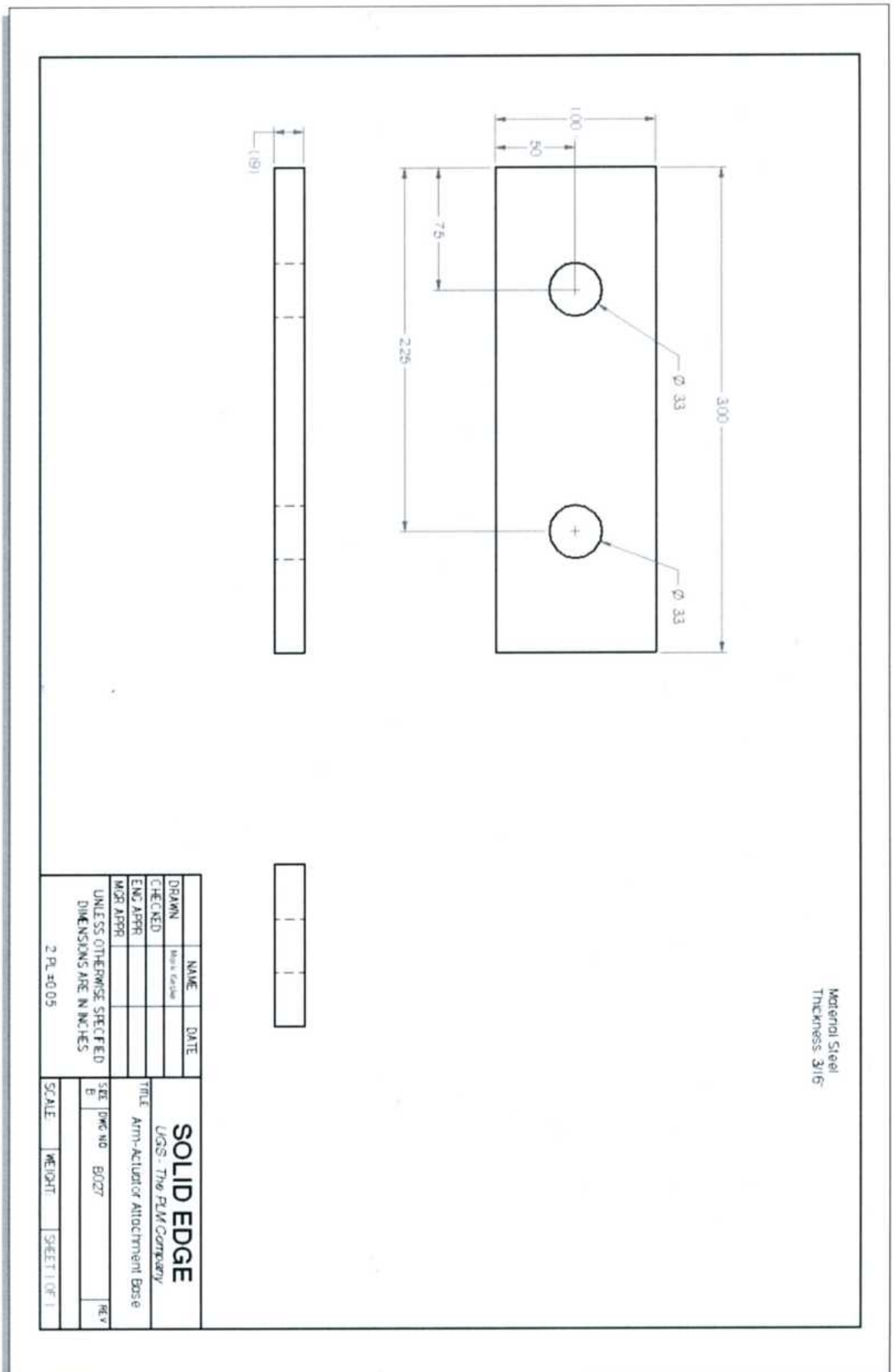

Material 1" Height x 1/4" Thickness Steel Weld Bar
.25
1.00
.78
2.00
3.00
2.00
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±.005
SOLID EDGE
UGS - The PLM Company
TITLE
Small Bucket Tooth
SIZE
B
DWG NO
B023
REV
SCALE:
WEIGHT:
SHEET 1 OF 1

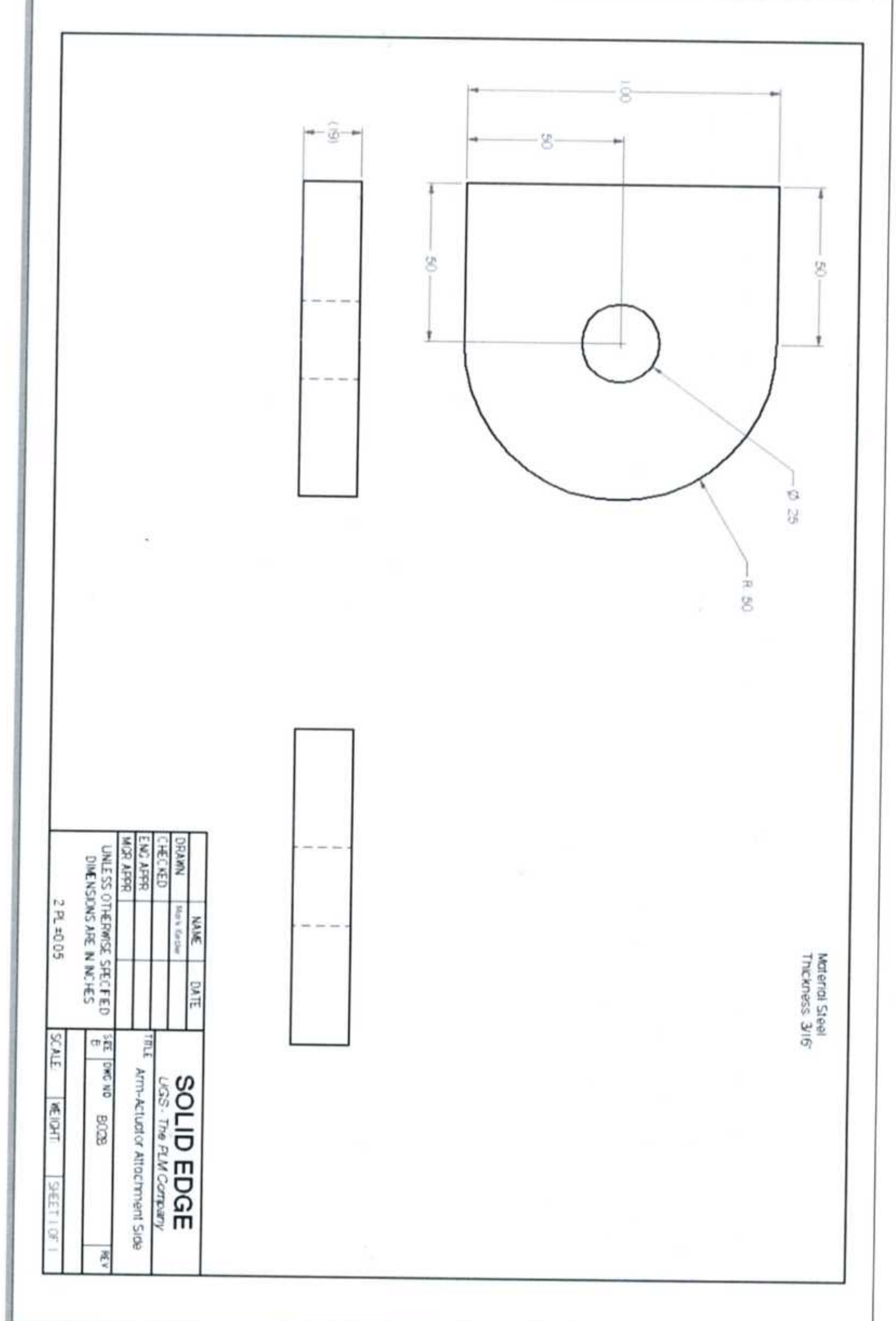

Material 1/4" Thickness 1" Width Steel Weld Bar
(.25)
(1.00)
24.00
.43
DETAIL A
A
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE Large Bucket Cutting Blade Addition
SIZE B
DWG NO B024
REV
SCALE
WEIGHT
SHEET 1 OF 1

