

Design of a Quadruped Walking Robot for Social Interaction

by

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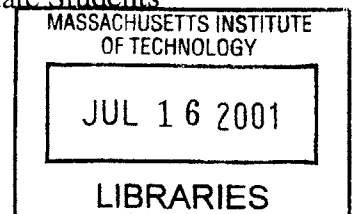
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Abstract

This thesis describes the design of Coco, a mobile robot for the study of social behaviors in machines. Coco acts as a platform for research on the full range of problems involved in the development of social machines¹, including vision and auditory processing, computational synthesis of affective behaviors², and motor control. In order to provide maximum benefit to these research efforts, the goals of the design focused on maximizing the sensory input and expressive output available to the computer algorithms controlling the robot. The result is a static walking quadruped modeled on the morphology of a gorilla that stands approximately 0.5m tall and weighs 10.2kg. Coco has ten degrees of freedom in the limbs for walking and gesture. There are an additional five degrees of freedom in a vision head consisting of one narrow-angle and two wide-angle cameras. Servomotors receiving low-level PID control from an on-board DSP system actuate Coco's joints. Joint trajectories are transmitted from off-board computers via a serial link. Members of the Coco Team have successfully implemented behaviors such as orienting to and approaching both visual and auditory stimulus.

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Chapter 1

Introduction

1.1 *Thesis Goal*

The goal of this research effort is to develop a mobile robotic platform with multiple sensing capabilities for the study of social interaction between humans and machines. The robot, named Coco in large part because of its apelike form, will need to sense, explore, and interact with its environment. The main elements in the design are as follows:

- **Recognizable and approachable form.** A social robot should inherently inspire social behavior in humans. As humans, we interact with our environment based on our experience. Since social machines are few, we generally reserve social behavior for animals and other humans. To bridge this gap, the robot should be biomimetic, i.e. it should look less like a car and more like a pet.
- **Small and light.** The robot should be approachable by children as well as adults. A robot that is markedly smaller than its human caregiver is more likely to be perceived as non-threatening.
- **Expressive.** The robot should have a large repertoire of gestures and postures to facilitate the synthesis of emotional displays
- **Complement vision processing.** Visual input will be a major part of the complete robotic system. Any inherent intelligence in the mechanical system that simplifies the processing of camera information will result in faster, and more useful, responses.
- **Robustness and ease of serviceability.** Since the mechanical system is only a part of the larger effort to create a social robot whose end goal is to behave as a continuously running, “living-breathing robot”, low mean time between failure and ease of assembly / disassembly are important.
- **Accommodating to future changes.** Coco’s role as a research robot means that changes and additions are likely. The design should allow for upgrades and modifications.

1.2 Summary of Thesis

This thesis is organized as follows:

Chapter 2 describes the development of the robot's main attributes

Chapter 3 describes the calculations and simulations that defined the robot's power requirements

Chapter 4 describes the hardware design and selection

Chapter 5 conclusions and future work

Chapter 2

Concept Development

2.1 Brief Overview

Coco (Figure 2-1) is a quadrupedal walking robot loosely modeled on the morphology of a Gorilla. The name Coco arises partly in homage to Koko, the famous Gorilla that has learned American Sign Language as part of an ongoing interspecies communication project³. Additionally, Coco is a repetition of the first two letters of cognitive which is also the root behind Cog⁴, Coco's sibling in the Humanoid Robotics Group. Mechanically, Coco is a ten degree of freedom walker with a five degree of freedom vision head. Coco weighs 10.2kg and stands approximately 0.48m tall. Brushed DC servomotors using digital encoder feedback actuate the robot. Low-level PID motor control is handled on board by a DSP in communication with off-board computers that process sensor data and supply high-level trajectory commands. Power is also supplied from off-board.

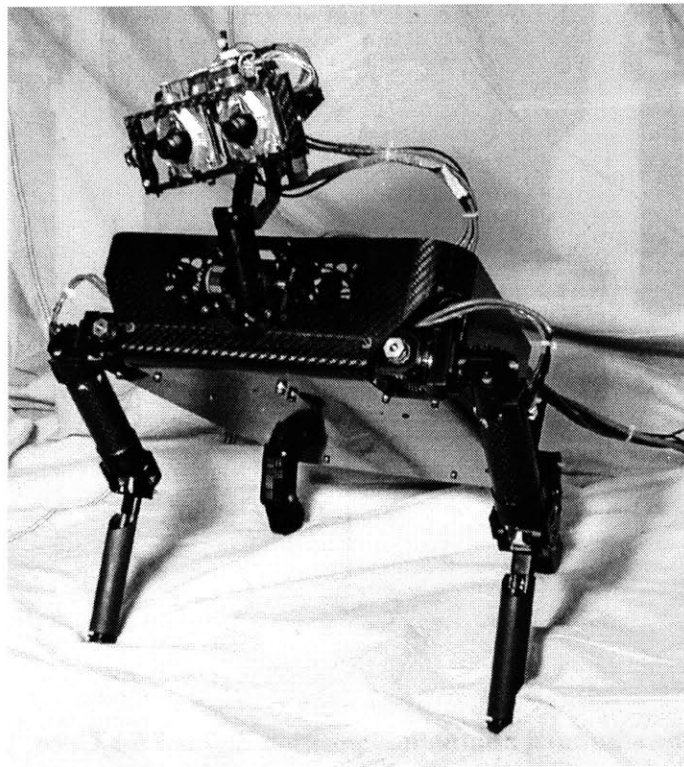


Figure 2-1: Coco is a ten degree of freedom quadruped walking robot with a five degree of freedom vision head.

