ACTIVE HIP ACTUATION FOR WALKING BIPED WITH PASSIVE OPTION

by

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Abstract

Biped robots are desired as the ideal solution over wheel vehicles when traversing over rough terrain due to the simplicity and efficiency when mimicking the natural and dynamic motion of a human gait. The Intelligent Systems and Automation Laboratory (ISAL) at the University of Kansas designed and built a three legged 2D biped walking robot to establish a testbed for future testing.

This paper focuses on the development and testing of a novel hip joint that allows actuation with the ability to remain passive. This study was completed concurrently with the development of a full robot as part of other projects.

The biped robot, known as the Jaywalker, is comprised of two main actuation systems: the Hybrid Parallel Ankle Actuator (HPAA) and the Hip Ratchet System (HRS). This study focused on the design and testing of the HRS which achieves hip actuation through the use of a locking mechanism integrated into each hip joint that couples the legs to a shared drive system. The ability to lock and unlock the hip joint through the HRS enables the Jaywalker to function in passive or actuated states at the hips.

Testing of the HRS was conducted in both passive and actuated states on the Jaywalker testbed. Testing of the hip provided proof in the concept of using a single drive in combination with a ratchet mechanism to actuate the hip while providing a passive option. The HRS also provided the capability to vary step lengths future testing that requires turning, rough terrain, and stair climbing.

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1 INTRODUCTION TO THE JAYWALKER, A 2D BIPED WALKING MACHINE TESTBED WITH A HIP RATCHET SYSTEM

1.1 Background of Biped Walking Machines

Biped robots have long been desired as the ideal solution over wheel vehicles when traversing over rough, uneven, and stepped terrain. One of the greatest challenges in the design and development of an efficient biped is that the supply of constant power is often limited. Results from past simulations and studies of energy analysis of biped walking can be used to develop future biped designs based on efficiency [2], [3].

Today, there exist multiple types of biped walking robots such as entirely passive walkers [4], passive dynamic walkers [5] and zero-moment-points (ZMP) robots [6]. Each was designed from a unique problem set and can be used as motivation for future work as learnings can be derived from each.

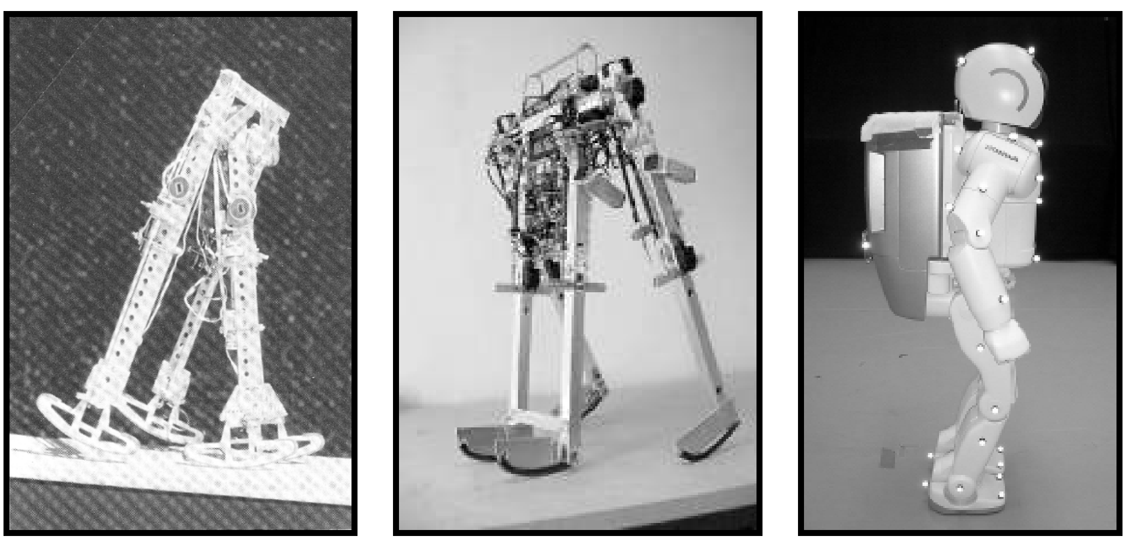

Figure 1.1.1: Three different types of biped walkers from left to right include McGeer's passive walker, Delft's 'Mike', and Honda's Asimo.

The Jaywalker design was modeled after McGeer's gravity powered 2D walker which is the example of dynamic walking [4]. It is the model for the development of a testbed for future analysis due to its anthropomorphic design, efficiency, and stability [7]. In this design the walker takes advantage of gravity by moving down a ramp. The Hip in this deign is simply a pivot point for the three legs. The Hip of the Jaywalker can function in a passive state such as McGeer's walker, but it can also provide actuation such as the Honda Asimo robot and Mike.

Like most robots, the Jaywalker requires the use of constant power consumption through an umbilical cord that provides electricity and compressed air. One of Honda's earliest Humanoid walker designs, P1, weighed 210 kg and required a 20 kg battery; only powering the robot for 15 min [8]. Later versions, such as Asimo, had greatly reduced weight of 54 kg but could still only be powered for one hour [9]. This dependency on power heightens the importance of efficiency.

At the Intelligent Systems and Automation Laboratory (ISAL) at the University of Kansas, the Jaywalker was developed to establish a testbed for future testing and analysis of robotic locomotion over rough terrain including turning, stair climbing, and backward movement. The Jaywalker components, such as the hip, were designed with these key constraints to promote the use of this robot for practical uses in the future [10]. Of principal importance in the design of the Jaywalker and its hip components was the manner in which the human gait cycle is completed.

1.2 The Human Gait Cycle and the Hip

As a human walks forward, the legs undergo a repetitive sequence known as the gait cycle. During the gait cycle one leg remains in contact with the ground, referred to as Stance, to support the upper body while the second leg advances, referred to as Swing. After contact is made with the Swing leg both legs provide support to the body. To continue moving forward, the legs alternate Stance and Swing roles to advance an additional step [12]. The gait cycle is depicted in Figure 1.2.1 by Perry outlining the two major divisions of the gait cycle [12].

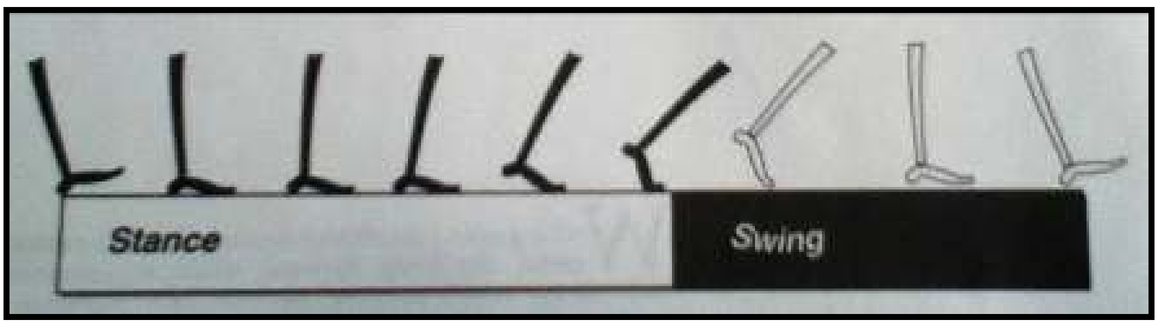

Figure 1.2.1: Stance and Swing divisions of the gait cycle with representation of each duration as shown by the clear and shaded bars. The limb segments indicate the subdivisions of stance during each major division provided by Perry [12].

Within the Stance division there exist multiple intervals including initial double stance, single limb stance, and terminal double limb stance [12]. As a human moves through these intervals of the gait cycle, the contact with the ground can be categorized as Heel Strike at the end of the Swing and Toe Off at the beginning of the Stance. These subdivisions are shown in Figure 1.2.2 from Inman [13].

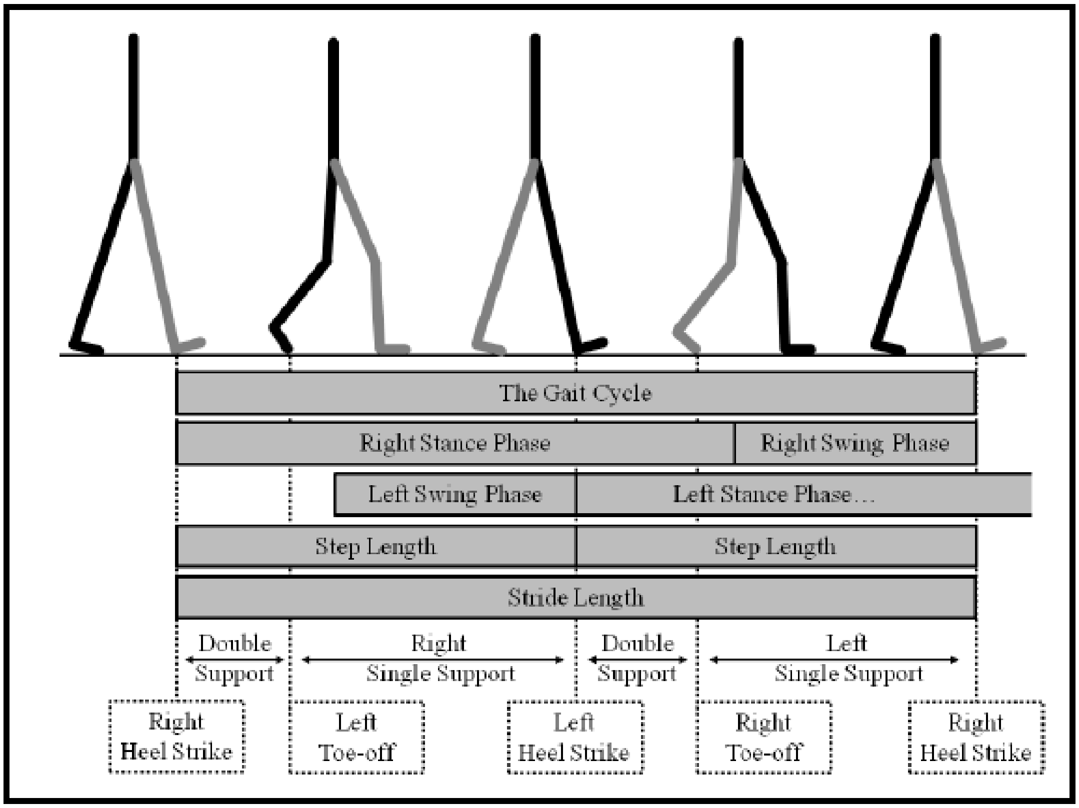

Figure 1.2.2: Subdivisions of the gait cycle stance and swing phases defining the double and single support provided by Inman [13].

Within the sagittal plane, the hip supports leg extension during the stance phase and leg flexion during the swing phase [14]. Table 1.2.1 outlines the hip function for each gait phase along with the position of the hip relative to the joint as defined by Perry [14].

Gait Phase	Action	Position
Initial Contact	Hip Flexion	$\geq 30^0$
Loading Response	Maintain	$=30^0$
Mid Stance	Hip Extension	$>30^0$
Terminal Stance	Hyperextension	$>>30^0$
Pre-Swing	Hip Flexion	$=0^0$
Initial Swing	Hip Flexion	$>0^0$
Mid Swing	Hip Flexion	$>0^0$
Terminal Swing	Maintain	$=30^0$

Table 1.2.1: Hip function by gait with the relative positions of the hip joint provided by Perry [14].

1.3 Motivation for the Hip Ratchet System

The motivation for this work is to aid in the study of human dynamics thought the construction of a dynamically actuated 2-D biped. A key aspect of this design is the robots ability to transform from a fully actuated state to a passive one. This is achieved at the hip joint through a cam-ratchet assembly, known as the Hip Ratchet System (HRS) that engages after toe-off to aid in leg lift and disengages at heel strike. The benefit of active hip actuation is that it can be used to control the location of the heel strike relative to the ground resulting in controlled stride lengths and optimal energy return during toe-off.

The HRS enables the biped's hip joint to be actuated during gait and also passive in order to achieve some level of dynamic walking. The hip design encompasses constraints for current and future goals such as walking up stairs, stepping backward, turning, and conquering rough terrain.

One cannot obtain a truly passive state when connecting a motor directly to a joint. Thus a ratchet system was implemented onto the hip design to switch between the two states. The ratchet system provides many advantages to the design of the 2-D biped. One of the key advantages is the ability to independently control multiple joints with the use of only one drive motor assembly resulting in energy and cost savings.

1.4 Author's contributions

The Jaywalker required a Hip system to link all three legs around a central pivot point, provide actuation during gait, provide the option for passive control, and the ability for connection to a support frame. This Author designed a prototype Hip system with the above constraints but also created a design with the intent to enable the hip to actuate all three legs independently, in reverse, and all at varying durations. This was achieved through the HRS, which provided the Hip with a passive option to emulate a dynamic or natural gait. This system was designed, fabricated, and tested in the Intelligent Systems and Automation Laboratory (ISAL) at the University of Kansas. The purpose was to develop a testbed for future analysis of robotic biped walking over rough terrain.

1.5 Overview of Jaywalker Testbed

The Jaywalker is a walking robot built from the torso down to the feet with its overall design influenced and modeled after McGeer's passive walker. Focusing only on walking in the sagittal plane, this robot was designed with three legs to simplify the design thus resulting in a 2-D walker [4]. Adding a third leg to the walker also allows for stable walking without shifting COM from side to side [1]. The Jaywalker was designed to function as a testbed for biped walking over rough terrain. Choosing to focus only on walking in the sagittal plane and the use of three legs greatly simplified the design.

The Jaywalker is comprised of three main subassemblies listed as the following: the lower leg assembly with the foot, ankle, shank and knee, which includes the Hybrid Parallel Ankle Actuators (HPAA); the thigh, which includes the Leg Extension Guiding System (LEGS); and the hip, which includes the Hip Ratcheting System (HRS). All three subassemblies can be seen in Figure 1.5.1.

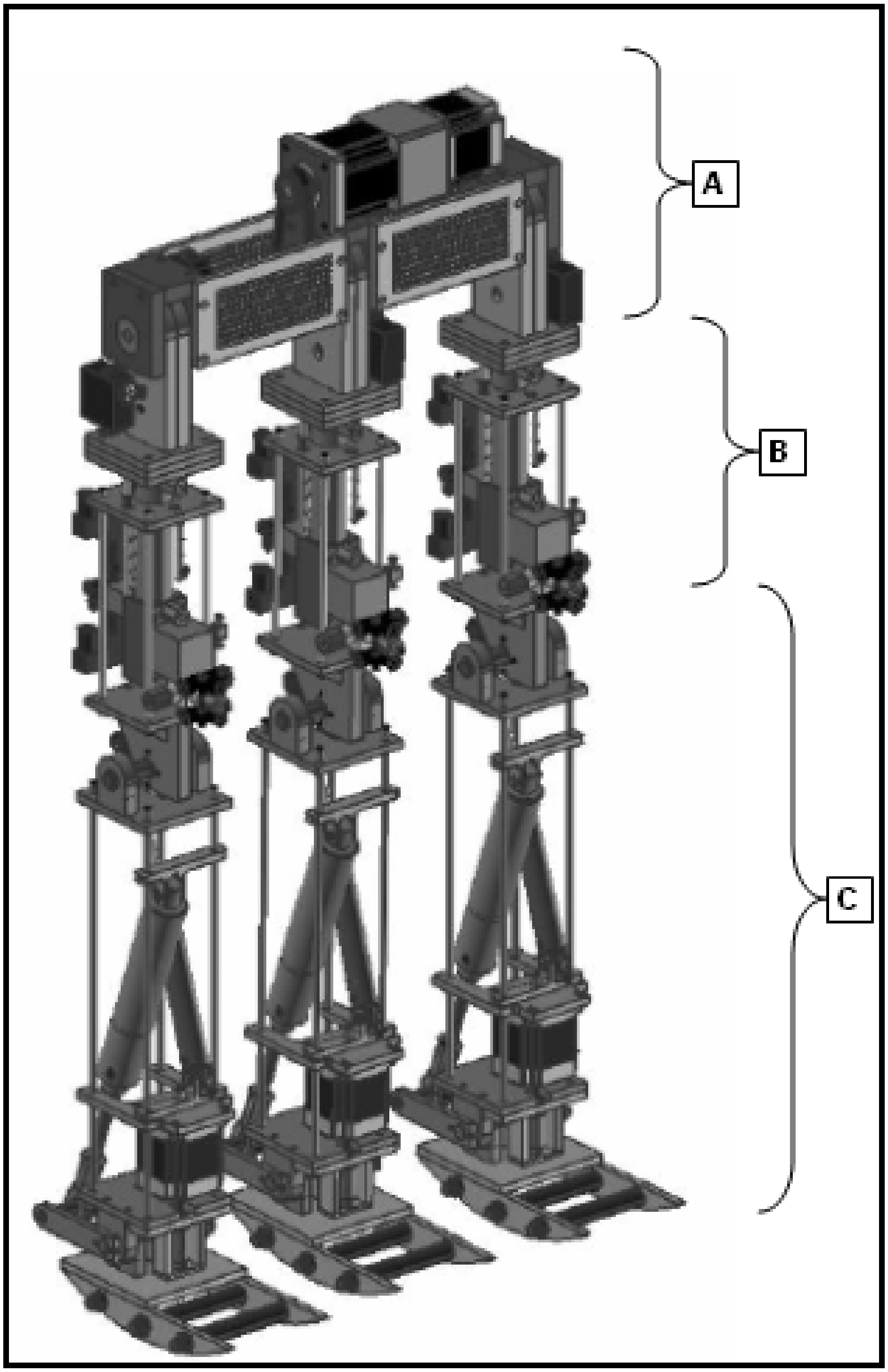

Figure 1.5.1. Unigraphics 3D model of the Jaywalker including the three major subassemblies shown above as the Hip (A), Thigh (B), and S (C).

The Jaywalker was connected at the Hip to a frame that provided stability, housing for most of the controls, and constrained movement to only the sagittal plane. The walker and frame will provide as a testbed for future testing, specifically achieving the conquering of rough terrain. The tether also provided safety and stability to the robot to minimize the impact of minor perturbations during walking. A photo of the Jaywalker testbed can be seen in Figure 1.5.2.

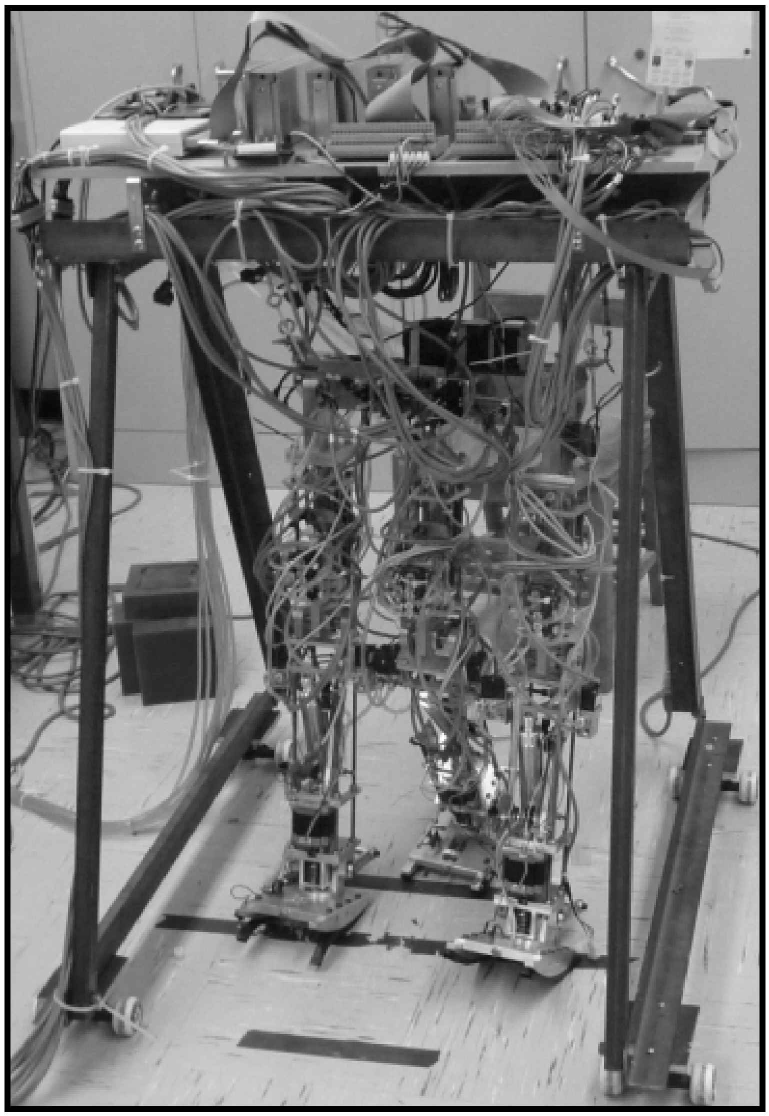

Figure 1.5.2: A photo of full Jaywalker tested connected to the frame with control systems and umbilical cord mounted on top.

1.6 Conclusions

Hip actuation with a passive option can provide the advantage of utilizing the natural dynamics of walking while also actuating the legs at key points during gait to provide necessary lift, resistance, and control. McGeer found that biped walking can be achieved without actuation, but actuation was necessary to walk over anything other than a downward slope. However, excess actuation such as with ASIMO, can lead to inefficiencies and a deviation away from natural walking. The novel design of the Hip Ratchet System encompasses the benefits of both actuation and passive control within the Jaywalker.

A prototype was designed, constructed, and tested that would allow for hip actuation with a passive option. Throughout most of the step testing conducted on the Jaywalker, the hip was configured for its passive state. On isolated occasions, the Jaywalker was used as a testbed to conduct proof of concept testing on the HRS, demonstrating the mechanisms ability to effectively toggle between active and passive states within the hip joints.

1.7 References

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2 MECHANICAL DESIGN OF A RATCHET SYSTEM ENABLEING ACTUATION OR PASSIVE CONTROL WITHIN A 2D BIPEDS HIP

2.1 Introduction to the Hip Ratchet System

The HIP system on the Jaywalker comprises of three main components which are the frame, drive system, and ratchet system. Each design underwent multiple revisions and modifications following testing resulting in a truly unique and efficient design with a drive system that can actuate the hip with an option to become passive.

In order to achieve an efficient dynamic walker, the hip joint was recognized as an opportunity to reduce development cost, energy usage, and dynamic constraints. The ratchet system provides many advantages for a 2-D biped. One advantage is the ability to independently control each joint with the use of only one drive motor assembly. With the stepper motor weighting 1.5 pounds and gearhead weighting 3.2 pounds, the HRS reduced the potential weight of the Jaywalker by 4.7 pounds plus the additional weight of wiring and controls. The HRS design also reduced the cost of the Jaywalker by at least $510, as seen by the individual component costs outlined in the Bill of Materials as part of Appendix A1.

In order to reduce effort and resources required to redesign the hip throughout different generations of prototypes, future goals were considered throughout the design. Future constrains include walking up stairs, turning, and backing-up; attributes that will all be necessary to conquer rough terrain were included in the design. A Unigraphics 3-D model of the hip design can be seen in Figure 2.1.1.

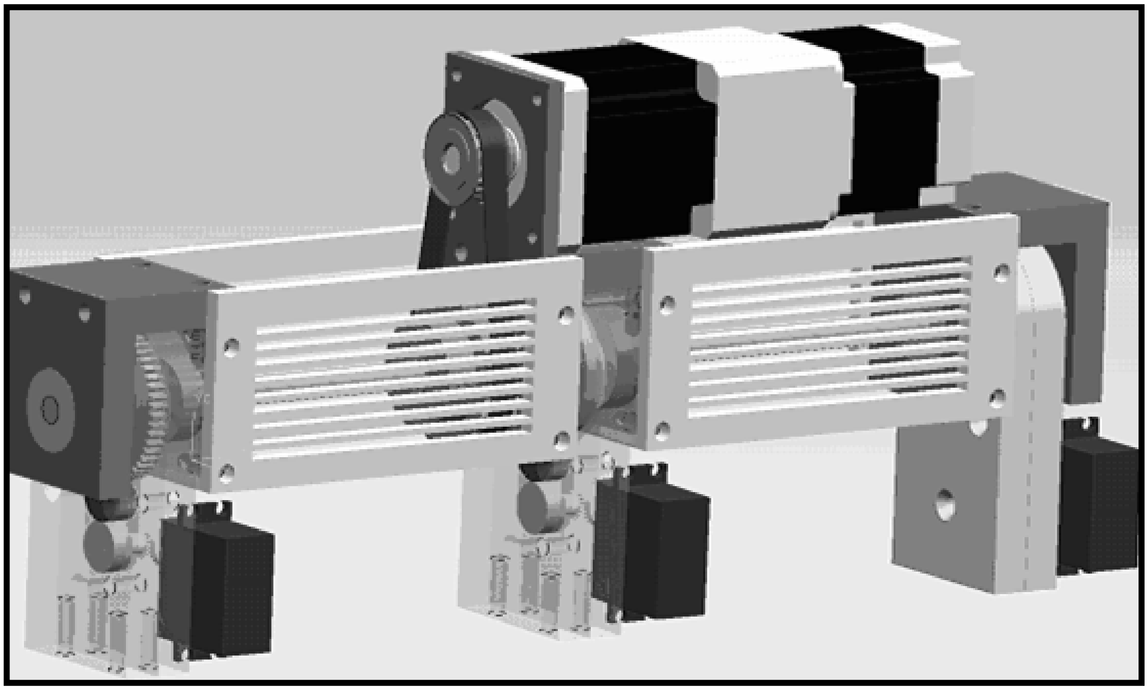

Figure 2.1.1: Unigraphics 3D model of the Hip system.