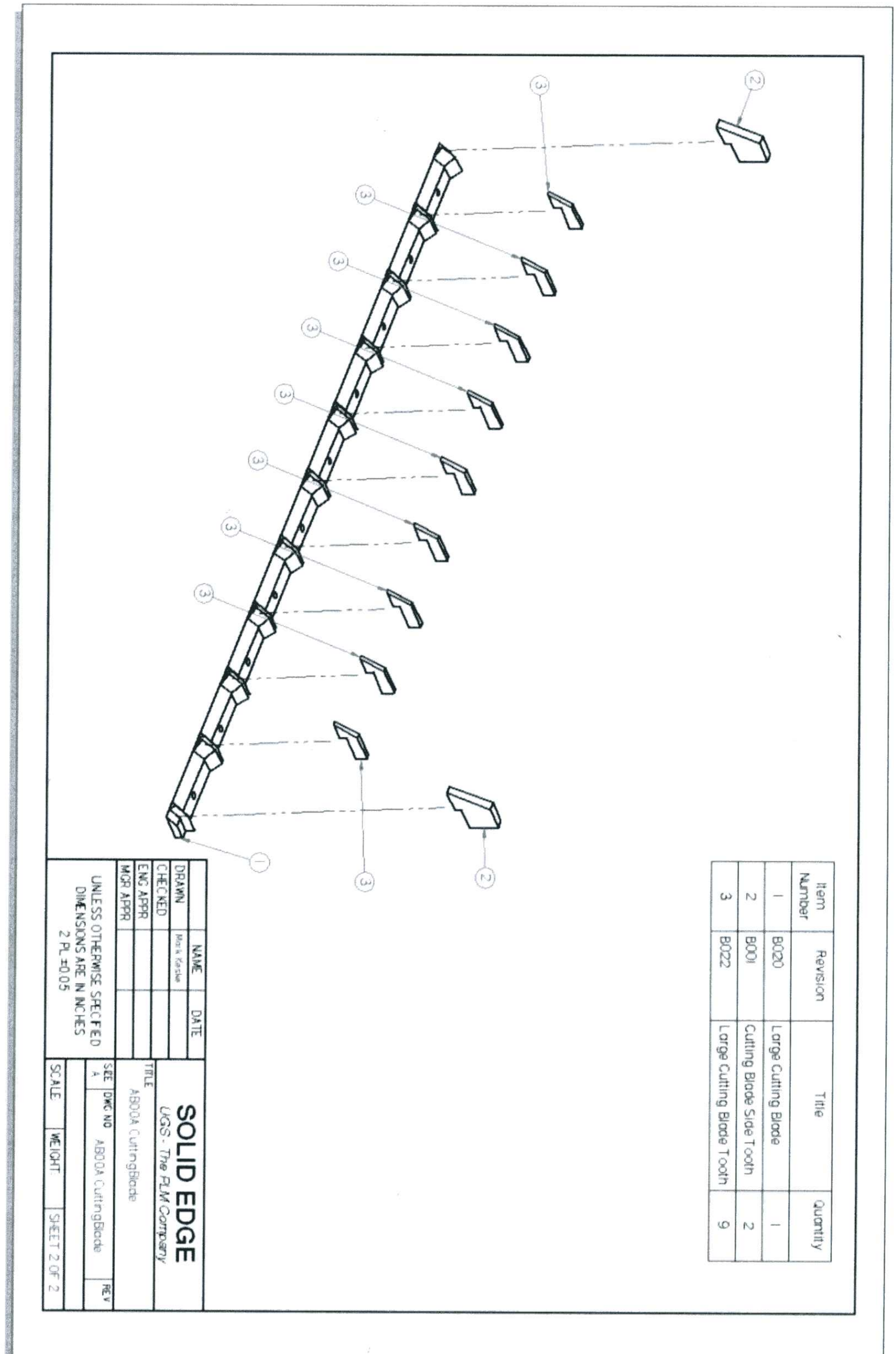

Material 3/8" Thickness 3/4" Width Steel Weld Bar
(.75)
.50
(.19)
.50
1.50
.50
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±.005
SOLID EDGE
UGS - The PLM Company
TITLE
Large Bucket Cutting Blade
Tooth Addition
SIZE
DWG NO
B
B025
REV
SCALE
WEIGHT
SHEET 1 OF 1



.50
2.50
Ø .25
.50
.75
Ø .33
4.25
5.00
Ø .33
All dimensions and material are defined by McMaster Part # 8982K21 unless otherwise noted
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
Bucket Actuator Attachment
SIZE
B
DWG NO
BC26
REV
SCALE
WEIGHT
SHEET 1 OF 1

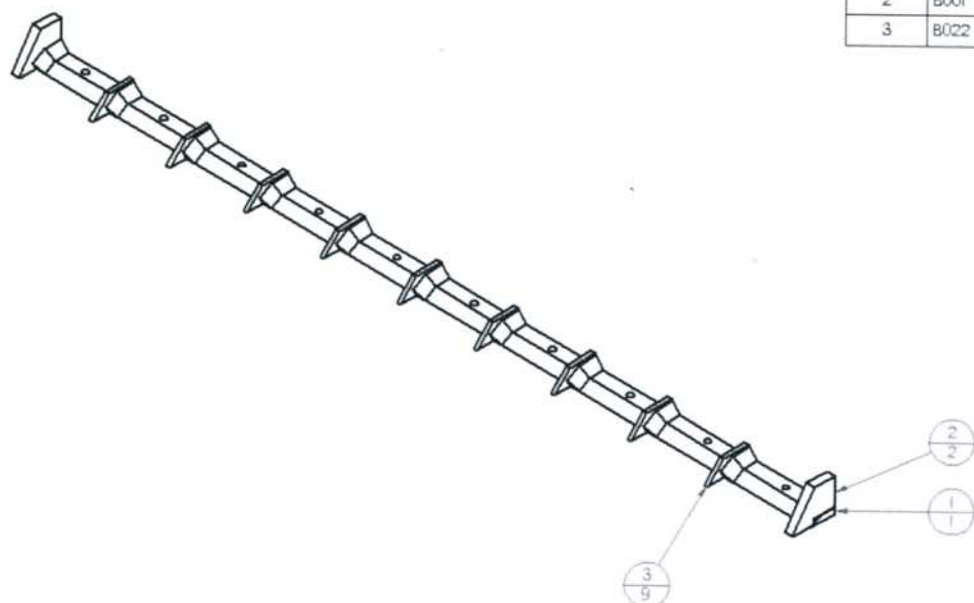

SOLID EDGE
UGS - The PLM Company
TITLE
Arm-Actuator Attachment Base
DWG NO
B027
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SCALE
WEIGHT
SHEET 1 OF 1
REV
Material Steel
Thickness 3/16"
Ø .33
Ø .33
3.00
2.25
.75
.50
1.00
(.19)


1.00
.50
.50
.50
(.19)
Ø .25
R .50
Material Steel
Thickness 3/16"
SOLID EDGE
UGS - The PLM Company
TITLE
Arm-Actuator Attachment Side
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SIZE
B
DWG NO
REV
SCALE
WEIGHT
SHEET 1 OF 1


SOLID EDGE
UGS - The PLM Company
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
2 PL ±0.05
TITLE
AB00A CuttingBlade
SIZE A
DWG NO
AB00A CuttingBlade
REV
SCALE
WEIGHT
SHEET 2 OF 2
Item Number | Revision | Title | Quantity
1 | B020 | Large Cutting Blade | 1
2 | B001 | Cutting Blade Side Tooth | 2
3 | B022 | Large Cutting Blade Tooth | 9

Teeth are welded to Cutting Blade

Item Number	Revision	Title	Quantity
1	B020	Large Cutting Blade	1
2	B001	Cutting Blade Side Tooth	2
3	B022	Large Cutting Blade Tooth	9



	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

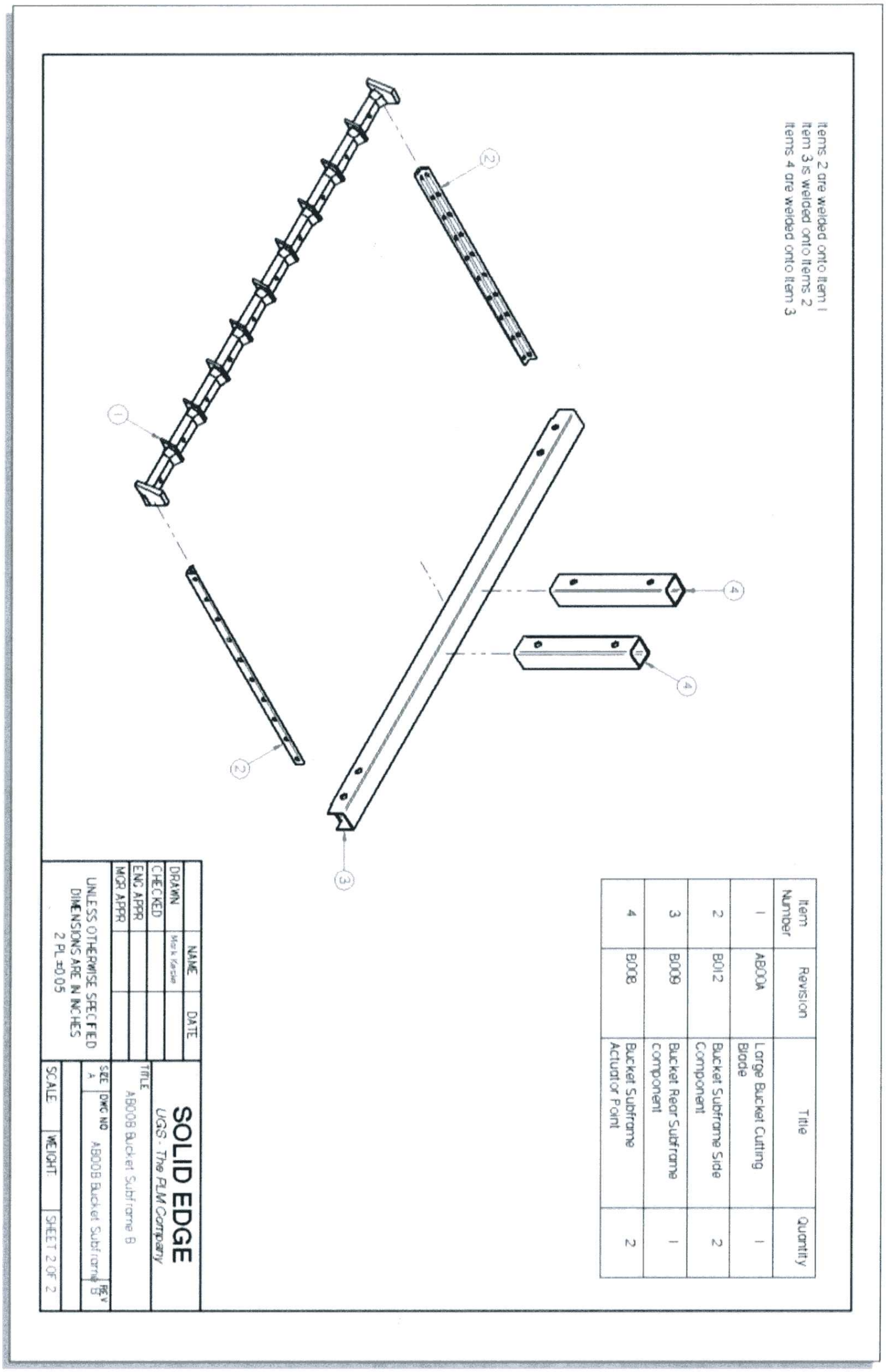
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