In order to describe the robot further, a standard orientation is needed to provide a basis for navigation and reference to parts of the anatomy. In human anatomy, this is called the standard anatomical position and is shown in appendix A. The standard anatomical position for Coco is defined in Figure 2-2 below. All references made to the robot are from this orientation.

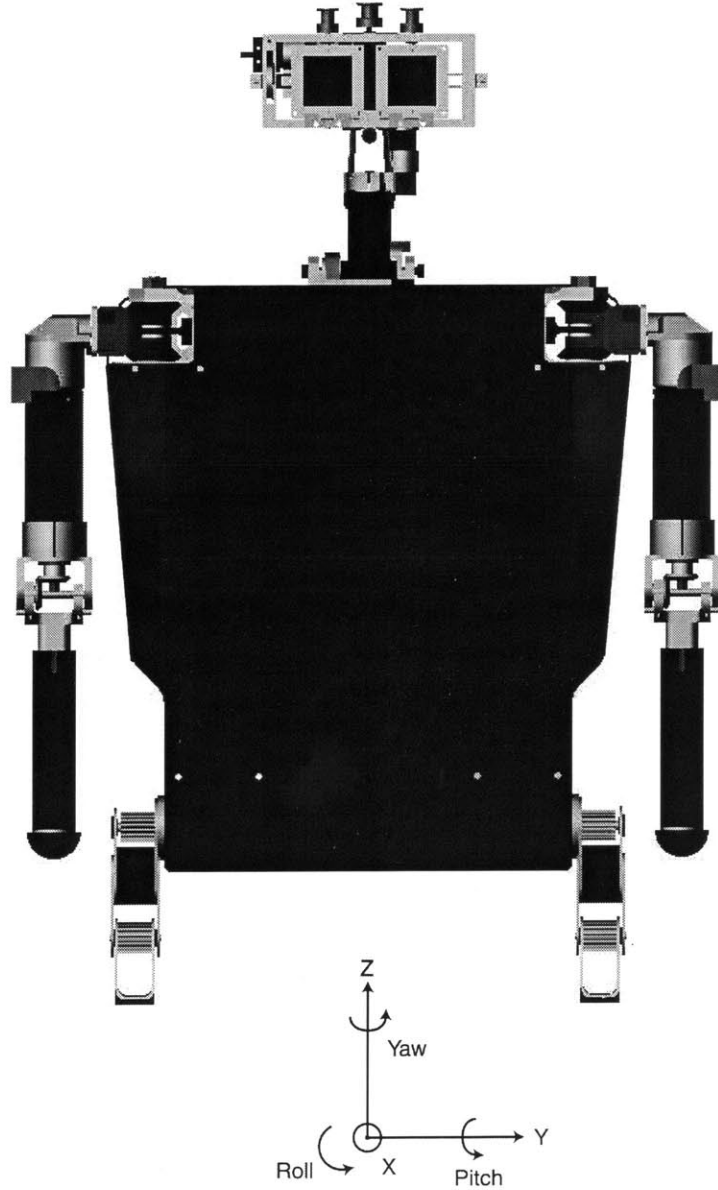


Figure 2-2: The standard anatomical position defined for Coco. All geometric references are made to this orientation of the robot

2.2 Design inspiration

2.2.1 Body

Among the myriad biological forms capable of serving as a model, the Coco Teamⁱ chose a gorilla. Gorillas possess several traits that map closely to our design goals. The most attractive trait of gorilla morphology is their dual-purpose front limbs. Gorillas use their front limbs for gesture and manipulation as humans do, but their primary mode of locomotion is quadrupedal.

The statically stable nature of slow quadrupedal locomotion makes it a far simpler task for a robot than bipedal locomotion. Statically stable locomotion as described by McGee and Frank⁵ and later Raibert⁶ dictates that the projection of the robot's center of gravity on the ground must remain inside the polygon of support formed by the three (or more) points in contact with the ground (Figure 2-3). It follows that the center of gravity must remain relatively centered over these points throughout the gait cycle to insure stability. As a limb is lifted and moved away from the body to make a stride, the center of mass necessarily shifts toward the edge of the polygon of support. Heavy limbs can reduce the length of stride by causing the robot to fall onto its swing leg. Spiders, horses, cheetahs, etc all have very centralized masses supported by thin, light limbs that enable either great stability or long stride length.

As seen in Figure 2-4, a Gorilla's front limbs are slightly longer than its hind limbs. The ratio of front to rear limb length is referred to as the intermembral index. For gorillas, the average intermembral index is 1.15⁷. This trait may have evolved along with their ability to use their front limbs for manipulation given the obvious benefits of a longer reach. Since gorillas have relatively short necks when compared to other animals of similar size, long front limbs also serve to raise the head thus allowing them to see farther. Long limbs also allow for a great deal of body language. A common behavior seen in many animals is to crouch when taking an aggressive or defensive stance. This is possibly to protect the vulnerable belly area and to facilitate an explosive bounding attack. In contrast, exposing the chest area is generally considered a nonaggressive or welcoming posture.