A single MS23C 110 oz-in stepper motor drives the HRS through a True Planetary Gearhead with a 30:1 gear ratio that is secured on top of the hip's frame. The shaft of the Gearhead is coupled to a 12-tooth pulley which drives a 22-tooth pulley connected through a timing belt. The 1.83:1 pulley ratio provides the necessary increase in torque and velocity for the drive shaft. In addition to the 22-tooth pulley, the drive shaft is connected to two spur gears on either end, rotating at all times within the hip joints positioned on the outer segments of the shaft. The HRS is mounted to each hip joint and is driven by a single 9 volt high torque servo. The servo is in direct contact with the dual pawl with a key that couples them together.

With the shaft rotating at a relatively low speed of around 15 RPM, a dual-pawl is shifted into a mating position with a rotating spur gear to engage the HRS. As a result, up to 378 in-oz of torque is supplied at the hip joints at 15 RPM. A graph of the systems torque output versus speed can be seen in Table A.5.1 of the Appendix A.4. This power aids the robot during normal gait much like the way humans walk. Further testing will enable the design of an energy efficient control system that will only actuate the hip at targeted times.

After heel strike, the leg will be free to complete the step without using any additional energy from the backdrive of the stepper motor or resistance in the drive itself [1]. Controlled testing was conducted at the hip joint to reduce timing lag of the HRS mechanism. With the HRS optimized, further field testing can be conducted with hip actuation integrated with the actuation of the other systems, such as knee actuation. Actuation of the hip just before heel strike may also be used to counter energy collision losses [2].

2.2 Design Constraints and Frame Design

Physical integration of the Hip within the Jaywalker required an anthropomorphic fit. This main constraint for the Hip was within the width which sets the spacing of each leg for the entire system. Therefore, it was critical that the Hip joints were set to the proper position and held during walking and other loading conditions.

As with all mobile systems, energy usage is a critical constraint as an unlimited power supply is not practical. To reduce energy usage, weight and efficiency were considered throughout each design step. This resulted in a design that uses a single motor to drive all three legs instead of individual motors for each leg. This greatly reduced the weight of the robot with less motors, wires, and power supplies.

Should the future version of the robot include a battery pack, the existing design is well suited with minimal power consumption and a simple design as with less power consumption and a single 9 volt battery to power the servos. Also, only two nine-volt batteries are required to power the servos, greatly reducing the cost of transport.

The Hip design, specially the dual pawl, provided the Jaywalker an ability to move in forward or reverse direction with a simple actuation from its servos mounted on the outer hips. The design of the Hip joints enabled the legs to actuate or freely swing in either direction.

The Hip was also designed with the ability to independently control each of the outer legs. This enabled the Jaywalker to have strides of varying length for use in applications such as walking on rough terrain or turning. This could complement the LEGS system, and when used in parallel, could have a positive effect on changing thigh length. As documented by Kuo, varying the stride length can be used as an approach for determining optimal stability by targeting ideal stance and swing velocities [3].

The ratchet system also allowed for the free failing return of the leg, emulating a passive walker while also returning power. This will allow for the most efficient gait possible when taking advantage of gravity. With proper push off entirely on downward or even slopped terrain, there is no energy required as gravity is used to complete the gait cycle resulting in an efficient process [4].

One of the final design constrains was the ability to walk up stairs. For the hip this meant the ability to achieve and maintain a full 90-degree step. This required 180-degrees of motion around the hip joint to complete a 90-degree step in either forward or reverse direction. Frame components were designed to allow full motion around each joint with sufficient clearance. Achieving a 90-degree step also meant higher torque requirements for the drive system.

During the design phase with the intent to minimize weight, thickness of the plates was reduced in some areas to ¼" which required the used fine treaded fasteners to ensure sufficient thread count.

Design selection of bushings was critical in order to achieve one of the key design constraints: dynamic walking. The bushings within each hip joint along the shaft are the key enabler for dynamic return of the legs after lift. Load, velocity, and load at velocity were all considered in the bushing design. The primary function of the busing was to reduce friction on the shaft while its secondary function was to center the gear within the hip joint. The PV rating was used to ensure that the bearing will sustain the load of the legs at actuation. A pair of bushing was pressed into each hip joint that contained the HRS.

2.3 Hip Ratchet System Design

A common constraint for dynamic walking bipeds is efficiency and energy consumption. This is perhaps the main influence to create a design based on the dynamics of human walking. In regards to locomotion, humans are among the most efficient in transportation using a metabolic cost of 0.2 when walking [1]. To satisfy such a design constraint a ratchet system was designed to allow actuated hip joints the ability to undergo a desired passive state.

One cannot obtain a truly passive state when connecting a motor directly to a joint. Thus a ratchet system was implemented onto the hip design. The system was modeled after the Craftsmen® quick release reversible ratchet wrench as seen in Figure 2.3.1.

Figure 2.3.1; Craftsmen quick release reversible ratchet

The pawl from the Craftsmen ratchet design is unique in that it is a dual pawl that can be used to reverse direction for the wrench. The use of a pawl that was dual allows the robot superior adaptability though the development of a control system for reversible movement.

The pawl was also ideal for use under the large loading conditions of the robot. The dual pawl and the supporting components such as the spur gear and locking mechanism can be seen integrated into the hip joint in Figure 2.3.2. This figure provides a cut-away view of one of the hip joints.

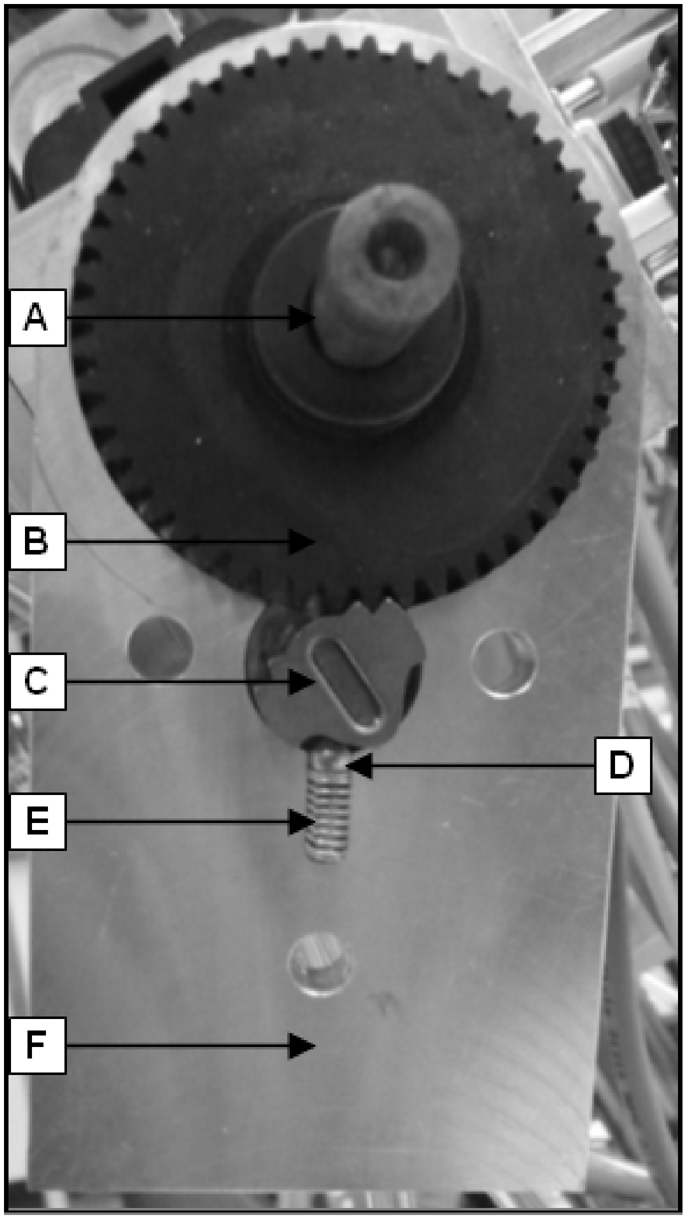

Figure 2.3.2: Photograph of the hip joint with inner components (left) along with the second piece of the enclosure (right). Connected to the shaft (A) is the spur gear that continually rotates as it's locked via two set screws. When engaged, as shown in the photo above, the pawl (C) locks with the spur gear and is held in place by the ball bearing (D), spring (E), and contour feature bored out of the frame (F).

2.4 Multipurpose Driveshaft Design

Spanning the width of the hip is a shaft used for multiple purposes. While its main function is to distribute power from the drive system to the legs, it's also used for alignment, position, and spacing of the Jaywalker's legs. This shaft was designed with the intent to operate in both an active and passive state with the legs naturally decoupled from the drive system through the use of the HRS.

In designing the shaft, a suitable diameter of ½" was chosen to meet power transmission requirements as calculated from a standard shaft design equation and considering a 2.0 factor of safety [5], [6]. The shaft is subject to fatigue stress caused by bending during the gait cycle, torsional loading during leg lift, and stress concentrations from the multiple features cut into the shaft. These were all considered to determine the worse case stress condition need for material selection.

Chromium-molybdenum steel 4140, chromium-nickel-molybdenum steel 4340, and other chromium alloy steels were the first choice for material as they offered both advantages in strength and machinability as they are commonly used for shafting. However, these would prove unsuitable given the high stress conditions encountered when coupling torsional loading and the stress concentrations resulting from securing the gears. Therefore, hardened high-tensile tool steel, P20, was the material of choice with a yield strength of 110,000 psi. The shaft stock underwent annealing, hardening, and nitriding to achieve its high strength characteristics, though it was difficult to machine.

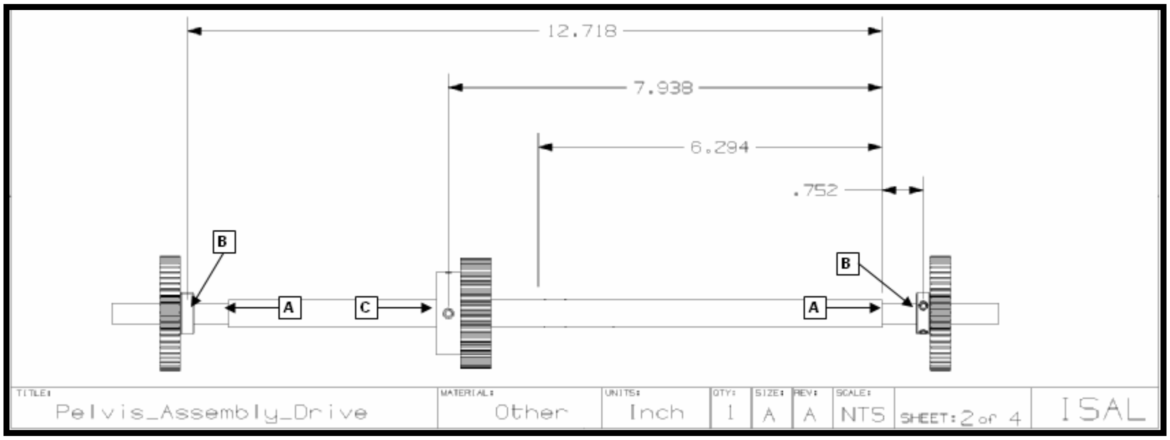

Figure 2.4.1: Shop drawing of drive shaft showing multiple machine features including two of the four steps (A). The locations for the six flat features required for the set screw seats are shown with the spur gears (B) and pulley (C).

The shaft profile consisted of 16 features that include six press fitted bearings, two flat features for each of the three gears, and four steps that were used to accurately assemble the legs ensuring proper spacing between each. Even the addition of press fitted bearings will have a stress concentration on the shaft [9]. The spur gears and pulley were each connected to the shaft with a pair of flat point set screws. Set screws were the more suitable option as milling key seats into the shaft would pose very high stress concentrations both under bending and torsion [8].

A multitude of features were designed into the shaft, resulting in stress concentrations of multiple levels at multiple locations [9]. The following are the primary motivations for each of the three types of shaft features:

1. Stepped Shaft Feature. The change in shaft diameter was used to accommodate assembling of parts on the shaft including bushings, bearings, spur gears and the pulley. When considering design for disassembly, it's not feasible to press fit each along the length of the entire shaft and the additional stress concentrations are not desired. The stepped feature also provides accurate and consistent axial location along the shaft as the steps are used as a reference point during assembly.
2. Press Fitting Feature. This was used for the ball bearings as they required an extra level of security along the shaft. Press fitting these parts will prevent small axial loads from moving the bearings out of the desired position.
3. Flat Feature. This was used to secure the spur gears and pulleys onto the shaft as a means to enable positive torque transmission. This was the choice over key seats as key seats they tend to have very high stress concentrations resulting from the sharp corners of the key and key seat.

The shaft and its features is a key component of the drive system.

2.5 Synchronous Drivetrain Design

The drivetrain of the hip is comprised of multiple components to distribute power to each of the Jaywalker's three legs. The three main components are the motor and gearhead, timing belt system, and the components coupled directly to the drive shaft. The system is designed to transmit up to 378 in-lb of torque depending on the efficiency of the 30:1 planetary gearhead which can have an efficiency loss as much as 15%.

To achieve the highest torque output, a US Digital MS23C stepper motor is connected to a 48 VDC 4 Amps power supply providing nearly 105 in-lb at 1100 rpm. This torque, multiplied by the 30:1 Micron EQ Series True Planetary Gearhead secured to the top of the frame, is transferred to the driveshaft through a timing belt system.

The output shaft of the Planetary Gearhead is coupled to a 12-tooth double flanged pulley which drives a 22-tooth double flanged pulley through a timing belt that make-up the timing belt system. The 1.83:1 pulley ratio provides the necessary increase in torque from the motor to the drive shaft. As with the spur gears, both pulleys were mounted using cone point set screws. Assuming accurate alignment within ¼ inch, belt damage and slipping will be at a minimum. A service factor of 2.0 was chosen due to the small pitch inherent in synchronous timing belt system design.

Of the many belt design options available, synchronous belts were chosen over V-Belts and flat timing belts. V-Belts would not have been suitable for the low speed application and flat belts would be subject to slipping under such high torque forces. A single sided Neoprene synchronous belt reinforced with fiberglass was the type of belt chosen for the hip drive.

To ensure sufficient tooth coverage and center distance, a 33 tooth belt was determined to be the best fit. At least 6 teeth were maintained in contact with each pulley at all times to attain maximum transfer of power and limit risks of slipping. The $^{3}/_{8}$ inch pitch with trapezoidal shaped teeth helps maintain contact with the teeth of the pulleys under high torque conditions.

Utilized to transfer motion from the stepper motor and gearhead to the drive shaft, two pulleys were mounted along a parallel plane for efficient transfer of motion. This also provided preferred placement of the two heaviest hip components, motor and gearhead on top of the torso frame. This was necessary in order to remain anthropomorphic as a lump sum mass was needed for stabilization [10].

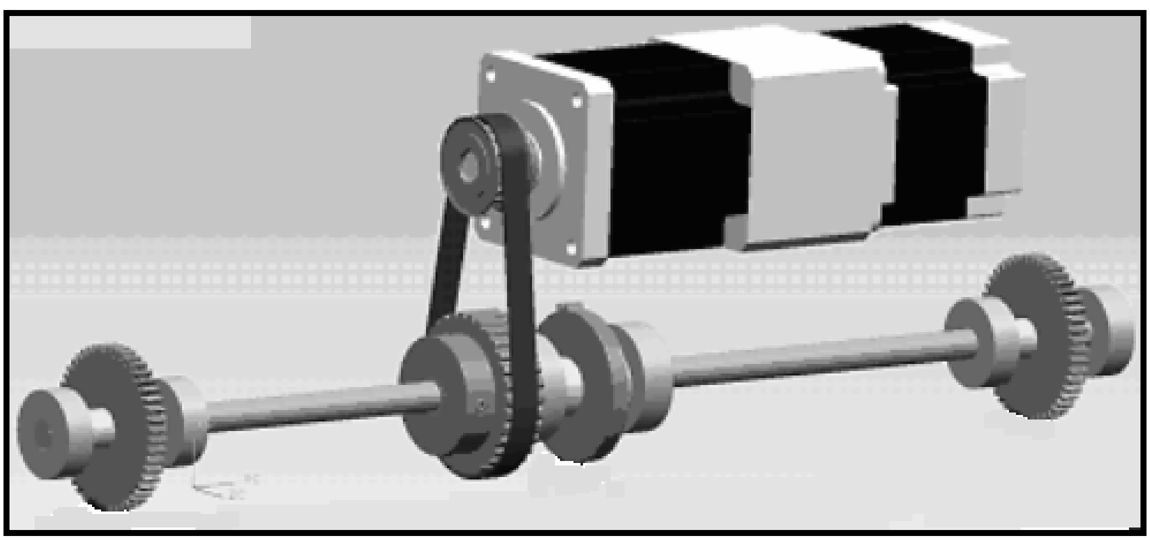

Figure 2.5.1: Synchronous Drivetrain of the Hip with supporting components.

2.6 Controls Design

The control system for the Hip is written for a micro controller and interfaces with the fuzzy logic control system used for the Jaywalkers other main components such as the HPAA. When conducting proof of concept testing of the HRS, no feedback was necessary so the control system was kept as simple as possible.

The details and motivation for the use of the fuzzy logic control system are described in detail in Baker's dissertation on the development of a powered 2D biped walker [11]. A diagram of the basic communication structure through the use of the fuzzy logic control system is shown in Figure 2.6.1 [11]. This logic controlled the stepper motor of the drive system along with providing power to the control system for the HRS.

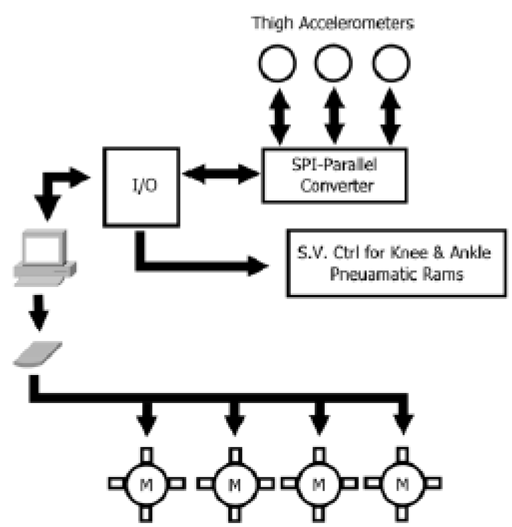

Figure 2.6.1: Fuzzy logic control

Two BASIC Stamp 2 programmable microcontrollers were used to control the position of each pawl within the HRS. The control logic was written in PBASIC to toggle the servos between three positions: Neutral, Forward, and Reverse. An electrical circuit housing the microcontroller was created for the X-leg and Z-leg in the Jaywalker and was also used to indicate the pawl position through the use of a pair of LED's.

2.7 Conclusions

The ability to actuate the hip joint while providing a passive option has many advantages for efficient gait. The Hip Ratchet System (HRS) as part of the hip joint allows for a passive option but also provides additional advantages. This includes independent leg actuation that could be used for turning or walking over uneven terrain and reverse actuation to walk backward.

Future testing will be required to determine if the HRS is suitable for switching between forward, reverse, and neutral states within the hip of the Jaywalker. It will also be important to conclude the designs of the multipurpose driveshaft and synchronous drivetrain. Testing provided to be a key process in the development of the hip system.

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3 TESTING AND RESULTS FOR THE HIP RATCHET SYSTEM

3.1 Introduction to Testing of the HRS

Testing of the hip system included two phases categorized as Static Checkout and Dynamic Testing with the major difference between the two being the addition of load forces applied to the hip joint during Dynamic Testing. These phases were identified to shakeout issues with the hip ratchet system and minimize risk of damage during testing.

The main objective for testing was to prove the concept of using multiple ratchet systems along a drive shaft as part of the Hip Ratchet System (HRS). The HRS is a novel approach with testing conducted to validate the proof-of-concept prototype. Multiple iterations of leg lifts were conducted by engaging the ratchet system simultaneously and independently in each of the two outer legs as described in greater details in the results section below.

3.2 Testing Procedure

During Static Checkout the hip was decoupled from the legs, the servo's decoupled from the pawls, and the main drive decoupled from the pulleys. This checkout included validating the wiring between the controller and the drives and the wiring between the microcontroller and the servo drives.

With all components decoupled, each test actuator was powered to confirm communication, direction, and finally speed. Only after each was completed, were the actuators reassembled to the system in preparation for Dynamic Testing.

At the start of Dynamic Testing the hip was tested without any loading from the legs. This was achieved by forcing the hip joints into their passive state. This allowed for insolated testing on the robot of the drive system without any risk to other components. The drive system and hip joints were actuated independent of each other during the initial phases of testing. Dynamic Testing concluded with coupling the legs to the joints and subjecting the system to loading conditions in two phases. The first test focused only on lifting one leg at a time to validate the mechanics of the HRS design. The second test focused on simultaneous lifting of the legs to subject the drive system to full loading conditions. It was ultimately through the design changes uncovered during testing, that the hip system underwent the necessary modifications to achieve success.

3.3 Evolution of the Hip Design

Initial testing proved difficult for the hip system as various components lacked suitable levels of robustness and repeatability as required during the gate cycle of the biped walker. Failures included the key for the pawl unseating, the spur gear set screws stripping, and the timing belt slipping. Through the issues that were uncovered during testing, the prototype design evolved into a more robust and effective model.

During early testing the pawl demonstrated that when engaged by the servo system, locking with the spur gear was achieved and was successful in moving the leg forward with the drive system. It was also observed that the entire load of the leg can be supported by the HRS, with the pawl and spur gear firmly coupled by the spring and ball bearing mechanism. These demonstrations were encouraging but the results were not repeatable. Initial testing, summarized in Table B.1.1 in the Appendix, found the setscrew and HRS key needed modification.

Each leg had a single setscrew that was used to secure the spur gear to the shaft. However, during initial testing a number of problems were uncovered in this area. The set screw threads were found to be stripped, likely during assembly, thus greatly impacting the holding force. Also, the cone type design cut away part of the shaft resulting from the higher than designed loading forces. As a result, the gear was not fully secured to the shaft which resulted in occasional slipping of the spur gear under load. This was confirmed when inspection of the shaft uncovered signs of wear along the setscrews positions. Therefore, the flat features of the shaft were cleaned and the single cone point setscrew was replaced with two flat point setscrews. In addition, a more durable material, with threads that would not strip during tightening, was chosen

Another issue that occurred with initial testing was when the HRS key, which is positioned on the servo, lost its home position. This resulted in the system loosing control of hip locking, therefore unable to toggle between passive and actuated states. The key system was redesigned and included a modification that locked the key into the servo resulting in a more robust mechanism.

The second round of testing focused on the actuation of two legs simultaneously to subject the entire system under the highest possible loads. While this testing confirmed the effectiveness of the modifications made to the setscrews and HRS key, more issues with the hip system were uncovered. The results of these tests, summarized in Table B.1.2 of the Appendix, found that the timing belt encountered slippage along the upper pulley and the drive system did not product sufficient torque to lift both legs.