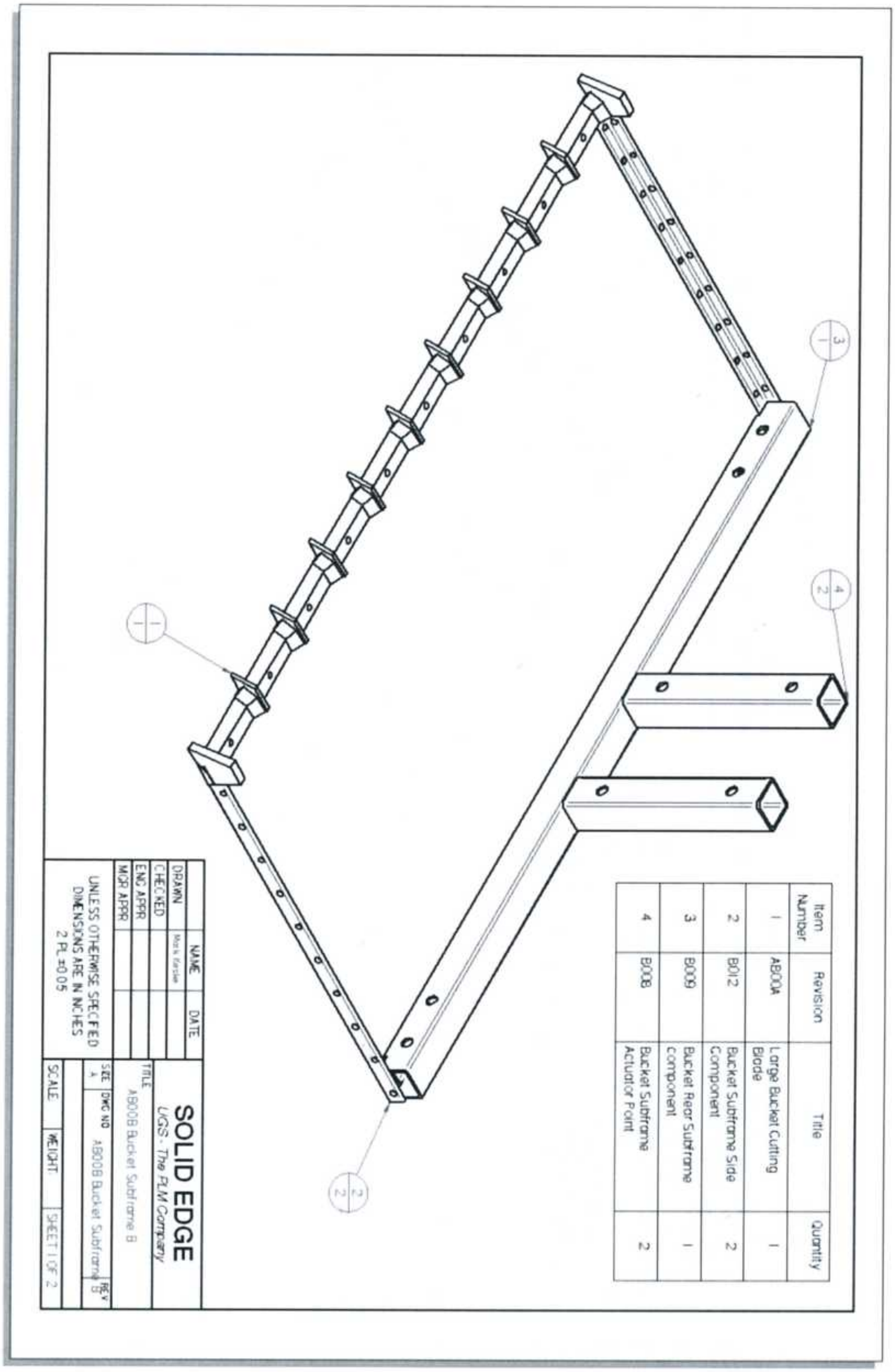
SOLID EDGE
UGS - The PLM Company

TITLE
AB00A CuttingBlade

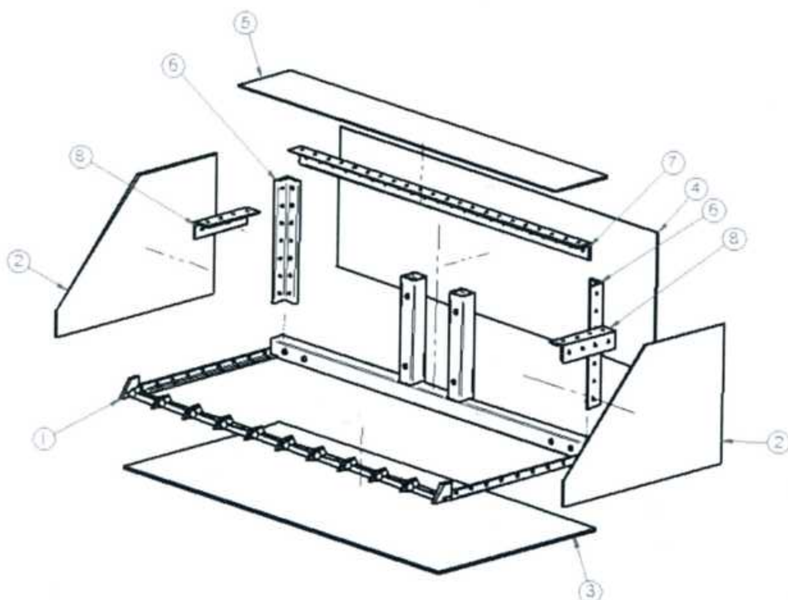
SIZE	DWG NO	REV
A	AB00A CuttingBlade	

SCALE	WEIGHT	SHEET 1 OF 2


Items 2 are welded onto item 1
Item 3 is welded onto items 2
Items 4 are welded onto item 3
1
2
2
3
4
4
Item Number | Revision | Title | Quantity
1 | AB00A | Large Bucket Cutting Blade | 1
2 | B012 | Bucket Subframe Side Component | 2
3 | B009 | Bucket Rear Subframe component | 1
4 | B008 | Bucket Subframe Actuator Point | 2
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
AB00B Bucket Subframe B
SIZE
A
DWG NO
AB00B Bucket Subframe B
REV
B
SCALE
WEIGHT
SHEET 2 OF 2


Item Number | Revision | Title | Quantity
1 | AB00A | Large Bucket Cutting Blade | 1
2 | B012 | Bucket Subframe Side Component | 2
3 | B009 | Bucket Rear Subframe component | 1
4 | B008 | Bucket Subframe Actuator Point | 2
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
AB00B Bucket Subframe B
SIZE A
DWG NO
AB00B Bucket Subframe B
REV B
SCALE
WEIGHT
SHEET 1 OF 2

All rivet holes in Side Panels are drilled to match those in the subframe components durring assembly



Item Number	Revision	Title	Quantity
1	AB00B	Large Bucket Subframe	1
2	B011	Large Bucket Side Panel	2
3	B018	Large Bucket Bottom Panel	1
4	B017	Large Bucket Back Panel	1
5	B019	Large Bucket Top Panel	1
6	B006	Large Bucket Aluminum Subframe Vertical Component	2
7	B002	Large Bucket Subframe Aluminum Horizontal Cgmponent	1
8	B004	Large Bucket Subframe Aluminum Side Component	2