Coco exaggerates the intermembral index to raise the head during locomotion, allowing the sensory receptors (such as video cameras and microphones) in the head a higher vantage point. Ancillary benefits to this ratio include: creating the ability to take a very welcoming posture, accentuating gestures, and making the dual use of the front limbs more apparent.

ⁱ The members of the Coco Team are: Professor Rodney Brooks, Charles Kemp, Christopher Morse, Naoki Sadakuni, Eduardo Torres-Jara, and Juan Velasquez

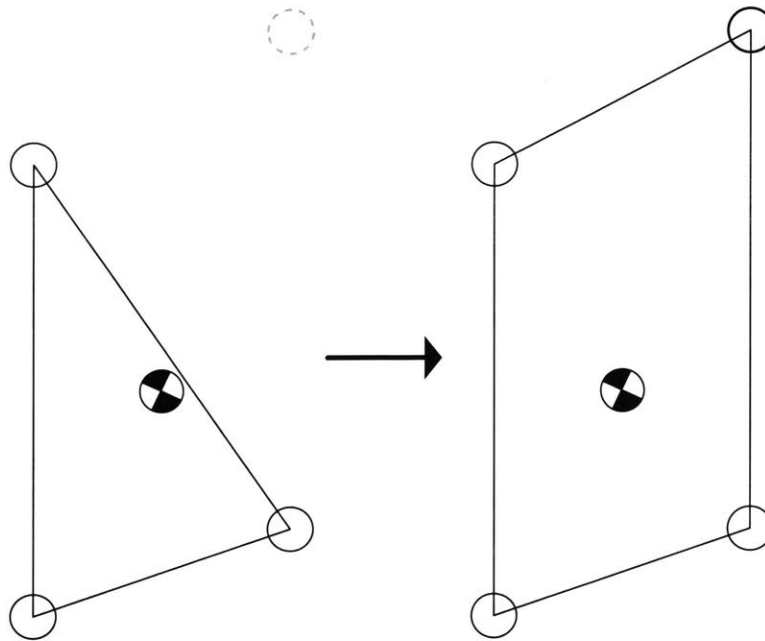


Figure 2-3: The polygon of support for statically stable walkers has vertices at the points where the limbs touch the ground. This figure shows the transition from triple support to quad support as the outstretched right front limb (gray dashed circle) touches down. For slow static walking, the center of gravity must always remain inside the polygon.

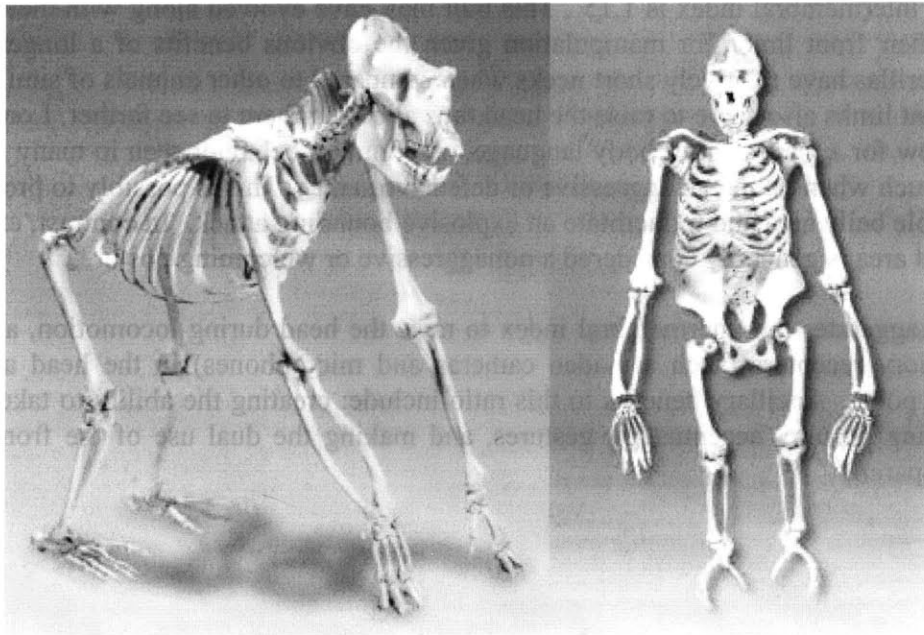


Figure 2-4: Replicas of gorilla skeletons that show the relative proportions of a gorilla's body (Reprinted with permission from Skulls Unlimited Int.⁸)

In keeping with the desire to make Coco approachable by people of nearly any age the robot's scale was chosen to be equivalent to a large cat or small dog; about 0.5m from head to tail and weighing 10-11kg. A larger, heavier robot would risk injuring itself or others while if it fell or hit something while gesturing. Since complex, multi-degree-of-freedom joints are generally more difficult to implement in small spaces, the robot only implements the major axes of motion necessary to enable the robot to walk and gesture and remain true to its biological inspiration. Feet and hands were eliminated since they involve some of the most complex mechanics of the body but are not required for quadrupedal locomotion. They are also small compared to the whole body so their absence does not markedly detract from the overall appearance. At the hip, the majority of motion is in flexion and extension. The other two axes of rotation provide negligible benefits to simple walking, and thus were eliminated. The shoulder must be used for pointing and gesturing as well as walking. A three-degree-of-freedom joint is desirable at the shoulder, but very complex to execute, so a two-degree-of-freedom joint, operating in yaw and pitch, was used. Knees and elbows in primates are essentially one degree of freedom and remain so on Coco. The result is ten degrees of freedom in the limbs. Figure 2-5 shows the joint configuration for Coco's body.

