Active Ankle Response for a 2-D Biped Robot with Terrain Contact Sensing

By

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Version of the following thesis:

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Abstract

This investigation explored the possibility of controlling a biped robot in the lateral direction as well as sensing terrain properties. A literature review was conducted to learn from and build off of previous research. Little research existed that deals directly with this topic, since most research dealing with biped robots deals with ambulation in the forward direction or control systems. The literature review supported the idea of controlling a biped in the lateral direction in theoretical terms, but has not ever been addressed by designing and fabricating a test bed and control system. Terrain sensing has been addressed in various aspects, but this research was aimed to acquire quantifiable values to determine how rigid the terrain is.

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1 Introduction

The Intelligent Systems and Automation Laboratory (ISAL) at the University of Kansas has been developing an anthropomorphic 3 legged 2-D biped robot. During ambulation, the two outer legs move together in the same motion, subsequently the middle leg will move through the corresponding swing phase.

Biped robots are more advantageous for walking over uneven surfaces as opposed to wheeled robots. Bipeds have improved stability when encountered with stairs, slopes, and surfaces containing uneven obstacles, but require a much more complex control system than their wheeled counterparts. All of these issues have been addressed, to some degree, in previous work. The work studied in this application deals with controlling the inversion/eversion of a 3 degree of freedom ankle to overcome obstacles that force the robot to become unstable in the lateral direction. The ankle needs to sense the soil properties and the geometry of the ground [1]. The robotic foot will have sensors and artificial intelligence to help determine the surface it is walking on. The artificial intelligence will analyze the data from the sensors and determine whether it is walking on hard concrete, deforming sand, or other surfaces and adjust the inversion/eversion to control the lateral stability of the robot. The best method of sensing the terrain would be to integrate a terrain mapping device to acquire visual data with force contact sensing.

2 Motivation

The motivation behind adaptation of inversion/eversion of a 3 degree of freedom ankle for a 2-D biped walker is aimed at two overall goals.

1) Continue and improve the existing 3 legged 2-D biped dubbed the "JayWalker" in the Intelligent Systems and Automation Laboratory (ISAL). Inversion/eversion adaptation of ground sensing ankles incorporates an advanced mechatronics problem rarely addressed in the study of biped walking.

2) To strive forward to a goal well beyond the scope of this study, where research performed on the Jaywalker is directly applicable to human prosthetics, thus improving the quality of life for people who do not have the physical ability to perform certain tasks.

3. Background and Significance

The main contributions of previous work are through path planning and 2D rough terrain walking. Path planning evaluates obstacles in front of the robot before the robot encounters them. 2D rough terrain walking evaluates some characteristic of the terrain the robot is walking on

Some previous studies have indicated that path planning will allow the robot to take the least complex, most "feasible path".[2] Low and Bai proposed an algorithm to determine the most feasible path by using laser and ultrasonic sensors to divide up forward areas into individual cells, then evaluating those cells based on foot placement. The cell was either acceptable or unacceptable for foot placement. If the cells were next to a boundary it was excluded from the possible cells for foot placement. The shortest distance between two points is a straight line, a robot with the ability to walk over normally impeding terrain will require less energy, but ultimately will still require the ability to avoid obstacles that cannot be walked over, such as walls. If the height of the object was higher than the height the leg could lift, the cell was unacceptable. Although this is an excellent method for path planning, it still does not address the issue of rough terrain. It is possible to detect obstacles, but not possible to detect terrain without contact. Guiding around slippery or rocky areas requires traveling a longer distance, which means more energy. Even so, with sensors it is difficult to sense the surface properties at a distance.[3] Using contact sensors seems to be the only true way to sense terrain that has not been encountered previously. Robust locomotion on rough terrain must be able to respond to the terrain condition after contact and before the robot falls.[3]

The equations of motion (EOM) are developed using direct kinematic models and inverse kinematic models. For control purposes, it is necessary to have an inverse kinematics expression [4] that allows one to find the actuator position angles as a function of inversion/eversion. $\varphi_1(\alpha_1))$. Where φ_1 is the inversion angle and α_1 is the position of the actuator controlling the inversion. Direct kinematic models may be used to validate the inverse kinematic models, but are not used for control purposes[4].

Inverse kinematic equations are used to determine the position of the actuator with feedback from the sensors on the foot. The actuator position is a function of the inversion/eversion angle of the ankle.[4]

The mechanical design of legs is more complex than that of wheeled robots. Legs have several advantages, but require subjective design decisions. For instance, since active dynamic walking requires power, there is a tradeoff of size versus power [5]. It is known that pneumatics have a high power to size ratio although they sacrifice precision position control. The precise, high speed control of pneumatic actuators is a complex topic because they are a high order system, time variant actuation dynamics, non-linearities from the compressibility of the fluid, static and coulomb friction, and a wide range of payload and pressure supply variations [6].

The control system design of biped robots is much more complex than the design of multi legged or wheeled robots because the system is naturally unstable [5]. The complexity is derived from the challenge of controlling the multiple inputs and outputs required to perform various functions and maintain balance. Basic anatomy demonstrates that the human body, when described in mechanical terminology, has a plethora of actuators that have evolved to perform specific tasks efficiently. These actuators are driven by a complex control system that responds to multiple sensors to react to the surrounding environment. When applicable to the study at hand, a biped that can sense ground reaction forces and compare to a terrain mapping algorithm may allow the control system to compute the most efficient solution to traversing rough terrain. Various mathematical models have been proposed to control biped robots in forward motion, although few have addressed a mathematical model that controls the lateral motion of the biped in the frontal plane. However complex a planar model might be, the problem of the lateral equilibrium around the edge of the foot has not been solved [7]. The number of joints drastically increases the complexity of the model, resulting in models that are usually limited to being planar [7].

4 Theoretical Development

4.1 Equations of Motion

The Equation of Motion to control the biped in the lateral direction can be modeled with a simple inverted pendulum. The design variable of this model is the height of the center of mass. There are pros and cons to the tradeoff of control and the energetic cost of raising the center of mass [7]. The higher the center of mass, the slower the initial motion of the pendulum and the more time to react to the lateral instability of the biped. This also means the control system will have more time to react and adjust to the instability. This is demonstrated theoretically by evaluating the inverted pendulum model with simple conservation of energy laws or the angular impulse-momentum principle[8].

Equation 1 – Conservation of Energy

$$\tfrac{1}{2} I \dot{\theta}^2 + mgh = 0 .$$

Where ‘I’ is the moment of inertia around about the inversion/eversion axis of the foot, $\dot{\theta}$ is the angular velocity at which the robot is falling laterally, m is the mass, and h is the height of the center of mass. “h” can also be expressed as $L\cos\theta$, where L is the length from the point of rotation to the center of mass. Applying initial conditions $\dot{\theta}_0 = 0$, the energy equation can be expressed as

Equation 2 – Applying Boundary Conditions

$$\dot{\theta} = \left(\frac{2mgL}{I} (\cos\theta_0 - \cos\theta) \right)^{1/2}$$

The time required to move from the initial position of $\theta = 90^o$ to a critical position is determined by the elliptic integral[7]

Equation 3 – Critical Position of COM

$$\Delta t = \Delta t(\theta_1) - \Delta t(\theta_0) = \left(\frac{I}{2mgL} \right)^{1/2} \int_{\theta_0}^{\theta_1} \frac{d\theta}{(\cos\theta_0 - \cos\theta)^{1/2}}$$

4.2 Degrees of Freedom

It has been discussed that as more joints are introduced into the model, the more complex the model becomes in order to control the degrees of freedom. Initially the model of the ankle incorporated 3 active degrees of freedom, Inversion/Eversion, Yaw, and plantar/flexor motions. In order to simplify the model, the inversion/eversion motions were kept as the main point of focus for this study. The yaw was made passive with springs in order to allow the mechanical system to deviate when implemented on the Jaywalker during heel strike and stance phase. The plantar/flexor motions will be utilized when the ankle being proposed is implemented on the Jaywalker.

In order to practically handle the torque values and critical points of the center of mass, 15 degrees of either inversion or eversion from the vertical plane is the maximum angle that the ankle will undergo. Controlling the full range of anthropomorphic values would be difficult and require a much more expensive motor/actuator capable of handling such high torques. It is also apparent, that as the center of mass extends in the horizontal direction towards the critical point of instability, there is less time available to recover from a potential fall. The requirements for a fast response time may require low level (assembly language) programming of a control system and high speed actuators with precision control.

5 Mechanical Development

Mechanical System Development Procedure

The design underwent more than 30 revisions. The final design was selected due to the constraints of space, desired ranges of motion, manufacturability, the amount of components that could be purchased off of the shelf, and obviously cost.

1. Determination of Footprint. The primary focus of this design was to keep the ankle as close to anthropomorphic as possible. For the foot to be truly anthropomorphic on the same scale as the Jaywalker, the foot should be 3 inches wide, the foot presented is 5.5 inches wide.
2. Determination of Degrees of Freedom. As a robot is designed with more degrees of freedom to be more anthropomorphic, the level of complexity increases for the mechanics and if the motion is active the control system complexity will also increase.
3. Manufacturing considerations. The majority of the custom components and modified purchased components were to be manufactured in the University of

Kansas Mechanical Engineering Machine Shop and assembled in the ISA Laboratory.

4. Cost considerations were taken into account when designing and purchasing the mechanical components.
5. Interface considerations with the forefoot were setup before the initial design. This allowed parallel design of the ankle and the fore foot.

5.1 Determination of a Footprint

The ankle was designed too wide to be considered anthropomorphic. This was required in order to aid in stability and resemble the current foot on the Jaywalker. Collins and Ruina stated that using a widely spaced foot achieves lateral stability by keeping the center of pressure in between the two foot rails and having a tighter radius for the inner foot rails. The side effect is the indeterminacy at heel strike collisions is significantly different than if the order were reversed, making computer simulation very difficult [9]. This is not the case for the Jaywalker because it has three feet as opposed to two. Three feet keep the COM at a stable condition during flat terrain ambulation. Computer simulation in the presented case is still difficult considering all of the active and passive degrees of freedom in the ankle alone. The Jaywalker is still stable on level ground because the foot does not have a rigid constant radius of curvature. The development of the flexing forefoot and the potential for a moving heel pad is an improvement on a constant 9” radius of curvature foot. The heel pad has rubber incorporated in order to absorb some of the shock of heel strike. It has been observed that disruptive impacts are provoked when the heels make contact with the terrain[7]. The rubber heel pad is also used to secure the piezoelectric force sensors on the heel.

5.2 Determination of Degrees of Freedom

The ankle was designed with all of the degrees of freedom that a human ankle possesses. The active ankle designed does not necessarily have the same ranges of motion as a human ankle, but the ability to rotate around all three axis has been achieved. The ankle on the current test bed only has inversion/eversion degrees of freedom that are controlled with active actuators. Implementation onto the Jaywalker will acquire an active degree of freedom by rotating the foot through plantar flexion and dorsiflexion. Future developments will increase the number of controlled degrees of freedom in the ankle.

5.3 Manufacturing Considerations/Cost Considerations

The equipment available for manufacturing restricted the complexity of the design. Standard components were purchased and modified, where possible, to save time and expense.

Numerous actions were taken to conserve cost. A majority of the components on the foot were fabricated from the same material stock. This dictated design decisions, but benefited cost optimization in other areas of development. Access to CNC equipment was available, but in order to optimize the results of the research, it was felt that the primary expense should be the focused on the more critical actuators.

5.4 Interface

The interface that connects the ankle and the fore foot was developed in order to make the design of the two sections parallel. The interface provided a structural member for both the forefoot and the ankle. The axis providing inversion/eversion, for example, has one bearing surface that is integrated into the interface.

6 Control System Development

Control System Development Procedure

1. Determination of terrain contact sensing method. This consisted of a selecting a suitable means to feedback to the controller values of force as pressure was being applied to the heel pad during gait. The sensors must hold up to the environment (i.e. dirt, oil, fatigue), and be able to mount on the heel pad with minimum disruption of gait.

2. Determining the method to measure the angle of tilt in the sagittal plane. This consisted of a method that would provide feedback to the controller to determine the stability of the robot in the lateral direction.

3. A control system would need to be able to interpret the feedback from the sensors and output a signal to a driving mechanism to correct for unbalance when the robot is stepping on uneven terrain.

4. Developing a driving mechanism to actuate the ankle to control inversion/eversion. This consisted of a mechanism that could be powered with a low voltage source and have the ability to feedback the position of the device.

5. Software development for the data acquisition and interpretation of real time data. Based on how the sensors interface with the physical movements and feedback to the controller, software would be needed to interpret the data acquired by the controller and analyze the results of the tests.

6.1 Determination of a Terrain Contact Sensing Method

The ankle needs to be able to sense the soil properties and the angle of the surface it is making contact with [1]. To determine the soil properties requires values of force feedback as a function of time. A step response would be indicative of a hard surface such has concrete, whereas a ramp response would be indicative of a deforming surface such as sand.

Potentiometers were used by Yamaguchi on a robot foot to determine unknown uneven terrain [10]. This was a viable method for their application of determining the gradient of unknown terrain. It is possible to acquire force values as a function of time indirectly by knowing the amount of force it takes to deform the heel pad. Acquiring the voltage from the change in resistance that occurs as the heel pad deforms and utilizing an analog to digital converter the force response can be found. The potentiometers used to determine gradient dictate the design due to their size, moving parts, and difficulty of placement.

Piezoelectric materials provide a thin, flat material that can be mounted directly to the bottom of the heel pad with limited protection. The piezoelectric material will create a varying voltage as it undergoes deformation. When the deformation is applied, the voltage is converted to a force response by an 8 bit analog to digital converter and read by the BS2 (Figure 1,2),[11]

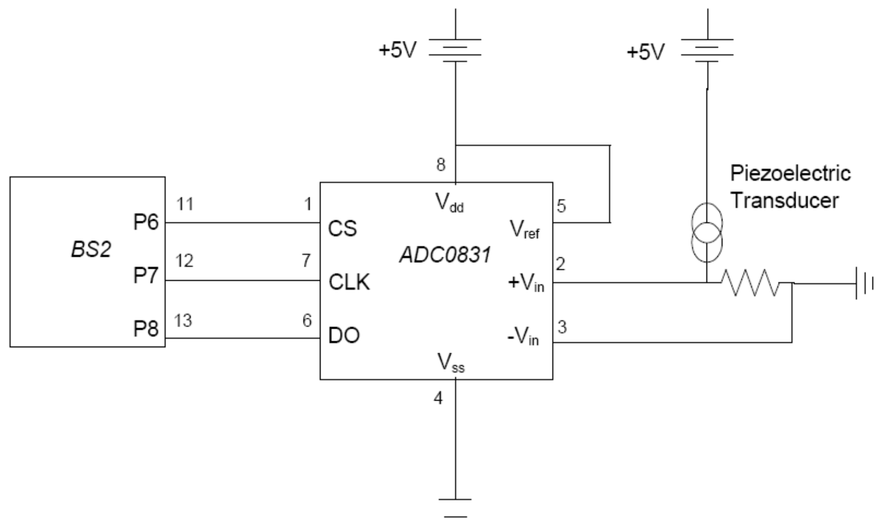


Figure 1 Analog to Digital Converter for Piezoelectric Transducer

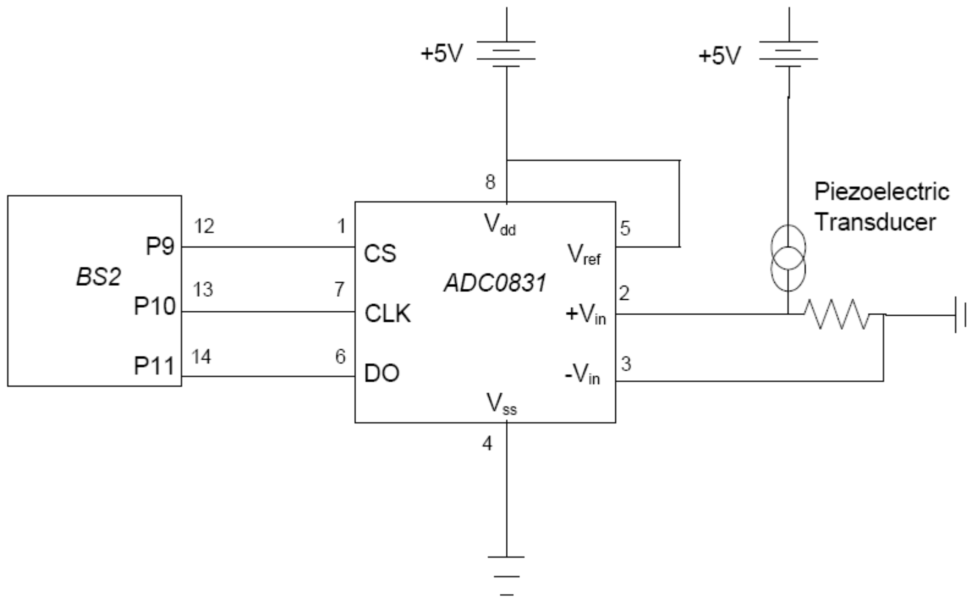


Figure 2 Analog to Digital Converter for Piezoelectric Transducer

The flat profile of the piezoelectric material allowed easy interfacing with the heel pad. This, along with the simplicity of interfacing the sensor with the controller, made it the primary candidate to pursue terrain contact sensing.