	NAME	DATE
DRAWN	Mark Kesler	
CHECKED		
ENG APPR		
MGR APPR		

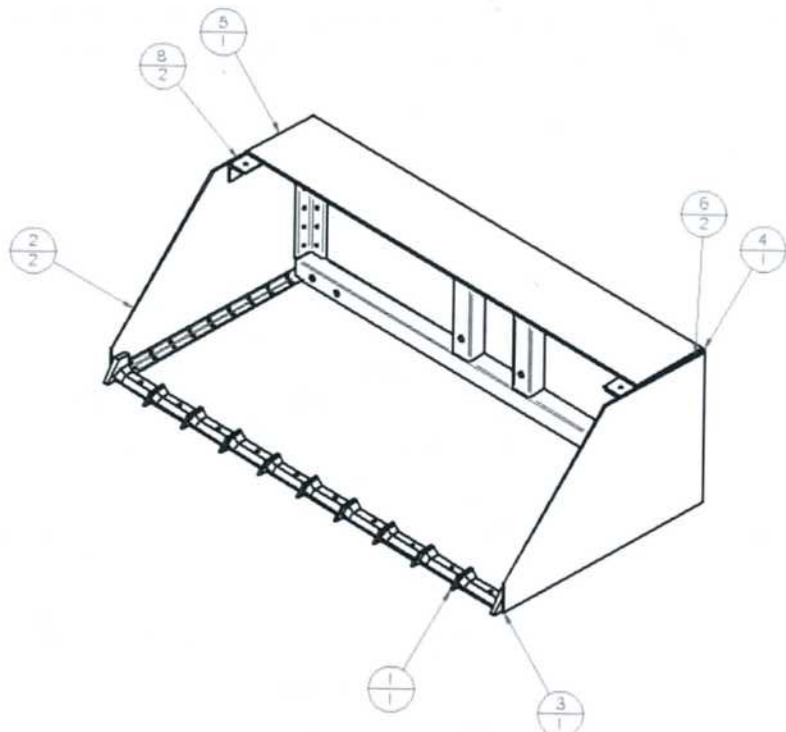
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES 2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE AB Large Bucket

SIZE A | DWG NO AB Large Bucket | REV

SCALE | WEIGHT | SHEET 2 OF 2



Item Number	Revision	Title	Quantity
1	AB008	Large Bucket Subframe	1
2	B011	Large Bucket Side Panel	2
3	B018	Large Bucket Bottom Panel	1
4	B017	Large Bucket Back Panel	1
5	B019	Large Bucket Top Panel	1
6	B006	Large Bucket Aluminum Subframe Vertical Component	2
7	B002	Large Bucket Subframe Aluminum Horizontal Component	1
8	B004	Large Bucket Subframe Aluminum Side Component	2

	NAME	DATE
DRAWN	Mark Kiesle	
CHECKED		
ENG APPR		
MGR APPR		

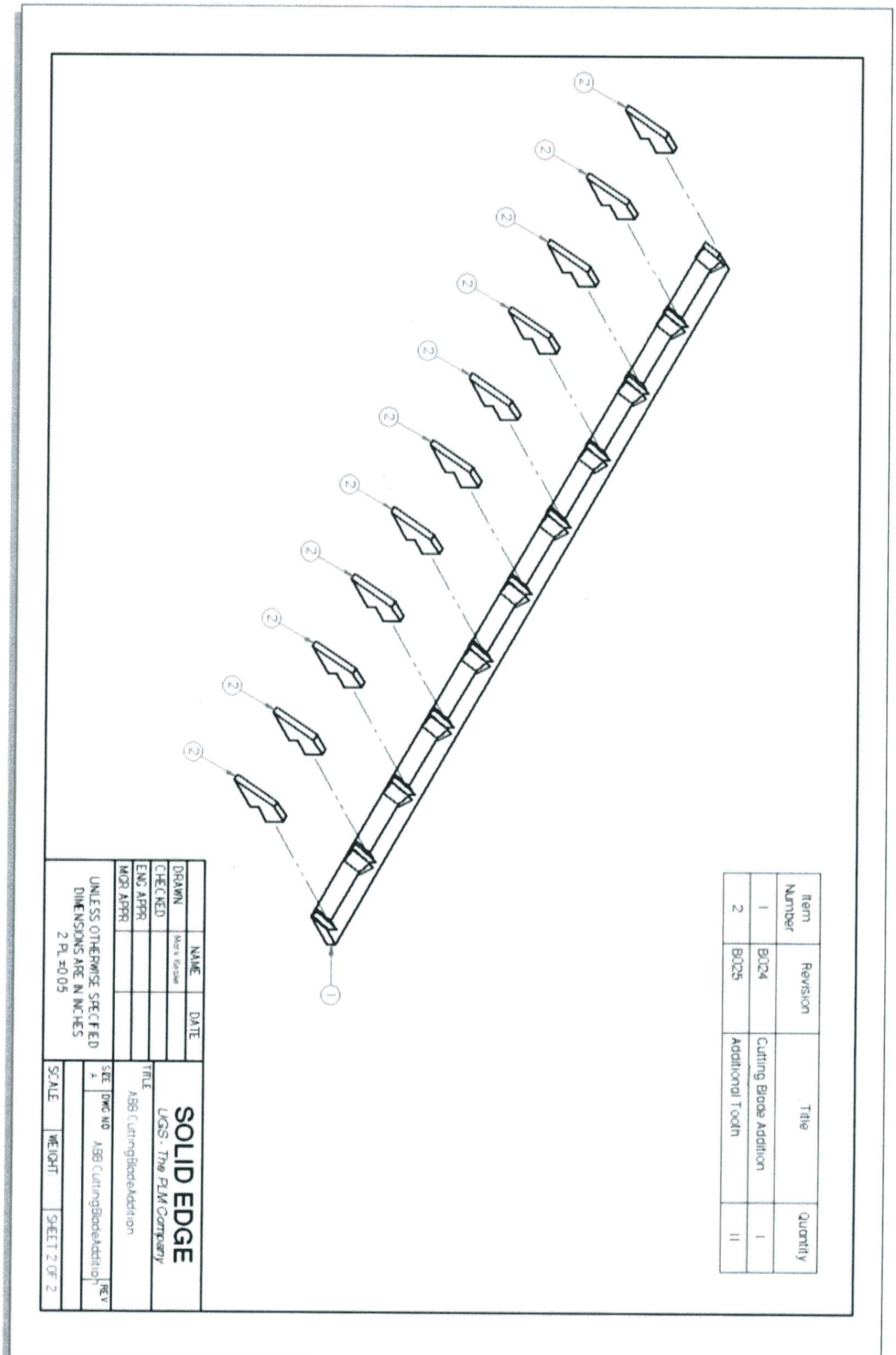
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