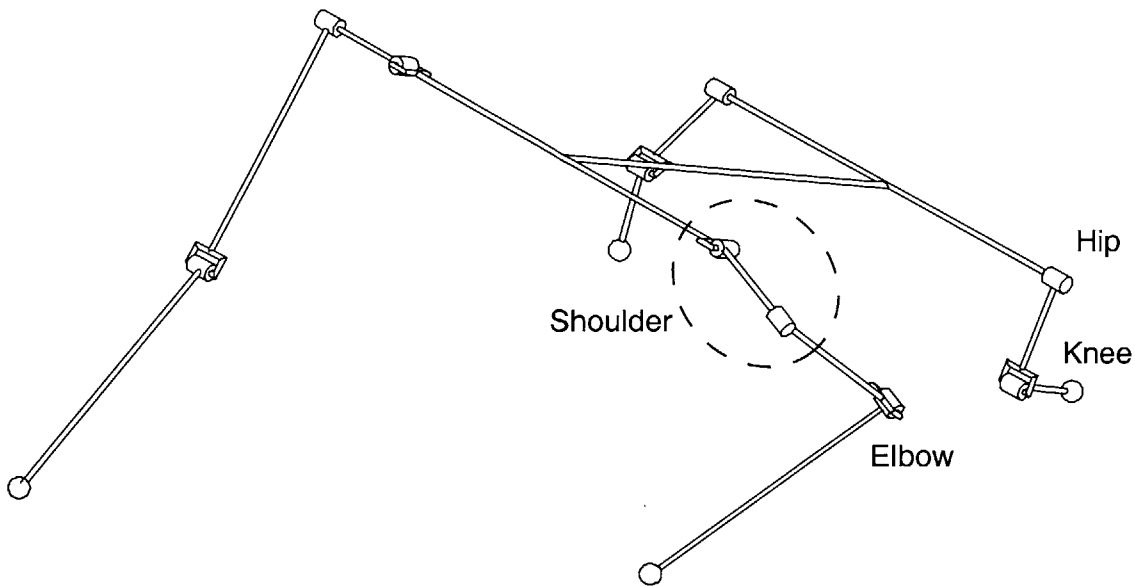


Figure 2-5: Stick figure drawing of Coco's body configuration. The hips, knees and elbows are simple one degree-of-freedom joints. The shoulder (dashed circle) has two degrees of freedom shown as two one degree-of-freedom joints with a small offset.

2.2.2 Head

There are three major considerations in the design of a vision head for a mobile platform: (1) Maximizing the workspace available to the cameras, (2) placing the axes so that they help instead of hinder vision processing, and (3) aggressively minimizing weight. In the case of Coco there are the added considerations of the ability to produce gestures that suggest emotion and the approximation of animal morphology.

The human head and neck is an excellent example of the type of highly articulate vision platform that is desired for Coco. The seven stacked vertebrae of the cervical spine –each acting like a 3 degree-of-freedom ball-and-socket joint– give the human head roughly 21 degrees of freedom. Adding this to the two degrees of freedom in each eyeⁱⁱ results in a total of 25 degrees of freedom in the workspace of the eyes. Unfortunately, this number would be nearly impossible to implement in a small mobile robot.

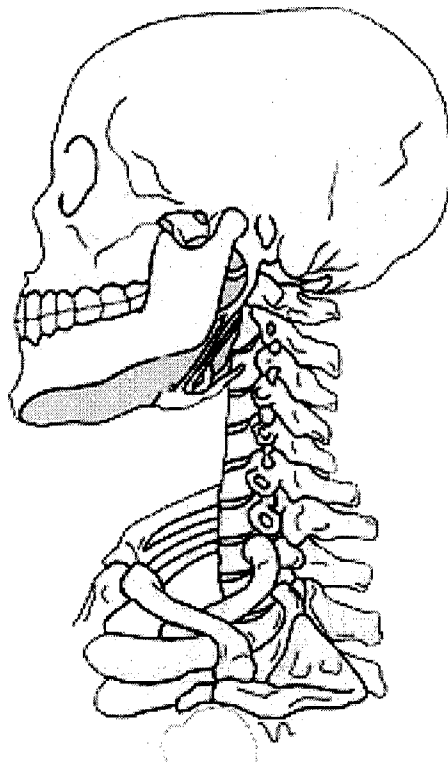


Figure 2-6: The human cervical spine and skull. Each vertebra acts as a 3 degree of freedom joint with limited range of motion. Taken together, the joints of the c-spine provide 21 degrees of freedom but the limited range of motion allow them to be represented by 6 degrees of freedom.

ⁱⁱ Independent pitch and roll of the eyes are very subtle and often neglected from consideration.