During ambulation, the piezoelectric material converts mechanical strain energy into electrical charge. This electrical charge is converted into a digital value that is fed back to the control system in order to determine the terrain hardness. It may be possible to determine the compressive properties of the terrain by comparing the time of initial contact to the peak force contact of the heel. A longer time required to reach full contact would signify a more compressive terrain such as sand. A short step response would signify a more rigid terrain such as concrete. The more deformation the sensor is subjected to, the higher the probability of determining the terrain type.

Initial development required this action to be a slow process, as compression forces have a very short response time. The piezoelectric sensors were placed between pieces of rubber in order to achieve more deformation and protect them from the rigorous environment of surface contact and dirt.

6.2 Measuring the Angle of Tilt in the Sagittal Plane.

The inverted pendulum model requires knowing the angle of tilt in the sagittal plane of the robot. A method of determining the angle of tilt would be through sensing the angle of the servo that is driving the inversion/eversion. To control inversion/eversion with servo angles, it is necessary to use the inverse kinematic expressions that allows one to find the servo angles as a function of the angle of tilt [4]. This would be the ideal method for controlling the inversion/eversion on the Jaywalker, but due to the selection of a linear actuator for inversion/eversion control on the active ankle's test bed, this method was not directly practical.

Another method that was considered for controlling inversion/eversion was mounting an optical encoder on the fulcrum point of the ankle. This was not implemented due to two main reasons. One, a decision had been made to mount accelerometers at the center of mass on the Jaywalker. Once the active ankle is implemented, the logical choice would be to tie into the axis of the accelerometer measuring the sagittal plane. Two, the size of the encoder would prove to be difficult to mount on the ankle. A pulley and cable system could have been used with the encoder mounted at a different location, but this option would have been difficult to implement.

The logical choice is measuring the angle of tilt with an accelerometer. A Hitachi H48C 3 axis accelerometer was chosen to interface with the controller. Only one axis is needed for this application, but the 3 axis sensor was chosen to allow for future options.

The accelerometer utilizes an onboard MCP3204 12-bit analog-to-digital converter to change the analog voltages to digital values. The voltage output of each axis is compared to a reference voltage, determining the angle of tilt. The schematic of the accelerometer can be seen in Fig.3.

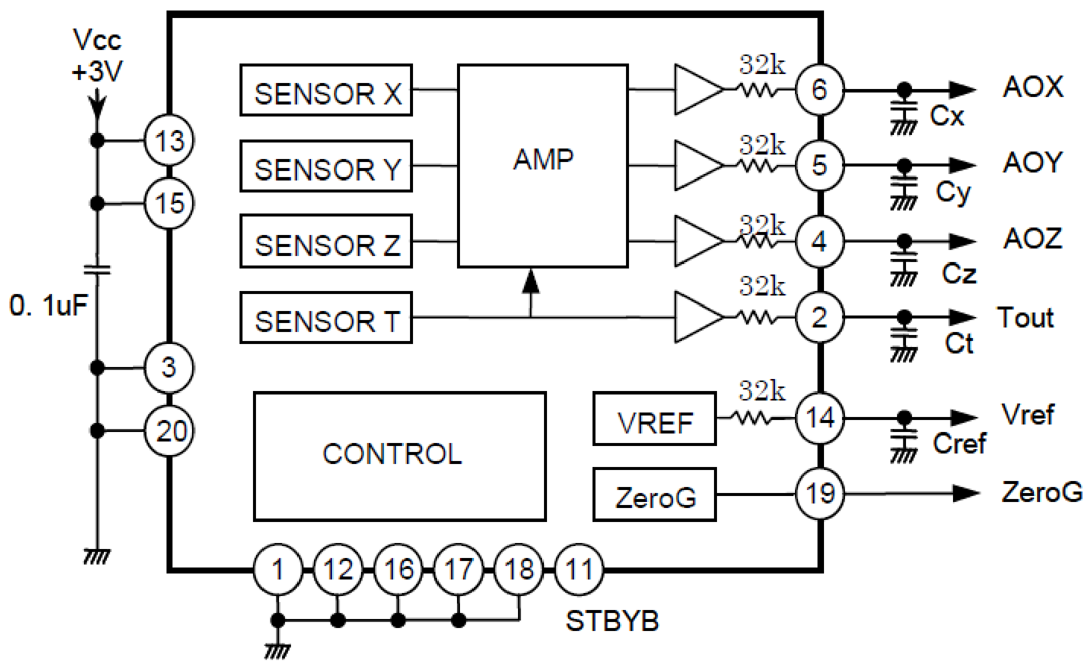


Figure 3 Hitachi 3-Axis Accelerometer

6.3 Determination of a Controller.

The Basic Stamp 2 (BS2) microcontroller was chosen for this application because the author was familiar with the device, and publicly available example code for sensor interfacing was readily available. This made the process of interfacing multiple sensors more efficient than developing each application from scratch. The software associated with this microcontroller makes debugging code straight forward. The BS2 does not have the processing power of many microprocessors, but it is sufficient for the application at hand. It consists of the following characteristics:

- 4,000 instructions/second
- 32 Bytes of RAM
- 2K Bytes
- 16 I/O Pins + 2 Dedicated Serial
- +5V output
- PBasic compiler
- Base code for sensors

6.4 Determination for Actuating Inversion/Eversion

Due to design constraints, the feasible method for actuation of the inversion/eversion is a linear actuator mounted to the ankle. The driving mechanism is a Warner, 12VDC linear actuator. This actuator was chosen due to its high load capacity of 100 lb_f,, a 10K ohm potentiometer for position feedback, and a reasonable cost. The 10K potentiometer is hard wired as part of a voltage divider circuit connected to an 8 bit ADC0831 analog-to-digital converter. When the shaft is fully retracted the A to D converter will output 0 bits, when fully extended it will output 255 bits (Figure 4).

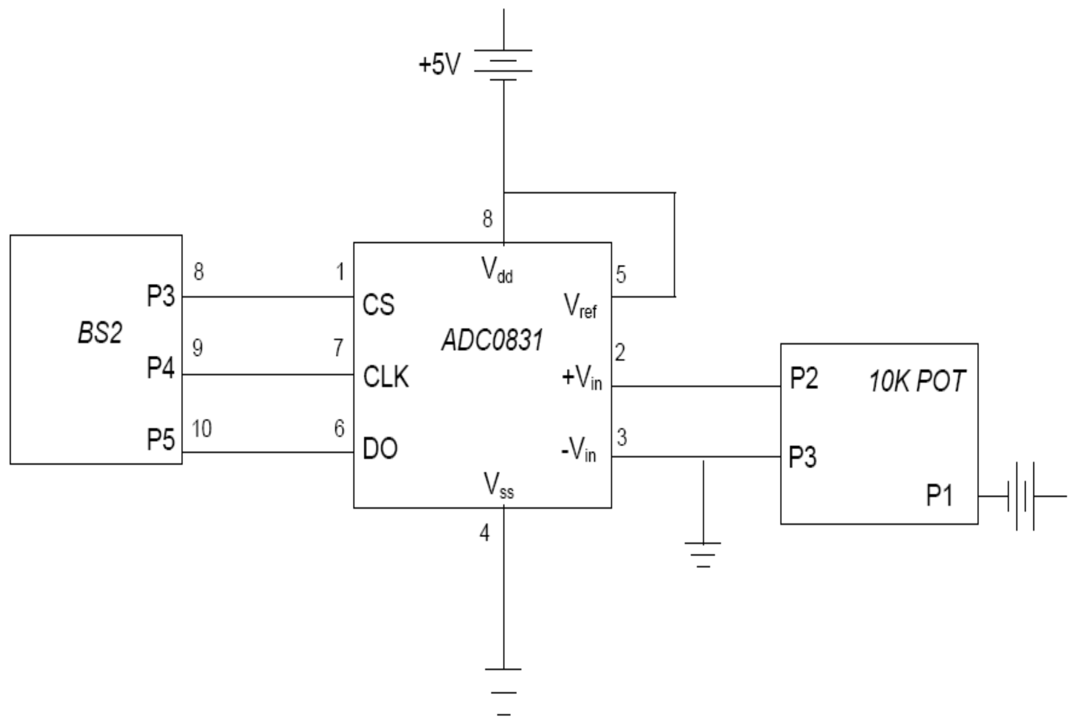


Figure 4 10K Pot to Determine Actuator Position

The motor is controlled by the BS2, and isolated from the 12VDC circuit mechanical relays. Figure X displays the circuit schematic. Pin 0 of the BS2 will determine the direction of the motor. When P0 is high, the actuator will retract. When P0 is low, the polarity of the circuit is reversed making the actuator extend. A high signal from P1 grounds the circuit to turn the motor on.

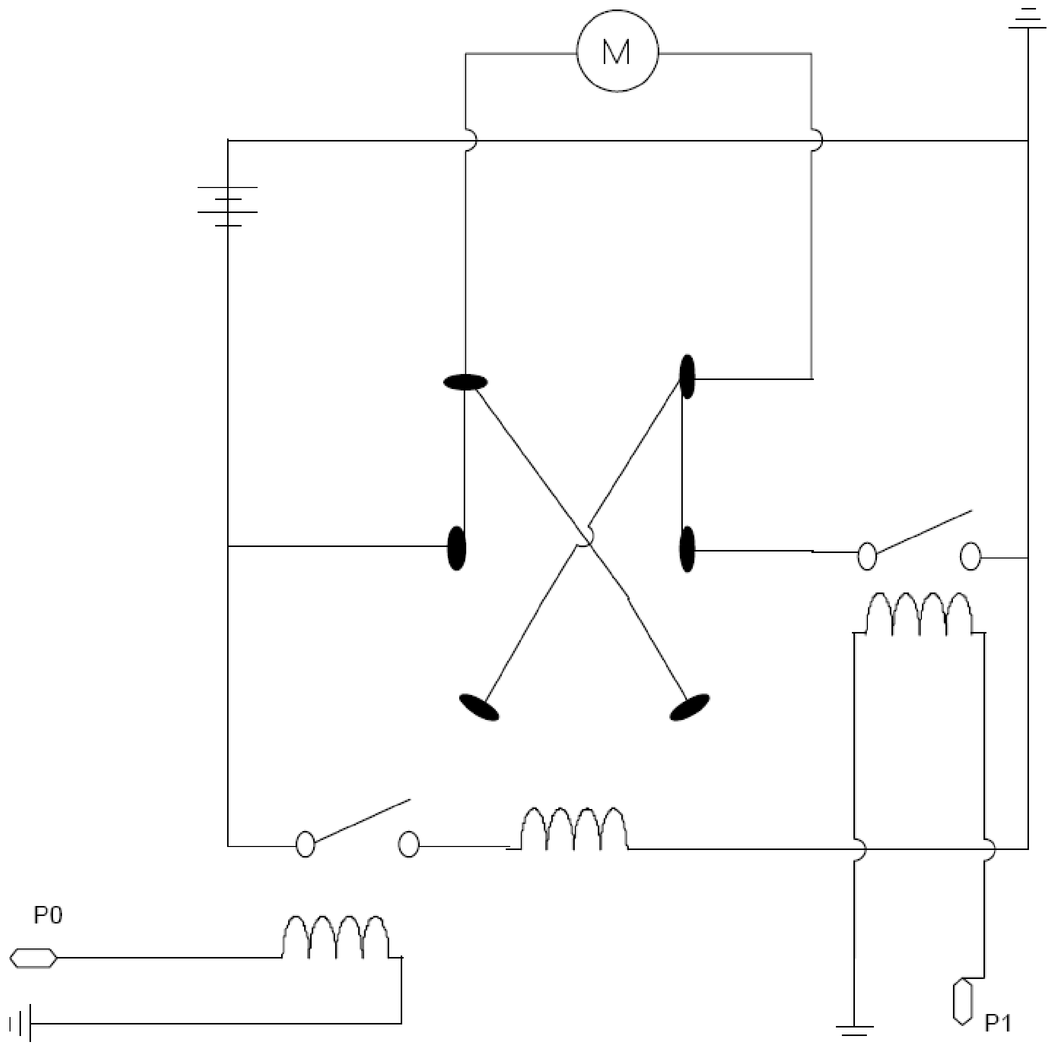


Figure 5 Motor Control for Inversion/Eversion

This actuator will only be used to develop the active ankle and will need to be replaced when the ankle is incorporated on the Jaywalker due to the actuator's large mass and lack of precise position.

6.5 Control Software Development

The Basic Stamp 2 was programmed with PBasic a modified version of Basic. The BS2 has an onboard compiler to tokenize the PBasic language for the system. The PBasic language has useful high level commands that make programming a much easier task.

Three different sensors' data were acquired with the BS2. The accelerometer sends a 12 bit number to the BS2 after the onboard A to D converter has converted the output voltage on the X-Axis. The BS2 will analyze this number to determine the angle of tilt and, if the case need be, correct the test bed so it does not become unstable. The 10K potentiometer on the Warner Linear Actuator is wired into a voltage divider circuit. The changing output voltage is converted to a digital signal by an 8 bit A to D converter so the Stamp can adjust the inversion/eversion of the active ankle. Voltages from the piezoelectric force transducers are converted to a digital signal by the ADC0831 so the Stamp can evaluate the soil properties. The feedback loops to the BS2 are utilized to control the actuator by means of the relays.

The data is stored by serial communication to an excel macro readily available from Parallax. PLX-DAQ stores time stamped values from the sensors as the testing is performed. A schematic of the BS2 and the corresponding pin assignments are shown in Figure 6.

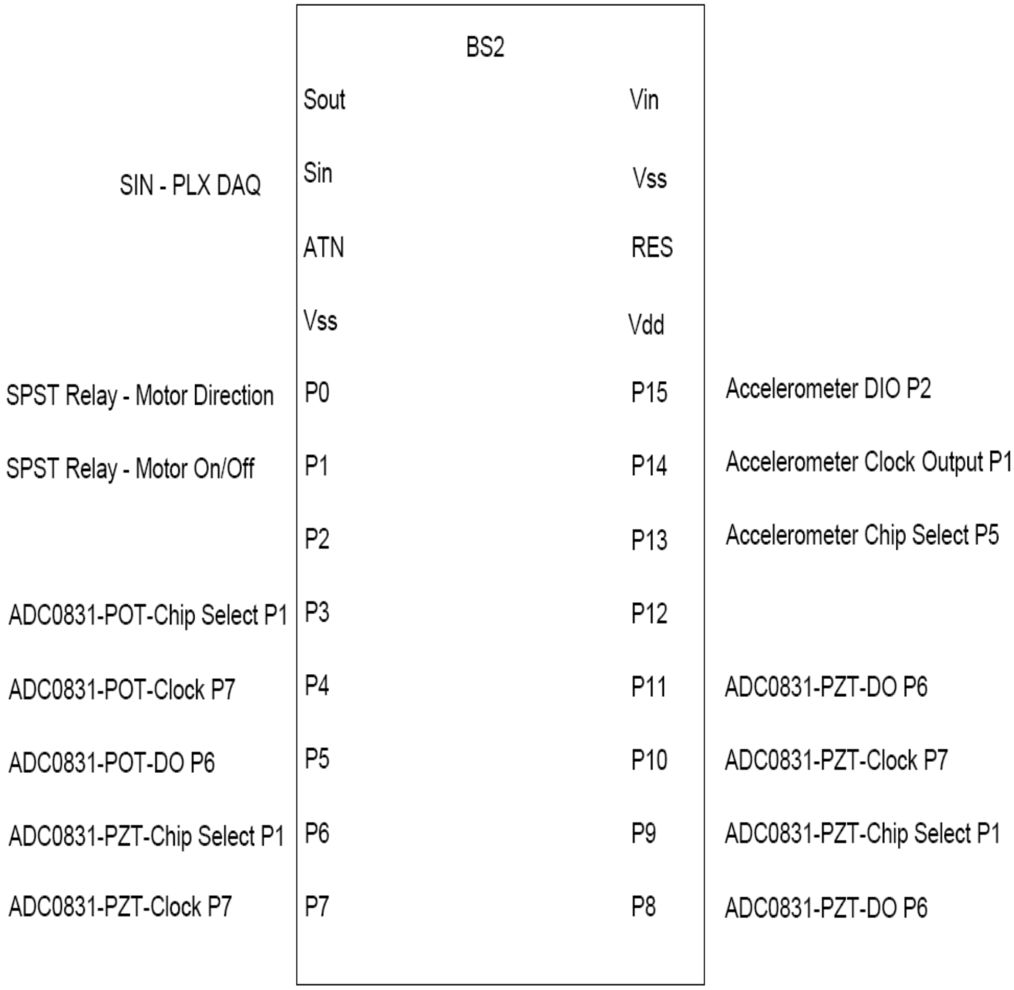


Figure 6 Basic Stamp 2 Pin Assignments

7 Methodology

7.1 Terrain Sensing Procedure

Prior to testing the force response of heel strike, the piezoelectric force sensors needed to be conditioned. The sensors were cyclically loaded at least twenty times prior to testing. The main focus of this test was to analyze the ramp response of the force with respect to time from a given terrain hardness. There were 20 tests per terrain type.