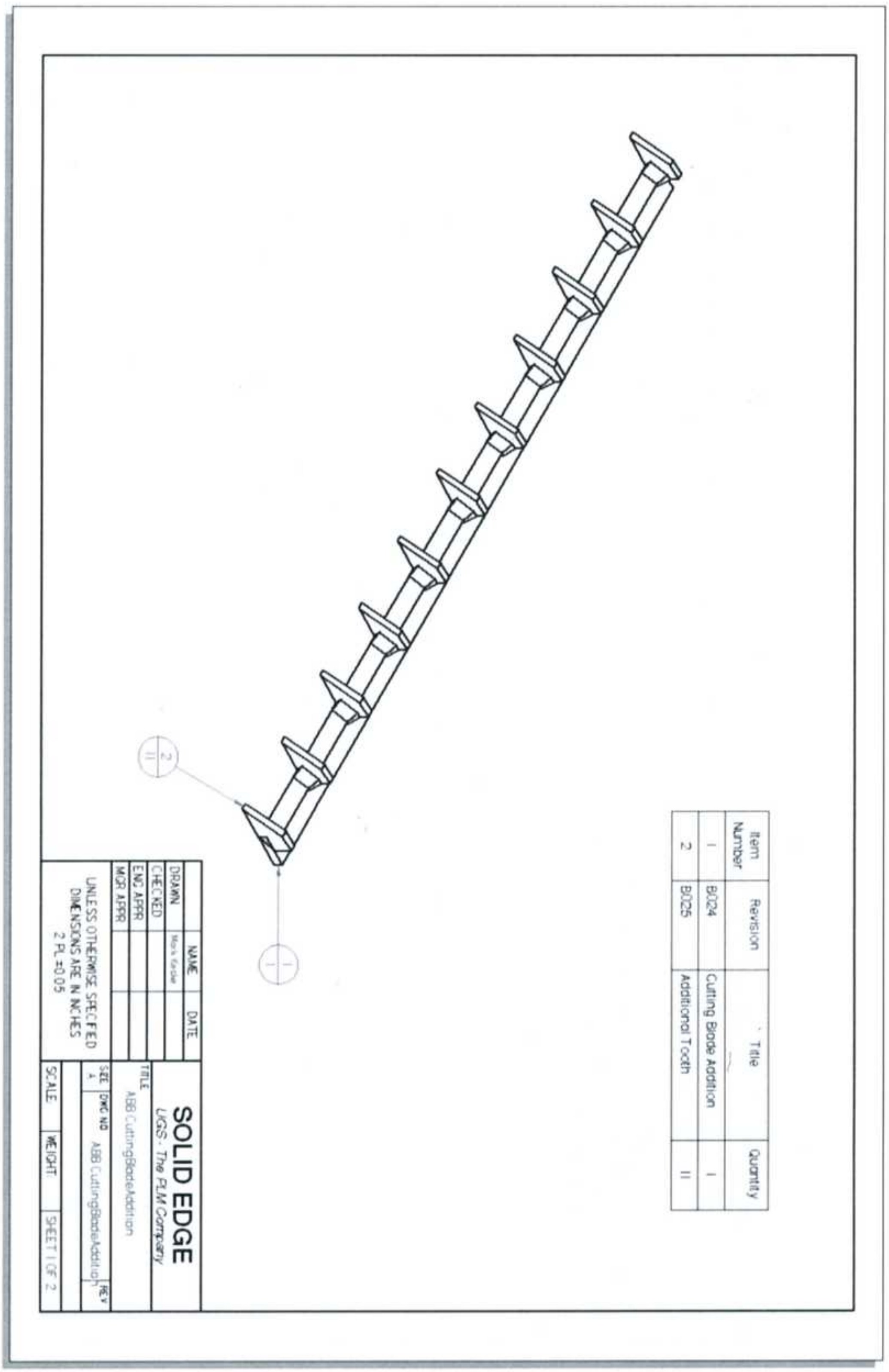
TITLE AB Large Bucket

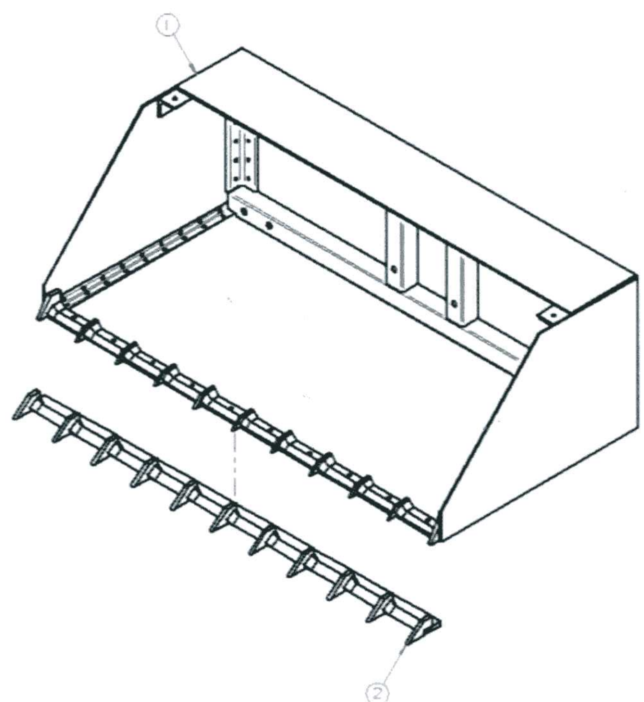
SIZE A | DWG NO AB Large Bucket | REV

SCALE | WEIGHT | SHEET 1 OF 2



Item Number	Revision	Title	Quantity
1	B024	Cutting Blade Addition	1
2	B025	Additional Tooth	11


Item Number
Revision
Title
Quantity
1
B024
Cutting Blade Addition
1
2
B025
Additional Tooth
11
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
ABB CuttingBladeAddition
SIZE
A
DWG NO
ABB CuttingBladeAddition
REV
SCALE
WEIGHT
SHEET 1 OF 2



Item Number	Revision	Title	Quantity
1	AB	Large Bucket	1
2	ABB	Cutting Blade Additional Assembly	1

The additional Blade is welded onto the Bottom of the Cutting Blade

	NAME	DATE
DRAWN	Mark Keske	
CHECKED		
ENG APPR		
MGR APPR		

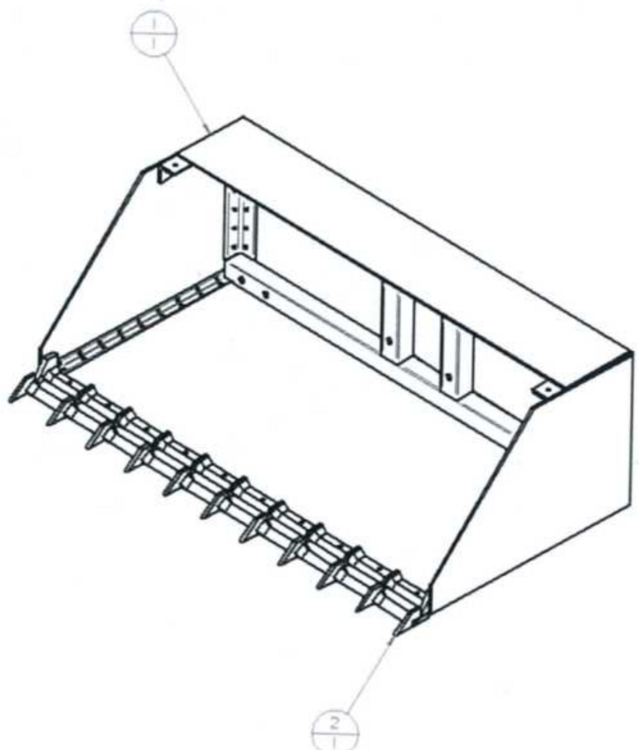
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE: ABA Large Bucket Addition

SIZE: A | DWG NO: ABA Large Bucket Addition | REV

SCALE | WEIGHT | SHEET 2 OF 2



Item Number	Revision	Title	Quantity
1	AB	Large Bucket	1
2	ABB	Cutting Blade Additional Assembly	1

	NAME	DATE
DRAWN	[illegible]	
CHECKED		
ENG APPR		
MGR APPR		

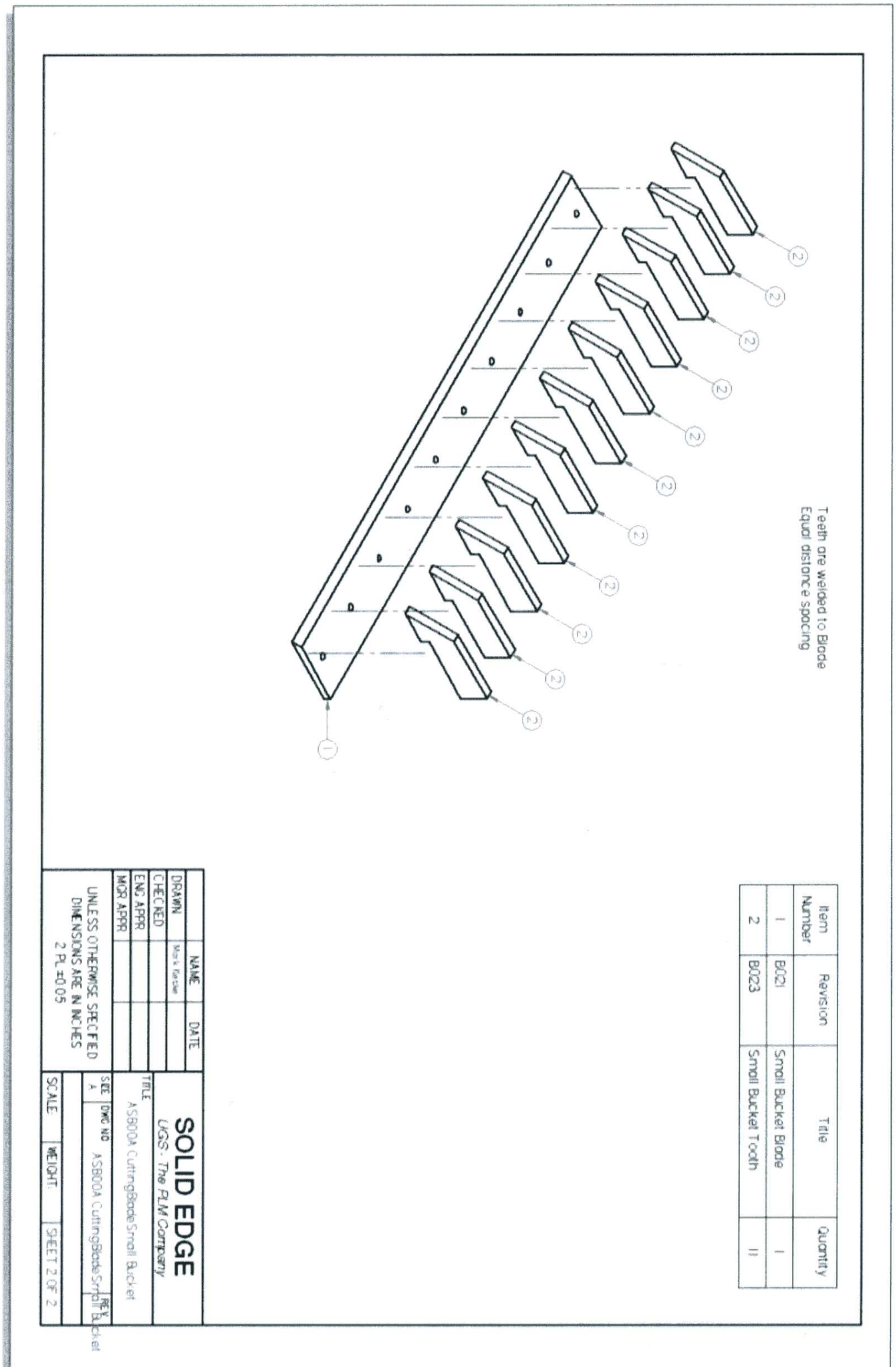
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