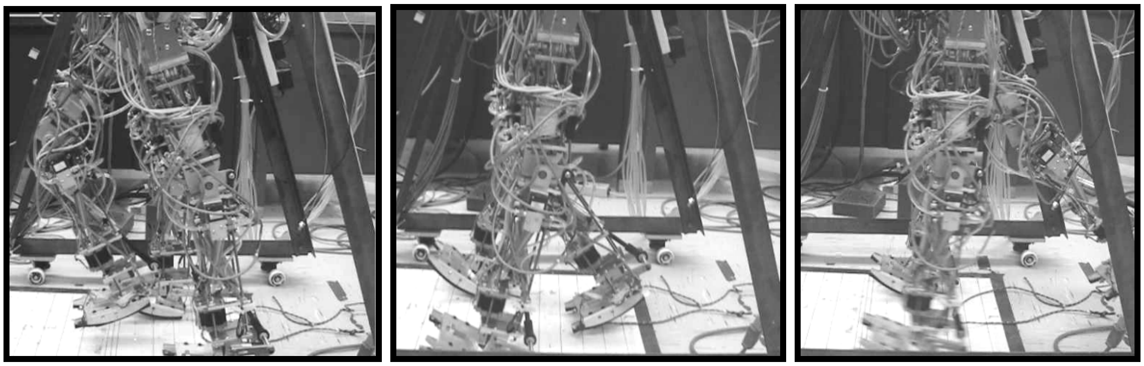
The actual mass of the legs were measured to find that they were approximately 50% heaver than originally designed as detailed in Table B.1.3 of the Appendix. While the original design weight of the Jaywalker was 20.5 kg, the actual weight at the time of testing was measured at 28 kg [1]. With 100% of the increased weight added to the legs. This can be attributed to the dozens of cables and wires used throughout the legs as part of the umbilical cord, the modification of various components, and the addition of a knee. Therefore, a more suitable type of timing belt and pulleys were designed that could withstand the new calculated loading. This included a wider belt, more aggressive tooth profile, and belt tensioners to increase the number of teeth on each pulley.

The increased mass of the legs consequently required higher torque output than what the drive system was capable of producing. During testing, the stepper motor was not capable of holding both legs as it failed to keep them erect. In order to increase the available torque output of the Hip System, the power supply for the US Digital MS23C stepper motor was increased from 24 VDC 4 Amps system to a 48 VDC 4 Amps system. This resulted in a substantial increase in torque of approximately 34% at toe-off and 68% during operating speed through the swing phase. The increase in power supply had no impact to the overall weight of the robot.

As the design for the hip evolved, the success of the modifications was demonstrated during the third and final test during which legs were independently and simultaneously lifted in forward and reverse. The results of these tests are summarized in the following section.

3.4 Active Hip Actuation with a Passive Option

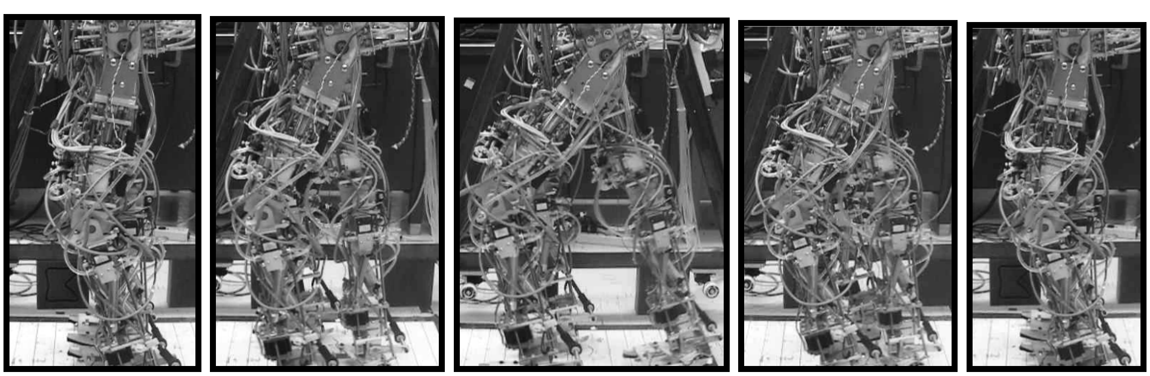
Testing proved the concept of using the HRS as a method to actuate the hip while providing an option to function in a passive state. Figure 3.4.1 shows the motion of the hip system actuating the center leg, referred to as the y-leg, forward while switching to a passive state before actuating the leg backward from a video of one of the successful trials. During the passive state the HRS moved the pawl to the natural position while the drive system was still running to simulate passive control. As desired, the legs did not move during this simulation with the system in neutral.



(A) (B) (C)

Figure 3.4.1: Motion capture of the three actuation states the HRS for the y-leg (center leg). As shown above this includes forward actuation in the active state (A), neutral actuation in the passive states(B), and reverse actuation in the active state (C).

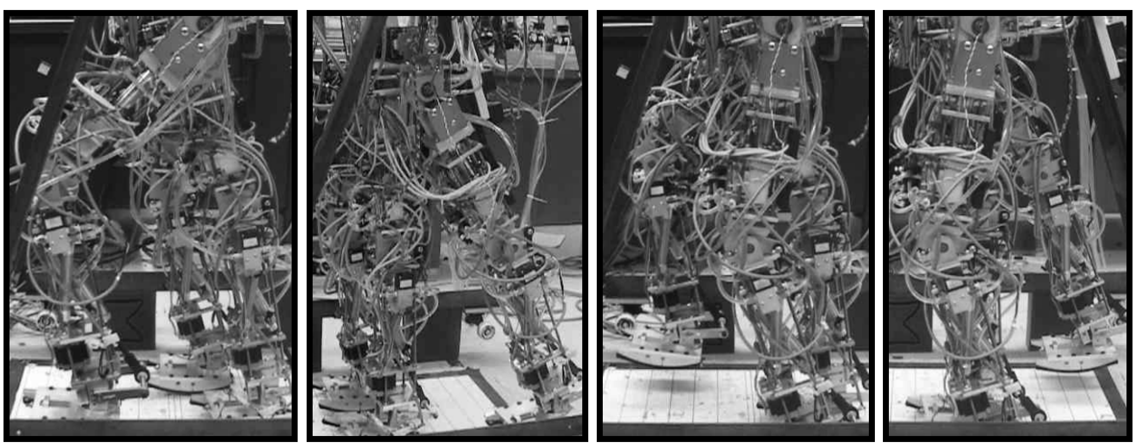
During another successful trial, as shown in Figure 3.4.2., the two outer legs, referred to as the x-leg (background) and z-leg (foreground), were simultaneously actuated forward and held at approximately a 45-degree position for seven seconds before returning to the home position. This trial was repeated five times to successfully demonstrate that the system was capable of lifting both legs with the design changes made to increase torque output. In addition, the system was proven reliable with the modifications in place as recognized in earlier testing.



(A) (B) (C) (D) (E)

Figure 3.4.2: Motion capture of the two outer legs simultaneously actuating forward in between two passive states. The two legs started the test with the hip in a passive state (A) before active hip actuation lifted the two out legs at the same time (B) & (C) before reversing to bring the legs back down (D) and shifting back to the passive state all while the drive system was running.

Of significant importance was the hip systems ability to seamlessly switch between active and passive states. The final trials actuated the outer legs independently while alternating between active hip control in the forward or reverse direction and running the hip system with the passive option. It was observed that while the driveshaft was rotating, the pawl successfully engaged with the moving shaft. This was determined as the most efficient method to lift the legs as the drive system and shaft could accelerate to desired speeds before being coupled to the leg for actuation. Figure 3.4.2 shows the motion capture for another video where the out legs are independently actuated with each iteration alternating between active and passive states.



(A) (B) (C) (D)

Figure 3.4.3: Motion capture of the two outer legs independently actuating forward. The z-leg is actuated forward (A) and in reverse (B) while the x-leg is held in position. The x-leg is actuated forward (C) and in reverse (D) while the z-leg is held in position.

The hip systems, including the HRS, demonstrated great success in the final trails of Dynamic Testing. The systems were observed to be more robust, reliable, and effective after the necessary modifications were completed. While the system was very successful in achieving proof on concept testing, there remained a number of minor problems that were not resolved.

3.5 Remaining Problems

Static Checkout uncovered communication issues between the main controller and the encoder. Troubleshooting was unsuccessful so the encoder was not used to aid in the positioning of the legs during actuation.

During Dynamic Testing when the outer legs were simultaneously actuated, it was observed that the final position of the two legs were not always exactly the same. This was attributed to the limited resolution of the HRS as solely defined by the number of teeth along the spur gear within each hip joint. A tolerance of 7.5-degrees was calculated for the 48-thooth spur gears. This would have been compensated for if the encoder had been operational.

3.6 Conclusions

With initial testing exposing a number of issues with the hip design, each system underwent an improvement review that evolved the hip system into a successful prototype. Two main observations uncovered the cause of the issues that arose during testing with the hip. First, the actual mass of the each leg was substantially larger then originally designed and second, the gate was more violent then anticipated. These two realizations coupled together, greatly impacted the hip systems reliability and ability to demonstrate success early on.

These issues were addressed with solutions implemented so that testing could continue to prove the concept of the HRS.

The mass of each leg was found to be 50% larger then originally planned. A comparison and its impact on torque requirements are outlined in Appendix A.3. This resulted in modifications to the power supply and Synchronous Drivetrain design to increase overall torque output.

To withstand greater then anticipated vibration and load tendencies during gate, functional deficiencies were successfully addressed to improve the robustness of the design. This included modifications to the HRS key and setscrews. It was concluded that the cone point setscrew concentrated too much stress at a single point that exceeded the yield properties of the shaft, causing it to cut into the shaft when turning resulting in the spur gear slipping. With the improved distribution of stresses, resulting from the increase in the number of set screws and the change in type to a flat cone point, the slipping of the spur gears ceased.

Testing of the hip provided proof in the concept of using a single drive in combination with the ratchet system to actuate the hip while providing a passive option. The main motivation for this design was to provide a testbed for future testing. Therefore, the author leaves much potential available for future work.

3.7 Recommendation for Future Work

Future testing can validate and quantify energy cost savings gained from the HRS. A baseline test would involve the actuation of all three hip joints in a controlled experiment. The resulting load will be derived from the current drawn by the stepper motor. Similar data will then be acquired during the function testing of the biped during its normal gait. A comparison of the results would yield the energy cost savings derived from the energy consumption.

As was observed during the trials, future testing will need to utilize a feedback system to optimize control and accuracy of hip actuation. In addition, a feedback control will aid in the integration of the HRS with the entire robot. The control system will determine at which periods in the gait cycle to actuate the hip and release the hip from actuation. In order for this to be accomplished, the communication issues with the encoder need to be resolved.

The resolution of the E6S encoder is 1800-lines resulting in 7200 pulses per revolution. This is gained from the two encoder channels for the controller. With the quadrature encoder, the direction of rotation can be determined from the order at which a line is recognized from the two sensors. The optical incremental encoder will convert the angular position of the shaft into a digital code. From the code, the angular position of the rotating shaft can thus be determined and controlled. Future work can use this information to determine the relative position of the spur gears to the shaft and relative leg position.

3.8 References

[1] Baker, B., 2010, "Development of a hybrid powered 2D biped walking machine designed for rough terrain locomotion," Ph.D. thesis, the University of Kansas, Lawrence, KS.

3.9 Acknowledgments

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APPENDIX A: HIP RATCHET SYSTEM DESIGN SUPPLEMENT

A.1. Bill of Materials

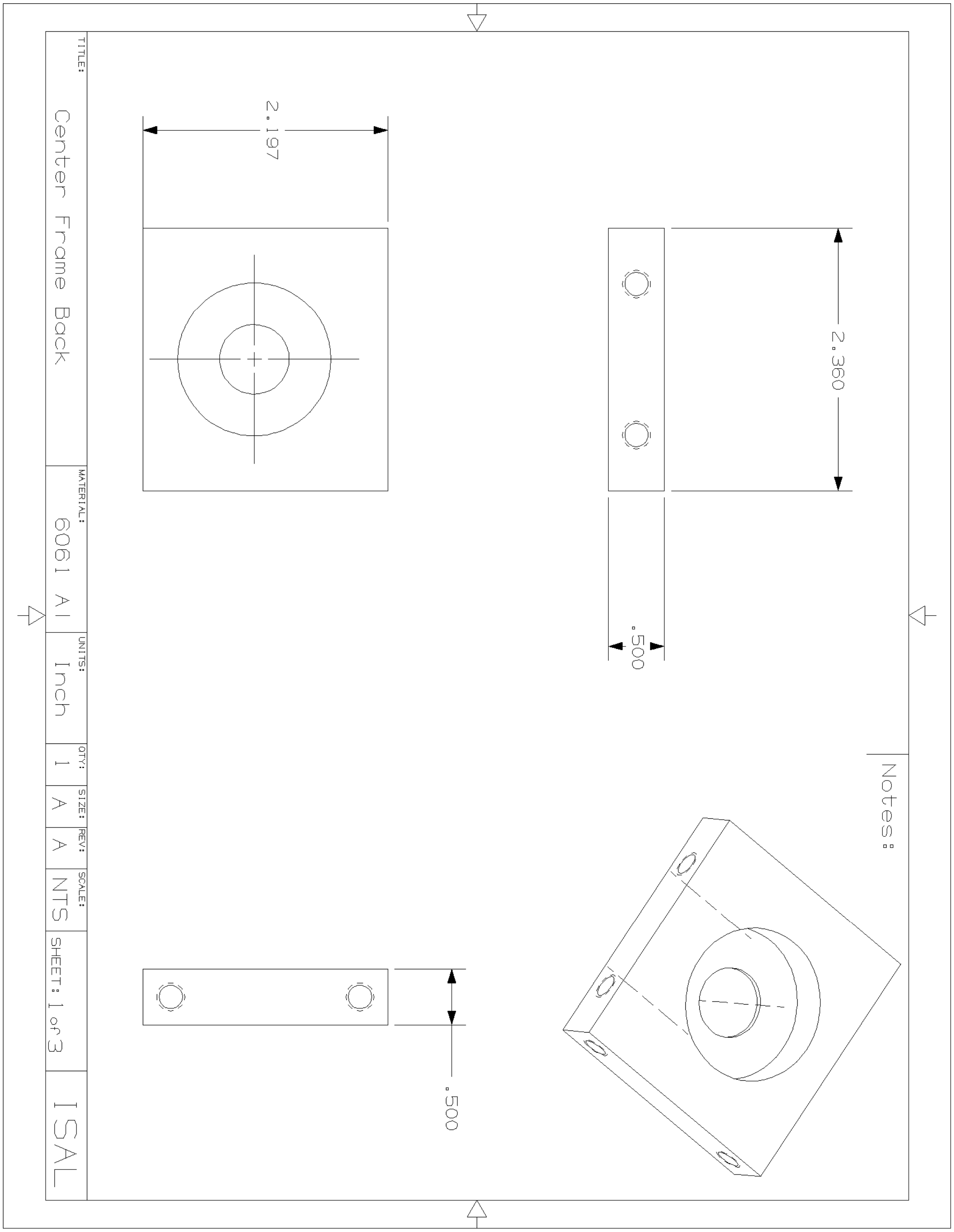
Descriptive Part Name	Quantity	Procurement	Supplier	Part Number	Unit Price	Total Cost	Status
PELVIS_ASSEMBLY	**1**	-----------	-----------	-----------	-----------	**$ 1,470.03**	
Pelvis_Center_Frame_Assembly	**1**	-----------	-----------	-----------	-----------	**$ 18.92**	**Built**
pelvis_center_frame	11.64 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 1.35	Built
pelvis_center_frame_back	5.19 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 0.59	Built
pelvis_hip_ball_bearing_0-500shaft_dia x 2	2	Order	MMC	Nice 1621	$ 5.00	$ 10.00	Stock
pelvis_frame_top	3.54 in^2	Order	MBTF	1/2" 6061 Al	$ 11.94	$ 0.40	Built
pelvis_frame_mounting x 4	63.88 in^2	Machine	MBTF	1/4" 5052 Al	$ 14.84	$ 6.58	Built
Pelvis_Center_Hip_Joint_Assembly	**1**	-----------	-----------	-----------	-----------	**$ 61.89**	
pelvis_center_hip_joint_left	11.02 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 1.25	Built
pelvis_center_hip_joint_right	11.02 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 1.25	Built
pelvis_dual_pawl	1	Order	eBay	-----------	$ 3.00	$ 3.00	Stock
pelvis_hip_bushing_0-504id_05lg	1	Order	MMC	6389K233	$ 1.21	$ 1.21	Stock
pelvis_hip_spur_gear_48teeth_0-500bore	1	Order	SDP-SI	S10C9Z-024H048	$ 38.12	$ 38.12	Stock
pelvis_hip_bushing_0-875id_125lg	1	Order	MMC	6389K555	$ 1.42	$ 1.42	Stock
Pelvis_Drivetrain_Assembly	**1**	-----------	-----------	-----------	-----------	**$ 601.60**	
pelvis_drive_shaft	1	Order/Modify	MMC	4416T16	$ 10.70	$ 10.70	Stock
pelvis_hip_motor_ms23_stepper	1	Order	IBT	MS23C	$ 60.00	$ 60.00	Stock
pelvis_hip_planetary_gearhead	1	Order	IBT	EQ60/23-030	$ 450.00	$ 450.00	Stock
pelvis_hip_timing_belt_55teeth_0-375wide_0-200XLpitch	1	Order	SDP-SI	A 6B 3-055037	$ 5.58	$ 5.58	Stock
pelvis_hip_timing_pulley_16teeth_0-375bore_0-200XLpitch	1	Order	SDP-SI	A 6A 3-16DF03712	$ 9.08	$ 9.08	Stock
pelvis_hip_timing_pulley_32teeth_0-500bore_0-200XLpitch	1	Order	SDP-SI	A 6A 3-32NF03716	$ 14.64	$ 14.64	Stock
pelvis_hip_e6_digital_encoder_0-500dia	1	Order	USD	E6S-1800-500	$ 51.45	$ 51.45	Stock
Pelvis_Outer_Frame_Assembly x 2	**2**	-----------	-----------	-----------	**$ 6.87**	**$ 13.74**	
pelvis_hip_ball_bearing_0-375shaft_dia x 2	2	Order	MMC	6383K32	$ 2.58	$ 5.16	Stock
pelvis_outer_frame_front	6.37 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 0.72	Built
pelvis_frame_top	3.54 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 0.40	Built
pelvis_outer_frame_back	5.19 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 0.59	Built
Pelvis_Outer_Hip_Joint_Assembly x 2	**2**	-----------	-----------	-----------	**$ 190.04**	**$ 380.07**	
pelvis_dual_pawl	1	Order	MBTF	-----------	$ 3.00	$ 3.00	Stock
pelvis_hip_bushing_0-375id_05lg x 2	1	Order	MMC	6389K445	$ 1.37	$ 1.37	Stock
pelvis_hip_servo_6vdc_54rpm_378oz-in	1	Order	On-line	DS8711	$ 139.99	$ 139.99	Stock
pelvis_hip_spur_gear_48teeth_0-375bore	1	Order	SDP-SI	S10C8Z-024H048	$ 38.12	$ 38.12	Stock
pelvis_hip_bushing_0-875id_125lg	1	Order	MMC	6389K555	$ 1.42	$ 1.42	Stock
pelvis_outer_hip_joint_left	11.02 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 1.25	Built
pelvis_outer_hip_joint_right	11.02 in^2	Machine	MBTF	1/2" 6061 Al	$ 11.94	$ 1.25	Built

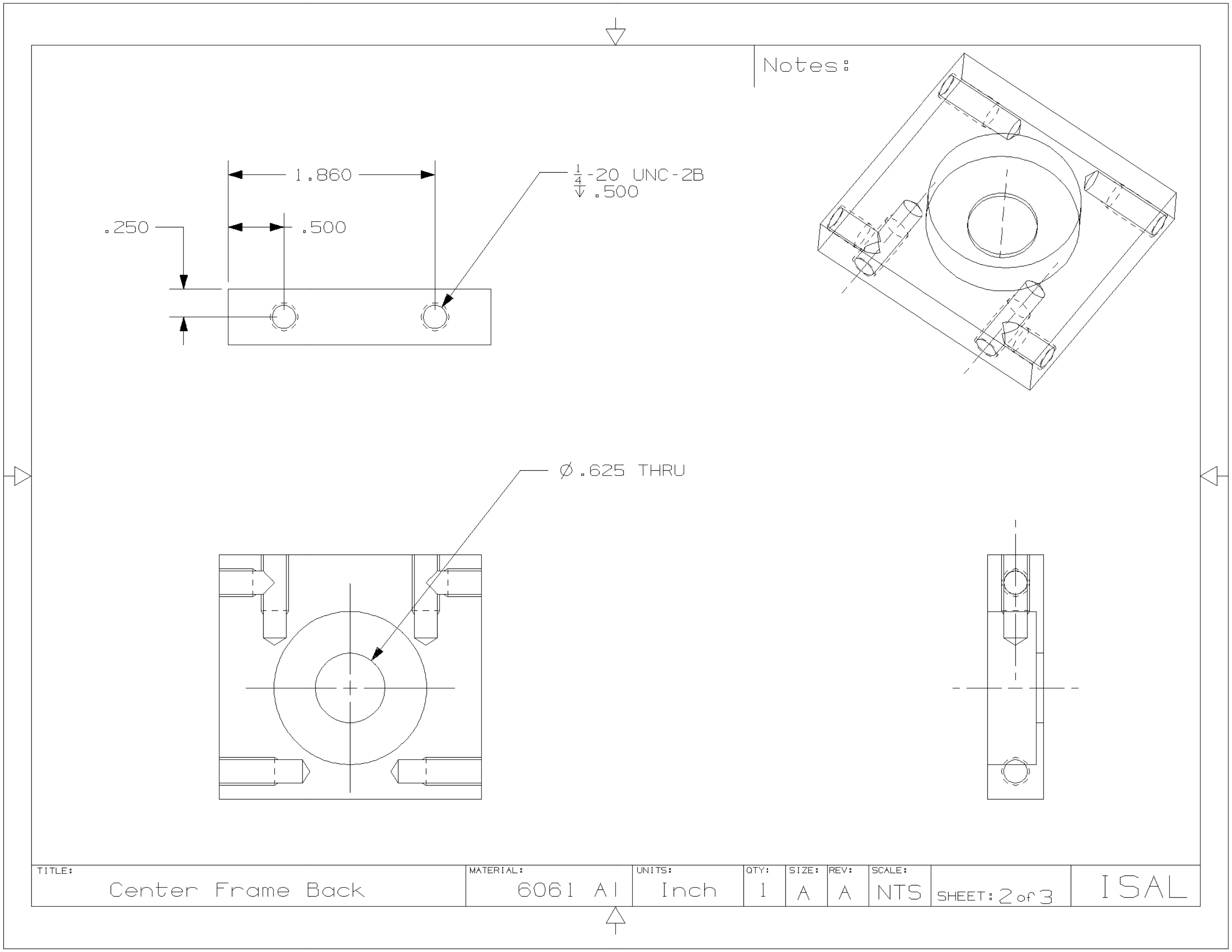
A.2. Control System Code

```
' ServoActuation for pawl movment
' Revision 2-14-2010
' {$STAMP BS2}
' {$PBASIC 2.5}

INPUT IN3
counter VAR Word
main:

IF (IN3 = 1) THEN GOSUB Fwd
IF (IN4 = 1) THEN GOSUB Rvs

LOW 10

DEBUG "Neutral", CR
DEBUG BIN IN3,CR
FOR counter = 1 TO 5              'Need to avoid bounce in switch

PULSOUT 14, 600                   'Position to hold pawl in neutral position
PAUSE 2
NEXT

GOTO main
END

' -----------------------------------------------------------------------------------------

Fwd:

DO WHILE (IN3 = 1)

HIGH 10
DEBUG BIN IN3,CR
DEBUG "Forward", CR
  FOR counter = 1 TO 5
  PULSOUT 14, 700                 'Position to lock pawl in forward position
  PAUSE 2
  NEXT

LOOP

RETURN

' -----------------------------------------------------------------------------------------
```

```
Rvs:

DO WHILE (IN4 = 1)

HIGH 11
DEBUG BIN IN4,CR
DEBUG "Reverse", CR
  FOR counter = 1 TO 5
  PULSOUT 14, 500                    'Position to lock pawl in reverse position
  PAUSE 2
  NEXT

LOOP

RETURN
```