The test procedure was as follows:

1. Place a type of material underneath the heel pad with the foot suspended by the test frame.
2. Start the DAQ.
3. Turn on the shank actuator to lower the foot.
4. DAQ acquires data from the force sensor.
5. End the test and repeat beginning with step 1.
6. Initially the PZT sensor was bonded in between two pieces of rubber. During initial testing it was found that it was difficult to get any output from the PZT sensor. One layer of rubber was removed, leaving rubber in between the heel pad and the PZT sensor so the PZT sensor could make direct contact with the terrain.

7.2 Lateral Stability Procedure

The 3-axis accelerometer does not require any pre testing maintenance other than writing the software. The procedure for testing the lateral stability is as follows.

1. Lower the foot with the shank actuator onto a given, uneven surface, so the test frame is tilted.
2. Start the DAQ. (Software was written to execute code when the user pushes "connect").

3. Let the system stabilize.

4. End the test and repeat beginning with step 1.

8 Experimental Results

8.1.1 Soft Terrain Sensing - Foam

The average final output of the force value is approximately 5.9 lbs, approximately 8 times less compared to stance phase on rigid terrain. This is due to only measuring the force at a point. The deforming terrain and the rigid heel pad do not allow the load to be distributed evenly. Combined with the deforming terrain, the sensor is not directly measuring the applied force because the piezoelectric material is not deformed as the soft terrain conforms to the heel pad and therefore the sensor does not output the full range voltage. Although, the sensor does not output the full load of the test bed, the response time is similar to other tests. The time required for the sensor to output the maximum value for each test is at 0.19 seconds (Figure 7,8,9).

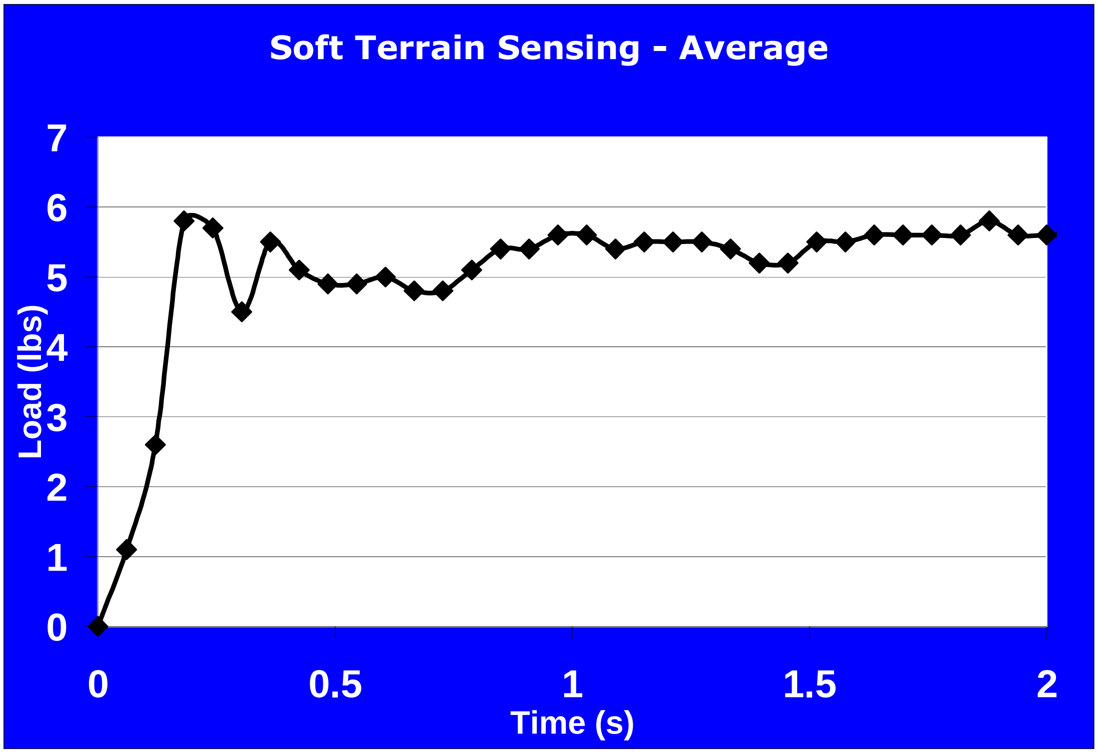


Figure 7 - Soft Terrain Response 0 - 2 sec

Terrain	Durometer	Force at .19 Sec lbs	Standard Deviation @ .19 sec	Slope @ 0.19 sec lbs/sec
Foam	5	6	1.5	53

Table 1 – Foam Terrain Average Test Values

The foam is easily deformed and will not output any values until it is almost completely compressed. The foam's characteristic of easy deformation yields a low output from the force sensor, even though the entire weight of the test bed is applied to the foot. The tests were very consistent and stabilized after the weight of the test bed was completely transferred to the foot. The slope of the force output during the weight transfer at 51.7 lbs/sec was as expected; stepping on foam is a subtle transition in terms of force.

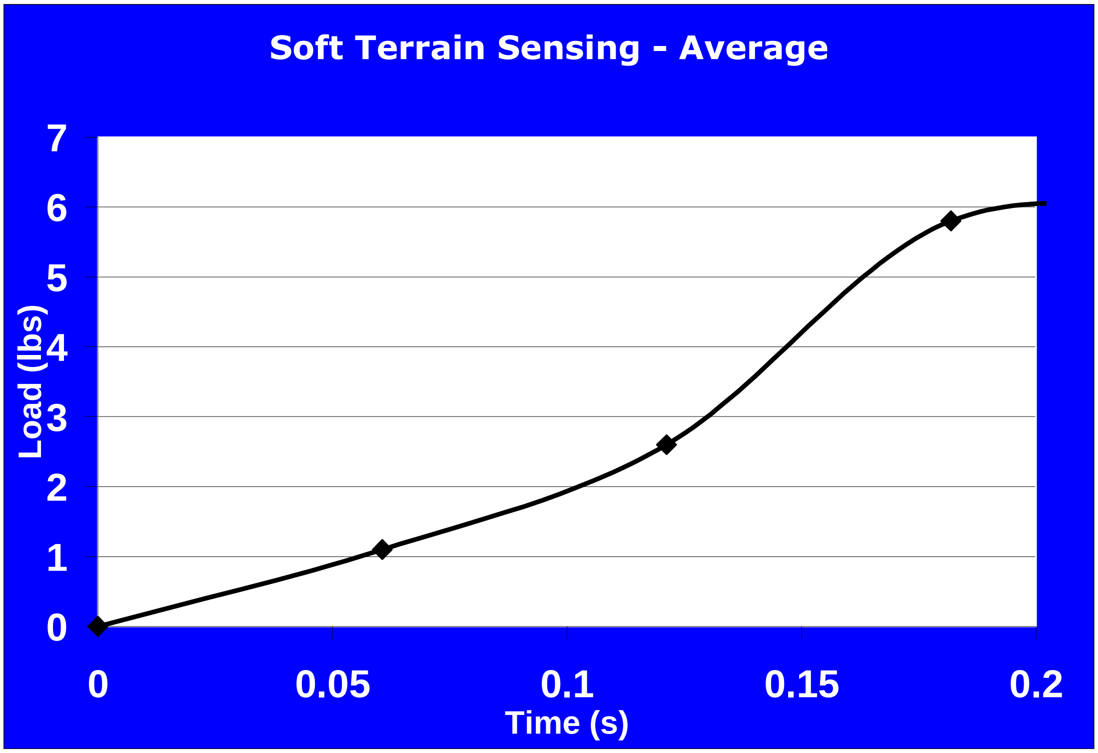


Figure 8 - Foam Terrain Sensing 0 - 0.2 sec

8.1.2 Medium Terrain Sensing - Rubber

The ramp response time was also 0.2 seconds for the rubber terrain. The maximum output from the analog to digital converter for the force response was 27 lbs. The sensitivity of the response for the transient was determined by the slope of the line from 0 to 0.19 seconds, yielding 86 lbs/sec.

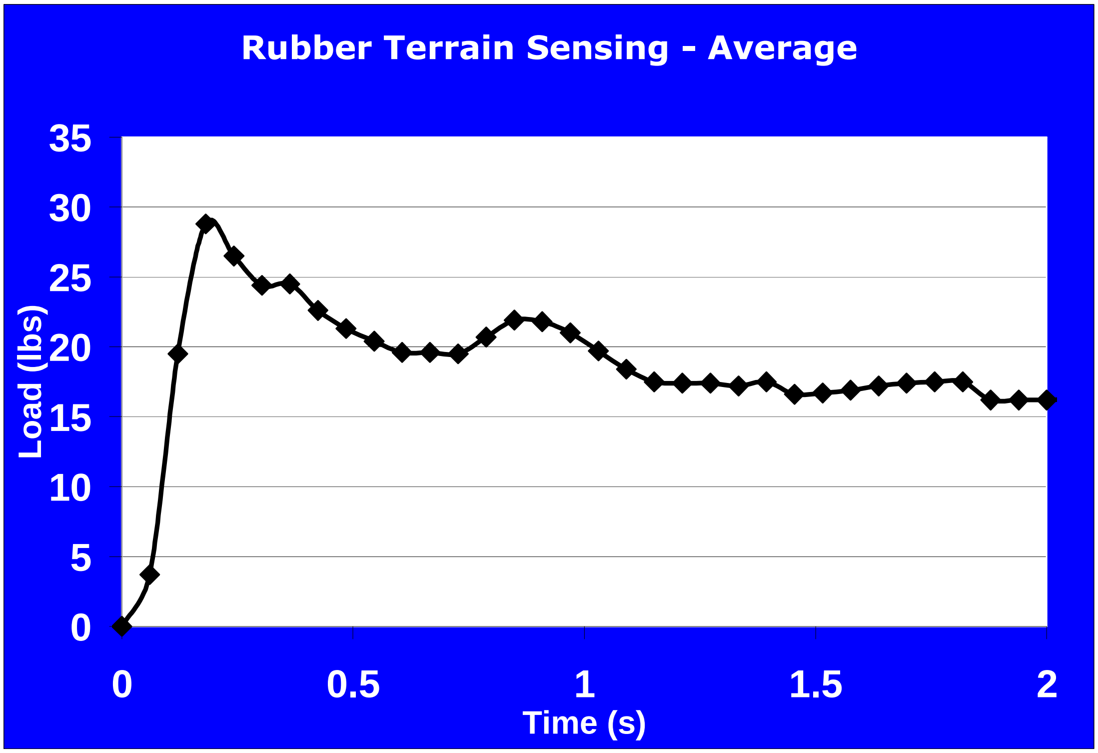


Figure 9 - Rubber Terrain Response 0 - 2 sec

Terrain	Durometer	Force at .19 Sec lbs	Standard Deviation @ .19 sec	Slope @ 0.19 sec lbs/sec
Rubber	61	27	2.1	88

Table 2 - Rubber Terrain Average Test Values

The varying output values after the weight transition phase do not have an effect on the empirical results. These oscillations are due to the test bed slightly swaying on the rubber terrain, but the focus is on the sensitivity of the initial contact of the foot and the terrain. The deviation of the force output at 0.19 seconds is approximately 2 lbs. The slope value of 86 lbs/sec suggests that the rubber terrain possess a force transition phase that is more sensitive and linearly proportional to the hardness of the terrain.

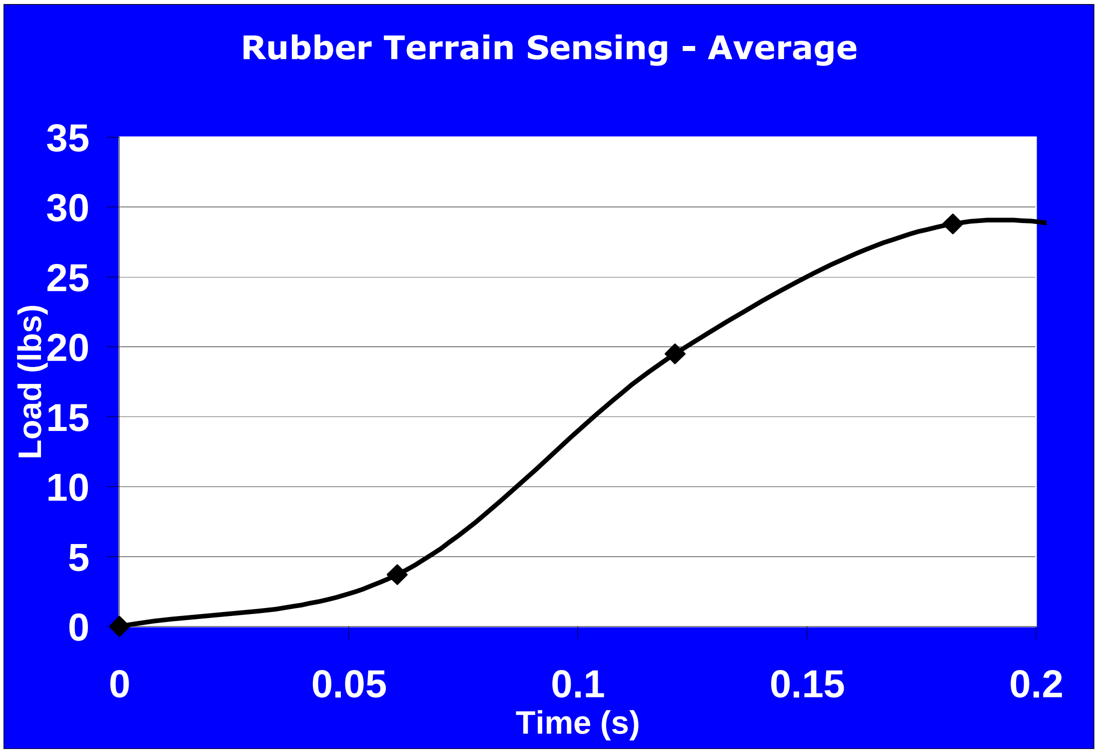


Figure 10 - Rubber Terrain Response 0 - 0.2 sec

8.1.3 Rigid Terrain Sensing – Hardwood Floor

The average output at the end of the force transition phase on non-deforming, or rigid terrain, is approximately 42 lbs. The force sensor between a rigid terrain and a rigid heel pad outputs the full force value of the test bed.

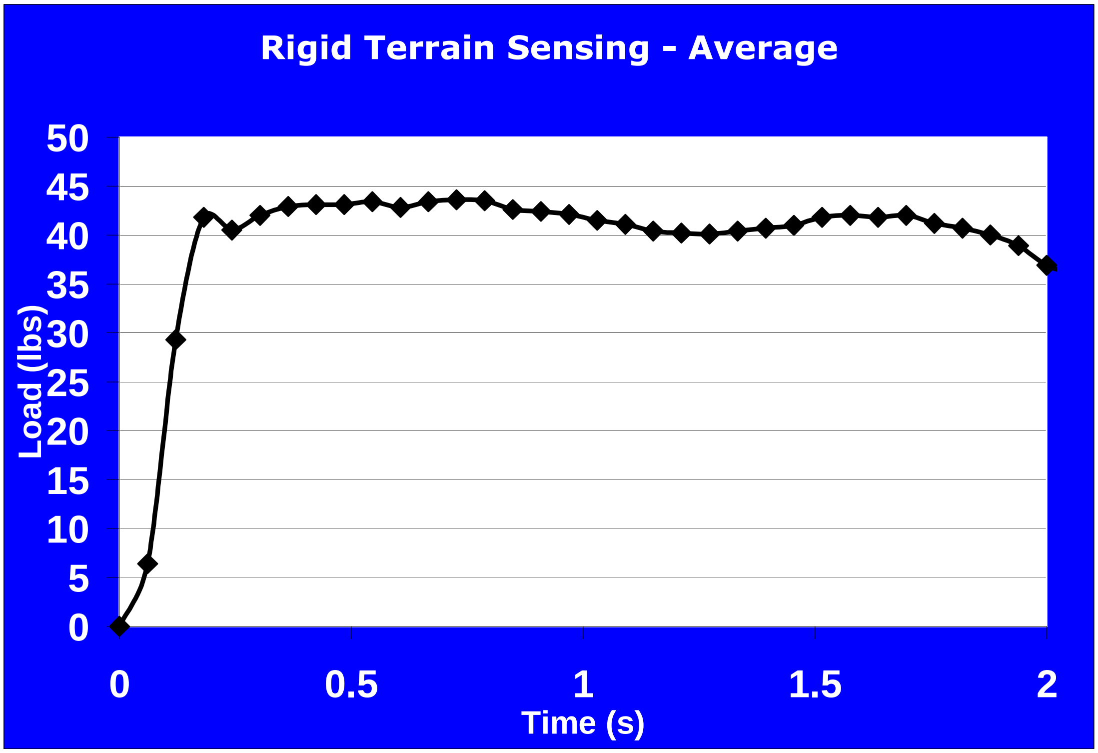


Figure 11 - Rigid Terrain Response 0 - 2 sec

Terrain	Durometer	Force at .19 Sec lbs	Standard Deviation @ .19 sec	Slope @ 0.19 sec lbs/sec
Rigid	150	41	3	206

Table 3 – Rigid Terrain Average Test Values

The rigid terrain does not deform when the weight of the test bed is transferred to the foot. The deviation is slightly higher for the rigid terrain at 3 lbs. The transition of the compression force was much more sensitive to the rigid terrain at 201 lbs/sec.