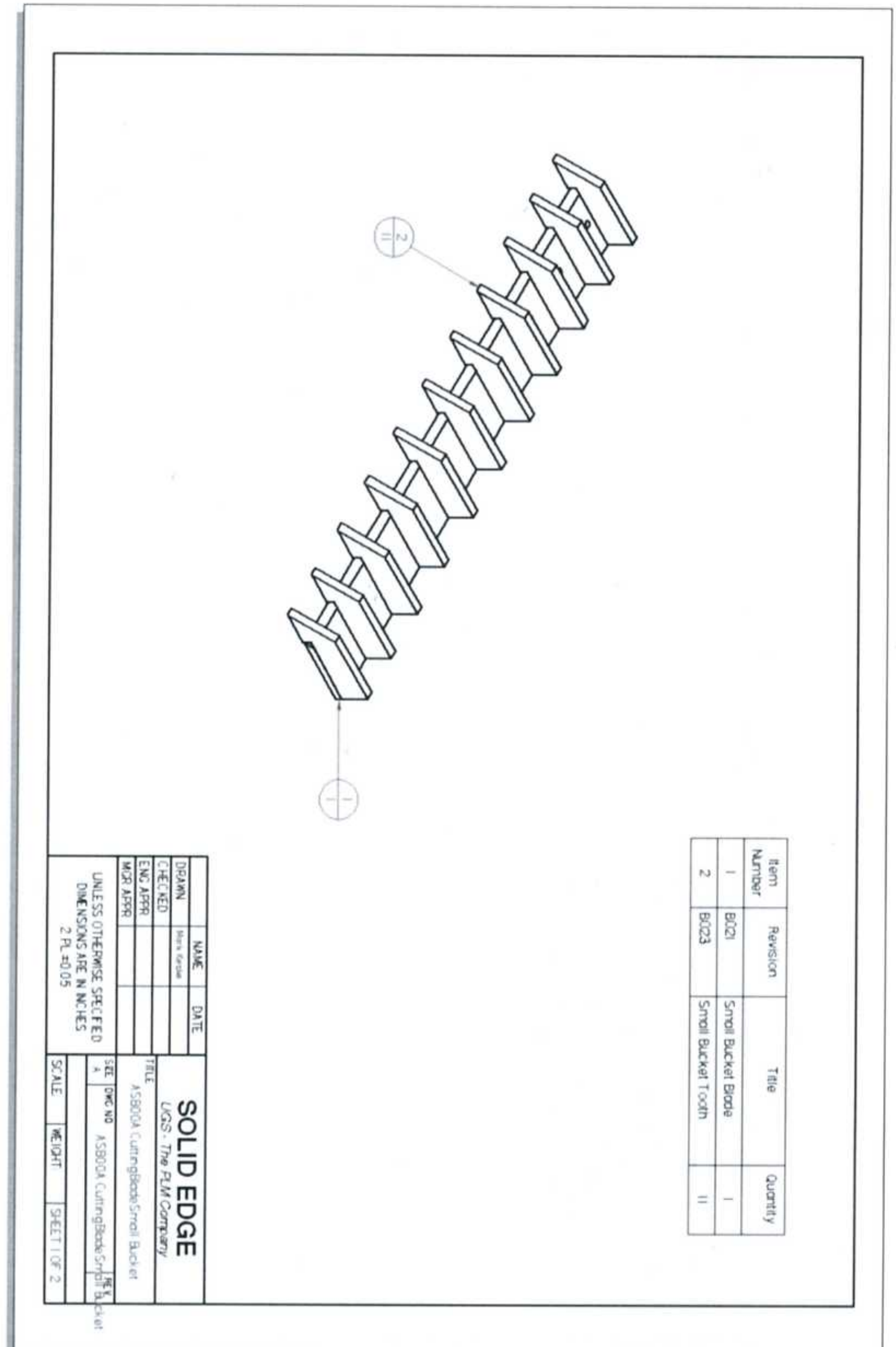
TITLE
ABA Large Bucket Addition

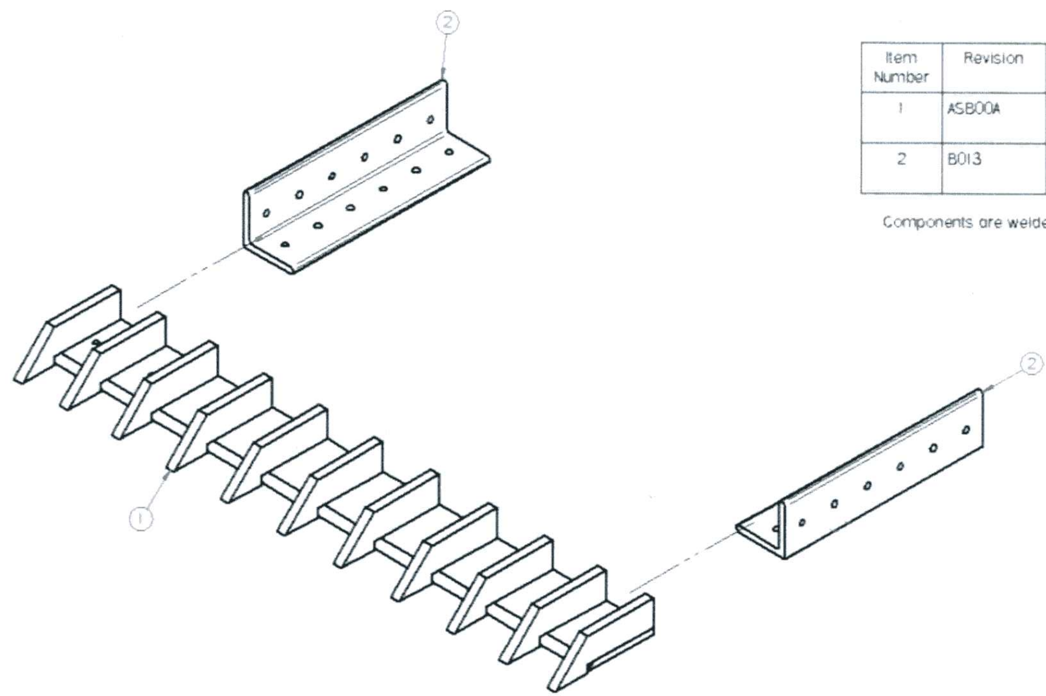
SIZE	DWG NO	REV
A	ABA Large Bucket Addition	

SCALE	WEIGHT	SHEET 1 OF 2



Item Number	Revision	Title	Quantity
1	B021	Small Bucket Blade	1
2	B023	Small Bucket Tooth	11


2
11
1
Item Number
Revision
Title
Quantity
1
B021
Small Bucket Blade
1
2
B023
Small Bucket Tooth
11
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
AS800A CuttingBlade Small Bucket
SIZE A
DWG NO
AS800A CuttingBlade Small Bucket
REV
SCALE
WEIGHT
SHEET 1 OF 2



Item Number	Revision	Title	Quantity
1	ASB00A	Small Bucket Cutting Blade	1
2	B013	Small Bucket Subframe Side Component	2

Components are welded to ASB00A Small Bucket Cutting Blade

	NAME	DATE
DRAWN	Mark Kerske	
CHECKED		
ENG APPR		
MGR APPR		

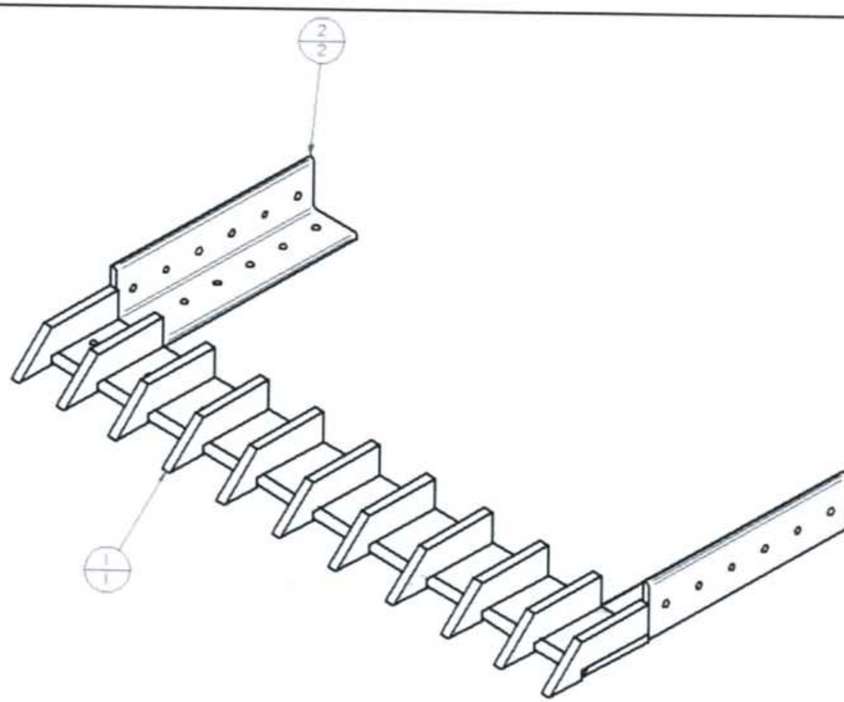
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE
ASB00B Small Bucket Frame