A.3. Detailed Part Drawings





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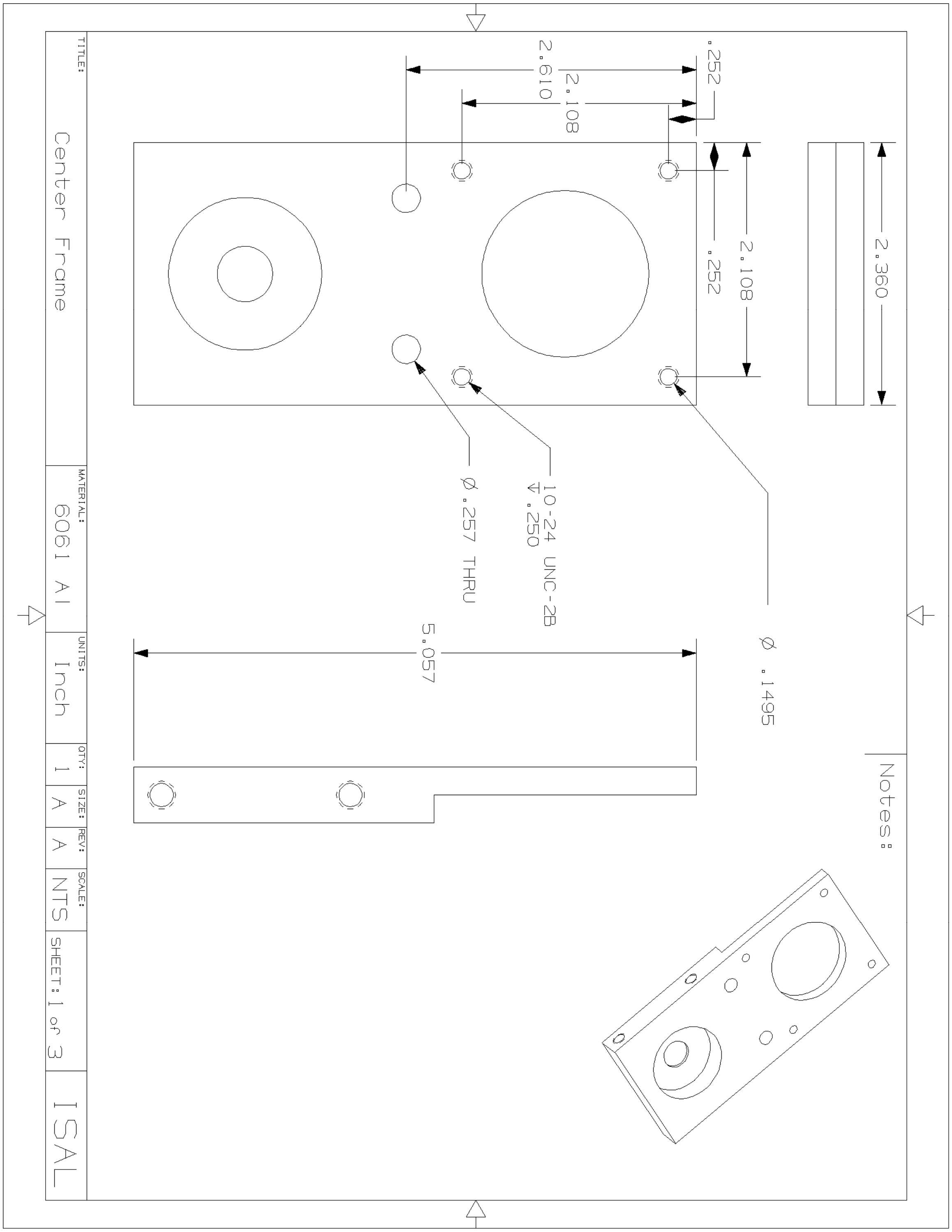

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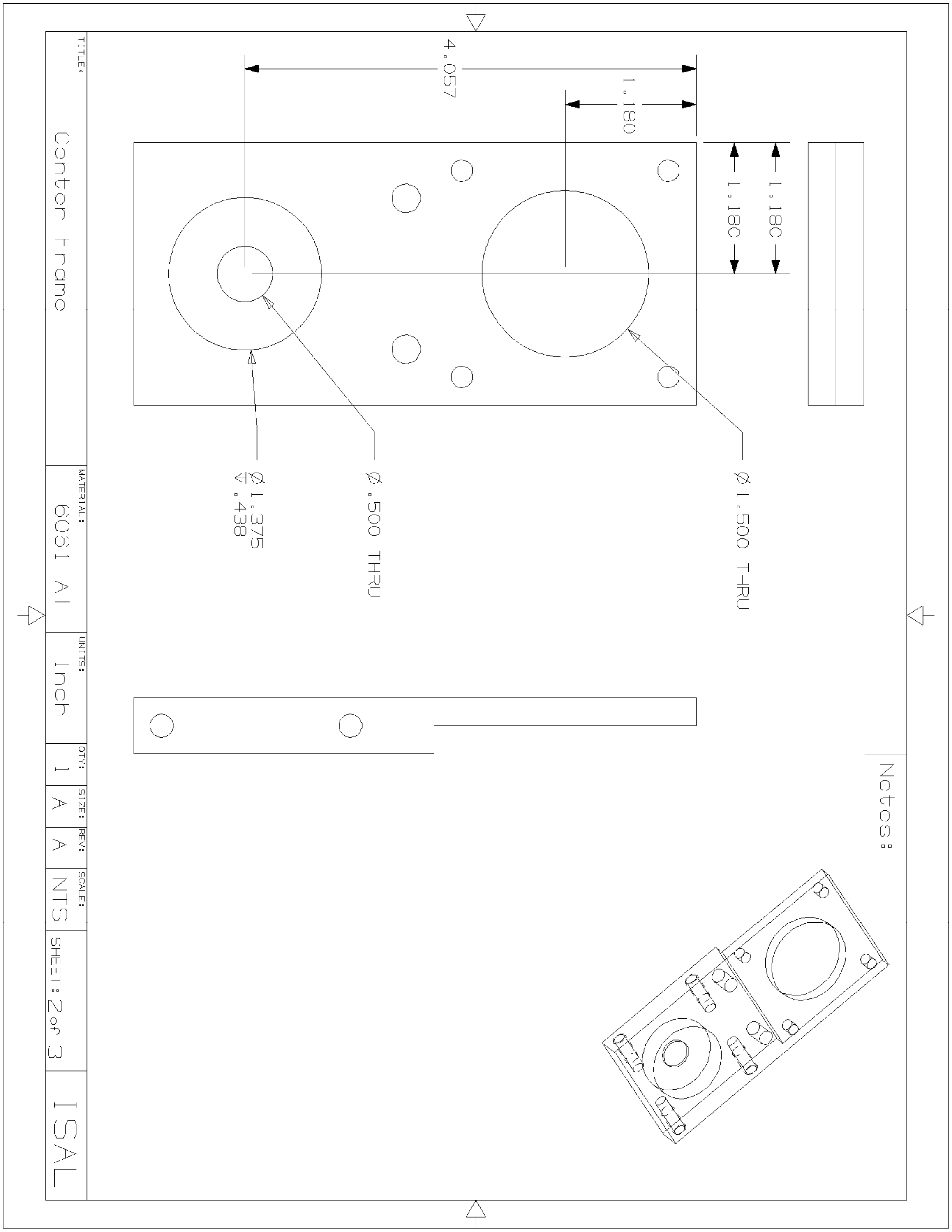
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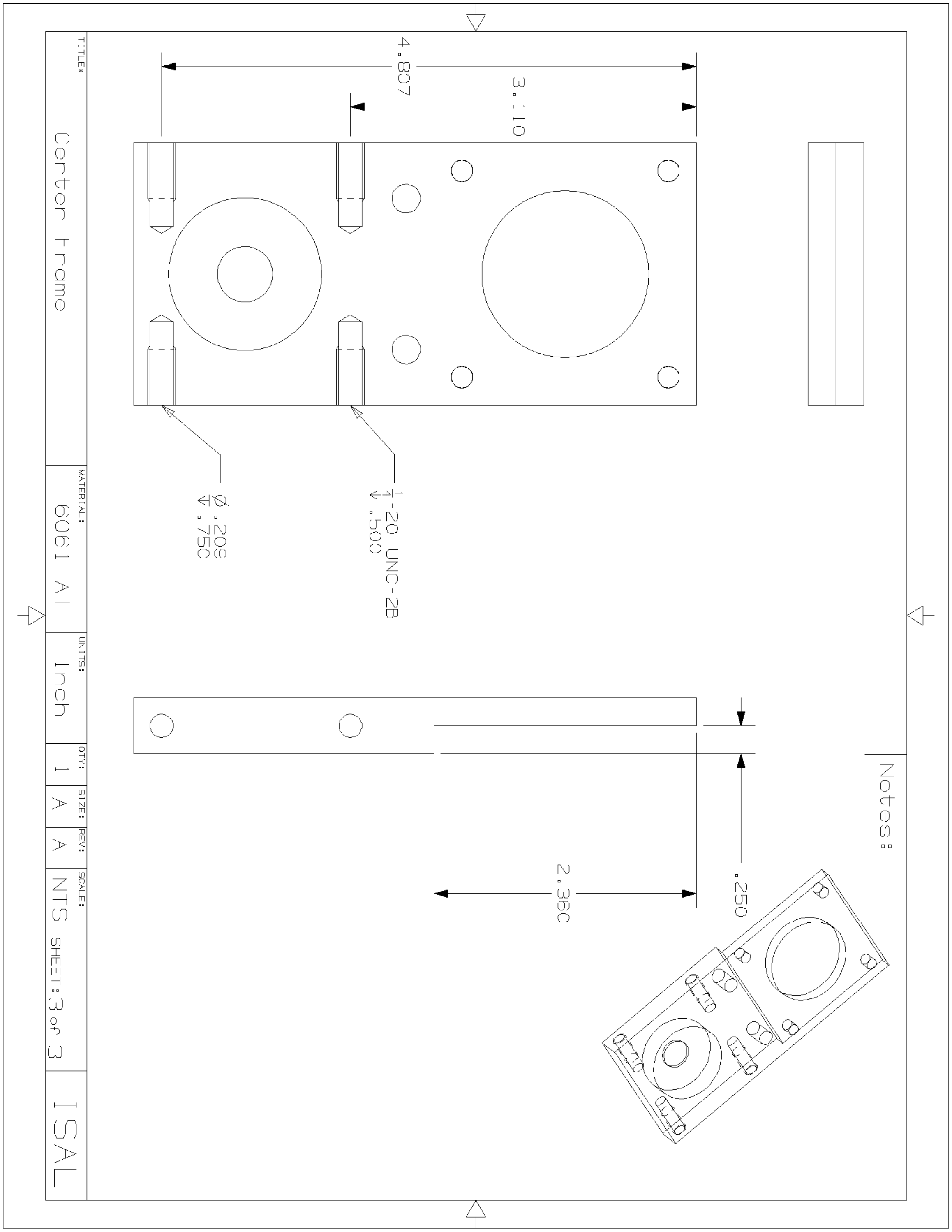
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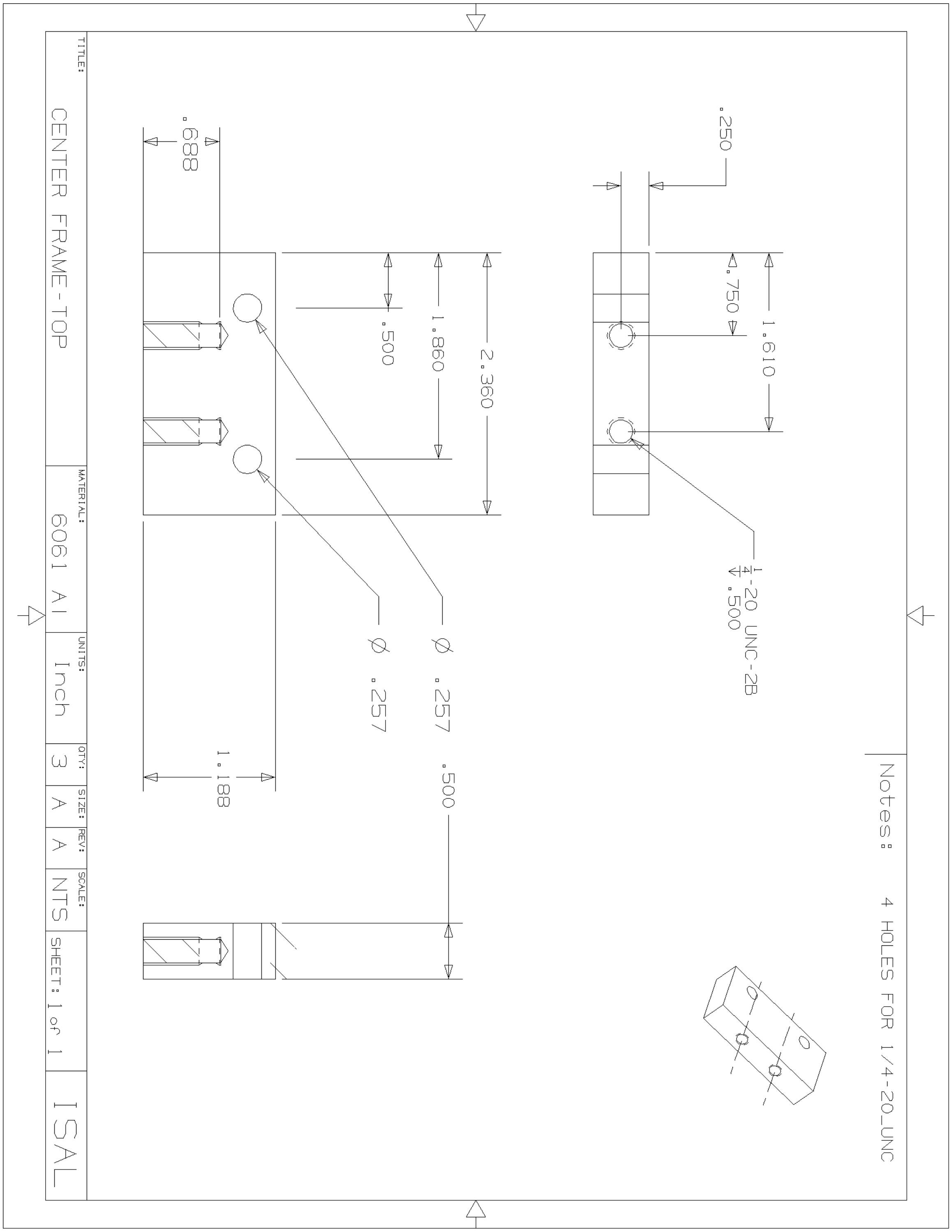
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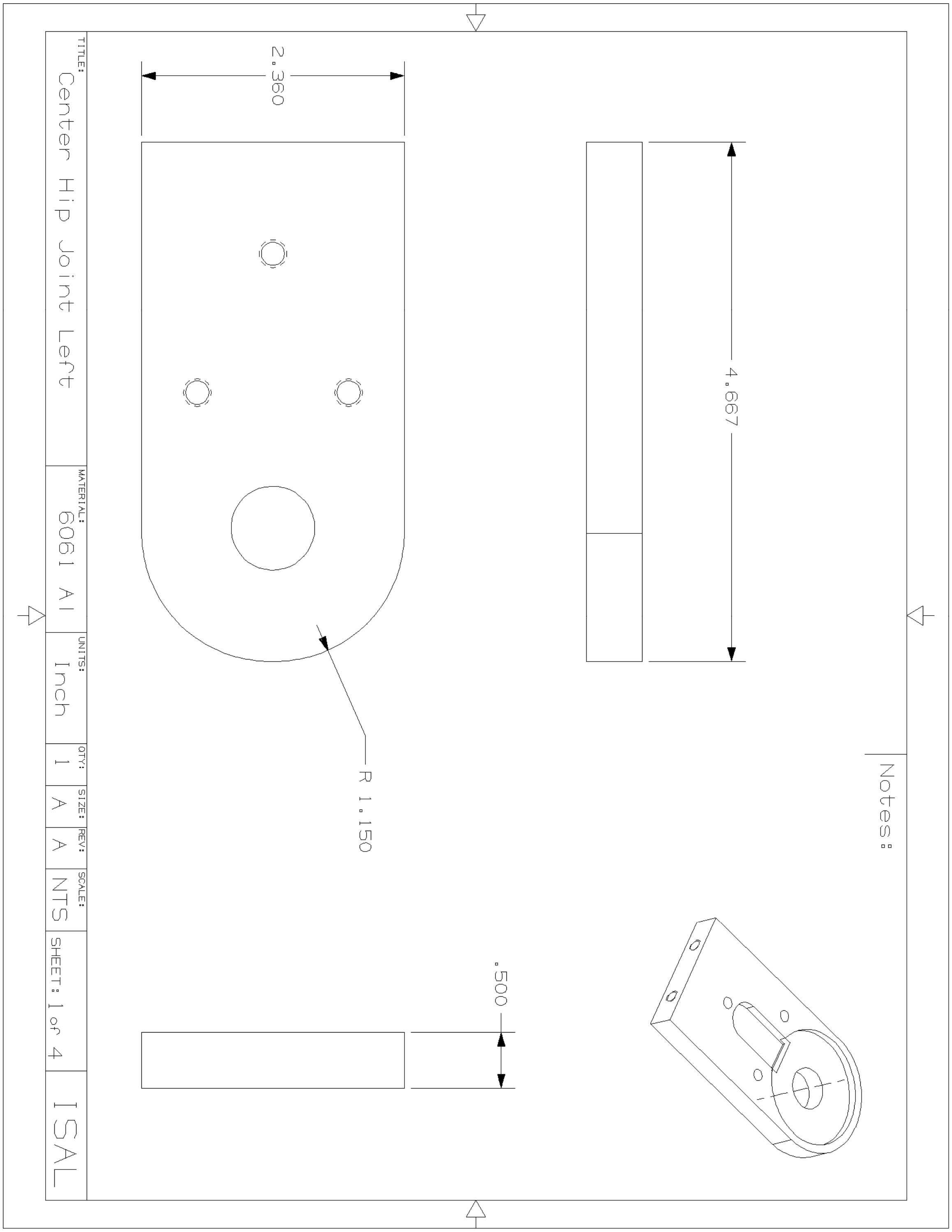
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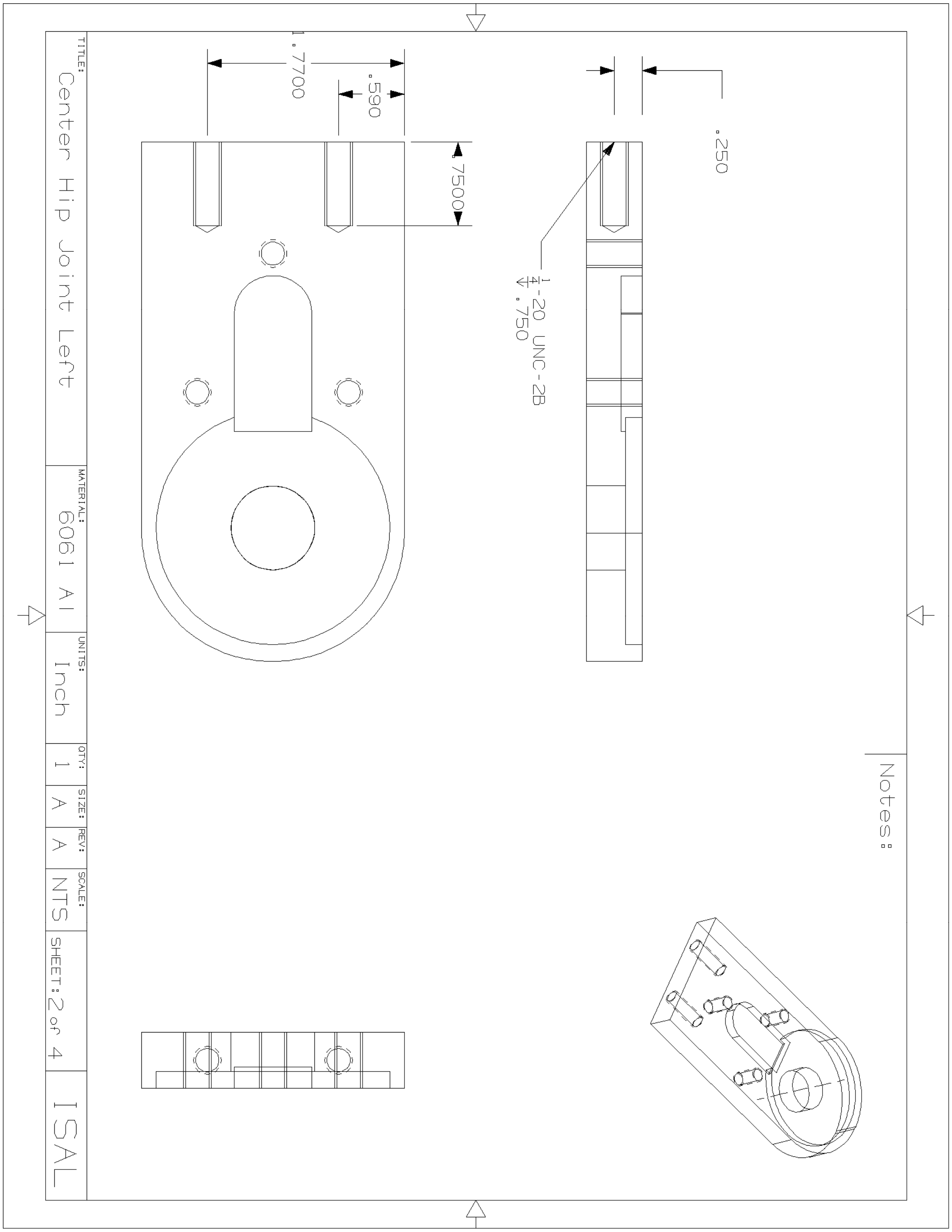
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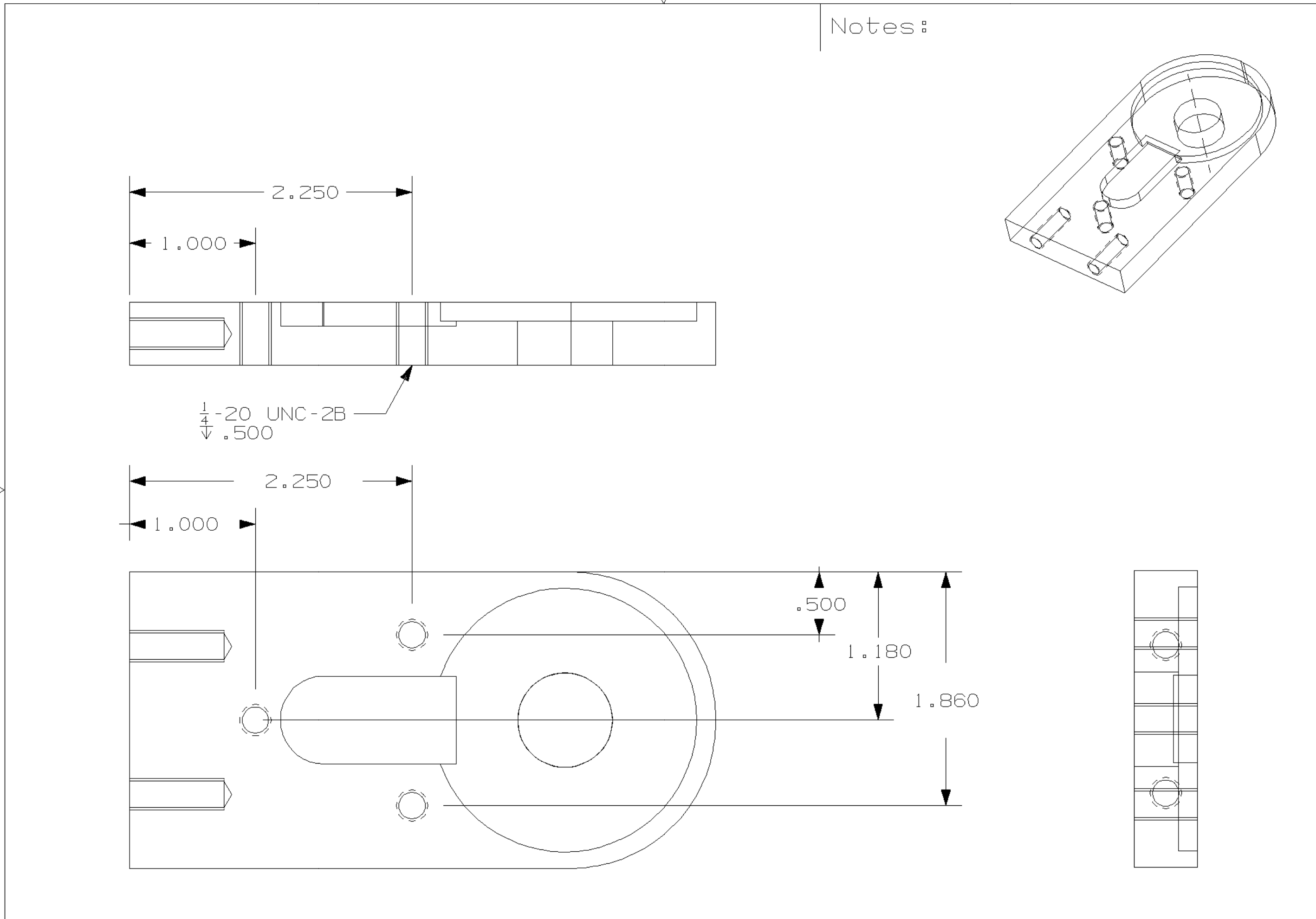