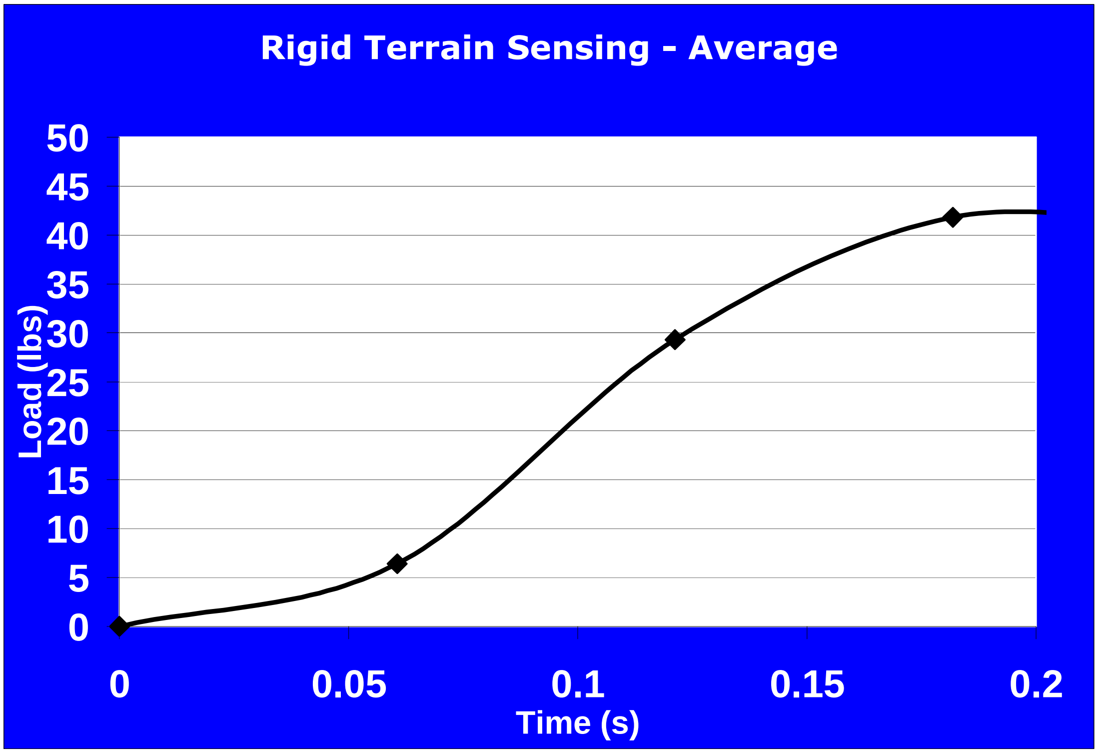


Figure 12 - Rigid Terrain Response 0 - 0.2 sec

Comparing the values of the terrain tests may allow some correlation between the output data and a force component

8.2 Lateral Stability

Multiple criteria for instability and convergence were tested with successful results. When using accelerometer feedback for position control, the momentum (depending on magnitude) can give false angles of tilt through the accelerometer. Depending on the control system and the determined range of stability, overshoot values may be given by the accelerometer feedback even though the system is actually in a stable position. Table 3 shows the average values for testing multiple criteria; 90˚ is defined as vertical to accommodate accelerometer output values. The inversion/eversion correction was tested with a stability tolerance of ±2.5˚ with a test bed weight of 16 lbs, and then tested with 41 lbs of total weight. Tests were repeated with the same weights and stability tolerance of ±5˚ from the vertical. The test bed bearing only its own weight has a COM 15" high. Adding the additional weight at the top of the test bed moves the COM up to 20.5."

Load	± 90˚	Initial Angle (deg)	Stabilized Angle (deg)	Elapsed Time to Stabilize (sec)	Critical Angle (deg)
Yes	2.5	108	94.2	4.5	112
No	2.5	74	95.2	9.5	68
Yes	5	108	94.3	3.6	104
No	5	74	89.8	7.5	74

Table 4 - Lateral Stability Test Values

The results show that increasing the COM height yields lateral stability that is more controllable with the given system. From Equation 3, this gives the control system more time to react before the test bed reaches the critical angle. The increased weight also decreased the time for the test bed to become stabile for two reasons: The increased weight decreased the rate of motion of the actuator shaft, decreasing angular momentum, and the feedback from the accelerometer had more time to react with the DAQ since the angular velocity had decreased, therefore acquiring more data before it sensed overshoot and converging.

9 Conclusions

9.1 Terrain Sensing

Initially the measure of success was achieved if the DAQ system could detect a difference in response times amongst terrains. The testing proved that the difference in time for a compression force among different terrains is difficult to detect. Essentially, one is trying to measure the time for the test bed to deform the terrain as its weight is transferred from the test bed to the heel pad. With a 20Hz sampling rate, only 4 points could be used to determine the ramp response time. This makes it difficult to distinguish amongst different terrain types in terms of response time. The output voltage from the piezoelectric circuit may be less on soft terrain due to the terrain deforming and not the sensor, but not enough data points exist to distinguish a significant, quantifiable difference in the response time amongst terrain hardness. An alternate method regarding the sensitivity of the response ultimately became the quantifiable way to determine a difference in terrain.

The type of terrain can be quantified by the output of the piezoelectric force transducer at a common rise time. At a given rate during ambulation, it is possible to determine the hardness of a terrain by evaluating the output value at consistent points in the gait cycle. Regardless of the terrain, the time it takes to transfer weight to the foot can be considered constant. The more rigid the terrain, the more the piezoelectric sensor deforms.

It appears intuitive at this point that the more rigid the terrain, the higher the output values of the force sensor.

9.2 Lateral Stability

Despite the momentum error, the accelerometer proved to be a viable way to determine if the test bed was stable. The control system code allows one to choose the parameters of instability and stability criteria, i.e. the angle of tilt at which the intelligent system detects the test bed is falling over and to what extent stability is corrected. For instance, the biped might be unstable at ± 15° relative to the vertical and the system will correct the test bed until it is within ± 5° relative to the vertical. It is common knowledge that a system will become unstable when the center of mass has a horizontal position beyond the base of the system. The time the system has before becoming unstable was given by the elliptical integral in Eq 3. This equation does not take into account momentum, which, as previously stated, the test bed will naturally have angular momentum about the Y-axis (eversion/inversion). This resulted in the test bed having an excessive oscillation from the acceleration value being over the threshold when it is summed with the momentum. Two methods were used to resolve this issue: One was to loosen the tolerance of the stabilized angle and the other was to increase the COM of the test bed by adding additional weight.

10 Recommendations

- Increased sampling rate for the DAQ system.
- Design modifications are required to allow for the force sensor to output full load of the test bed regardless of terrain.
- Feedback data for lengthening/shortening the thigh actuators to adjust the COM.

- Harvest heel strike energy return with the incorporation of a mass-spring damper system.

- A material besides a metal, which will deform upon contact with the ground is needed.

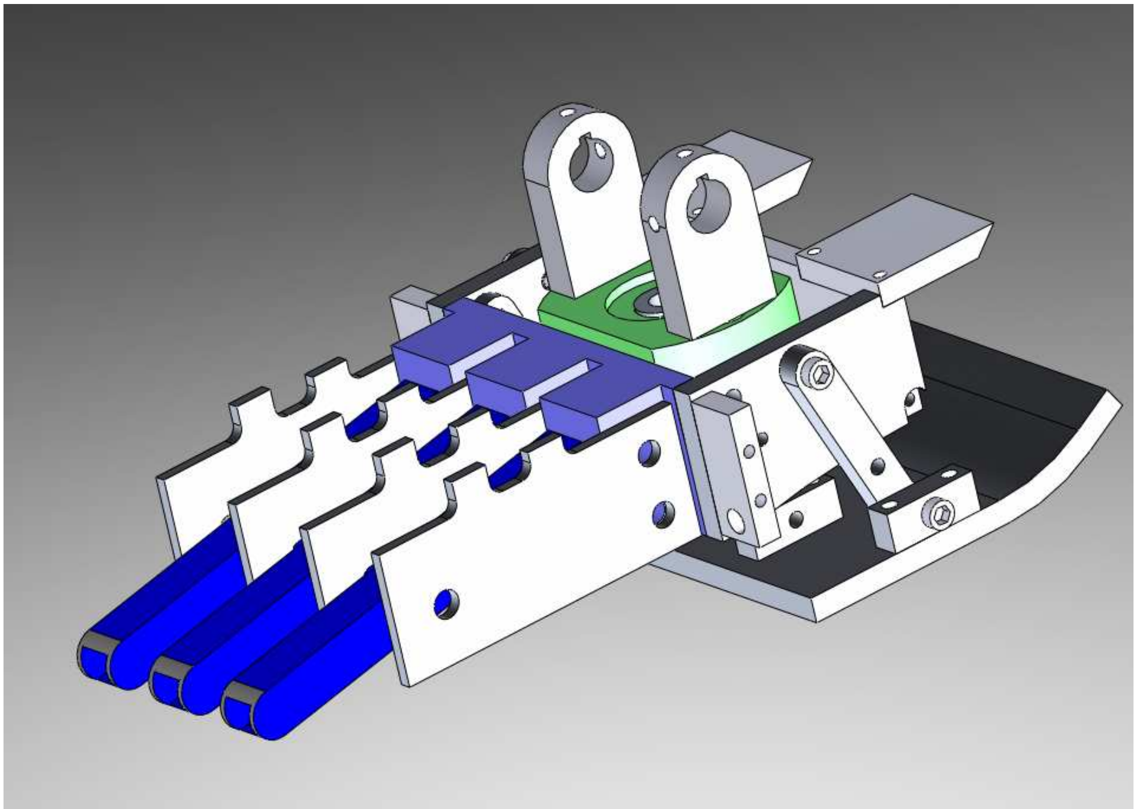
- Control damping coefficients for different walking speeds.

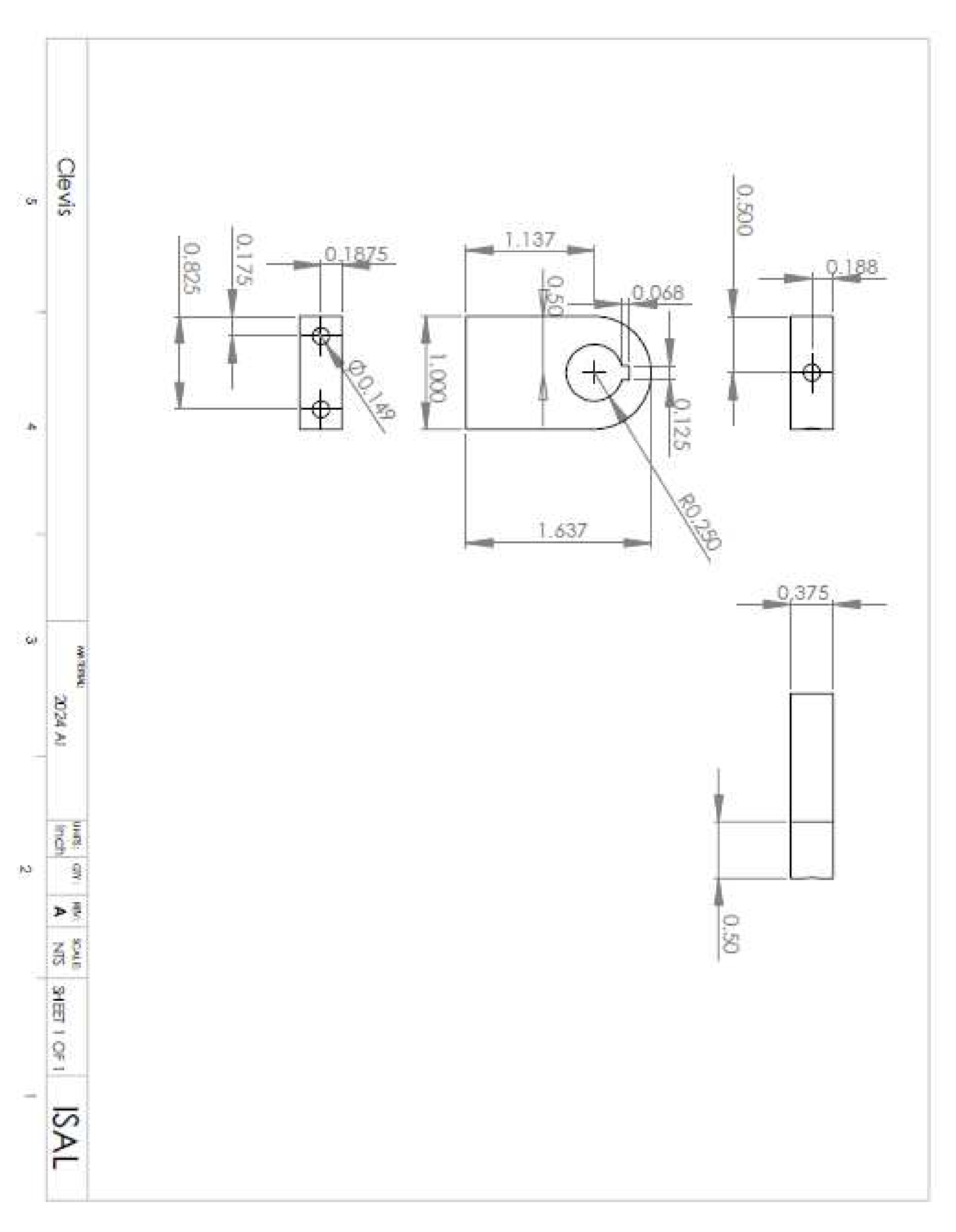
- Various sensitivities for PZT sensors to improve terrain contact sensing.