It is possible, however, to reduce this number while still retaining much of the capabilities of a human. Although the individual vertebrae in the neck act as 3 degree-of-freedom ball-and-socket joints their range of motion is limited and the actuating musculature couples them together. Thus the neck can be approximated by a two-degree-of-freedom joint at the base of the neck and a three degree of freedom joint at the top with a linear slide between. The angular movements originating at the base of the neck are small, resulting in small length changes along the neck so it is also reasonable to neglect the linear slide. Although vergence (independent movement of the eyes on the yaw axis) plays a large role in some aspects of human vision processing, the majority of gross eye motion is conjunctive. This allows emulation of a pair of eyes with only two degrees of freedom. Thus it is possible to recreate most of the capabilities of the human vision platform with only seven degrees of freedom. Although manageable, seven is still a large number for a mobile robot, given the desire for low weight. Also, the two neck joints are multi-degree of freedom. As one adds axes to a joint the complexity increases greatly. Therefore, we reduced the neck axes from five to three giving Coco a total of five degrees of freedom for its vision system.ⁱⁱⁱ

The location and orientation of the axes of the vision head play an important role in determining how well the entire vision system operates. The system must account for how its movements will affect what the cameras see. In an ideal camera the lens focuses a large image on the imaging plane by inverting it through a single point known as the optical center (Figure 2-7). As shown in Figure 2-8-A&B if the camera rotates around the optical center, the image that is projected will be rotated relative to the original image whereas rotation around any other point will cause both a translation and rotation. Unless the camera is rotated about the optical center, it is impossible to orient the camera to objects viewed on the optical plane without depth information as shown in Figure 2-8-C. Camera translation also changes the size of objects in view, which can confuse vision algorithms.

If it is impossible to locate the axis of rotation and the optical center, additional degrees of freedom can be used to create a virtual axis of rotation. The drawbacks to this solution are errors introduced by inaccuracies in positioning and the complexity of programming smooth coordinated movements by two actuators. Therefore, in Coco the optical center of the cameras played a key role in the design of the head. The main camera's yaw and pitch axes both intersect their optical center. A third camera used for detailed inspection of smaller areas shares the pitch axis with the two main cameras but its optical center is offset due to lack of space. A roll axis was also placed in plane with the optical center's of the main cameras to allow them to always remain parallel to the ground. In the neck, a second yaw axis was placed in line with the high detail camera's optical center. The final degree of freedom is a pitch axis at the base of the neck, which allows the robot to nod. The best overall description of this system is a double two-degree-of-freedom gimbal that

ⁱⁱⁱ Charles Kemp, a fellow Coco group member familiar with vision processing, collaborated on the abstract head design and in particular focused on determining the critical degrees of freedom.

is wholly rotated by on a pitch axis at its base. Figure 2-9 shows the final head configuration.

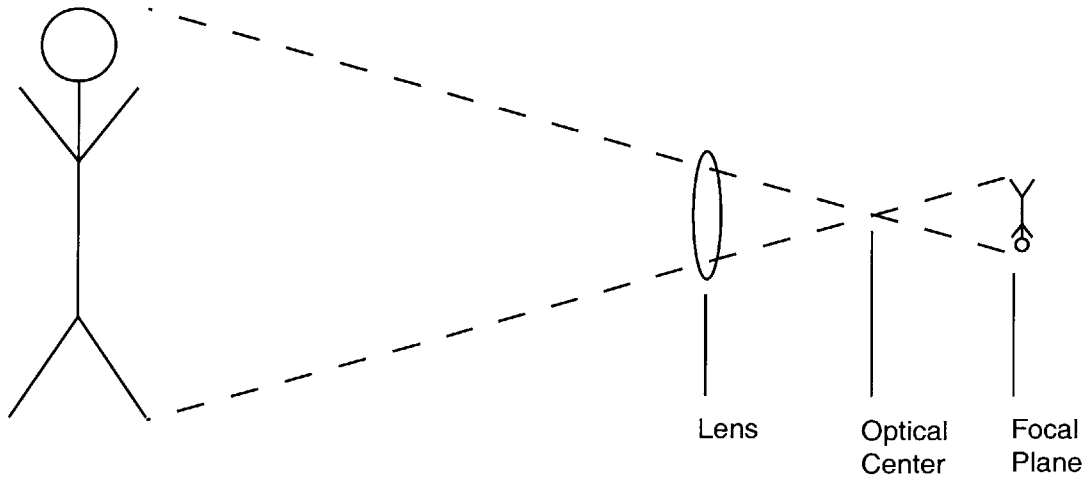


Figure 2-7: Simplified representation of how a lens focuses an image on the camera's focal plane.