SIZE	DWG NO	REV
A	ASB00B Small Bucket Frame	

SCALE	WEIGHT	SHEET 2 OF 2



Item Number	Revision	Title	Quantity
1	ASB00A	Small Bucket Cutting Blade	1
2	B013	Small Bucket Subframe Side Component	2

	NAME	DATE
DRAWN	Mark Kerske	
CHECKED		
ENG APPR		
MGR APPR		

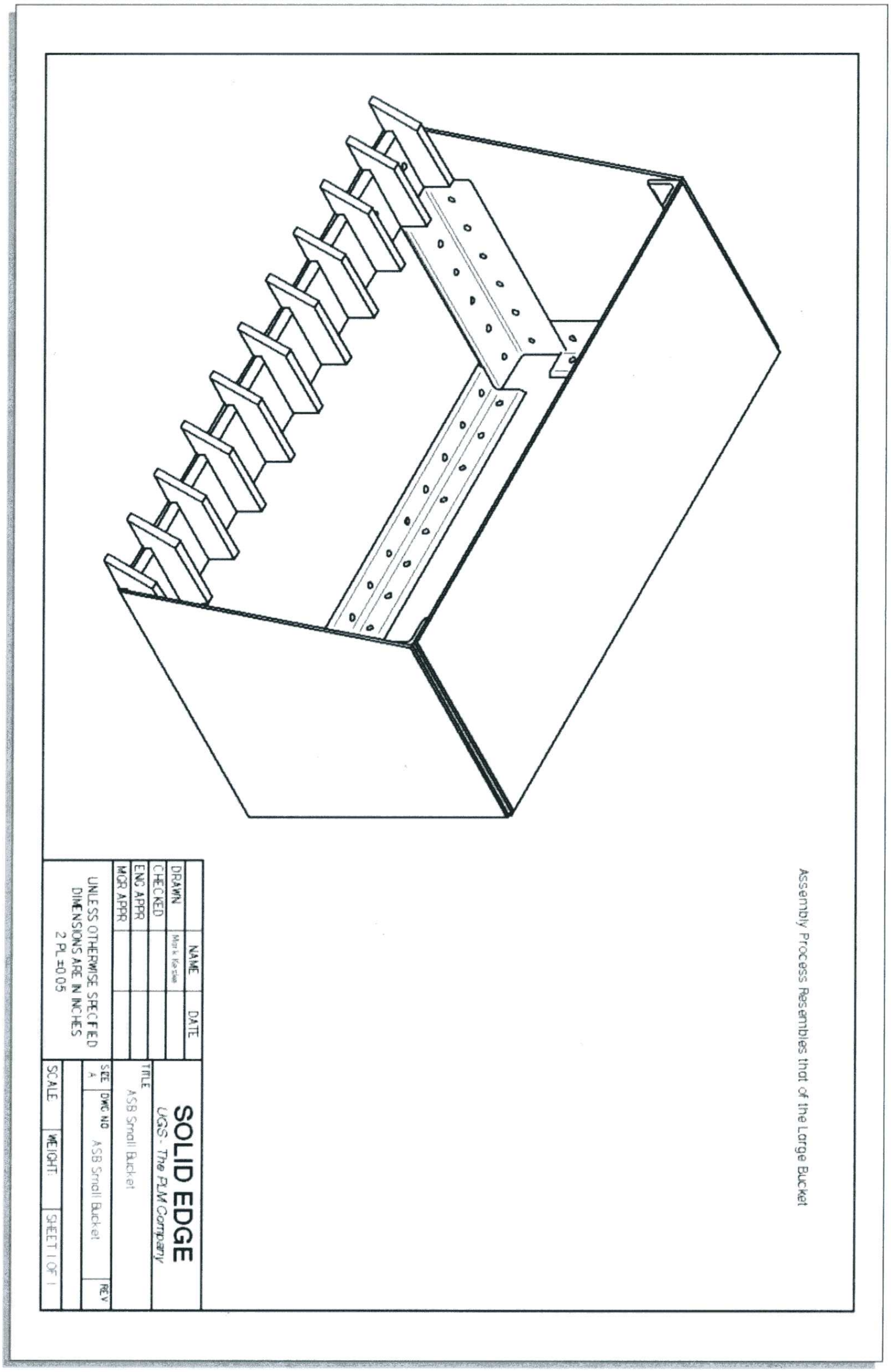
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05

SOLID EDGE
UGS - The PLM Company

TITLE
ASB00B Small Bucket Frame

SIZE A | DWG NO ASB00B Small Bucket Frame | REV

SCALE | WEIGHT | SHEET 1 OF 2


Assembly Process Resembles that of the Large Bucket
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
2 PL ±0.05
SOLID EDGE
UGS - The PLM Company
TITLE
ASB Small Bucket
SIZE
A
DWG NO
ASB Small Bucket
REV
SCALE
WEIGHT
SHEET 1 OF 1

APPENDIX N: Arm Component Spec Sheets

Northern Industrial Linear Actuator — 12 Volt, 11 13/16in. stroke

Key Specs

Load Capacity (lbs.)	1,350
Manufacturer Warranty	12 months parts / 12 months labor
Ship Weight	7.0 lbs
Item#	125012

Additional Specs

8mm per second travel speed

Center-to-center closed pin distance is 17 5/16in. (440mm)

Northern Industrial Linear Actuator — 12 Volt, 7 7/8in. stroke

Key Specs

Load Capacity (lbs.)	1,350
Manufacturer Warranty	12 months parts / 12 months labor
Ship Weight	7.0 lbs
Item#	125011

Additional Specs

7 7/8in. stroke

8mm per second travel speed

Center-to-center closed pin distance is 13 3/8in. (340mm)

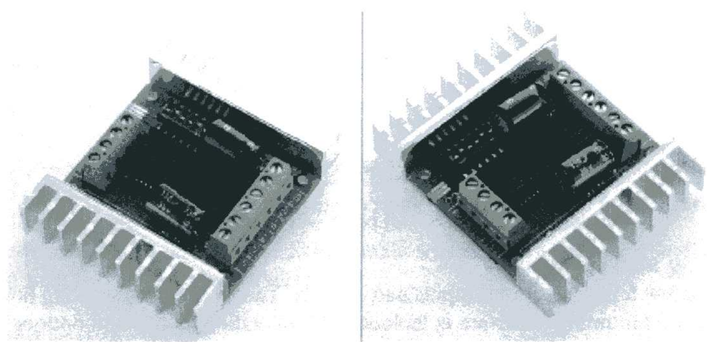
Measures 14 9/16in.L x 9in.H

APPENDIX O: Electrical System Component Spec Sheets

DimensionEngineering

Sabertooth 2x10 User's Guide

February 2007



Input voltage: 6-24V nominal, 30V absolute max.

Output Current: Up to 10A continuous per channel. Peak loads may be up to 15A per channel for a few seconds. These ratings are for input voltages up to 18v in still air without additional heatsinking. Power dissipation derates linearly to 8A/channel continuous when used between 18v and 24v.

Recommended power sources are:

- 5 to 18 cells NiMH or NiCd
- 2s to 6s lithium ion or lithium polymer. Sabertooth motor drivers have a lithium battery mode to prevent cell damage due to over-discharge of lithium battery packs.
- 6v to 24v lead acid
- 6v to 24v power supply (when in parallel with a suitable battery).

Dimensions:

Size: 2.3" x 3" x .7"	59 x 75 x 17mm
Weight: 2.1oz	

Features

Mixed and independent options:

Sabertooth features mixed modes designed especially for differential drive robots, where two motors provide both steering and propulsion. It also has independent options in all operating modes. This is useful for if you have two motors to control, but they aren't necessarily being used to drive a differential drive robot. The motors do not need to be matched or even similar, as long as they both are within Sabertooth's operating limits.

Synchronous regenerative drive:

Going one step farther than just regenerative braking, a Sabertooth motor driver will return power to the battery any time a deceleration or motor reversal is commanded. This can lead to dramatic improvements in run time for systems that stop or reverse often, like a placement robot or a vehicle driving on hilly terrain. This drive scheme also saves power by returning the inductive energy stored in the motor windings to the battery each switching cycle, instead of burning it as heat in the motor windings. This makes part-throttle operation very efficient.

Ultra-sonic switching frequency:

Sabertooth 2x10 features a PWM frequency of 32kHz, which is well above the maximum frequency of human hearing. Unlike some other motor drivers, there is no annoying whine when the motor is on, even at low power levels.