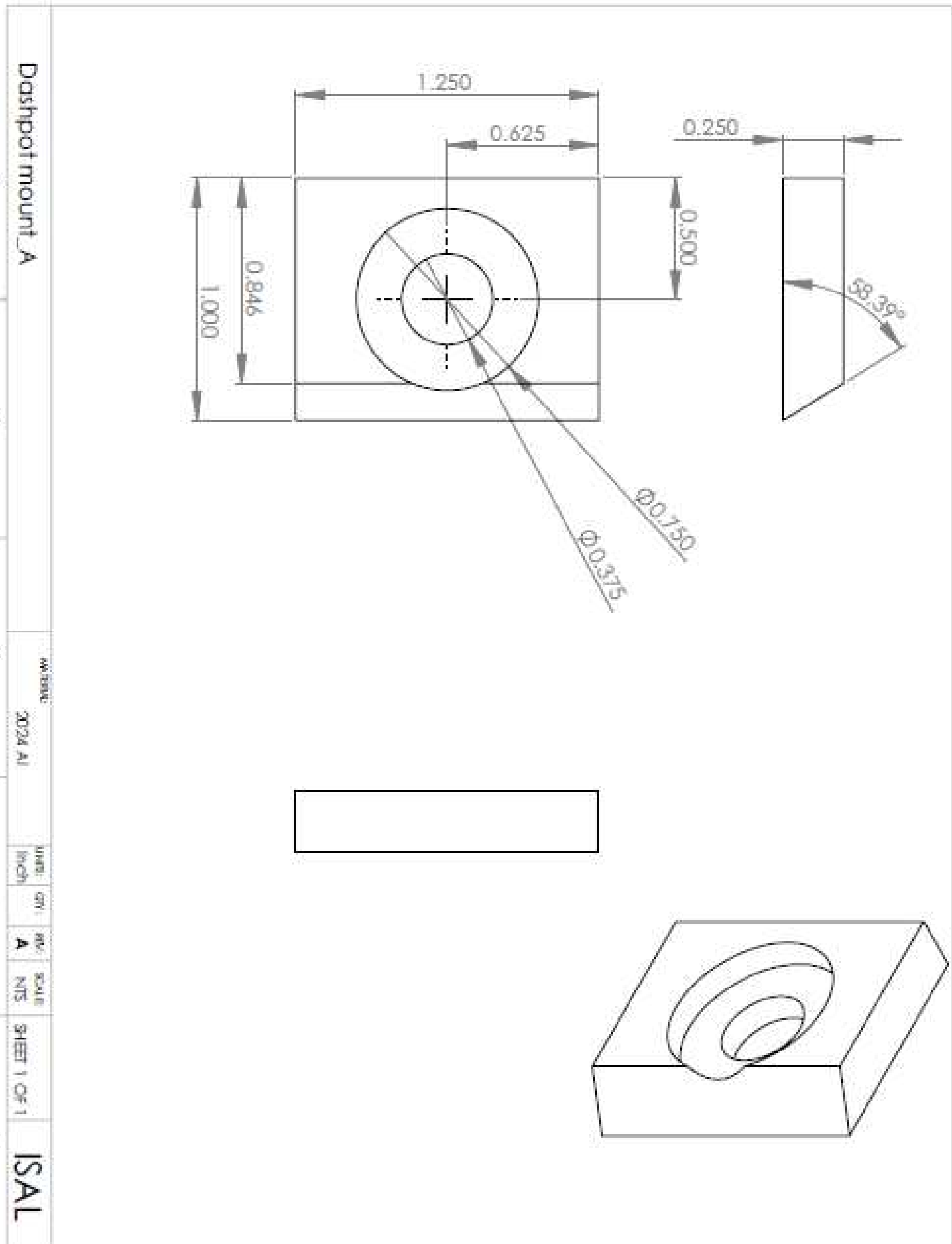
Bibliography

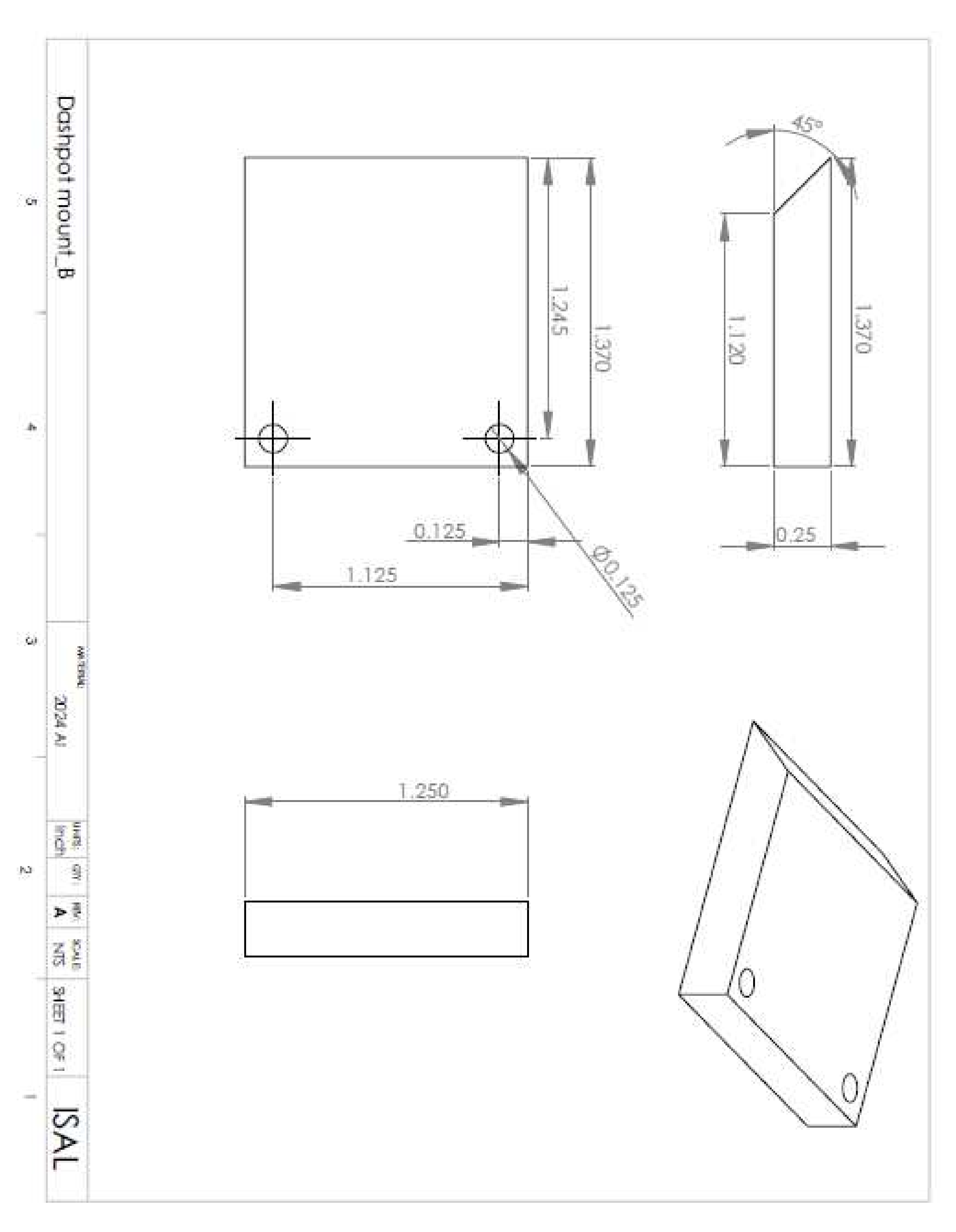
1. Berns, V.K.a.K., *A Concept for Walking Behaviour in Rough Terrain.* Professional Engineering Publishing, 1999: p. 7.
2. Bai, K.H.L., *Terrain-Evaluation-Based Motion Planning for Legged Locomotion On Irregular Terrain.* . Advanced Robotics, 2002. **17**(8): p. 18.
3. Hodgins, G.N.B.a.J.K., *Slipping and Tripping Reflexes for Bipedal Robots.* Autonomous Robots, 1997. **4**: p. 12.
4. Menegaldo, L.L.S., Rogerio Eduardo S.; De Toledo Fleury, Agenor, *Kinematical Modeling and Optimal Design of a Biped Robot Joint Parallel Linkage.* Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2006. **28**(4): p. 7.
5. Espiau, B., *The Anthropomorphic Biped Robot BIP2000.* Proceedings of the 2000 IEEE, 2000(April 2000): p. 6.
6. Takemura, F., *Control of a Hybrid Pneumatic/Electric Motor.* Proceedings of the 2000 IEEE, 2000: p. 6.
7. Sardain, P., *Biped robots: Correlations between technological design and dynamic behavior.* Control Engineering Practice, 1998. **7**: p. 10.
8. Palm(III), W.J., *Mechanical Vibration*. 1 ed. 2007, Hoboken, NJ: John Wiley & Sons, Inc. 3.
9. Collins, S.H., *A Bipedal Walking Robot with Efficient and Human-Like Gait*.*
10. Yamaguchi, *Multisensor Foot Mechanism with Shock Absorbing Material for Dynamic Biped Walking Adapting to Unkown Uneven Surfaces.* IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems, 1996: p. 6.
11. Gilliland, M., *The Microcontroller Application Cookbook.* Vol. 1. 2002: Wddoglen Press. 6.
12. Starner, T., *Human Powered Wearable Computing.* IBM Systems Journal, 1996. **35**: p. 11.
13. Paradiso, J.A., *Energy Scavenging for Mobile and Wireless Electronics.* Pervasive computing, 2005: p. 10.

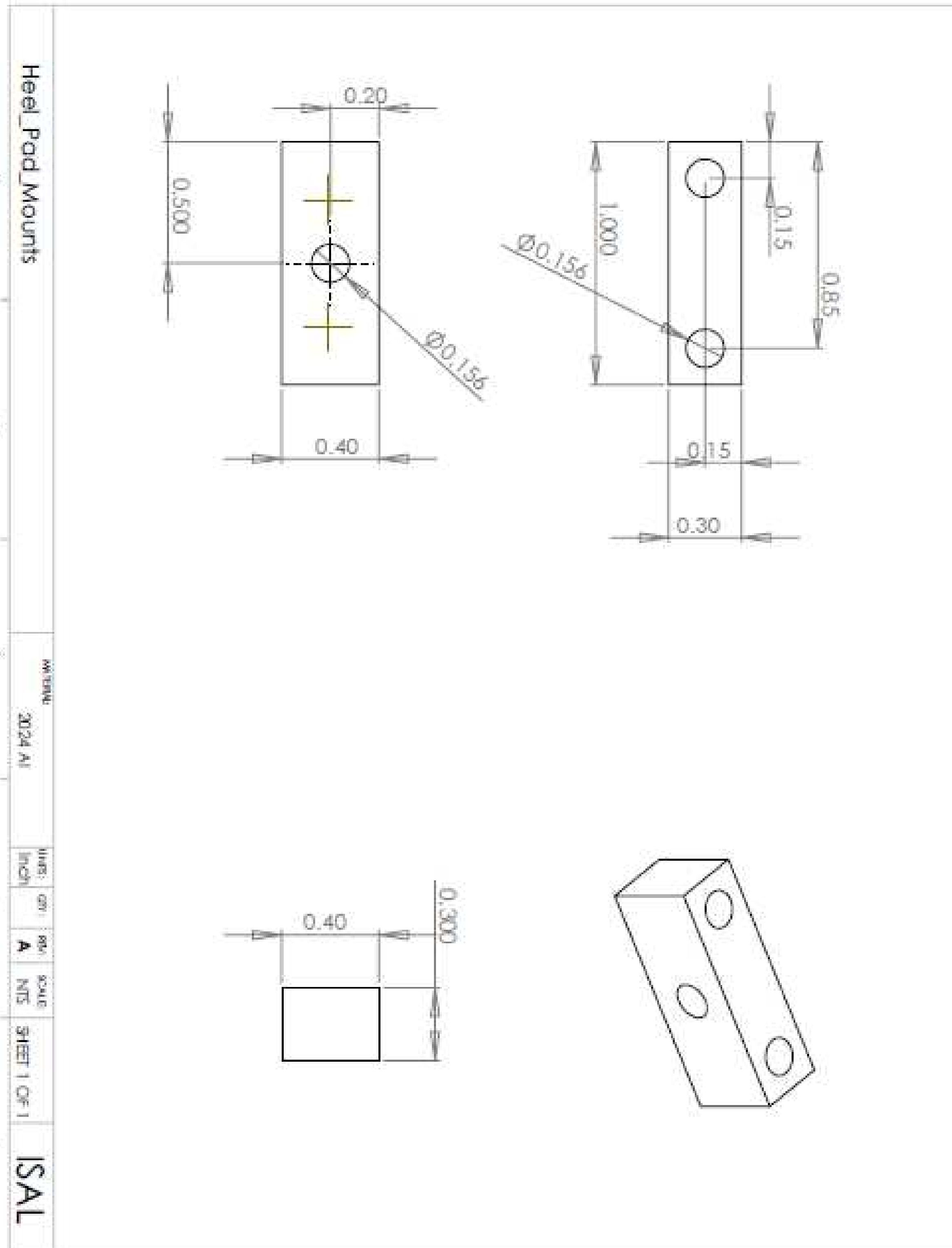
11 APPENDIX A: Mechanical Drawings

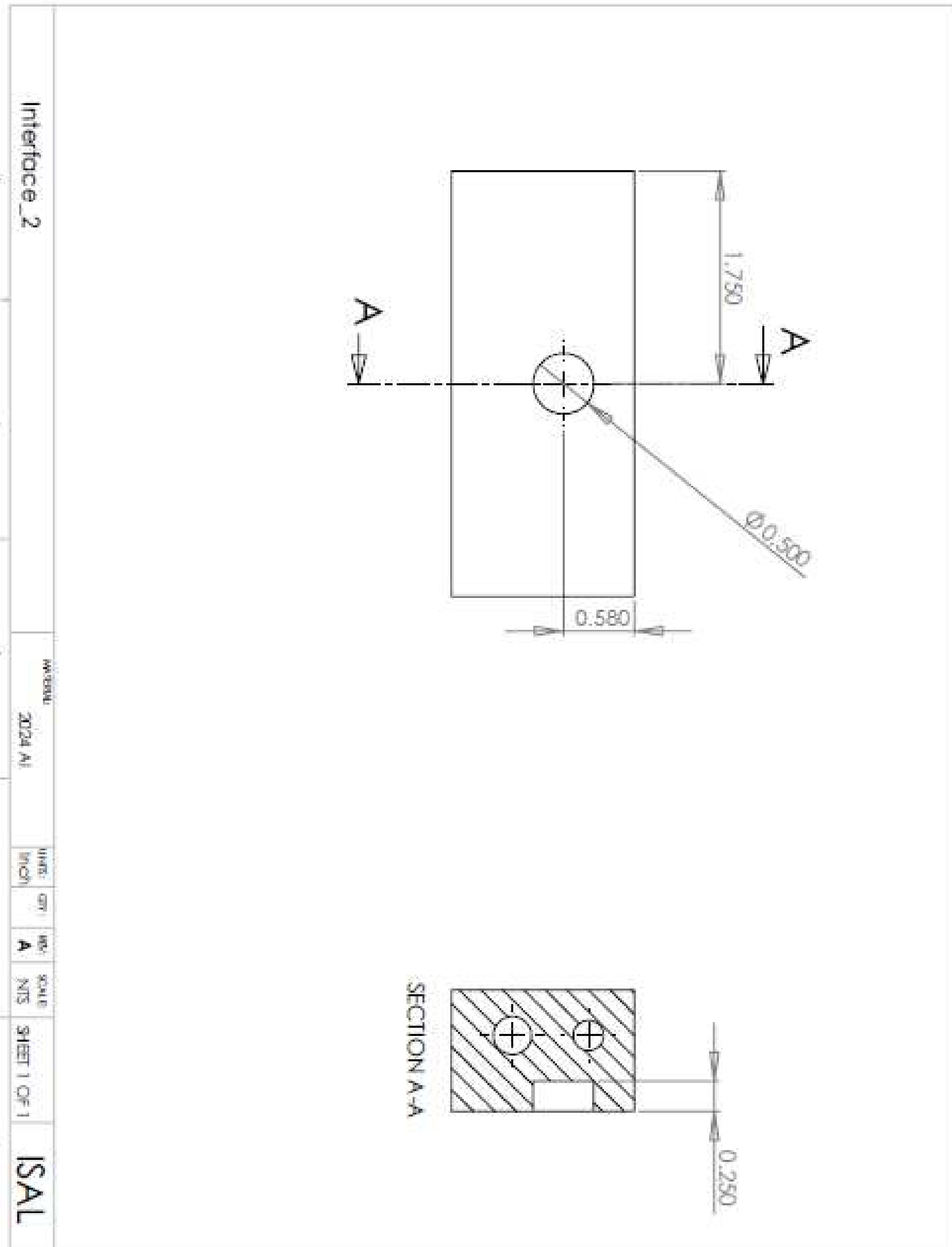


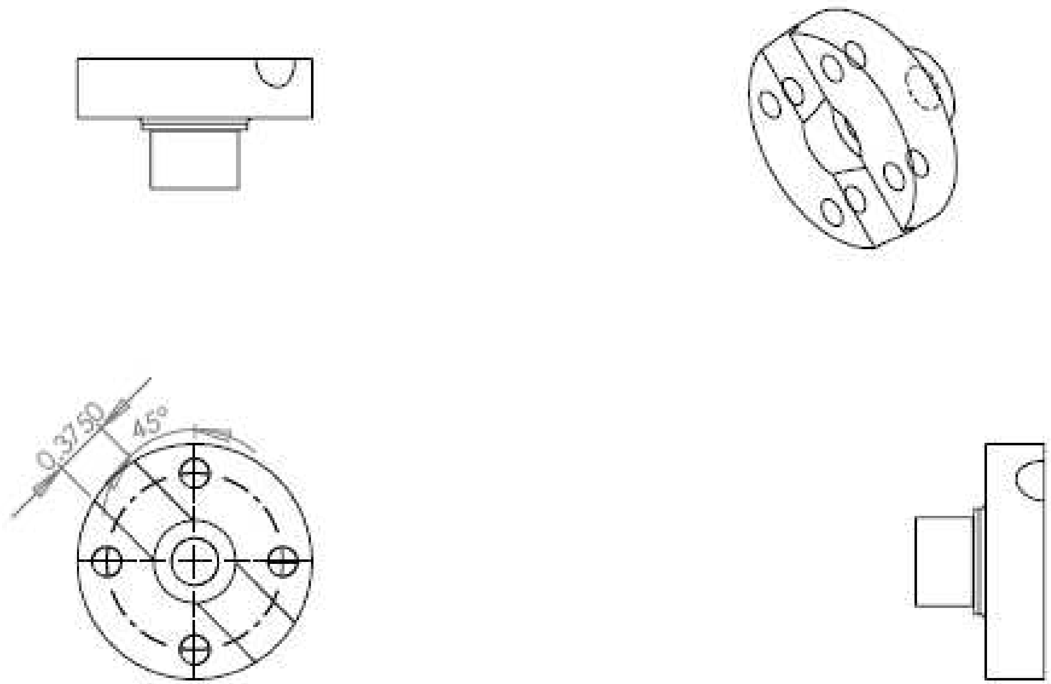

Clevis
2024 Al
Inch
A
NTS
SHEET 1 OF 1
ISAL
0.825
0.175
0.1875
Ø0.149
1.137
0.50
0.068
1.000
0.125
R0.250
1.637
0.500
0.188
0.375
0.50


Dashpot mount_A
1.250
0.625
0.250
0.500
0.846
1.000
58.39°
Ø0.750
Ø0.375
2024 Al
Inch
A
NTS
SHEET 1 OF 1
ISAL


Dashpot mount_B
1.245
1.370
1.120
1.370
45°
0.125
1.125
Ø0.125
0.25
1.250
2024 Al
inch
A
NTS
SHEET 1 OF 1
ISAL


Heel_Pad_Mounts
0.20
0.500
Ø0.156
0.40
1.000
Ø0.156
0.15
0.85
0.15
0.30
0.40
0.300
2024 Al
Inch
A
NTS
SHEET 1 OF 1
ISAL