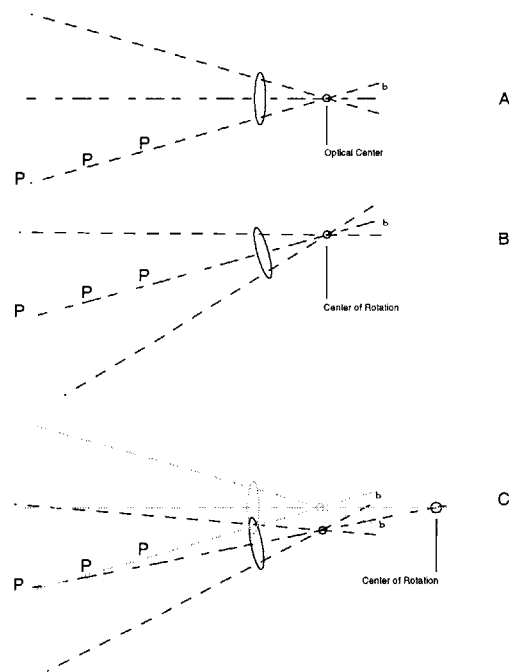


Figure 2-8: An object of unknown depth is projected onto the focal plane (A). If the camera is rotated through its optical center the object can be easily centered in the field of view (B). If the camera is rotated through any other point, the object cannot be centered without depth information (C).

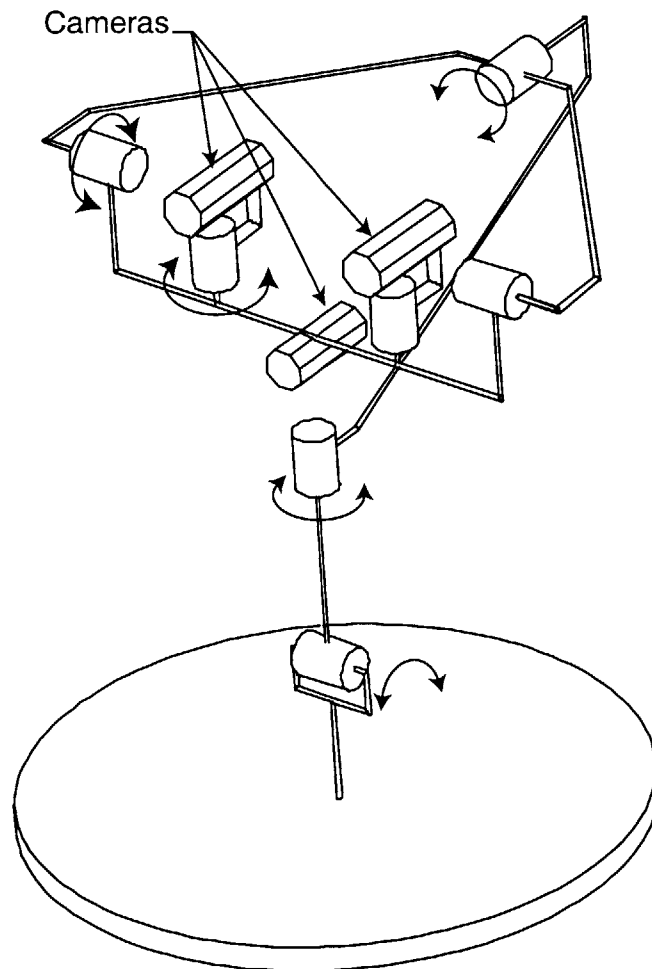


Figure 2-9: A stick figure diagram of Coco's head configuration. Two cameras are coupled to rotate in pitch and yaw about their optical center. A third camera shares the pitch axis. Arrow denote axes of rotation.

Coco's design balances expressiveness and biomorphism with mobility and low weight. The robot's long arms, contrasted with short legs, enable broad hand gestures and an open, friendly posture. The head configuration accommodates the needs of the vision system and maximizes the workspace while minimizing both weight and complexity. The result is a fifteen degree-of-freedom robot inspired by the morphology of gorillas.

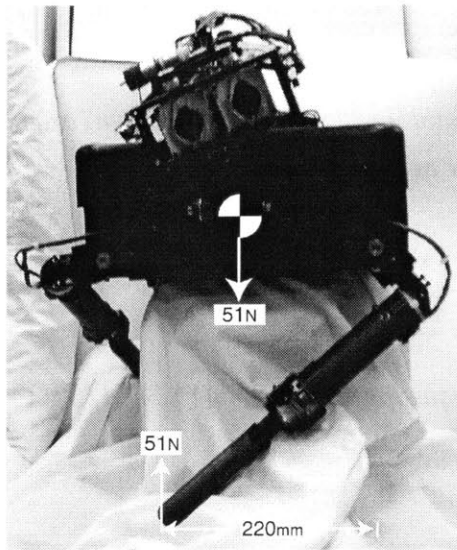
Chapter 3

Calculations and Simulation

Designing a mobile robot is an iterative process. In order to calculate how much power each axis of the robot requires one must know how much it weighs and how fast it has to move. However, the weight is largely dependent on the size of the motor that is delivering the power. In the case of Coco, the maximum joint speed was determined by comparisons to humans. In human limbs, joint speeds are 6-13rad/s (1-2Hz)⁹ for slow to average walking. Using human speed data means that the overall speed of the robot will be scaled in proportion to the ratio of limb length between humans and the robot. This scaling fits the overall model for Coco as a slow, nonaggressive being. In the head, the average joint speeds are 13-18rad/s (2-3Hz). Scaling does not play as big a role in the head since it is much closer to actual human proportions. As a starting point, the robot's total weight was estimated at 10kg.