Thermal and overcurrent protection:

Sabertooth features dual temperature sensors and overcurrent sensing. It will protect itself from failure due to overheating, overloading and short circuits.

Easy mounting and setup:

Sabertooth has screw terminals for all inputs and outputs. There are four mounting holes, which accept 4-40 screws. Mounting hardware is included. All operating modes and options are set with DIP switches – there are no jumpers to struggle with or lose. No soldering is required.

Compact Size:

Sabertooth utilizes surface mount construction to provide the most power from a compact package. Its small size and light weight mean you have more space for cargo, batteries, or can make your robot smaller and more nimble than the competition.

Carefree reversing:

Unlike some other motor drivers, there is no need for the Sabertooth to stop before being commanded to reverse. You can go from full forward immediately to full reverse or vice versa. Braking and acceleration are proportional to the amount of reversal commanded, so gentle or rapid reversing is possible.

Many operating modes:

With analog, R/C and serial input modes, as well as dozens of operating options, the Sabertooth has the flexibility to be used over and over, even as your projects grow more sophisticated. Yet it is simple enough to use for your first robot project.

Operating Modes Overview

Mode 1: Analog Input

Analog input mode takes one or two analog inputs and uses those to set the speed and direction of the motor. The valid input range is 0v to 5v. This makes the Sabertooth easy control using a potentiometer, the PWM output of a microcontroller (with an RC filter) or an analog circuit. Major uses include joystick or foot-pedal controlled vehicles, speed and direction control for pumps and machines, and analog feedback loops.

Mode 2: R/C Input

R/C input mode takes two standard R/C channels and uses those to set the speed and direction of the motor. There is an optional timeout setting. When timeout is enabled, the motor driver will shut down on loss of signal. This is for safety and to prevent the robot from running away should it encounter interference and should be used if a radio is being used to control the driver. If timeout is disabled, the motor driver will continue to drive at the commanded speed until another command is given. This makes the Sabertooth easy to interface to a Basic Stamp or other low-speed microcontrollers.

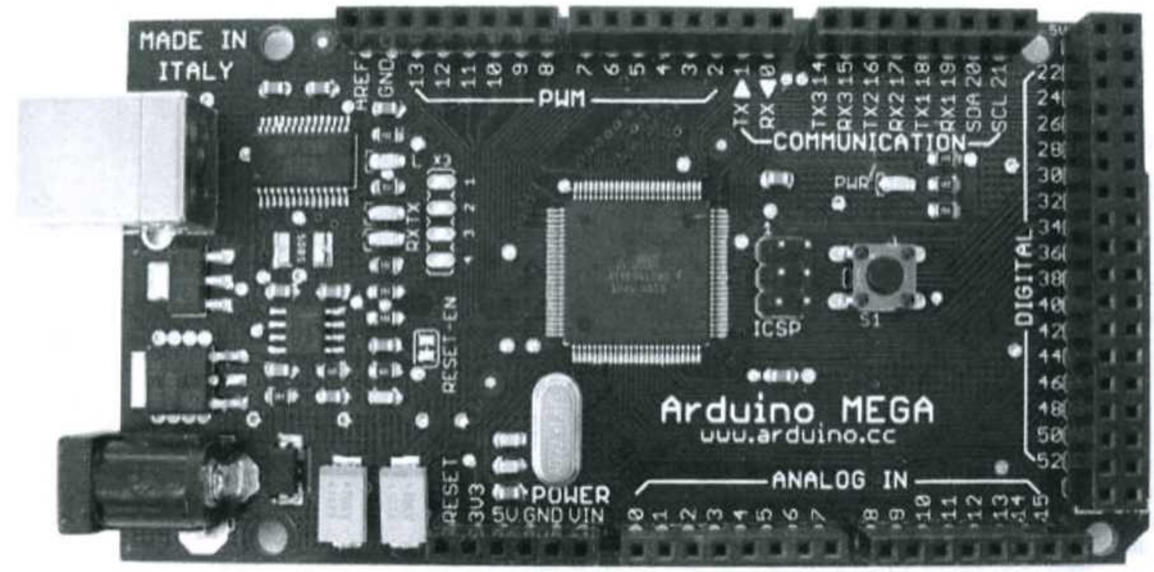
Mode 3: Simplified serial.

Simplified serial mode uses TTL level RS-232 serial data to set the speed and direction of the motor. This is used to interface the Sabertooth to a PC or microcontroller. If using a PC, a level converter such as a MAX232 chip must be used. The baud rate is set via DIP switches. Commands are single-byte. There is also a Slave Select mode which allows the use of multiple Sabertooth 2x10 from a single microcontroller serial port.

Mode 4: Packetized serial

Packetized serial mode uses TTL level RS-232 serial data to set the speed and direction of the motor. There is a short packet format consisting of an address byte, a command byte, a data byte and a 7 bit checksum. Packetized serial automatically detects the transmitted baud rate based on the first character sent, which must be 170. Address bytes are set via dip switches. Up to 8 Sabertooth motor drivers may be ganged together on a single serial line. This makes packetized serial the preferred method to interface multiple Sabertooths to a PC or laptop. Because Sabertooth uses the same protocol as our SyRen single motor drivers, both can use used together from the same serial master.

Arduino Mega



Overview

The Arduino Mega is a microcontroller board based on the ATmega1280 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila.

Schematic & Reference Design

EAGLE files: arduino-mega-reference-design.zip
Schematic: arduino-mega-schematic.pdf

Summary

Microcontroller	ATmega1280
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	128 KB of which 4 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Power

The Arduino Mega can be powered via the USB connection or with an external power supply. The power source is selected automatically.

External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.

The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The power pins are as follows:

VIN. The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.

5V. The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an on-board regulator, or be supplied by USB or another regulated 5V supply.

3V3. A 3.3 volt supply generated by the on-board FTDI chip. Maximum current draw is 50 mA.

GND. Ground pins.

Memory

The ATmega1280 has 128 KB of flash memory for storing code (of which 4 KB is used for the bootloader), 8 KB of SRAM and 4 KB of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 54 digital pins on the Mega can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

Serial: 0 (RX) and 1 (TX); Serial 1: 19 (RX) and 18 (TX); Serial 2: 17 (RX) and 16 (TX); Serial 3: 15 (RX) and 14 (TX). Used to receive (RX) and transmit (TX) TTL serial data. Pins 0 and 1 are also connected to the corresponding pins of the FTDI USB-to-TTL Serial chip.

External Interrupts: 2 (interrupt 0), 3 (interrupt 1), 18 (interrupt 5), 19 (interrupt 4), 20 (interrupt 3), and 21 (interrupt 2). These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.

PWM: 0 to 13. Provide 8-bit PWM output with the analogWrite() function.

SPI: 50 (MISO), 51 (MOSI), 52 (SCK), 53 (SS). These pins support SPI communication, which, although provided by the underlying hardware, is not currently included in the Arduino language. The SPI pins are also broken out on the ICSP header, which is physically compatible with the Duemilanove and Diecimila.

LED: 13. There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

I^2C: 20 (SDA) and 21 (SCL). Support I^2C (TWI) communication using the Wire library (documentation on the Wiring website). Note that these pins are not in the same location as the I^2C pins on the Duemilanove or Diecimila.

The Mega has 16 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and analogReference() function.

There are a couple of other pins on the board:

AREF. Reference voltage for the analog inputs. Used with analogReference().

Reset. Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

Communication

The Arduino Mega has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega1280 provides four hardware UARTs for TTL (5V) serial communication. An FTDI FT232RL on the board channels one of these over USB and the FTDI drivers (included with the Arduino software) provide a virtual com port to software on the computer. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board will flash when data is being transmitted via the FTDI chip and USB connection to the computer (but not for serial communication on pins 0 and 1).

A SoftwareSerial library allows for serial communication on any of the Mega's digital pins.

The ATmega1280 also supports I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation on the Wiring website for details. To use the SPI communication, please see the ATmega1280 datasheet.

Programming

The Arduino Mega can be programmed with the Arduino software (download). For details, see the reference and tutorials.

The ATmega1280 on the Arduino Mega comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).

You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

Automatic (Software) Reset

Rather then requiring a physical press of the reset button before an upload, the Arduino Mega is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the FT232RL is connected to the reset line of the ATmega1280 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.

This setup has other implications. When the Mega is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Mega. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened. If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.

The Mega contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

The Arduino Mega has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Physical Characteristics and Shield Compatibility

The maximum length and width of the Mega PCB are 4 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

The Mega is designed to be compatible with most shields designed for the Diecimila or Duemilanove. Digital pins 0 to 13 (and the adjacent AREF and GND pins), analog inputs 0 to 5, the power header, and ICSP header are all in equivalent locations. Further the main UART (serial port) is located on the same pins (0 and 1), as are external interrupts 0 and 1 (pins 2 and 3 respectively). SPI is available through the ICSP header on both the Mega and Duemilanove / Diecimila. *Please note that I^2C is not located on the same pins on the Mega (20 and 21) as the Duemilanove / Diecimila (analog inputs 4 and 5).*