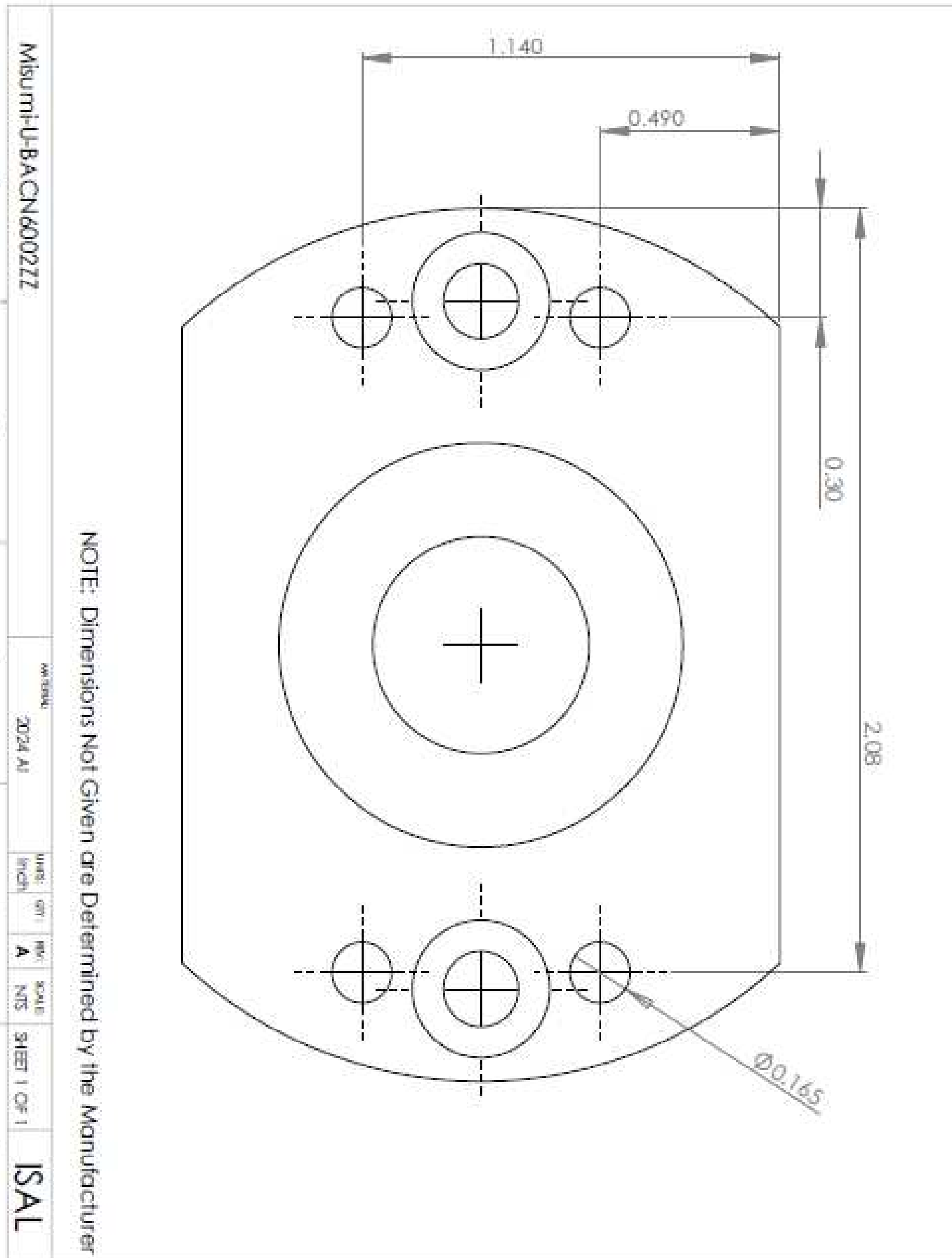

Interface_2
2024 Al
Inch
A
NTS
SHEET 1 OF 1
ISAL
A
A
1.750
Ø0.500
0.580
SECTION A-A
0.250

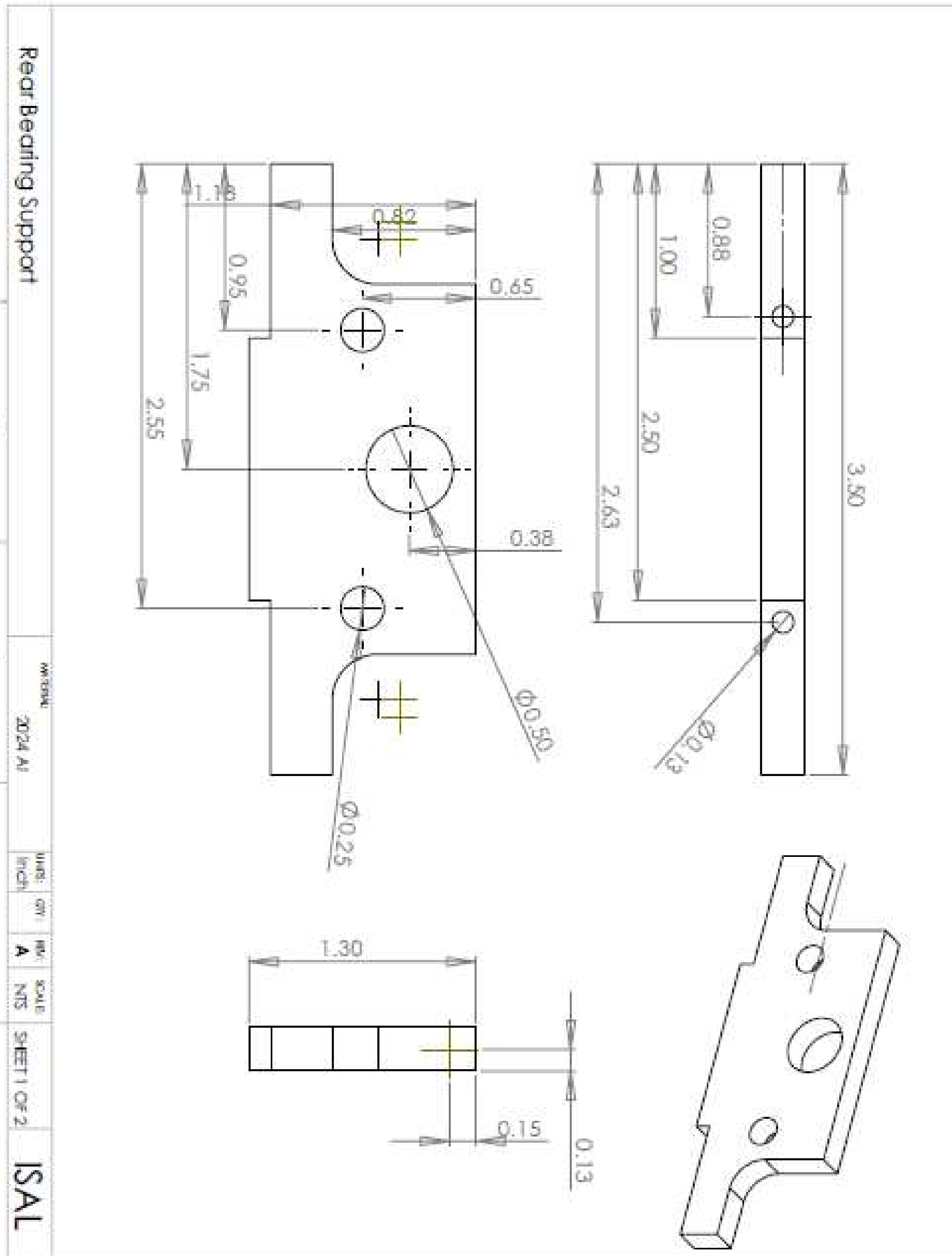


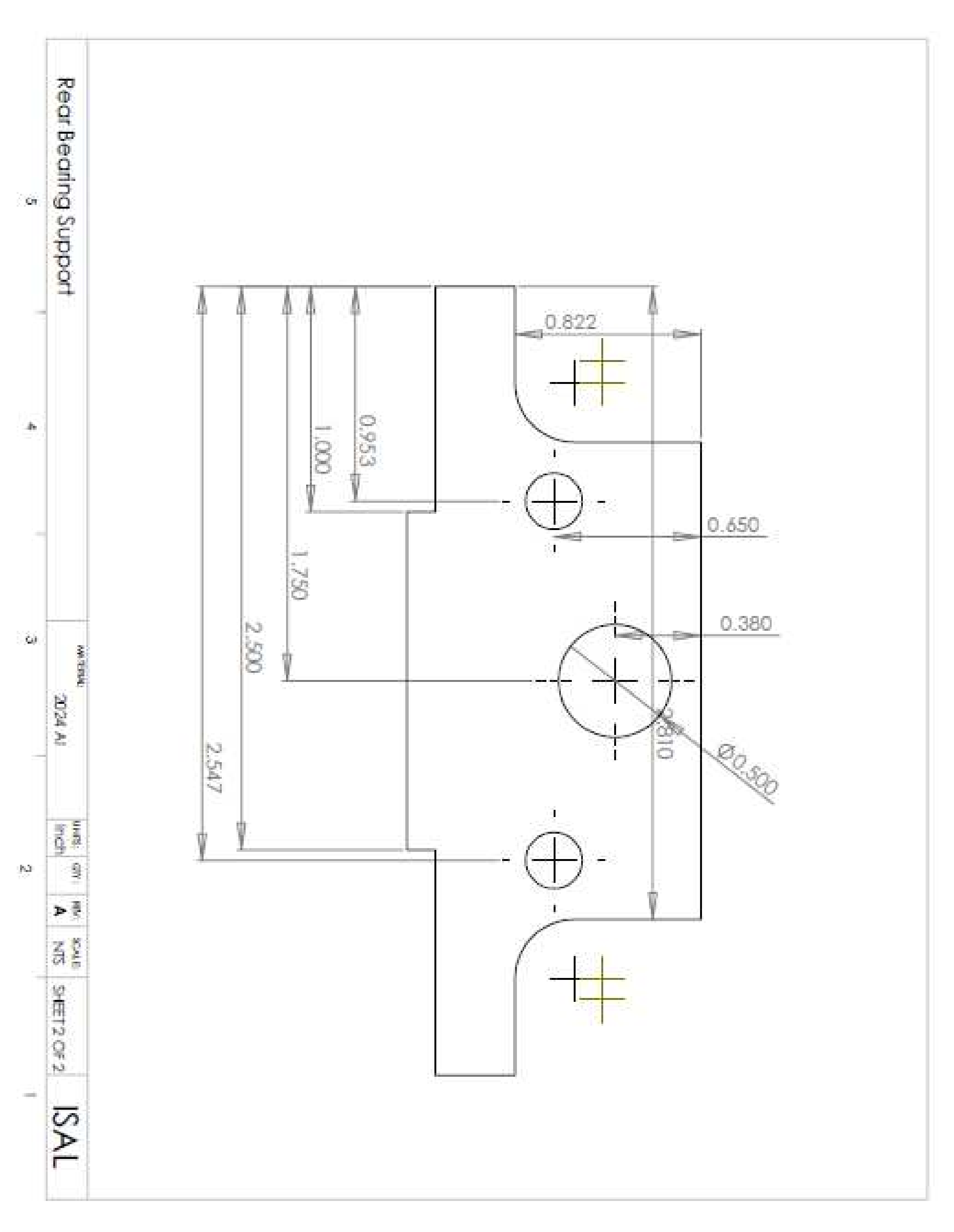
NOTE: Dimensions Not Given are Determined by the Manufacturer

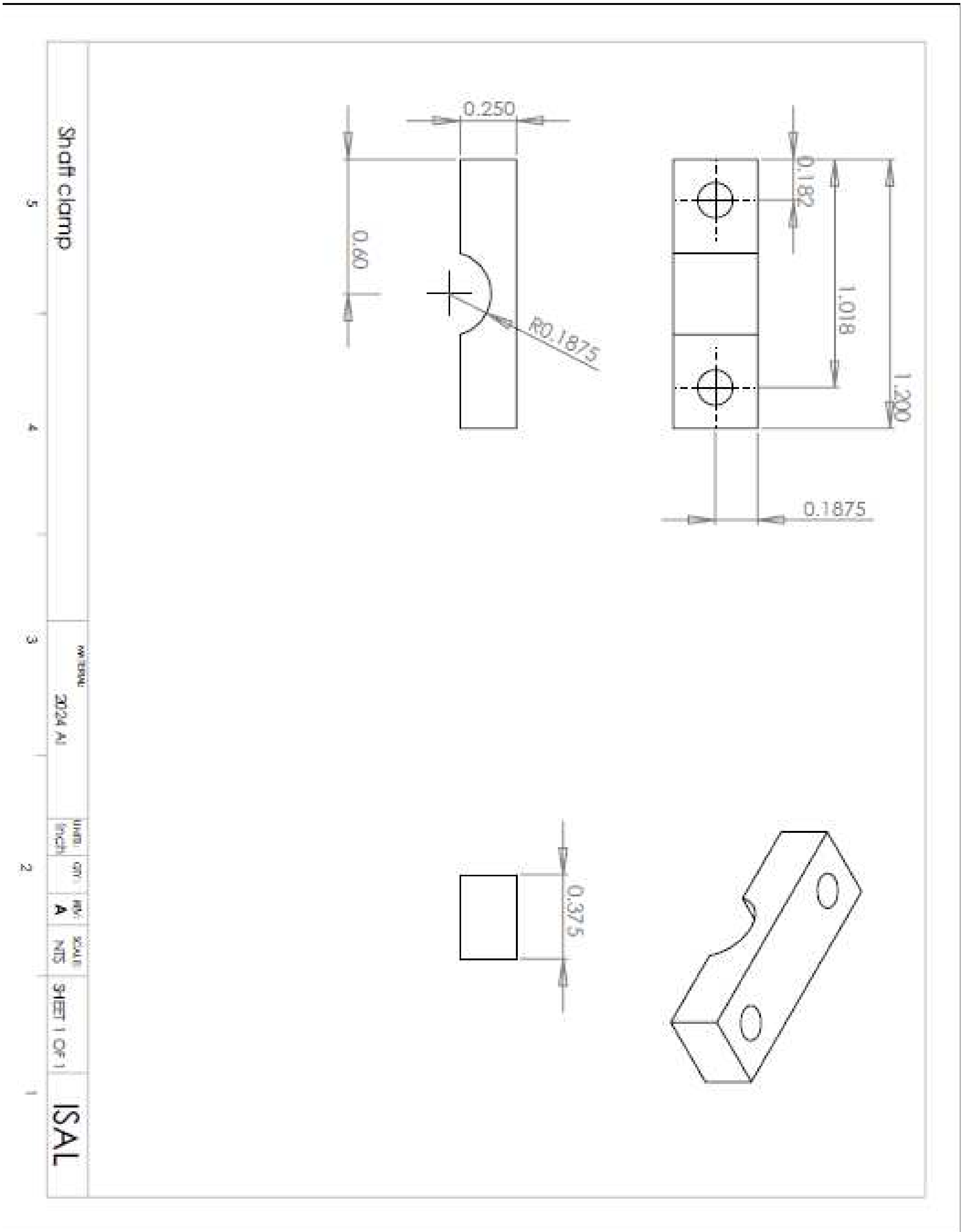
Misumi-FXFB15-12-F10-M8	MATERIAL 2024 Al	UNITS: Inch	QTY:	REV: A	SCALE: NTS	SHEET 1 OF 1	ISAL