The motor torque requirements were determined using the weight estimation and a set of worst-case joint loading scenarios (Figure 3-1) that resulted from examination of the expected modes of operation (IE walking, standing, sitting, crouching, etc). Each limb is assigned half of Coco's full weight to account for circumstances in which Coco is in triple support and load is evenly distributed front and back or Coco is in near double support as occurs in the transition to and from sitting. The estimation of maximum dynamic torque is based on the assumption that no joint will more than $\pm 45^\circ$ from vertical during walking. Coco's orientation in the two photo's in Figure 3-1 is not meant to represent an actual loading situation. It is, however, possible for Coco to endure equivalent loads to one or more joints at the same time.

The loadings described above represent the maximum or motor-stall torques that are likely to be seen by the robot. In walking and other normal situations the robot is not expected to bend it's limbs past $\pm 45^\circ$ from vertical with a nonzero motor velocity; thus, the expected maximum dynamic torque was decreased by $\sqrt{2}$ (Figure 3-1). The limbs will be operating at the maximum dynamic torque when they are the extremes of their range-of-motion. At these points the joint speed will be the lowest and will increase as the limb moves closer to vertical. To estimate power, the joint speed at maximum torque was estimated to be one tenth of the maximum joint speed of 13rad/s or 1.3rad/s. Using these estimations of torque and speed, the power requirements for the joints in the body were estimated to be between 2-14Watts. Equation 1 details this process for the shoulder's pitch axis.



Joint	Max. Torque (Nm)	Max. Dyn. Torque (Nm)
Elbow	7.65	5.4
Shoulder yaw	11.22	7.9
Shoulder pitch	15.3	10.8
Hip	5.61	3.9
Knee	2.29	1.6

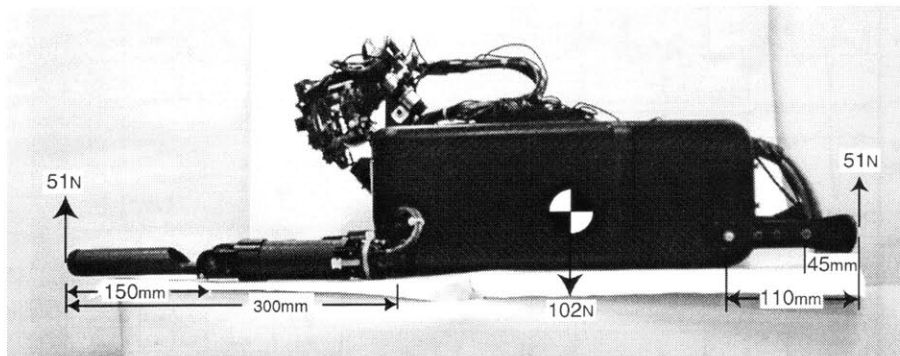


Figure 3-1: Worst case joint loading scenarios. Coco may experience the loadings shown though not necessarily in the manner shown. The estimation of maximum dynamic torque is based on the assumption that no joint will be more than $\pm 45^\circ$ from vertical during walking.

The static figures were tested using two separate dynamic simulations. Working Model(tm) is a dynamic modeler that imports geometry directly from the CAD system and allows the implementation of simple joint controllers. This system allows for improved analysis because it accounts for dynamic effects and weight distribution. The Creature Library is a dynamic simulator used by the MIT Leg Laboratory to develop walking robots. The emphasis in this system is on control. Since creatures are specified using simple geometric shapes the weight distribution is rudimentary, on par with the static calculations. Figure 3-2 shows joint torque plots output from the Creature library simulation^{iv} that corroborates the static calculations.

^{iv} Naoki Sadakuni, a fellow member of the Coco group performed the walking simulations in Creature Library, which provided this data.

$MaxTorque$ = The maximum torque expected at the joint
 $MaxDynTorque$ = The maximum torque expected during while moving
 $MaxJointSpeed$ = The maximum speed of the joint
 $HighTorqueSpeed$ = The speed of the joint while supplying $MaxDynTorque$
 $RqdPower$ = The estimate of the power needed by the joint [1]