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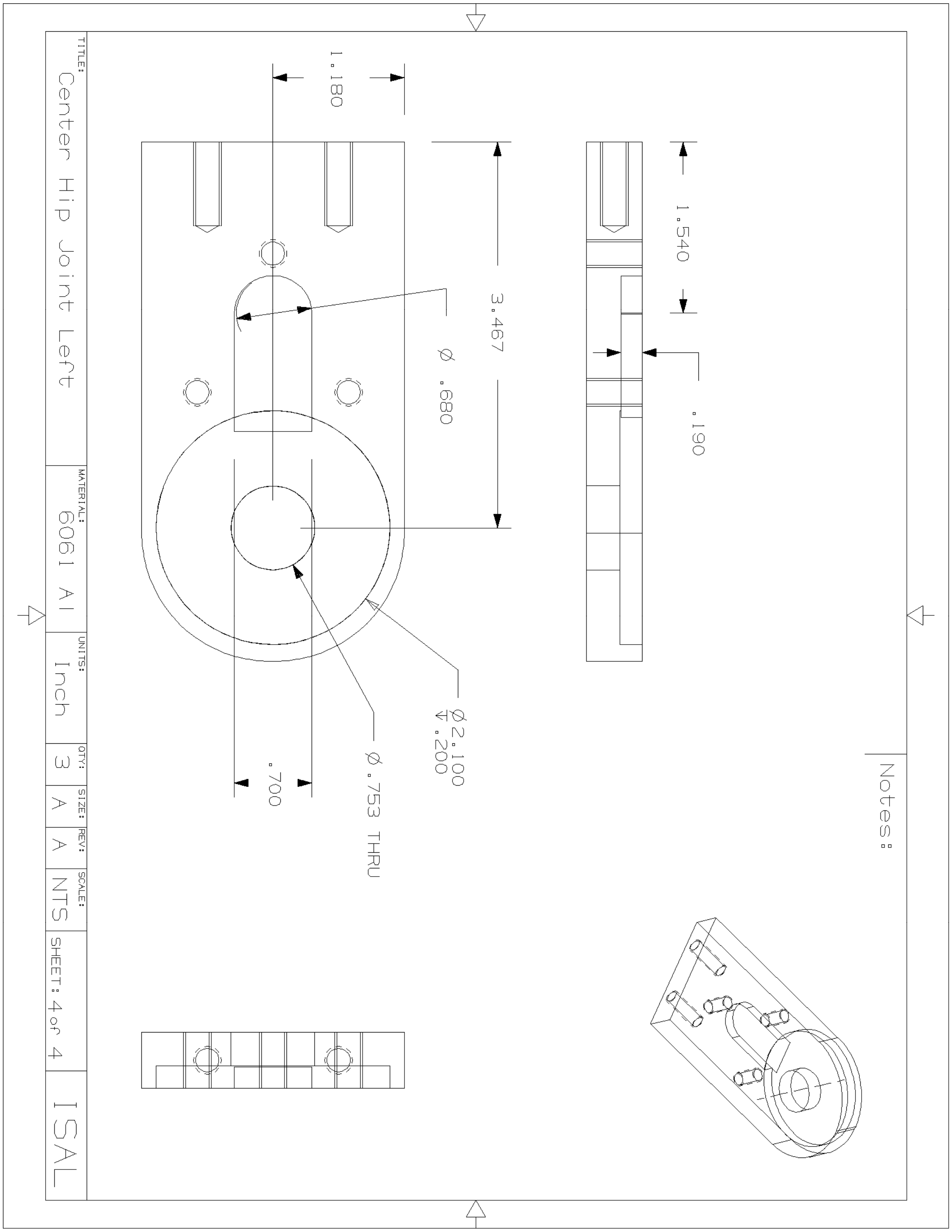
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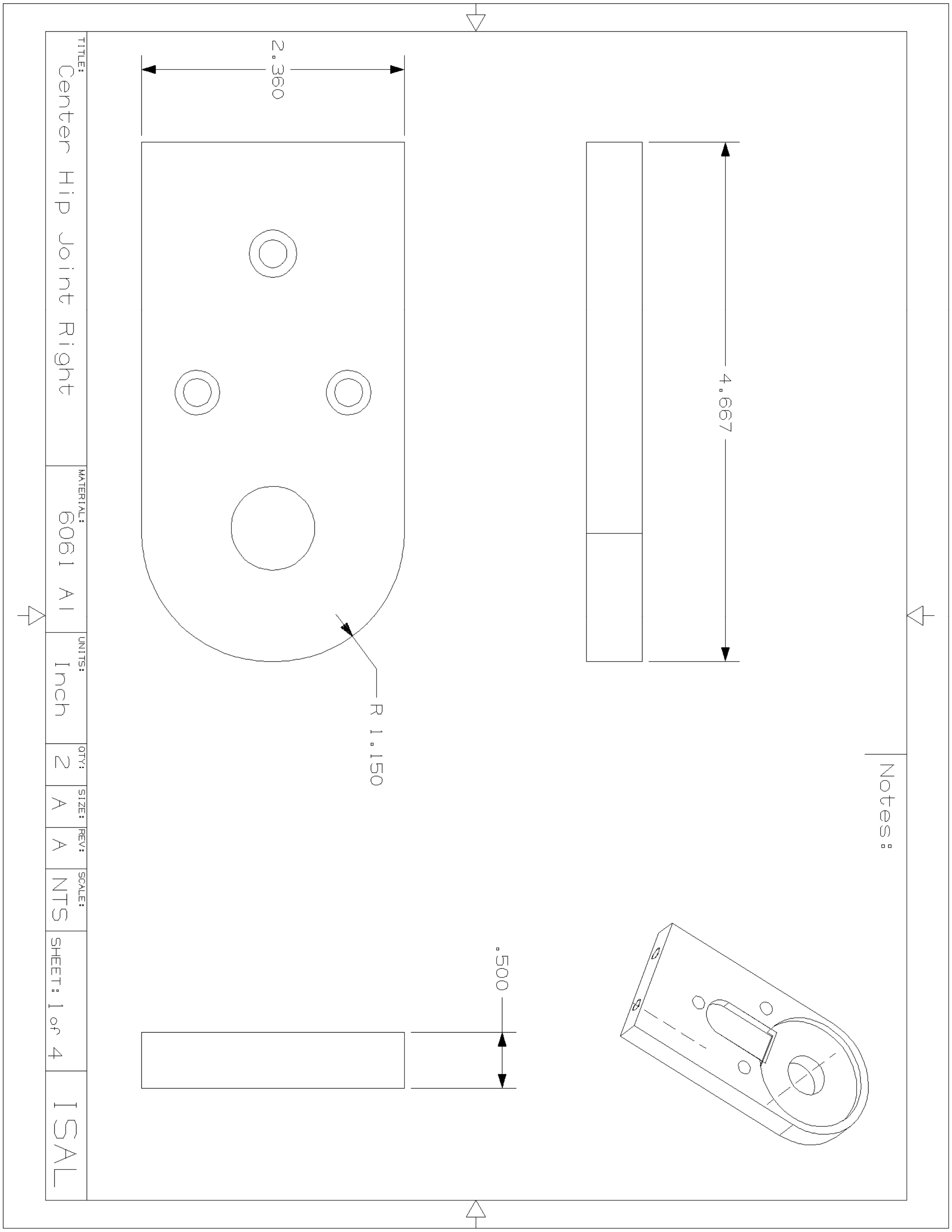
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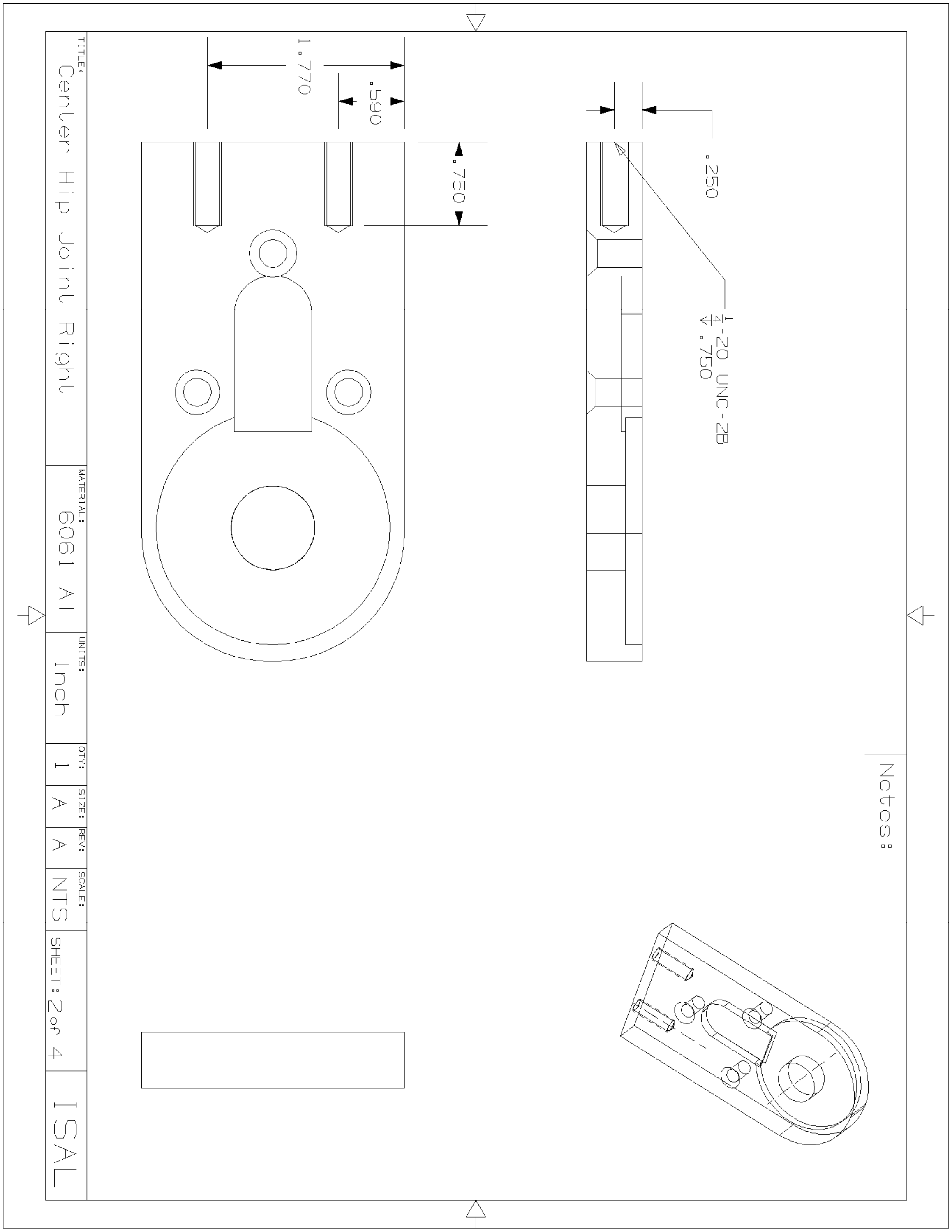
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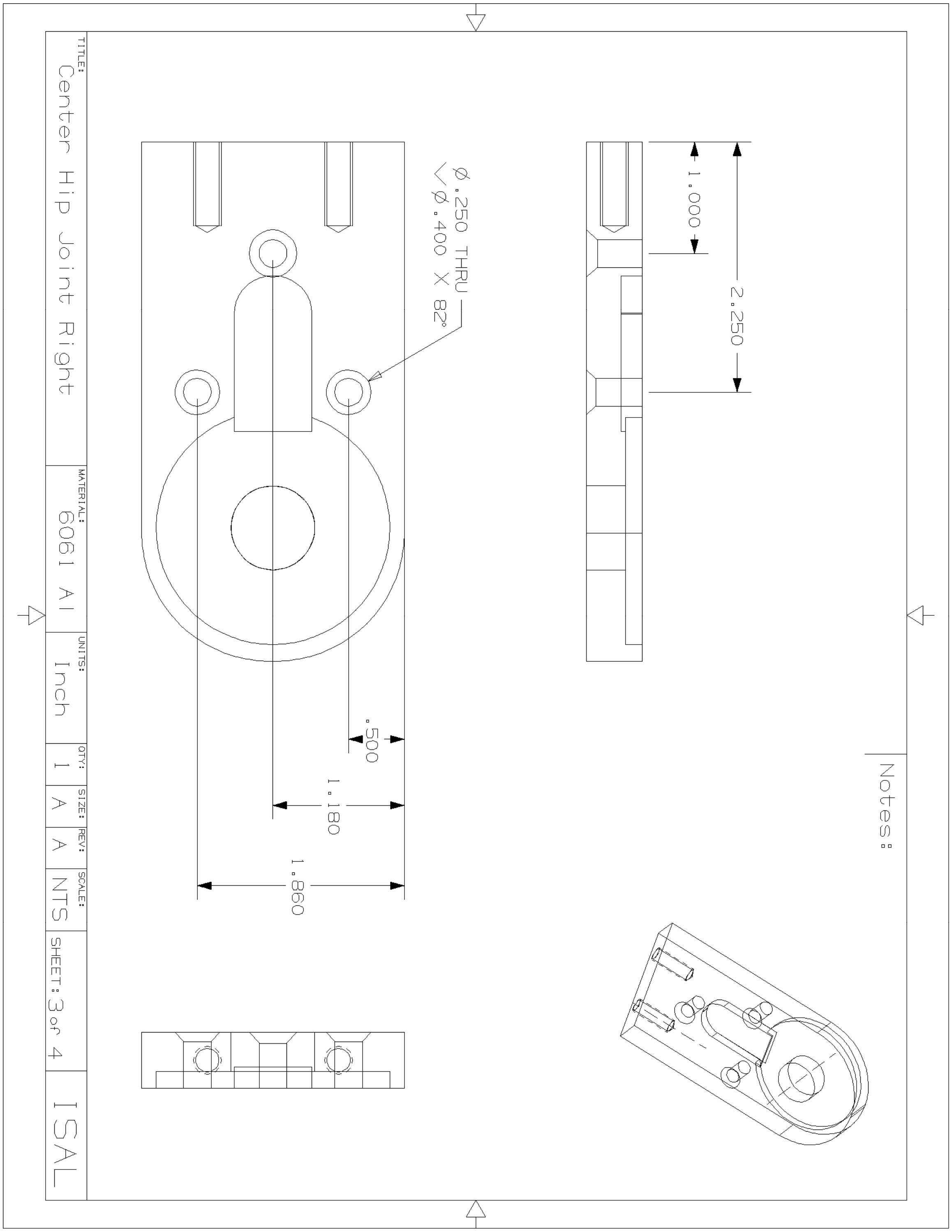
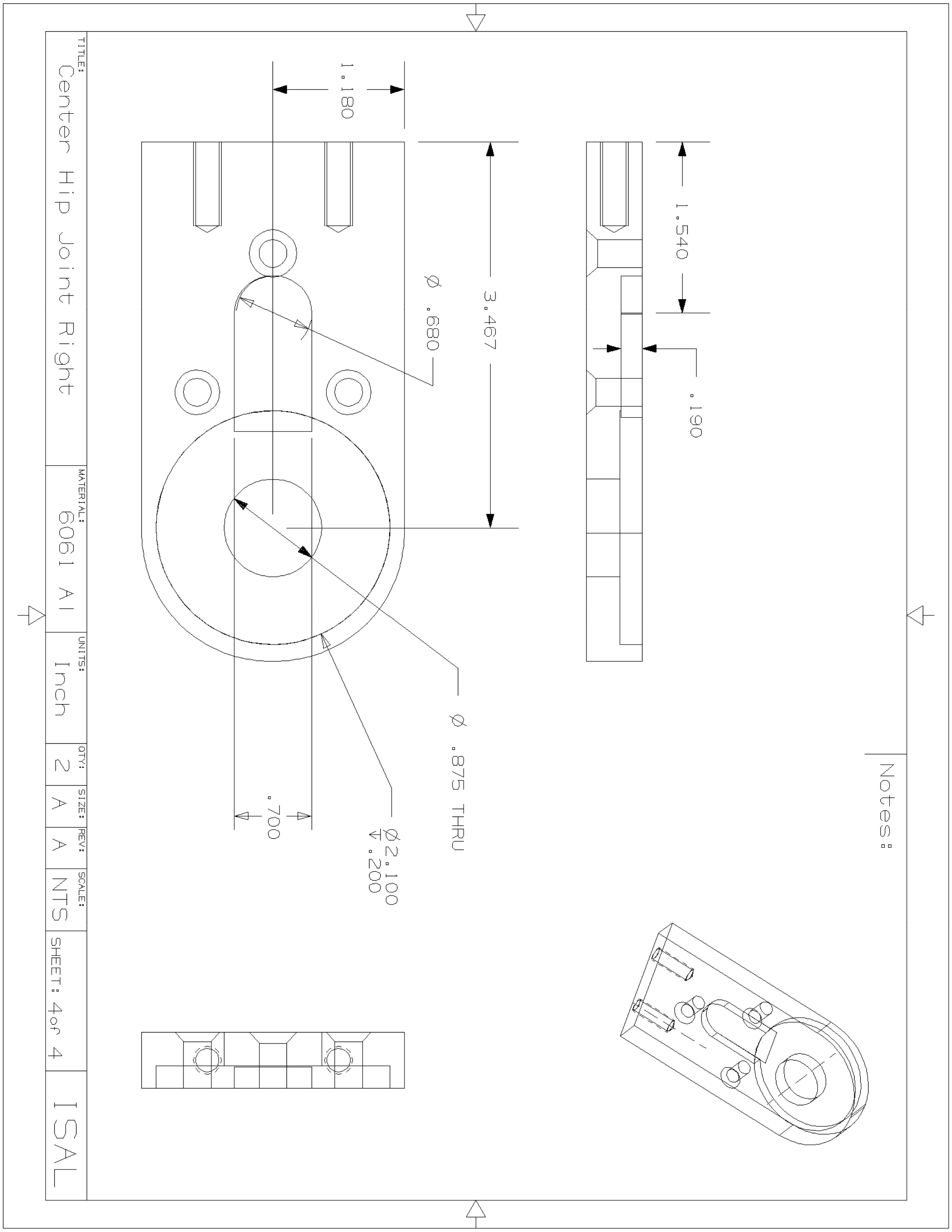
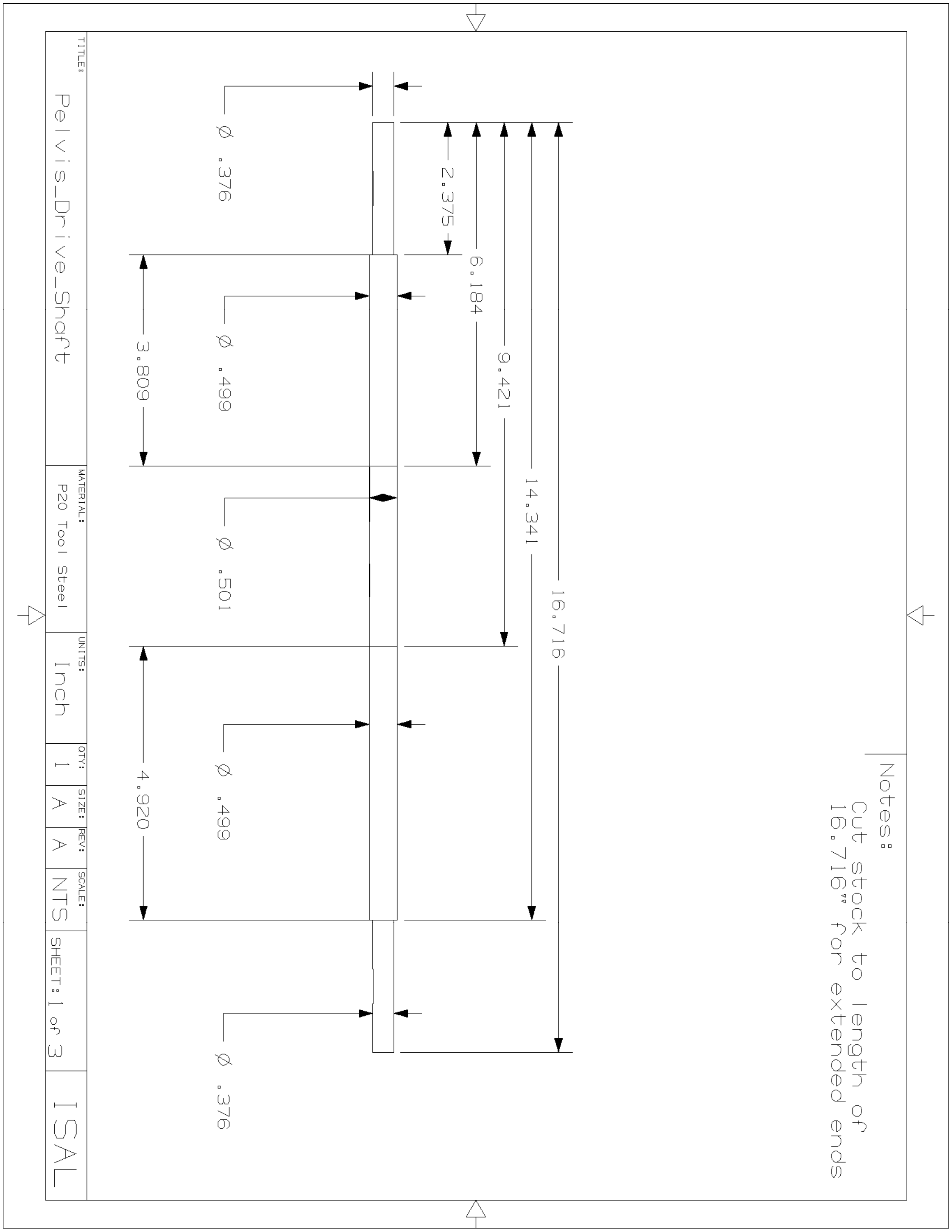
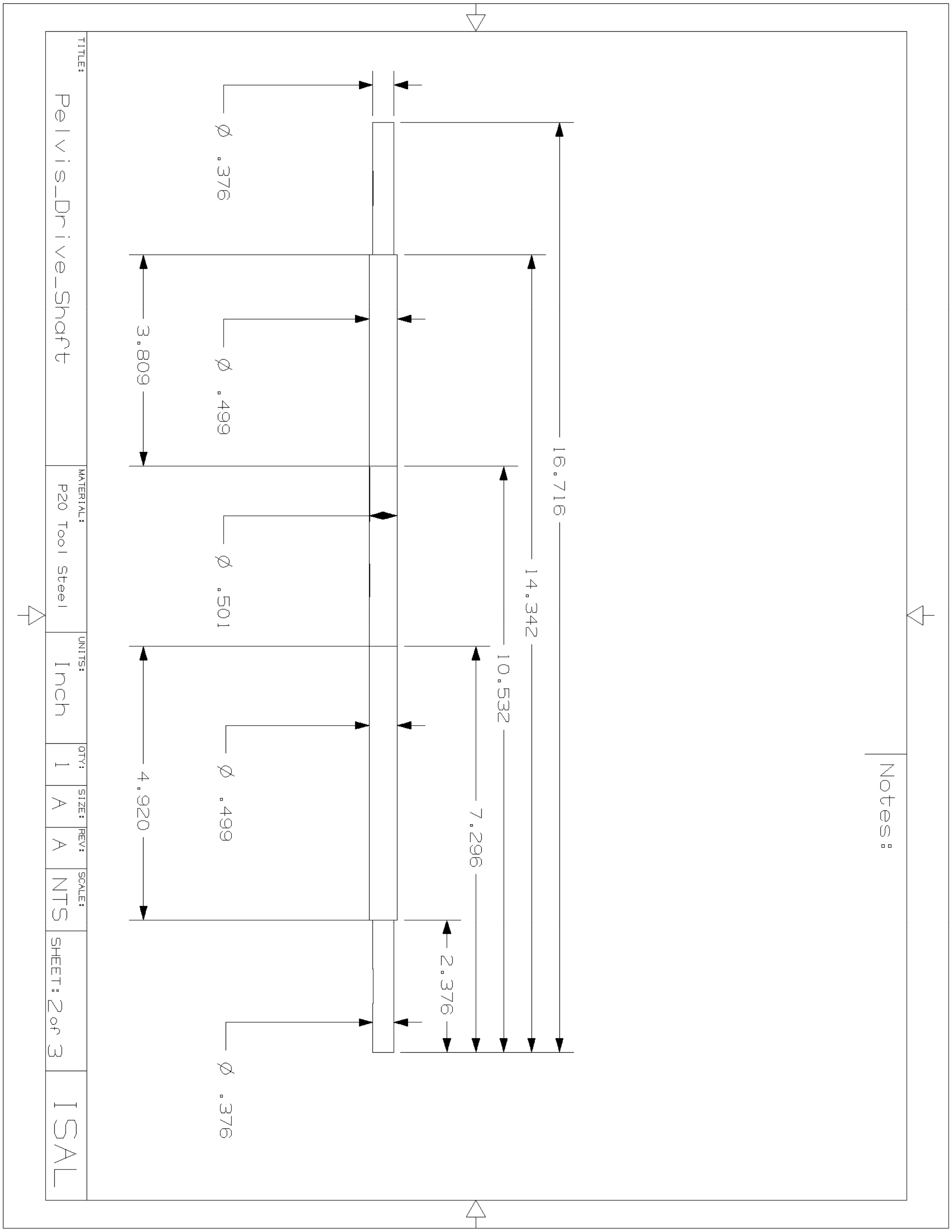
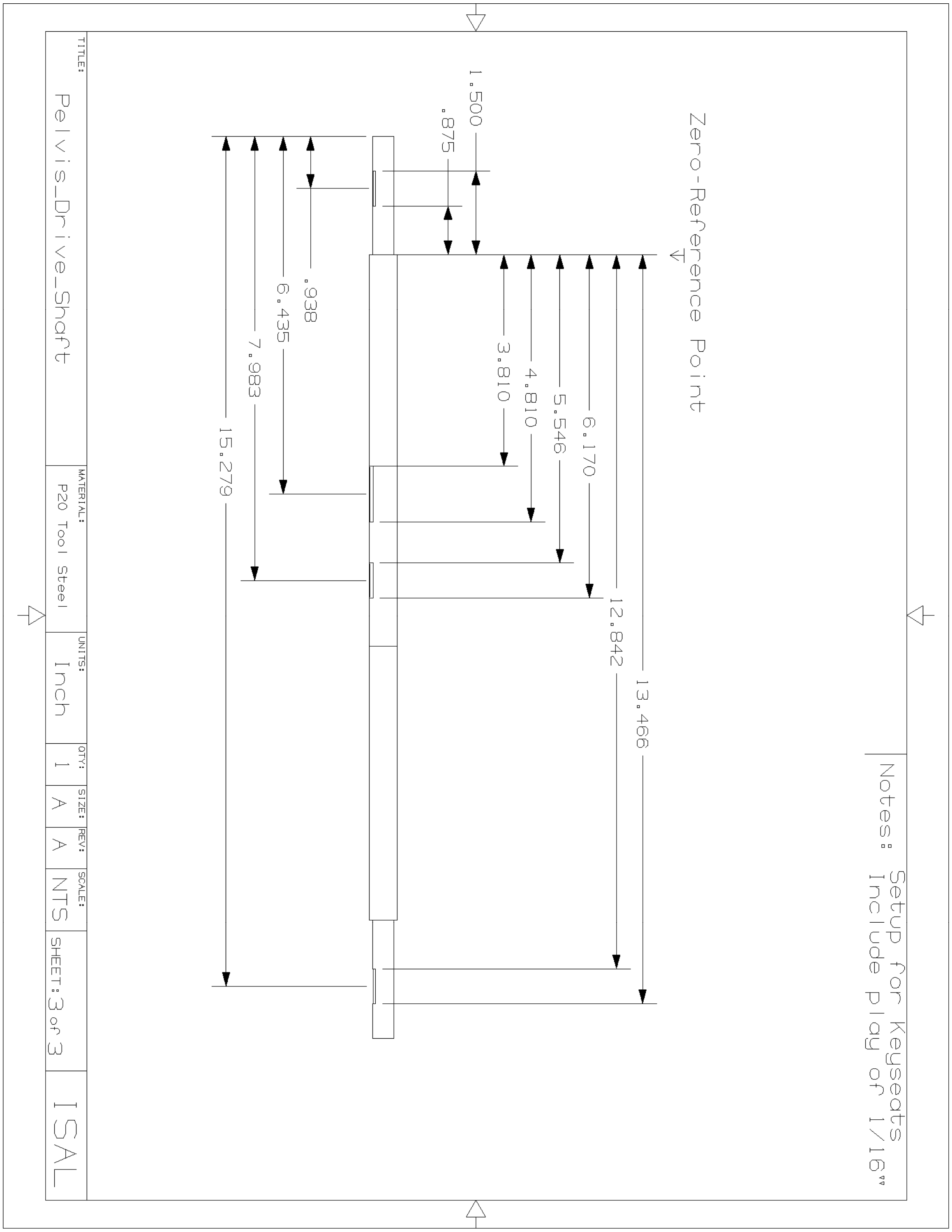
REV:
A
SCALE:
NTS
SHEET: 2 of 4
ISAL
1.770
.590
.750
.250
1/4-20 UNC-2B
↧ .750
Notes:

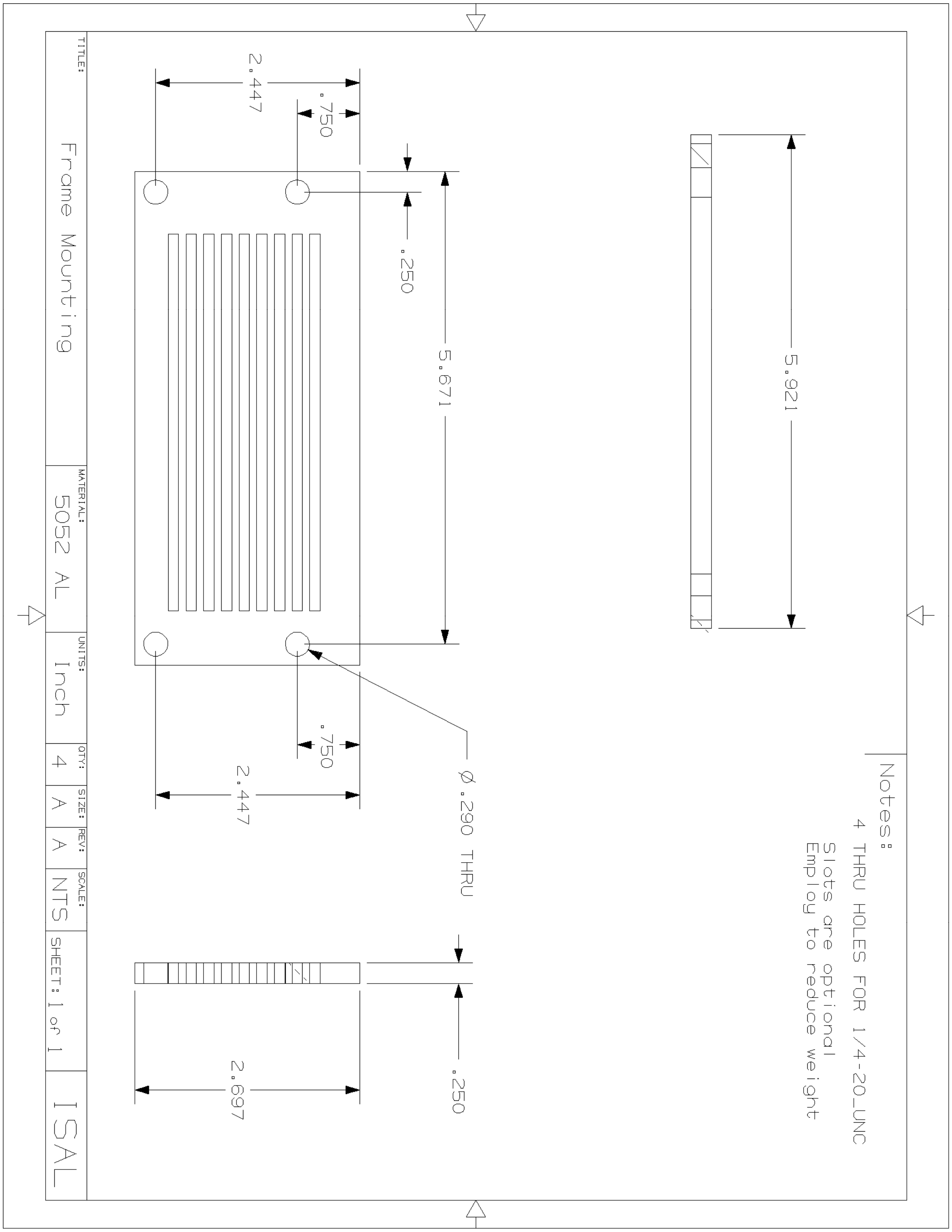

TITLE: Center Hip Joint Right
MATERIAL: 6061 Al
UNITS: Inch
QTY: 1
SIZE: A
REV: A
SCALE: NTS
SHEET: 3 of 4
ISAL
Ø.250 THRU
⌵ Ø.400 X 82°
1.000
2.250
.500
1.180
1.860
Notes:

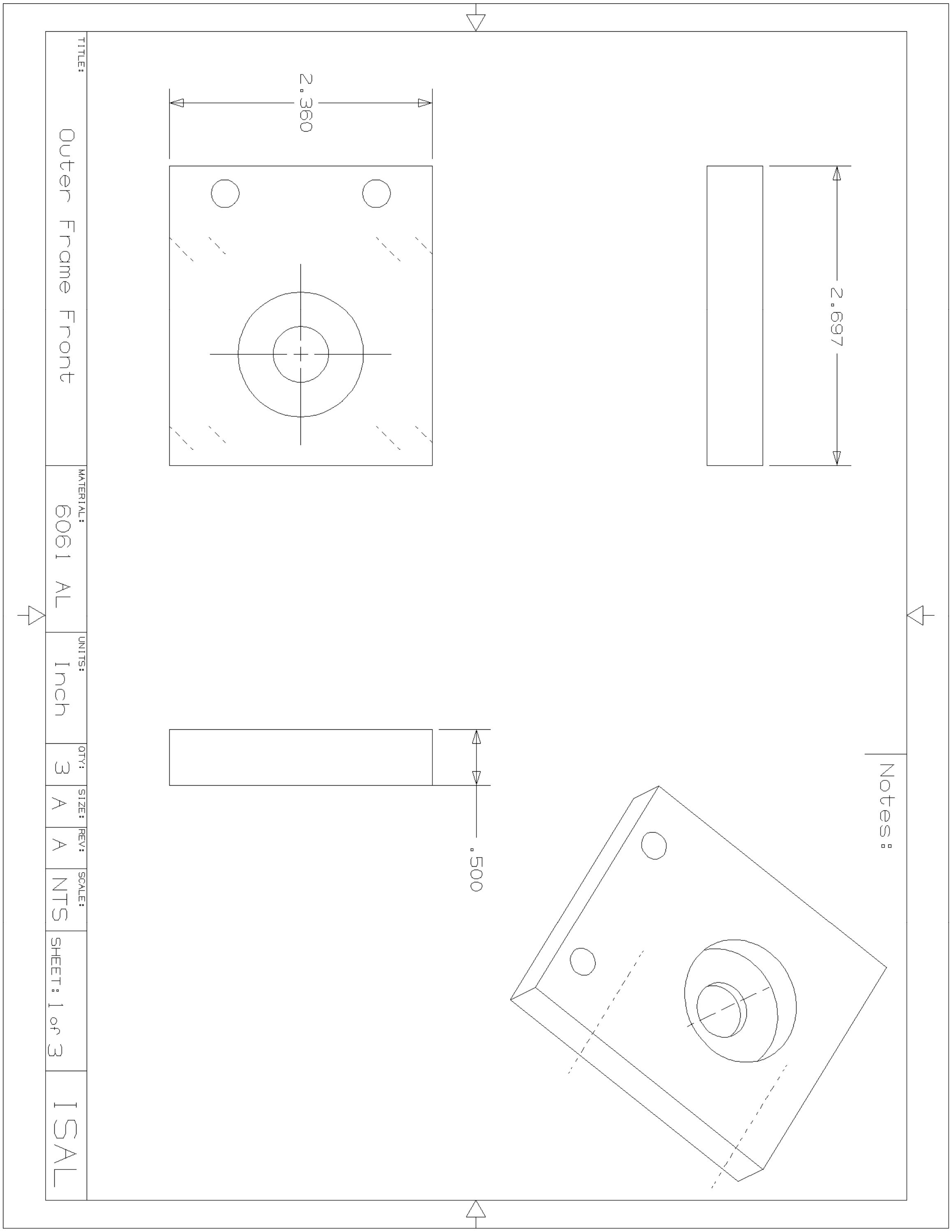

TITLE:
Center Hip Joint Right
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 4 of 4
ISAL
Notes:
1.180
3.467
Ø .680
1.540
.190
Ø .875 THRU
.700
Ø2.100
.200

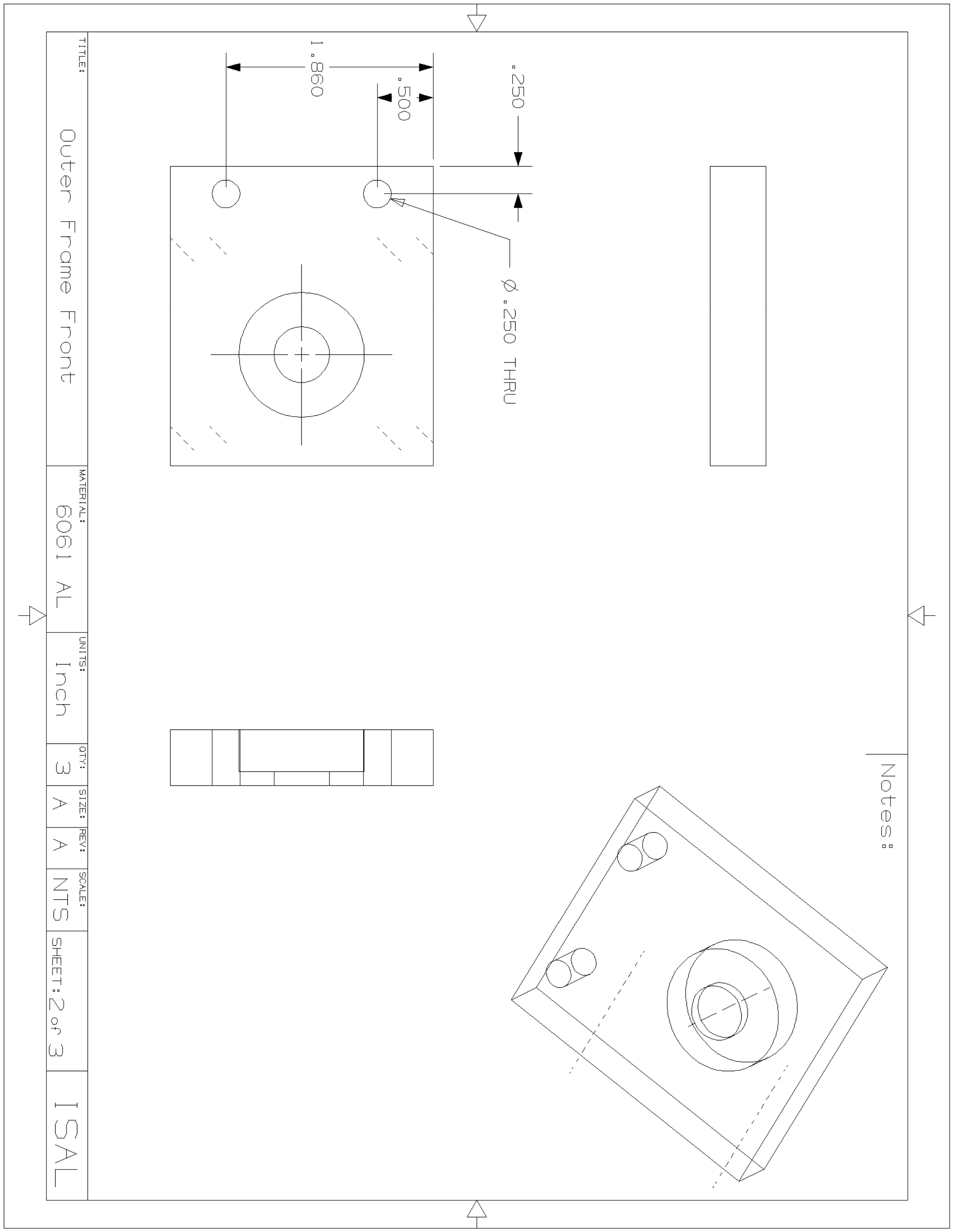

TITLE:
Pelvis_Drive_Shaft
MATERIAL:
P20 Tool Steel
UNITS:
Inch
QTY:
1
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 1 of 3
ISAL
Notes:
Cut stock to length of
16.716" for extended ends
Ø .376
Ø .499
Ø .501
Ø .499
Ø .376
2.375
6.184
9.421
14.341
16.716
3.809
4.920

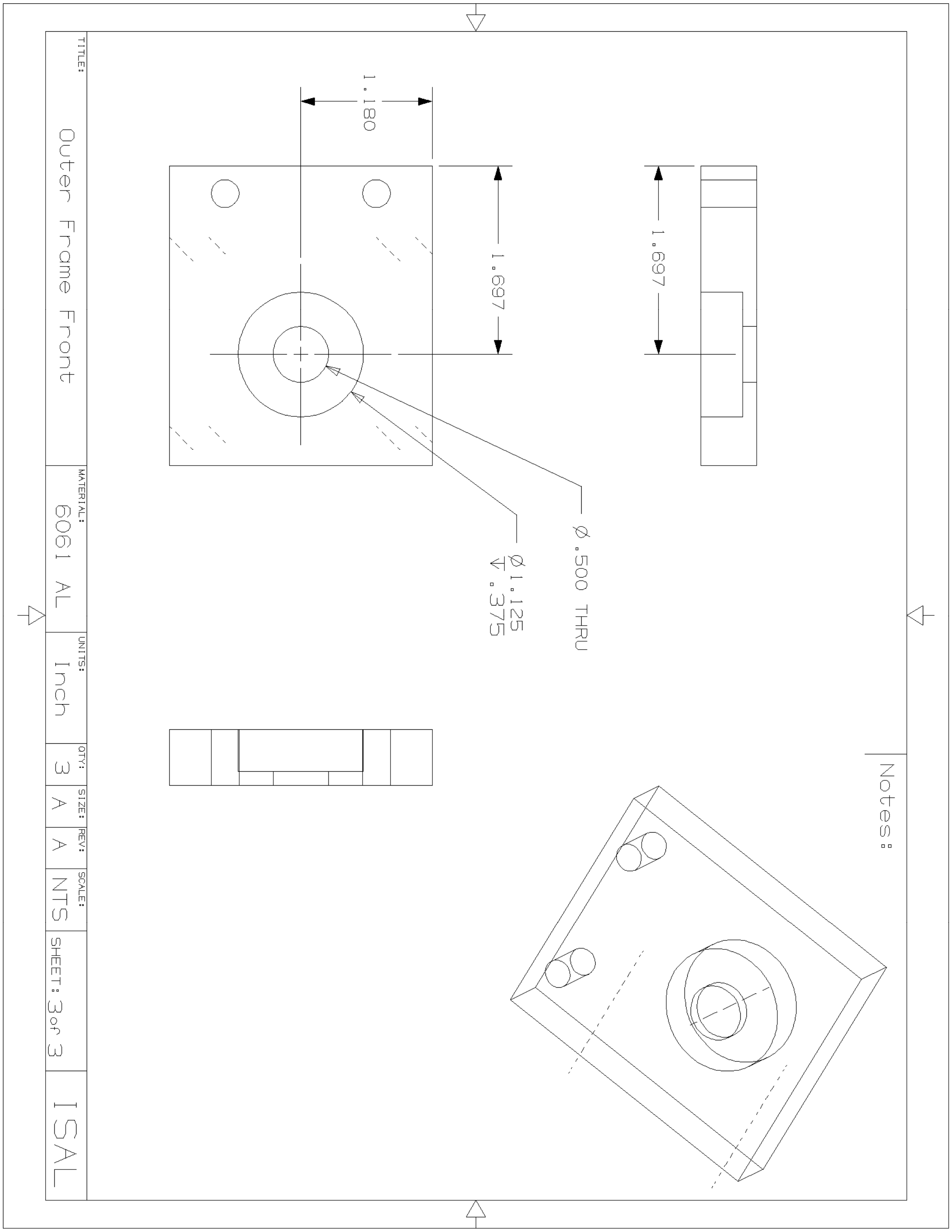

TITLE:
Pelvis_Drive_Shaft
MATERIAL:
P20 Tool Steel
UNITS:
Inch
QTY:
1
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 2 of 3
ISAL
Notes:
Ø .376
Ø .499
Ø .501
Ø .499
Ø .376
3.809
4.920
16.716
14.342
10.532
7.296
2.376

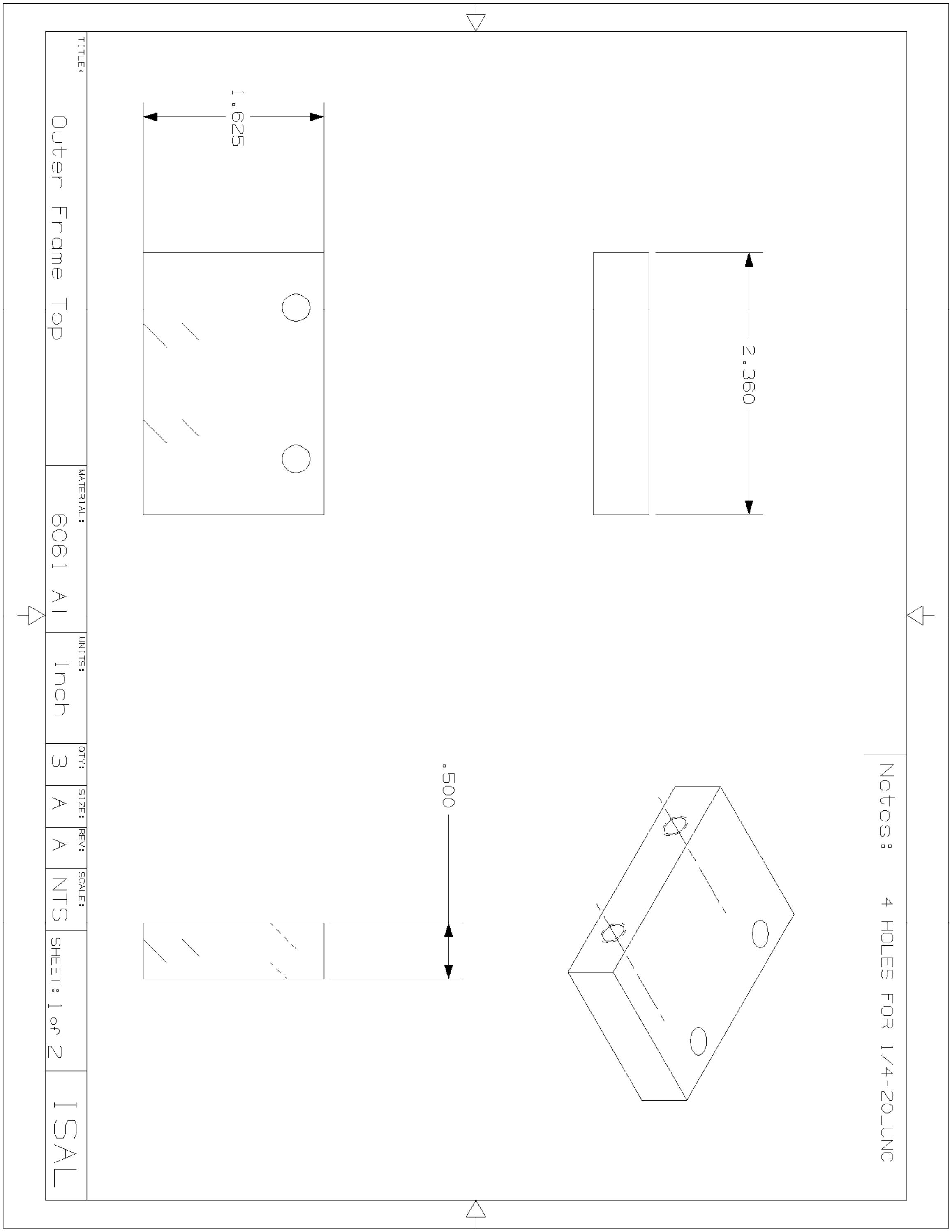

Zero-Reference Point
1.500
.875
.938
6.435
7.983
15.279
3.810
4.810
5.546
6.170
12.842
13.466
Notes: Setup for Keyseats
Include play of 1/16"
TITLE:
Pelvis_Drive_Shaft
MATERIAL:
P20 Tool Steel
UNITS:
Inch
QTY:
1
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 3 of 3
ISAL