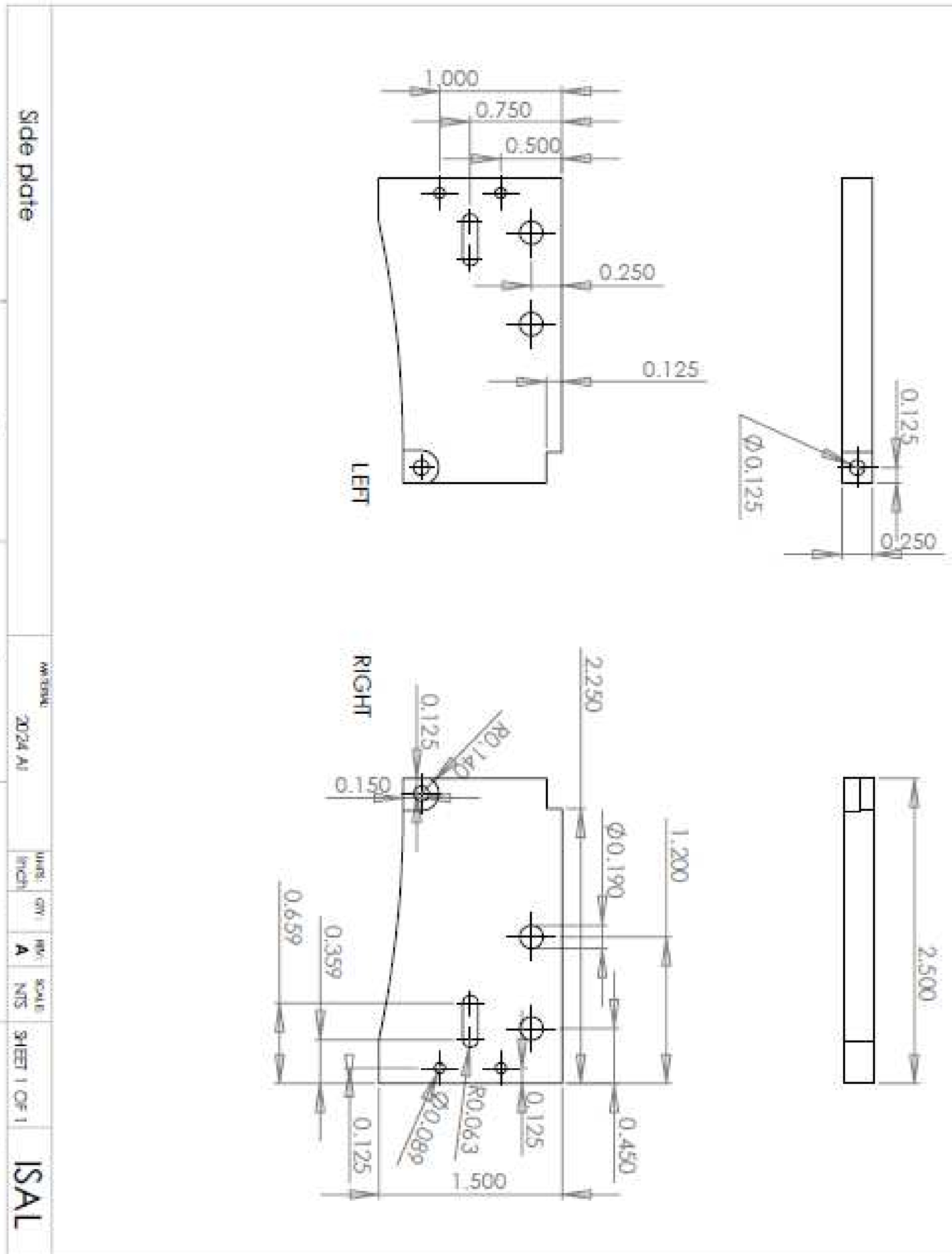
5 4 3 2 1

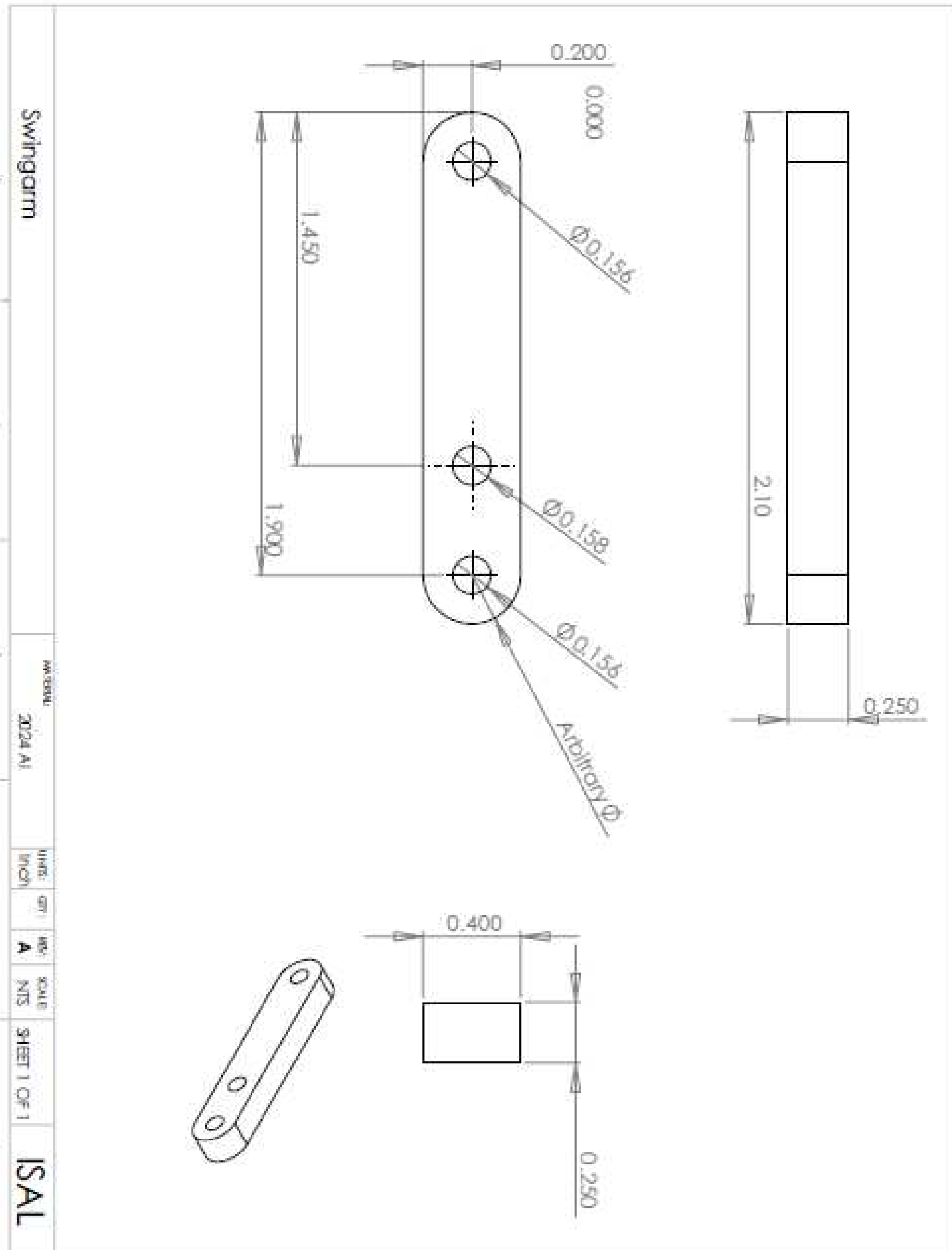

1.140
0.490
0.30
2.08
Ø0.165
NOTE: Dimensions Not Given are Determined by the Manufacturer
Misumi-U-BACN6002ZZ
2024 Al
Inch
A
NTS
SHEET 1 OF 1
ISAL

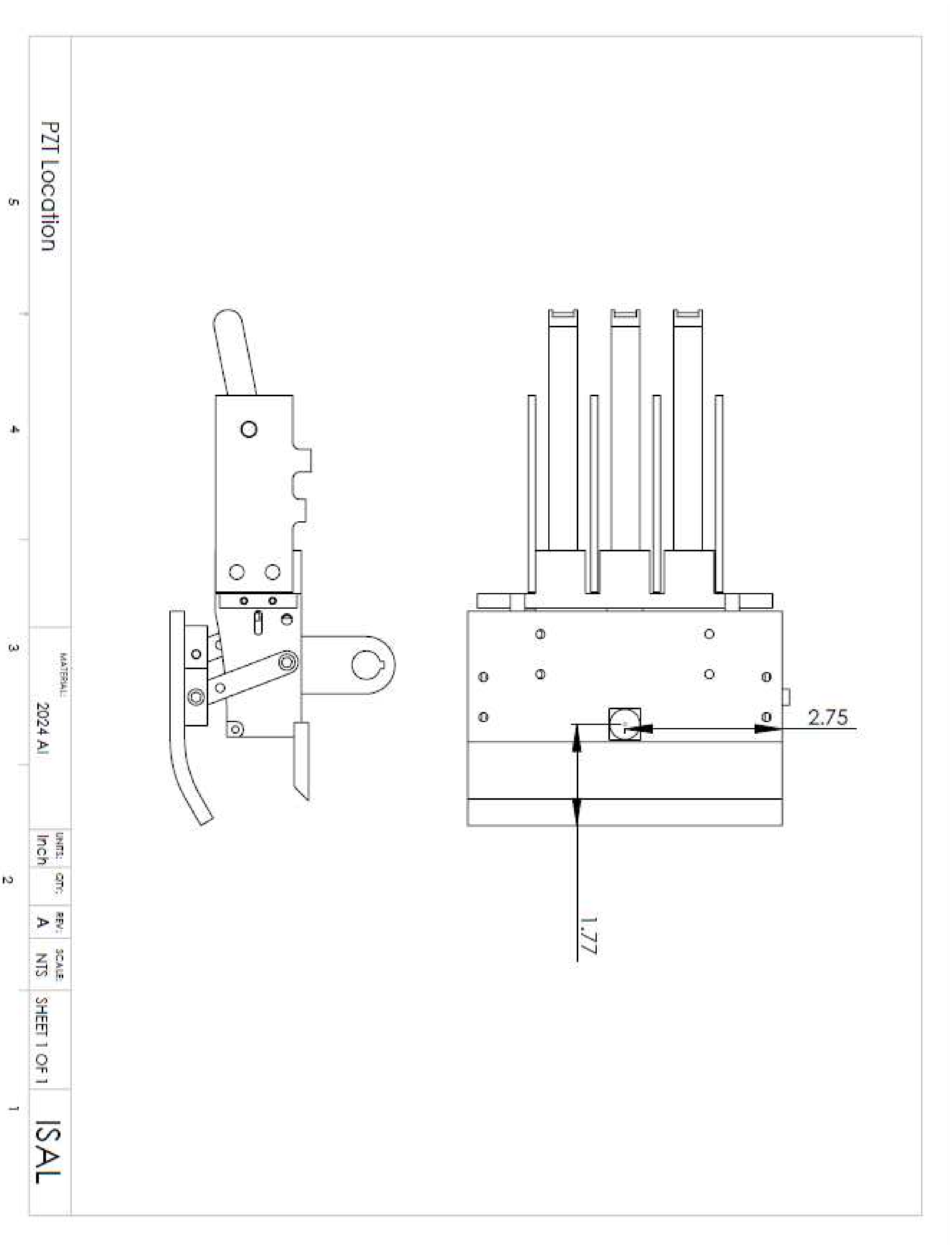

Rear Bearing Support
2024 Al
Inch
A
NTS
SHEET 1 OF 2
ISAL
1.18
0.82
0.95
0.65
1.75
2.55
0.38
Ø0.50
Ø0.25
0.88
1.00
2.50
2.63
3.50
Ø0.13
1.30
0.15
0.13


Rear Bearing Support
2024 Al
Inch
A
NTS
SHEET 2 OF 2
ISAL
0.822
0.953
1.000
0.650
1.750
0.380
2.500
2.547
Ø0.500

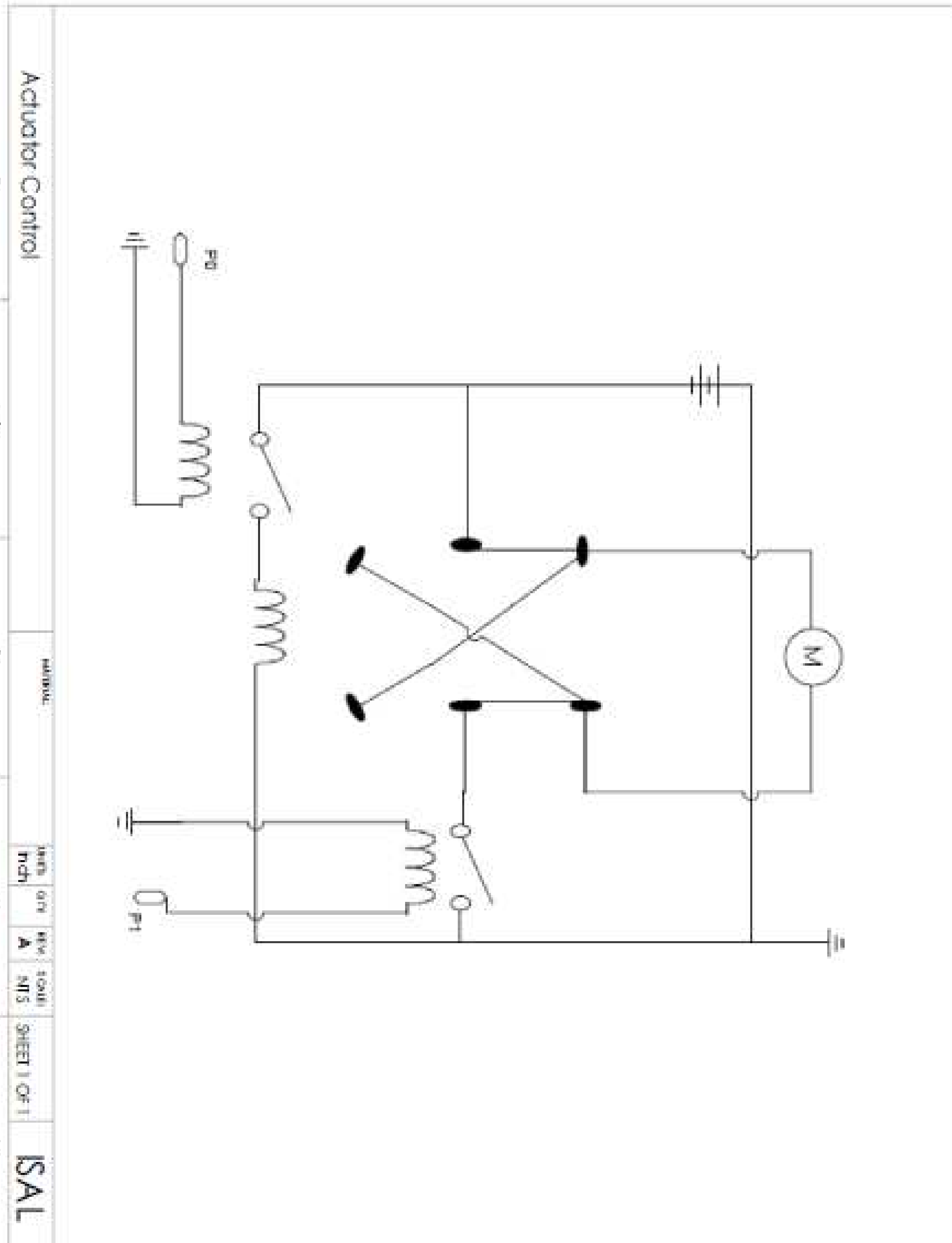

Shaft clamp
2024 Al
inch
A
NTS
SHEET 1 OF 1
ISAL
0.250
0.60
R0.1875
0.182
1.018
1.200
0.1875
0.375

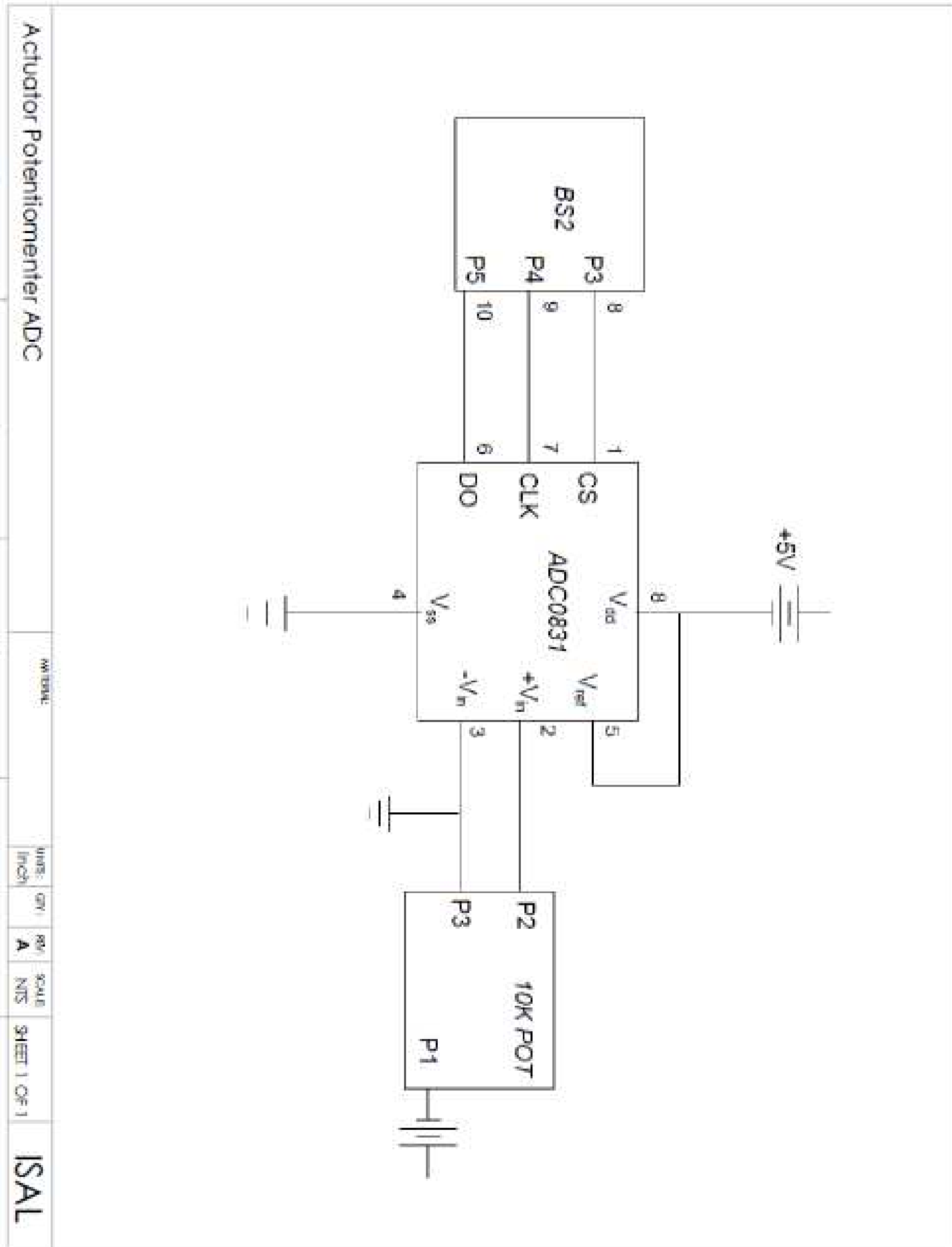

Side plate
MATERIAL
2024 Al
UNITS: inch
QTY
REV. A
SCALE NTS
SHEET 1 OF 1
ISAL
LEFT
RIGHT
1.000
0.750
0.500
0.250
0.125
0.125
Ø0.125
0.250
2.250
0.125
R0.140
0.150
Ø0.190
1.200
0.659
0.359
2.500
0.125
Ø0.089
R0.063
0.125
0.450
1.500


Swingarm
0.200
0.000
Ø0.156
1.450
1.900
Ø0.158
Ø0.156
Arbitrary Ø
2.10
0.250
0.400
0.250
2024 Al
inch
A
NTS
SHEET 1 OF 1
ISAL

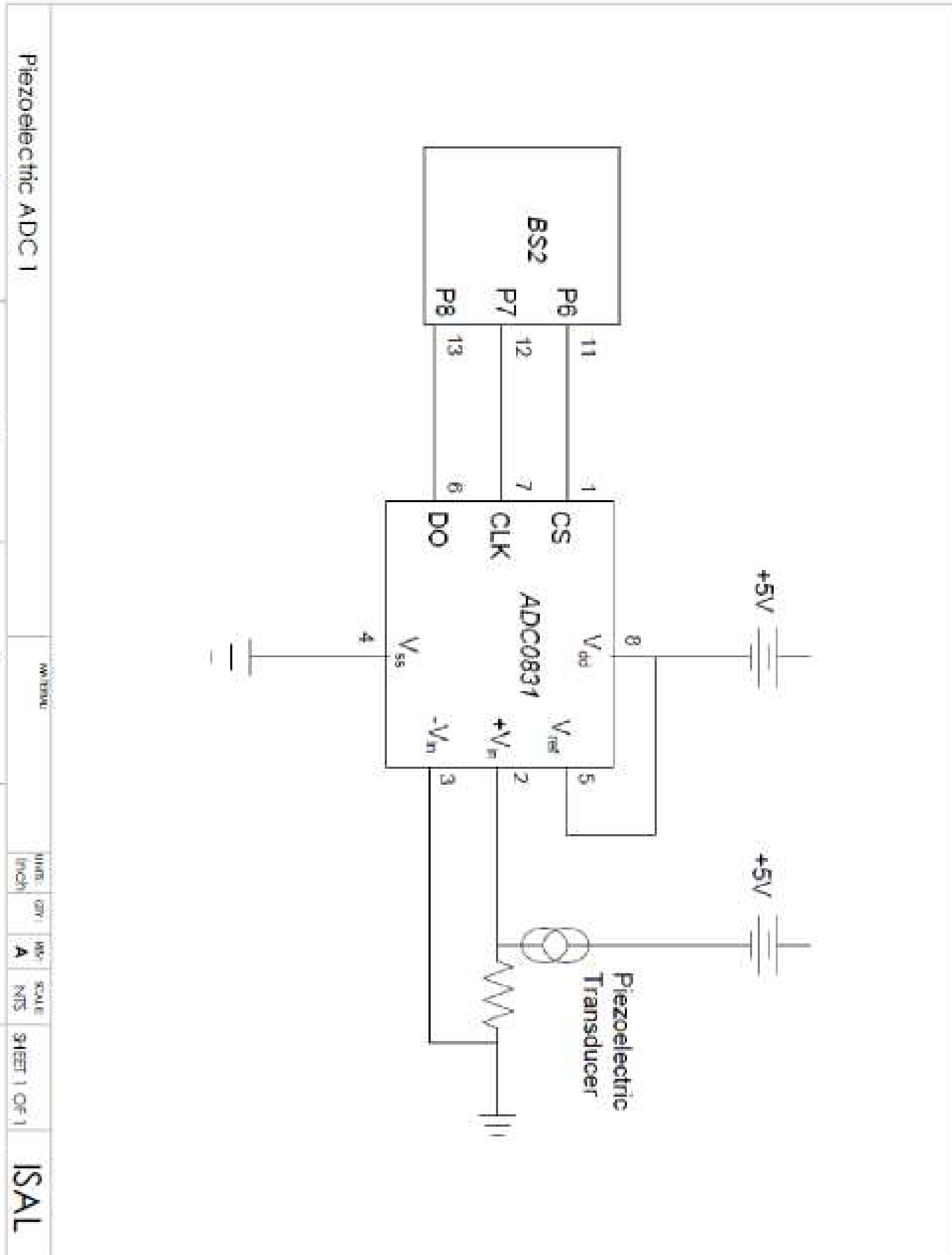

PZT Location
MATERIAL:
2024 Al
UNITS:
Inch
QTY:
REV:
A
SCALE:
NTS
SHEET 1 OF 1
ISAL
2.75
1.77

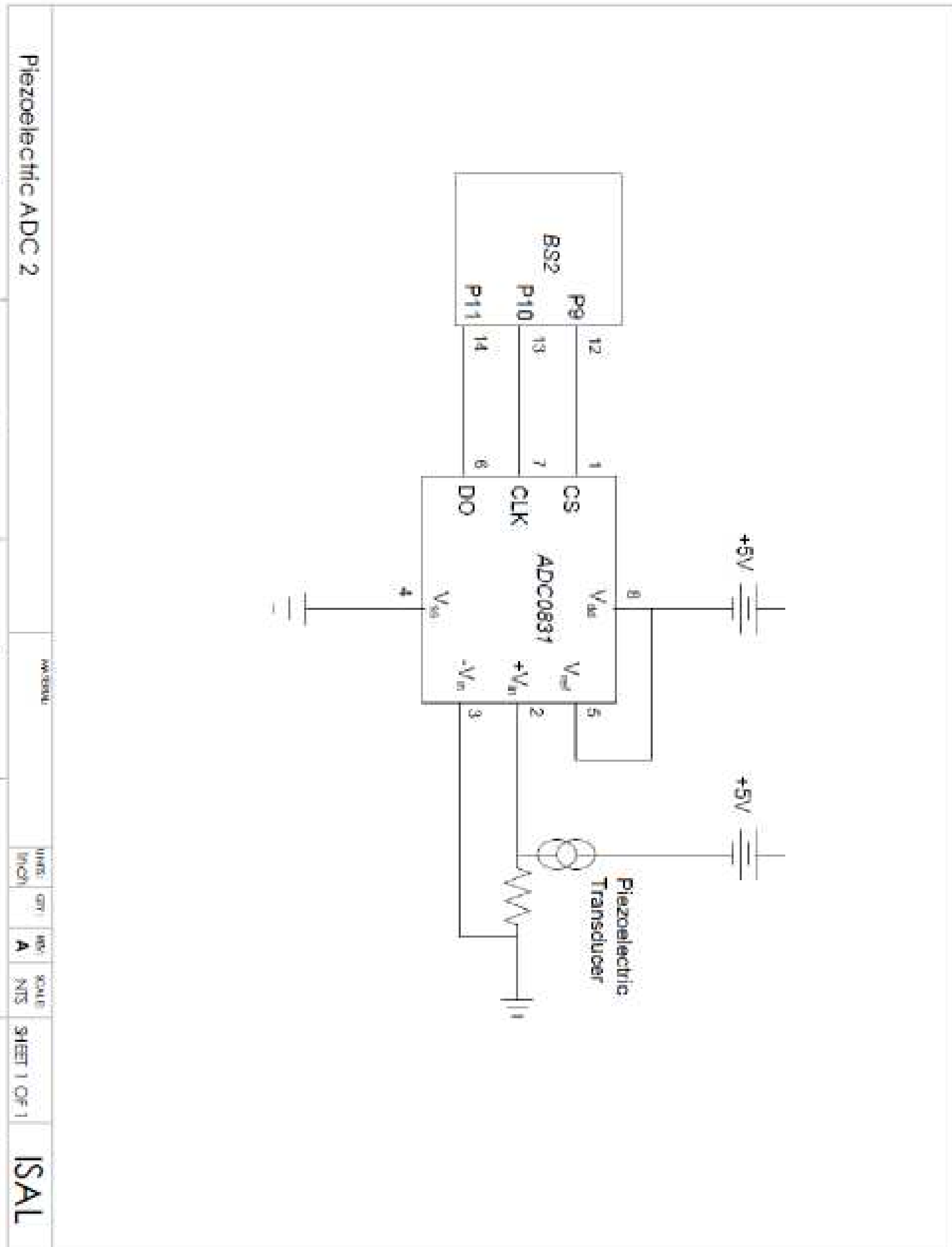
12 APPENDIX B: Electrical Circuit Drawings


Actuator Control
P1
M
inch
A
NTS
SHEET 1 OF 1
ISAL


Actuator Potentiomenter ADC
ISAL
SHEET 1 OF 1
SCALE NTS
REV A
UNITS: Inch
QTY
BS2
P3
P4
P5
ADC0831
CS
CLK
DO
+5V
10K POT
P1
P2
P3


BS2 Pin Assigments
BS2
SIN - PLX DAQ
SPST Relay - Motor Direction
SPST Relay - Motor On/Off
ADC0831-POT-Chip Select P1
ADC0831-POT-Clock P7
ADC0831-POT-DO P6
ADC0831-PZT-Chip Select P1
ADC0831-PZT-Clock P7
Sout
Sin
ATN
Vss
P0
P1
P2
P3
P4
P5
P6
P7
Vin
Vss
RES
Vdd
P15
P14
P13
P12
P11
P10
P9
P8
Accelerometer DIO P2
Accelerometer Clock Output P1
Accelerometer Chip Select P5
ADC0831-PZT-DO P6
ADC0831-PZT-Clock P7
ADC0831-PZT-Chip Select P1
ADC0831-PZT-DO P6
Inch
A
NTS
SHEET 1 OF 1
ISAL
5
4
3
2
1


BS2
P6
P7
P8
11
12
13
1
7
6
CS
CLK
DO
ADC0831
+5V
8
Vdd
4
Vss
Vref
+Vin
-Vin
5
2
3
+5V
Piezoelectric
Transducer
Piezoelectric ADC 1
inch
A
NTS
SHEET 1 OF 1
ISAL


Piezoelectric ADC 2
BS2
P9
P10
P11
12
13
14
1
7
6
CS
CLK
DO
ADC0831
+5V
+5V
Piezoelectric
Transducer
SHEET 1 OF 1
A
NTS
ISAL

13 APPENDIX C: Basic Stamp Code

13.1 Terrain Sensing Code

```
'Terrain Sensing 1.bs2
'Author:  Francis Hitschmann
'Revised Date: 4/10/2009
'Terrain Sensing - Program to stream PZT force values directly to Parallax's
'DAQ macro written in excel

' {$STAMP BS2}
' {$PBASIC 2.5}

 Left  VAR Word
 Right  VAR Word
 y  VAR Word

Row VAR Byte
sPin CON 16
Baud CON 84

SEROUT sPin,Baud,[CR,"LABEL,Time,Seconds,Left, Right",CR]
SEROUT sPin,Baud,["CLEARDATA",CR]              'Clear all data columns (A-J) in
          Excel
SEROUT sPin,Baud,["RESETTIMER",CR]             'Reset Timer to 0
PAUSE 80                             'Allow data communications to stabilize
SEROUT sPin,Baud,[CR]                          'Send a lone CR to ensure PLX-DAQ
          buffer is ready

 Main:
  LOW 6
  LOW 9                              'chip select, active low ADC, get pot value
  PULSOUT 7,1
  PULSOUT 10,1
  Left = 0
  Right = 0
  FOR y = 1 TO 8
    PULSOUT 7,1
    PULSOUT 10,1
    Left=Left*2
    Right=Right*2                            'shift bits to left
    Left=Left+IN8
    Right=Right+IN11                            'assign new bit to lsb
  NEXT
  HIGH 6
  HIGH 9
```

```
SEROUT sPin,Baud,["DATA,TIME,TIMER,", DEC Right, ",",  DEC Left, CR]
        ' Send String with data for Excel
SEROUT sPin,Baud,["ROW,GET",CR]                                ' Request last
        row of data
SERIN sPin, Baud,[DEC Row]
GOTO Main
```

13.2 *Lateral Stability Code*

```
'AccelerometerPositionControl_PLX-DAQ.bs2
'Author:  Francis Hitschmann
'Revised Date: 4/10/2009
'Accelerometer Position Control - A program to control the lateral stability
'of the test bed when it is subjected to uneven terrain.



' {$STAMP BS2}
' {$PBASIC 2.5}


x   VAR Byte
y   VAR Byte
Row VAR Byte
sPin CON 16
Baud CON 84
acclow  CON 1975
acchigh CON 2125
accblow CON 2025
accbhigh CON 2075

Dio        PIN    15           ' data to/from module
Clk        PIN    14           ' clock output
CS         PIN    13           ' active-low chip select
dir        PIN    0            'motor direction high = extends / low = retracts
mot        PIN    1            'high = on / low = off

XAxis      CON    0            ' adc channels
VRef       CON    3            ' accelerometer reference voltage
```

```
axis          VAR    Nib                  ' axis selection
rvCount        VAR    Word                 ' ref voltage adc counts
axCount        VAR    Word                 ' axis voltage adc counts
dValue         VAR    Word                 ' display value
idx           VAR    Word
Reset:
  HIGH CS                              ' deselect module
SEROUT sPin,Baud,[CR,"LABEL,Time,Seconds,AccValue,POT",CR]
SEROUT sPin,Baud,["CLEARDATA",CR]     'Clear all data columns (A-J) in Excel
SEROUT sPin,Baud,["RESETTIMER",CR]    'Reset Timer to 0
PAUSE 100                        'Allow data communications to stabilize
SEROUT sPin,Baud,[CR]                'Send a lone CR to ensure PLX-DAQ buffer is
          ready
  Main:
DO
    GOSUB Get_H48C                       ' read vRef & axis counts

    dValue = axCount                     ' display axis count
        LOW 3                            'chip select, active low ADC, get pot value
  PULSOUT 4,1
  x = 0
    FOR y = 1 TO 8
    PULSOUT 4,1
    x=x*2                        'shift bits to left
    x=x+IN5                        'assign new bit to lsb
  NEXT
  HIGH 3
     SEROUT sPin,Baud,["DATA,TIME,TIMER,",  DEC dValue, ",", DEC x, CR]
          ' Send String with data for Excel
     SEROUT sPin,Baud,["ROW,GET",CR]                      ' Request last row of
          data
     SERIN sPin, Baud,[DEC Row]


   IF dValue <=acclow THEN
   GOSUB retract
   ELSEIF dValue >= acchigh THEN
   GOSUB extend
   ENDIF
   LOW mot

LOOP
```

```
' -----[ Subroutines ]---------------------------------------------------

' Reads VRef and selected H48C axis through an MCP3204 ADC
' -- pass axis (0 - 2) in "axis"
' -- returns reference voltage counts in "rvCount"
' -- returns axis voltage counts in "axCounts"

retract:


  DO
   GOSUB Get_H48C                          ' read vRef & axis counts
    dValue = axCount
     SEROUT sPin,Baud,["DATA,TIME,TIMER,",  DEC dValue,"",DEC x, CR]
          ' Send String with data for Excel
     SEROUT sPin,Baud,["ROW,GET",CR]                          ' Request last row of
          data
     SERIN sPin, Baud,[DEC Row]
    HIGH mot
    HIGH dir

   LOW 3                              'chip select, active low ADC, get pot value
  PULSOUT 4,1
  x = 0
    FOR y = 1 TO 8
    PULSOUT 4,1
    x=x*2                         'shift bits to left
    x=x+IN8                         'assign new bit to lsb
  NEXT
  HIGH 3
 LOOP UNTIL dValue => accblow
    LOW mot
  RETURN

extend:
  DO
   GOSUB Get_H48C                          ' read vRef & axis counts
    SEROUT sPin,Baud,["DATA,TIME,TIMER,",  DEC dValue, CR]          ' Send
          String with data for Excel
     SEROUT sPin,Baud,["ROW,GET",CR]                          ' Request last row of
          data
     SERIN sPin, Baud,[DEC Row]
    dValue = axCount                       ' display axis count
      LOW 3                              'chip select, active low ADC, get pot value
```

```
 PULSOUT 4,1
 x = 0
  FOR y = 1 TO 8
  PULSOUT 4,1
  x=x*2                         'shift bits to left
  x=x+IN8                          'assign new bit to lsb
 NEXT
 HIGH 3

   HIGH mot
   LOW dir


 LOOP UNTIL dValue < accbhigh
 LOW mot
 RETURN

Get_H48C:
 LOW CS
 SHIFTOUT Dio, Clk, MSBFIRST, [%11\2, VRef\3]  ' select vref register
 SHIFTIN  Dio, Clk, MSBPOST, [rvCount\13]      ' read ref voltage counts
 HIGH CS
 PAUSE 1
 LOW CS
 SHIFTOUT Dio, Clk, MSBFIRST, [%11\2, axis\3]  ' select axis
 SHIFTIN  Dio, Clk, MSBPOST, [axCount\13]      ' read axis voltage counts
 HIGH CS
 RETURN
```