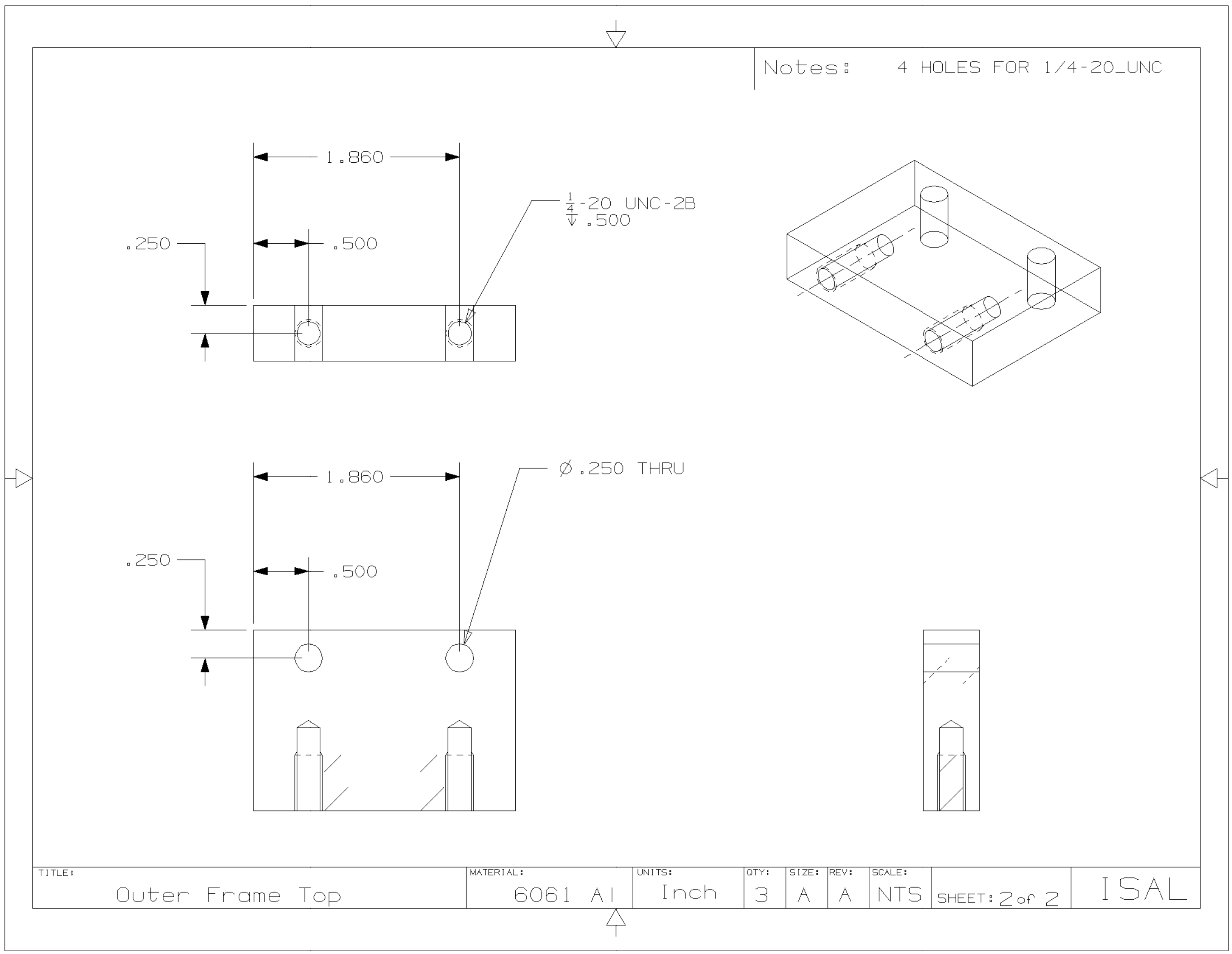

TITLE:
Frame Mounting
MATERIAL:
5052 AL
UNITS:
Inch
QTY:
4
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 1 of 1
ISAL
Notes:
4 THRU HOLES FOR 1/4-20_UNC
Slots are optional
Employ to reduce weight
2.447
.750
.250
5.671
5.921
.750
2.447
Ø.290 THRU
2.697
.250

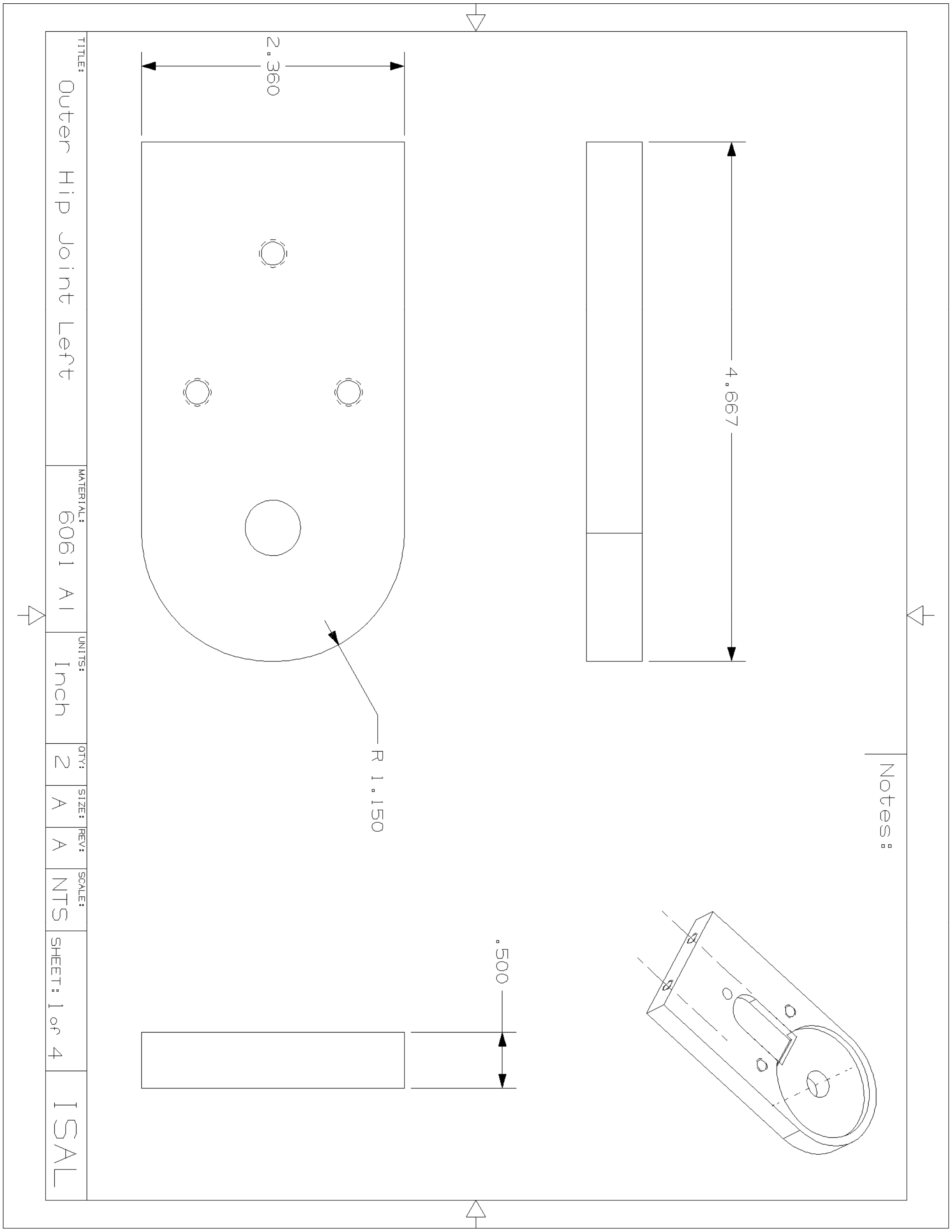

TITLE:
Outer Frame Front
MATERIAL:
6061 AL
UNITS:
Inch
QTY:
3
SIZE:
A
REV:
A
SCALE:
NTS
SHEET:
1 of 3
ISAL
2.360
2.697
.500
Notes:

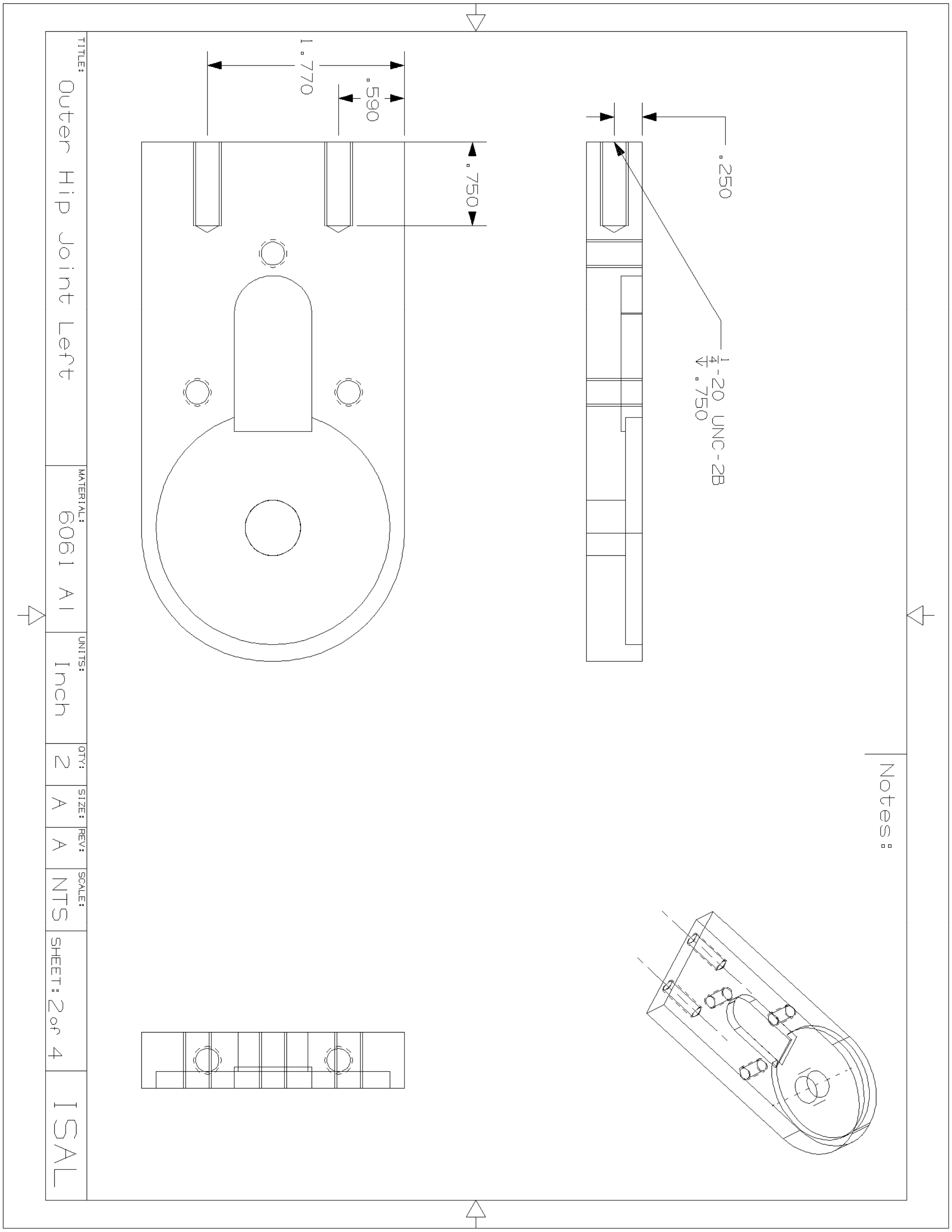

1.860
.500
.250
Ø.250 THRU
Notes:
TITLE:
Outer Frame Front
MATERIAL:
6061 AL
UNITS:
Inch
QTY:
3
SIZE:
A
REV:
A
SCALE:
NTS
SHEET:
2 of 3
ISAL

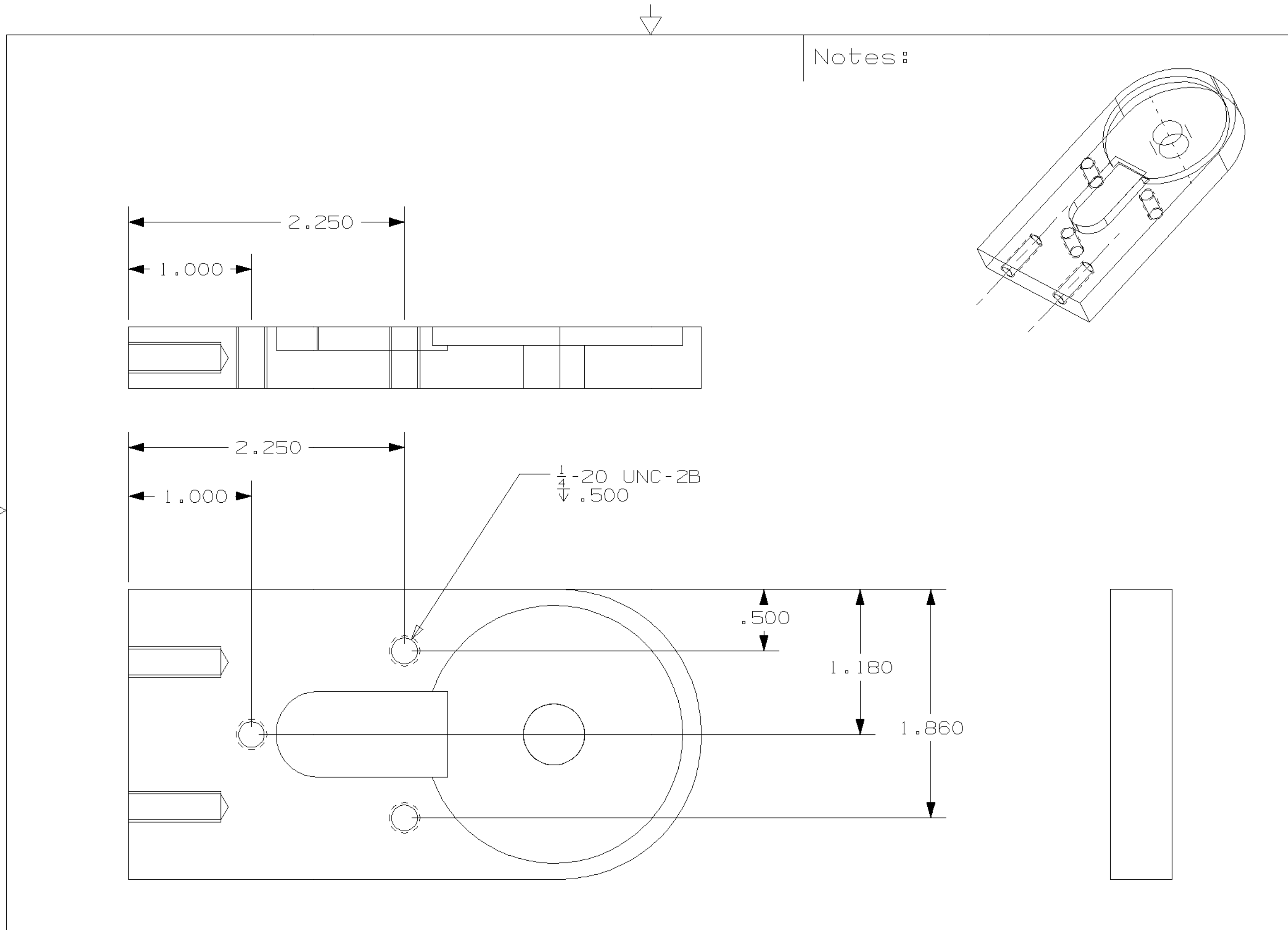

TITLE:
Outer Frame Front
MATERIAL:
6061 AL
UNITS:
Inch
QTY:
3
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 3 of 3
ISAL
Notes:
1.180
1.697
1.697
Ø.500 THRU
Ø1.125
↧.375


TITLE:
Outer Frame Top
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
3
SIZE:
A
REV:
A
SCALE:
NTS
SHEET:
1 of 2
ISAL
Notes: 4 HOLES FOR 1/4-20_UNC
1.625
2.360
.500

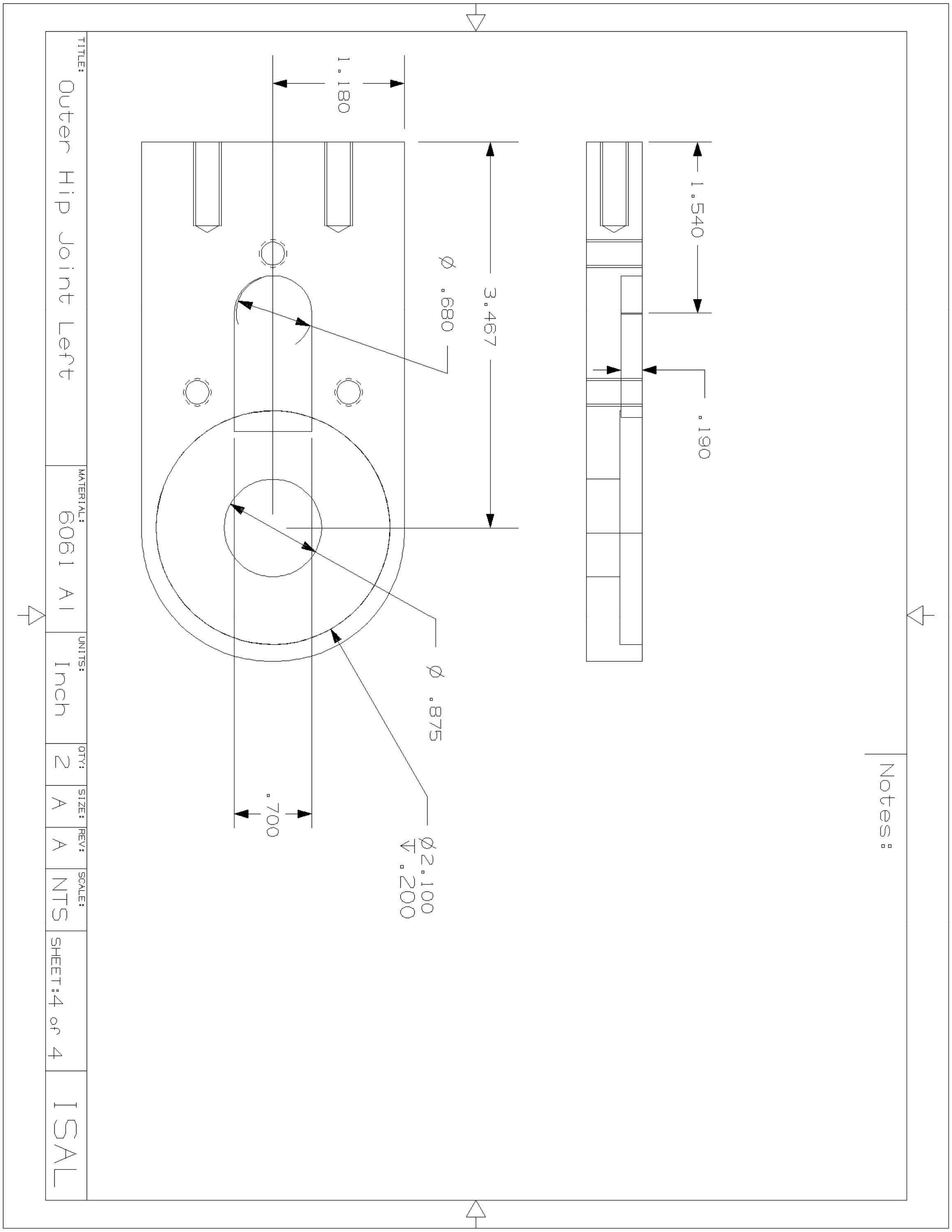

Notes: 4 HOLES FOR 1/4-20_UNC
1.860
.250
.500
1/4-20 UNC-2B
.500
1.860
.250
.500
Ø.250 THRU
TITLE:
Outer Frame Top
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
3
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 2 of 2
ISAL

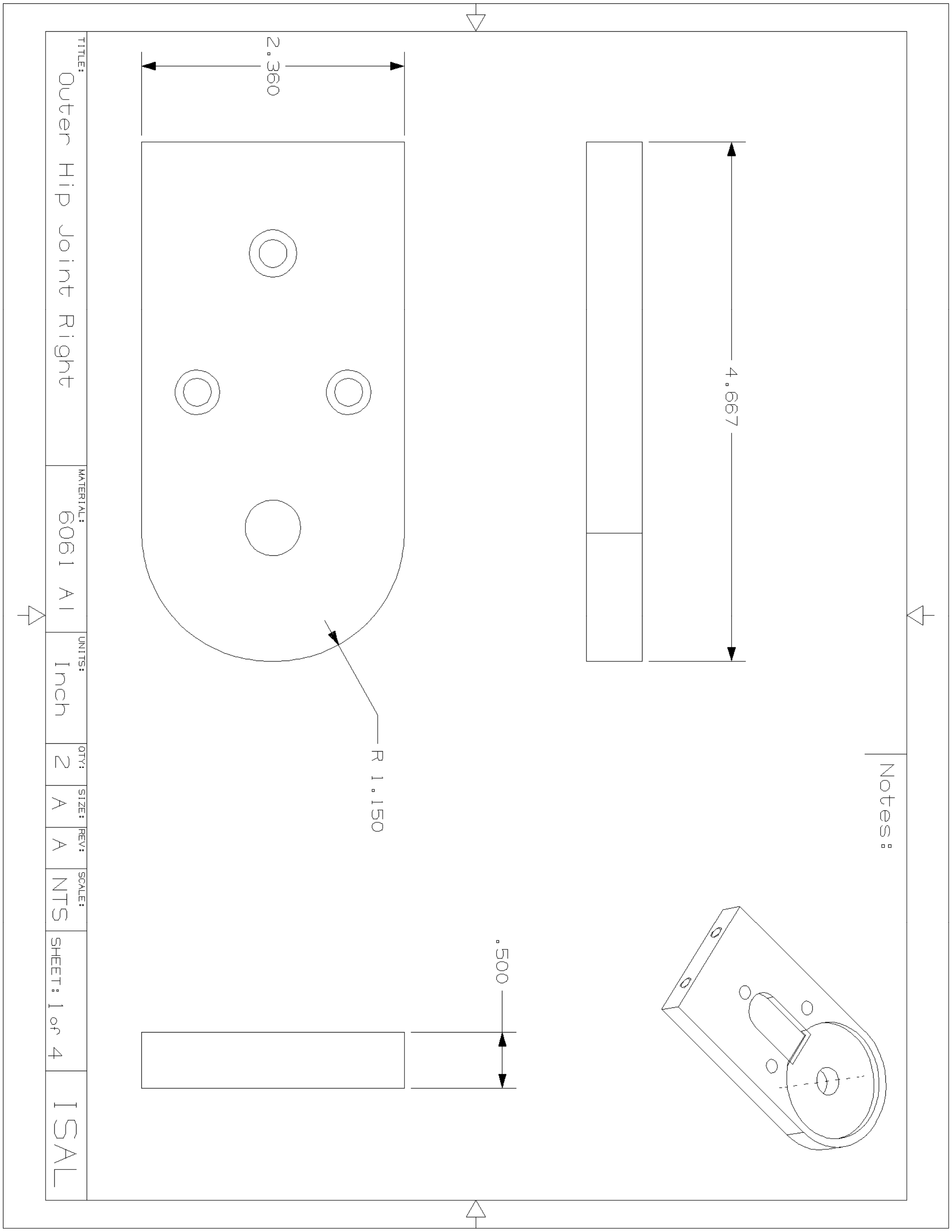

TITLE:
Outer Hip Joint Left
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 1 of 4
ISAL
Notes:
2.360
4.667
R 1.150
.500

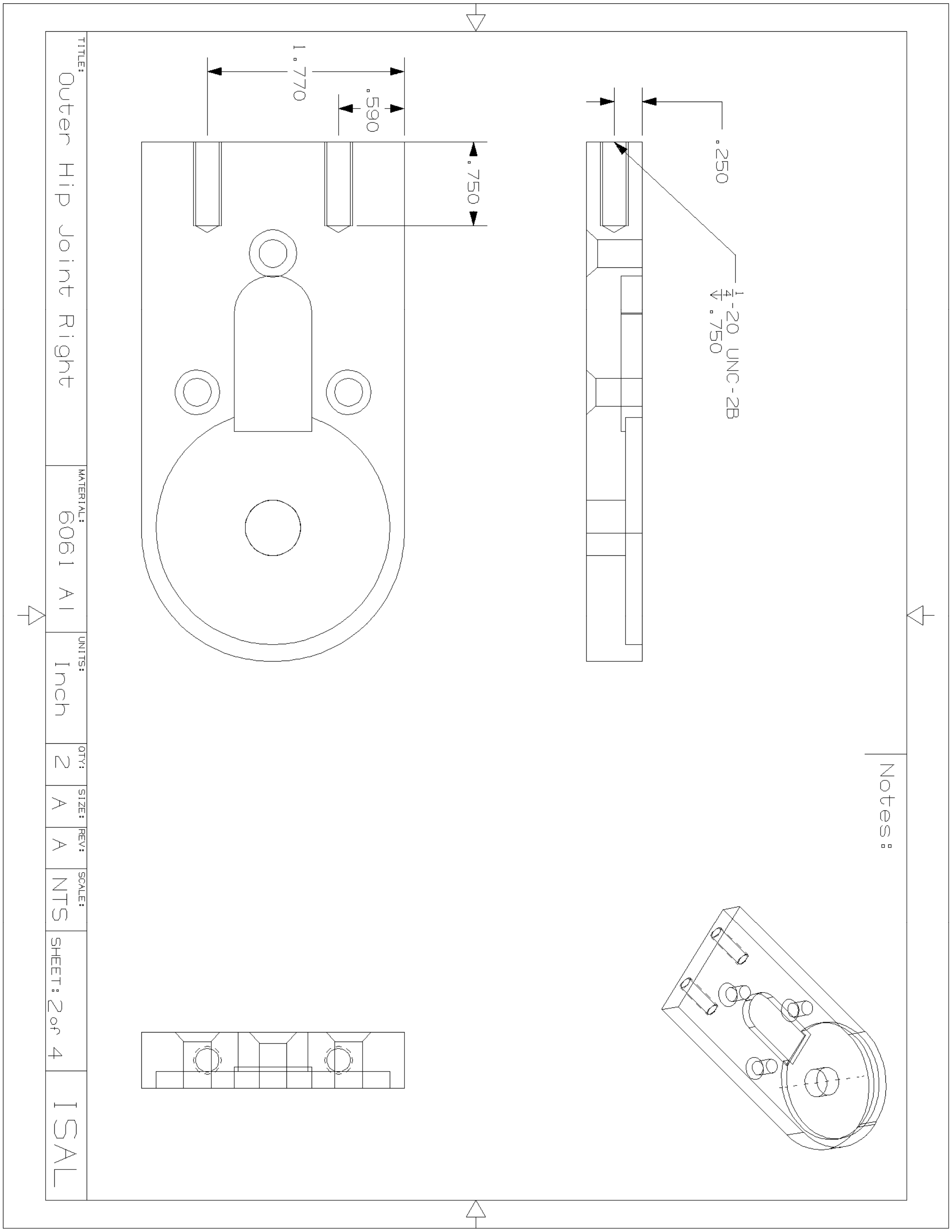

TITLE:
Outer Hip Joint Left
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 2 of 4
ISAL
Notes:
1.770
.590
.750
.250
1/4-20 UNC-2B
.750

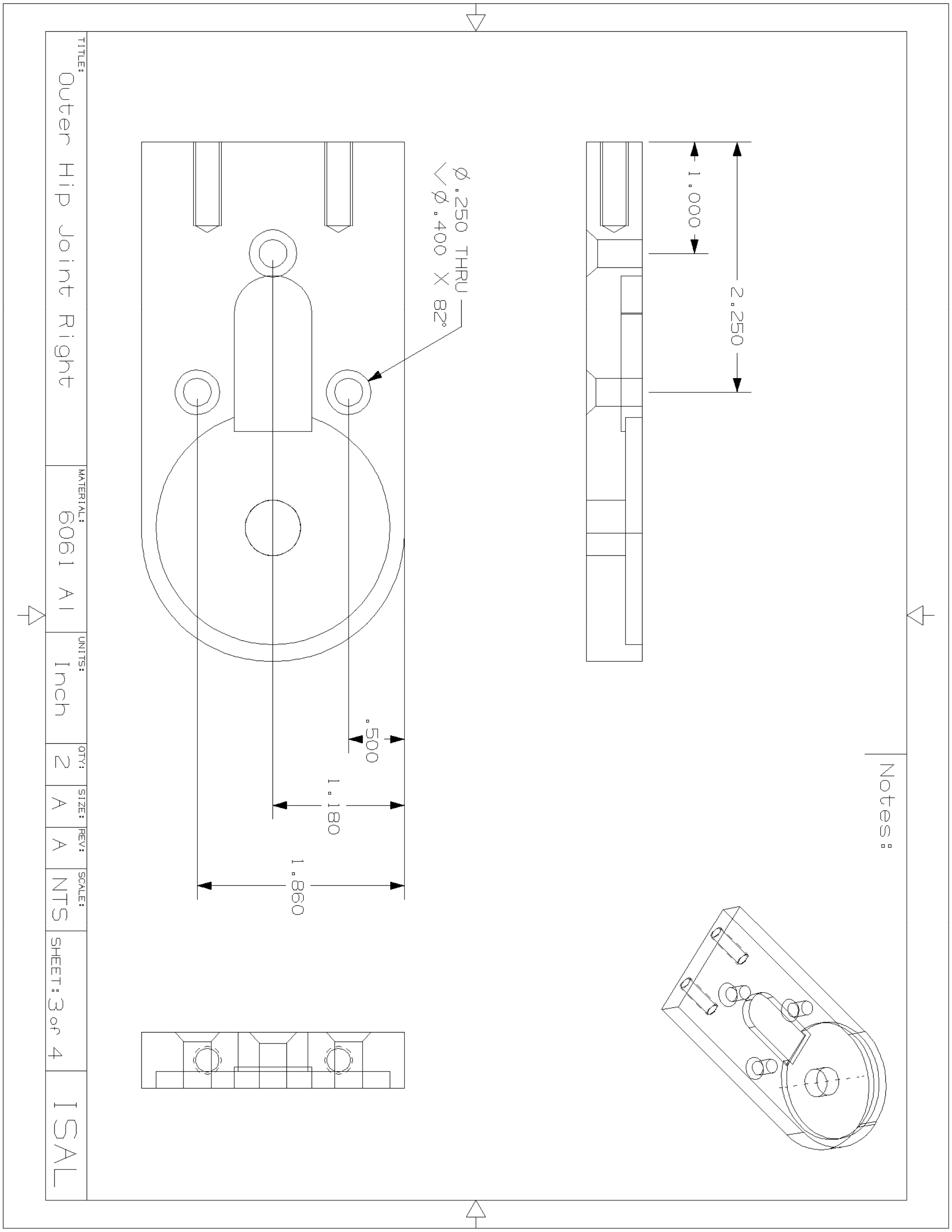


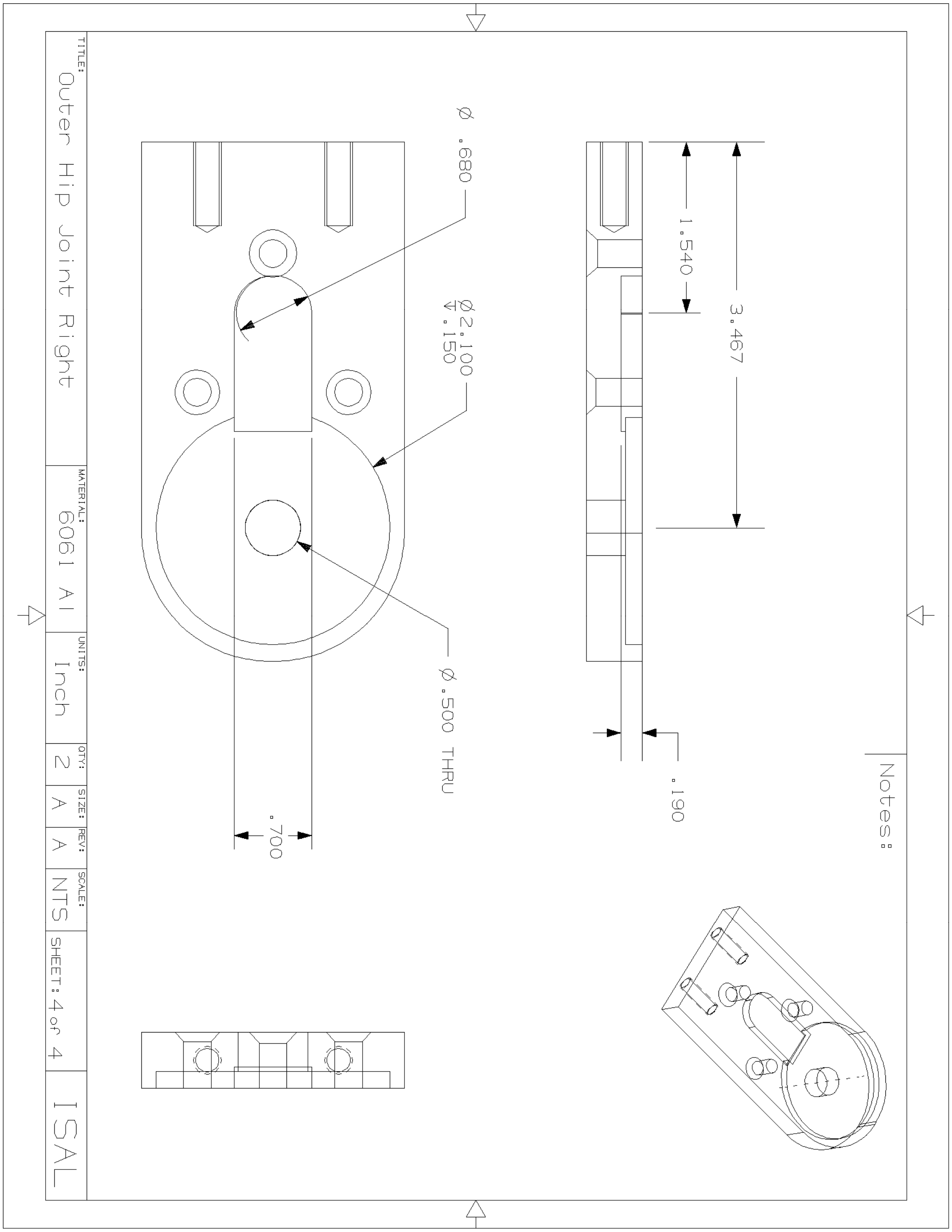
TITLE:	MATERIAL:	UNITS:	QTY:	SIZE:	REV:	SCALE:		
Outer Hip Joint Left	6061 Al	Inch	2	A	A	NTS	SHEET: 3 of 4	ISAL

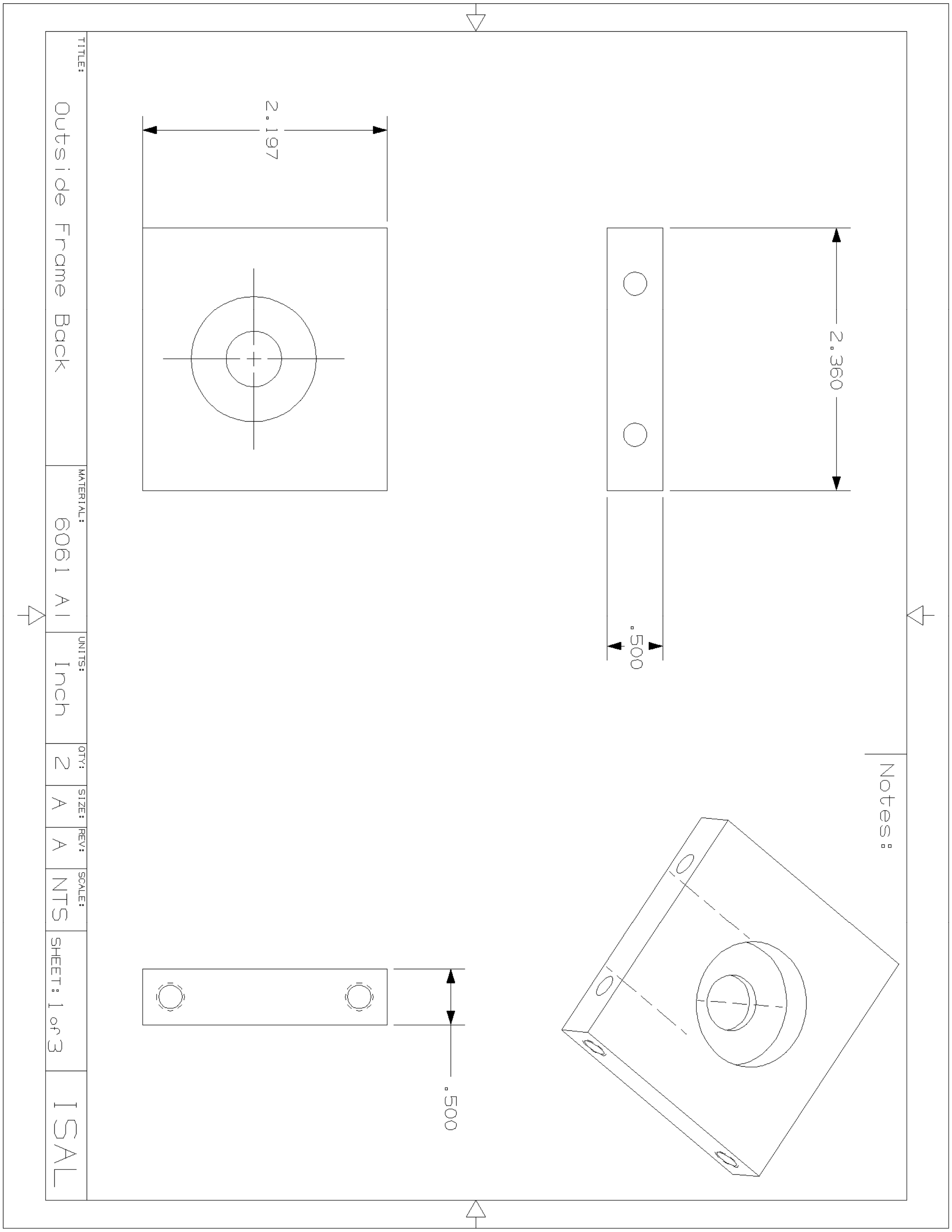

TITLE: Outer Hip Joint Left
MATERIAL: 6061 Al
UNITS: Inch
QTY: 2
SIZE: A
REV: A
SCALE: NTS
SHEET:4 of 4
ISAL
Notes:
1.180
3.467
1.540
ø .680
.190
ø .875
.700
ø2.100
↧.200

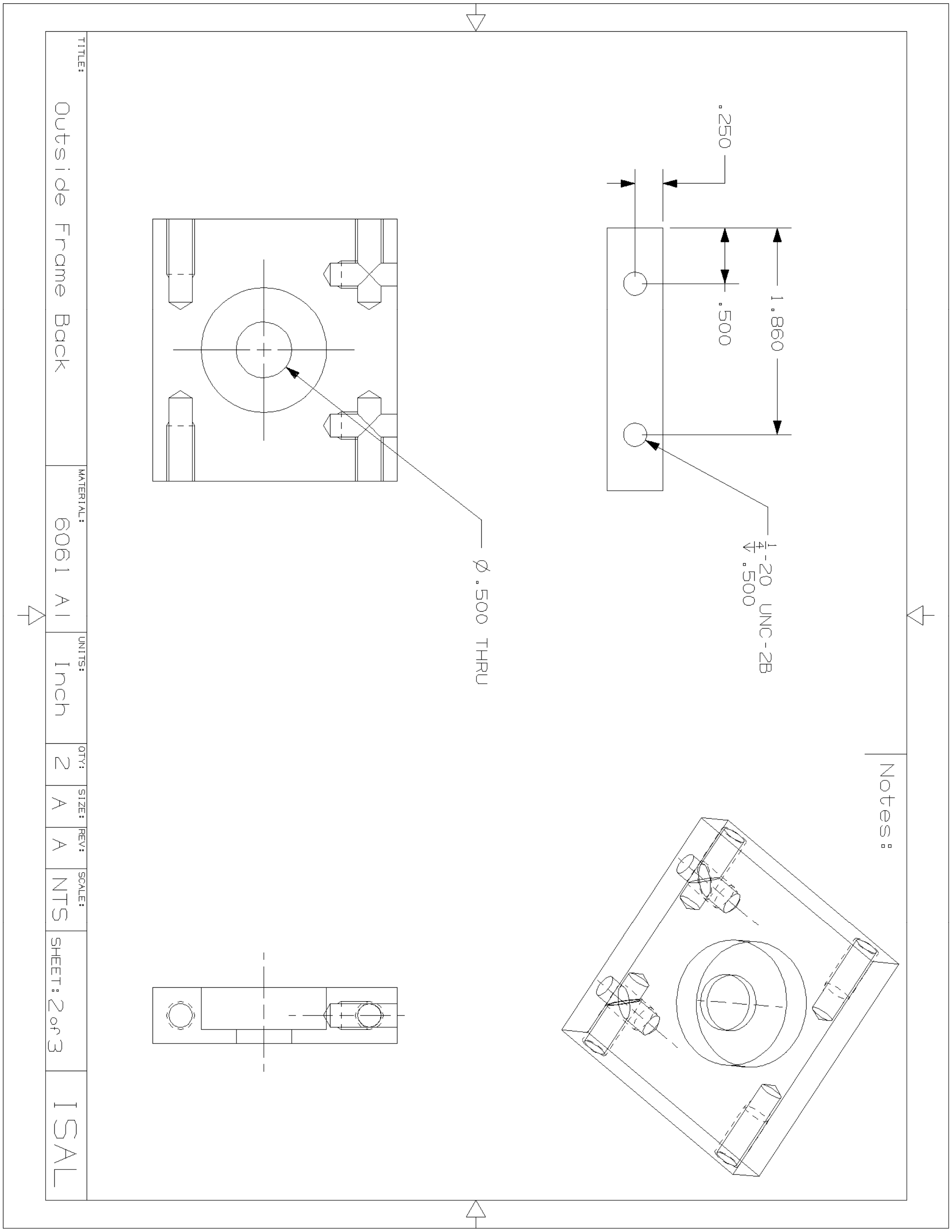

TITLE: Outer Hip Joint Right
MATERIAL: 6061 Al
UNITS: Inch
QTY: 2
SIZE: A
REV: A
SCALE: NTS
SHEET: 1 of 4
ISAL
2.360
4.667
R 1.150
.500
Notes:

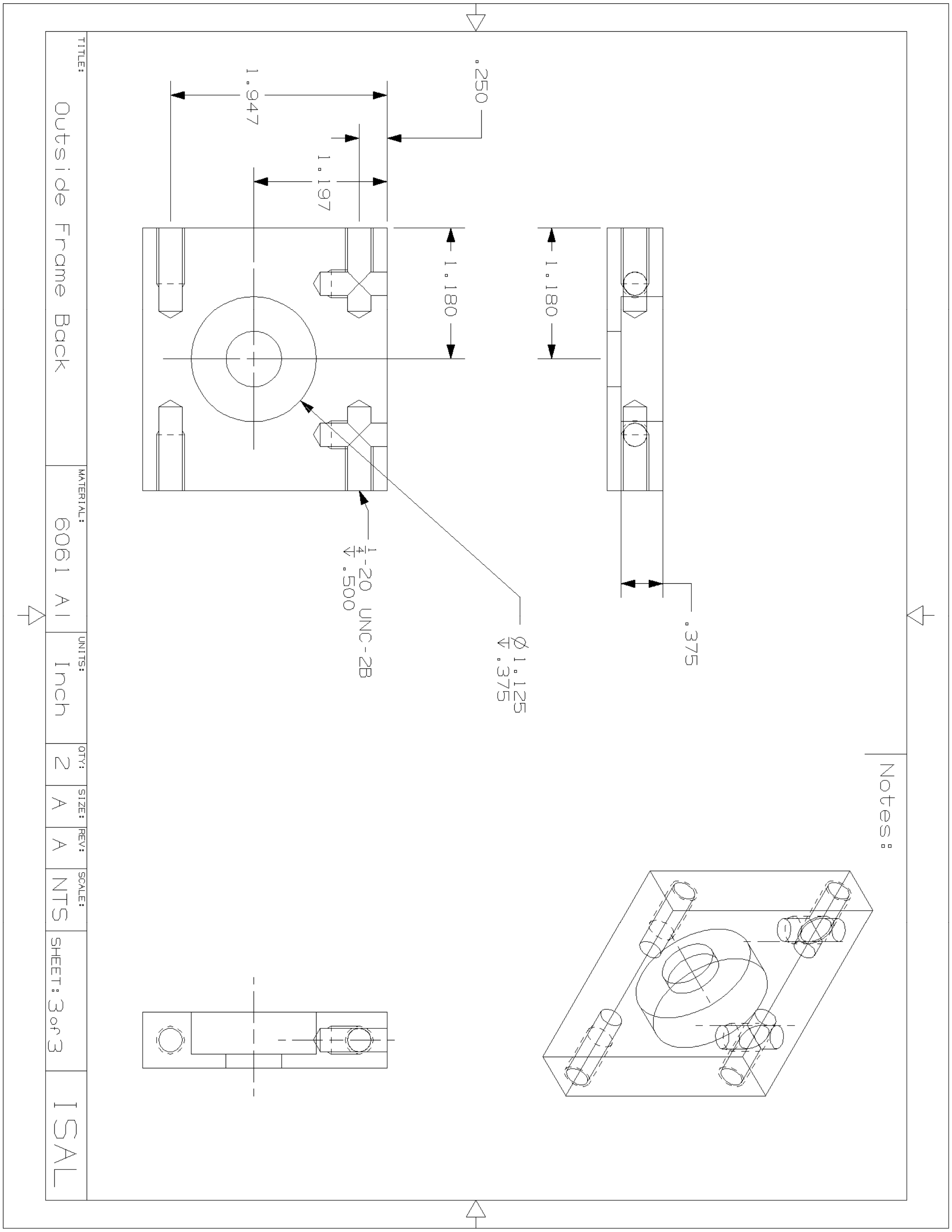

TITLE:
Outer Hip Joint Right
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 2 of 4
ISAL
1.770
.590
.750
.250
1/4-20 UNC-2B
↧.750
Notes:


TITLE:
Outer Hip Joint Right
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 3 of 4
ISAL
Notes:
Ø.250 THRU
⌵Ø.400 X 82°
1.000
2.250
.500
1.180
1.860


TITLE: Outer Hip Joint Right
MATERIAL: 6061 Al
UNITS: Inch
QTY: 2
SIZE: A
REV: A
SCALE: NTS
SHEET: 4 of 4
ISAL
Notes:
Ø .680
Ø2.100
↧.150
Ø .500 THRU
.700
1.540
3.467
.190


TITLE:
Outside Frame Back
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 1 of 3
ISAL
Notes:
2.197
2.360
.500
.500


TITLE:
Outside Frame Back
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 2 of 3
ISAL
Notes:
.250
.500
1.860
1/4-20 UNC-2B
↧ .500
Ø .500 THRU



TITLE:
Outside Frame Back
MATERIAL:
6061 Al
UNITS:
Inch
QTY:
2
SIZE:
A
REV:
A
SCALE:
NTS
SHEET: 3 of 3
ISAL
Notes:
.250
1.947
1.197
1.180
1.180
.375
1/4-20 UNC-2B
↧.500
Ø1.125
↧.375

A.4. Torque Calculations

24VDC @ 4 Amps						48VDC @ 4 Amps					
At Stepper Motor		At Gear Head		At Driveshaft		At Stepper Motor		At Gear Head		At Driveshaft	
RPM	TORQUE	RPM	TORQUE	RPM	TORQUE	RPM	TORQUE	RPM	TORQUE	RPM	TORQUE
100	111	3.33	208	1.82	380.87	100	111	3.33	208.13	1.82	380.87
200	110	6.67	206	3.64	377.44	200	110	6.67	206.25	3.64	377.44
300	115	10.00	216	5.46	394.59	300	115	10.00	215.63	5.46	394.59
400	115	13.33	216	7.29	394.59	400	115	13.33	215.63	7.29	394.59
500	107	16.67	201	9.11	367.14	500	112	16.67	210.00	9.11	384.30
600	105	20.00	197	10.93	360.28	600	111	20.00	208.13	10.93	380.87
700	94	23.33	176	12.75	322.54	700	114	23.33	213.75	12.75	391.16
800	82	26.67	154	14.57	281.36	800	114	26.67	213.75	14.57	391.16
900	74	30.00	139	16.39	253.91	900	113	30.00	211.88	16.39	387.73
1000	68	33.33	128	18.21	233.33	1000	110	33.33	206.25	18.21	377.44
1100	62.5	36.67	117	20.04	214.45	1100	105	36.67	196.88	20.04	360.28
1200	57	40.00	107	21.86	195.58	1200	97	40.00	181.88	21.86	332.83
1300	53	43.33	99	23.68	181.86	1300	92	43.33	172.50	23.68	315.68
1400	48	46.67	90	25.50	164.70	1400	88	46.67	165.00	25.50	301.95
1500	45	50.00	84	27.32	154.41	1500	85	50.00	159.38	27.32	291.66
1600	43	53.33	81	29.14	147.54	1600	80	53.33	150.00	29.14	274.50
1700	40	56.67	75	30.97	137.25	1700	77	56.67	144.38	30.97	264.21
1800	37.5	60.00	70	32.79	128.67	1800	75	60.00	140.63	32.79	257.34
1900	36	63.33	68	34.61	123.53	1900	71	63.33	133.13	34.61	243.62
2000	34	66.67	64	36.43	116.66	2000	68	66.67	127.50	36.43	233.33

Table A.4.4.1: Torque, shown as in-lb, calculations for 24VDC and 48VDC power supply options.