$$MaxDynTorque = \sqrt{2} * MaxTorque = \sqrt{2} * 15.3Nm = 10.8Nm$$

$$HighTorqueSpeed = \frac{MaxJointSpeed}{10} = \frac{13rad/s}{10} = 1.3rad/s$$

$$RqdPower = MaxDynTorque * HighTorqueSpeed = 10.8Nm * 1.3rad/s = 14W$$

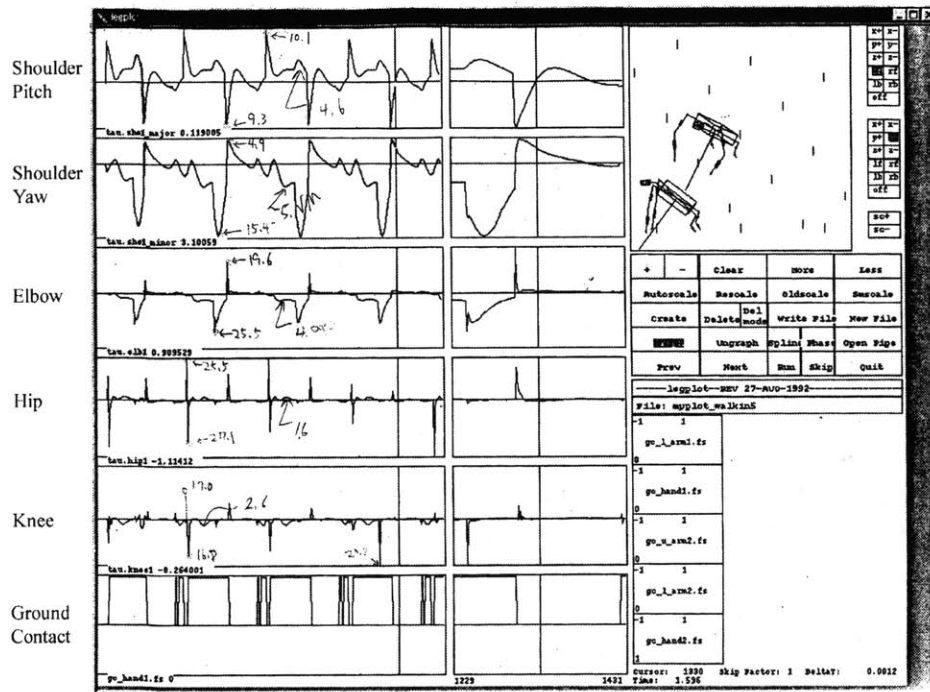


Figure 3-2: Output from the Creature Library showing the torque in Coco's joint throughout the walking cycle. Axis labels were not available so various torque values are noted on the plots.

Based on the simulations and static calculations, we chose a 24V, Maxon, ReO25 brushed, DC motor, rated for 20W to actuate the limbs. This motor was chosen based on its package size and its ability to mount a gearhead strong enough to handle the high torques the robot must endure. Other, smaller motors had the ability to supply suitable

power but could not be easily mated to the proper transmission. The motor can supply 0.029Nm continuously with a stall torque of 0.24Nm. Output speed is limited to 5000-6000 RPM by the gearhead. Table 3.3.1 shows the configuration selected for each joint.

Joint	Gear ratio	Gear efficiency	Max.Speed (RPM)	Continuous Torque (Nm)	Stall Torque (Nm)	Mass (g)
Shoulder*	51:1	0.70	117	1.07	12.24	330
Elbow	86:1	0.70	70	1.81	20.64	330
Hip	120:1	0.70	50	2.78	31.68	330
Knee	111:1	0.70	54	2.33	26.64	330

Table 3.3.1: Gear ratio selections for each joint of the body and the resulting joint performance data. (*The shoulder uses a differential arrangement which allows each axis to combine the output of two motors.)

The process for the design of the head is in marked contrast to the design of the legs. As previously mentioned, designing the legs was a continuously iterative process; since all ten degrees of freedom are dependent on each other there is no distinct starting point. The head was simpler to design since it is essentially a serial robot arm with a well-defined payload: the cameras. Starting at the most distal point with the known mass of the cameras, each degree of freedom could be independently designed using the preceding inertial characteristics.

Joint	Req'd Torque (mNm)	Gear Ratio	Gear efficiency	Max.Speed (RPM)	Continuous Torque (mNm)	Stall Torque (mNm)	Mass (g)
Camera Yaw	50	41:1	0.73	146	99	269	48
Camera pitch	100	66:1	0.70	90	152	416	53
Roll	150	66:1	0.70	90	152	416	53
Neck Yaw	300	66:1	0.70	90	309	1039	140
Neck pitch	1000	231:1	0.49	25	866	2703	135

Table 3.3.2: Torque requirements, gear ratio selections and resulting output capabilities and mass of the head motors.

The torque requirements and motor selection for each joint in the head are shown in Table 3.3.2. The yaw, pitch, and roll axes of the head all use MicroMo 1524 motors that can produce 9mNm at stall and 3.3mNm continuously. The neck yaw motor uses a MicroMo 2224 motor that provides 6.7mNm continuously and 22.5mNm at stall. The neck pitch motor is a Maxon, A-max22 capable of 7.56mNm continuously and 23.4mNm

at stall. Like the motors selected for the body, motor speeds are limited to approximately 6000RPM by the gearheads.

The power estimations lead to motor selections with a total mass of 3.7 kg. Adding to this the 0.15kg per degree-of-freedom weight of the motor control electronics resulted in approximately 6.0kg of mass necessary to power a 10.kg robot. The remaining 40% in the weight budget was available for additional transmission components and structure. Had these elements exceeded the weight budget the torque estimates would need to be revised and another iteration required.

Chapter 4

Hardware Design

4.1 Shoulders

Coco's head, long arms, broad shoulders, and the extra degree of freedom in the front limbs all tend to draw the center of gravity forward, making it harder to maintain the polygon of support. For this reason it was desirable to keep the shoulder motors inside the body and oriented parallel to the Z-axis of Coco's body. Coco's long arms also increase the expected torque. The need to supply high torque and a parallel motor configuration led to the selection of a differential drive system. Differential drives couple the two degrees of freedom allowing the motors to be mounted together and it enables each motor to equally share the load applied to the joint. This configuration also simplifies wiring the motors since the motors are stationary and inside the body. Running wires around joints increases the chances of failure and entanglement. Figure 4-1 shows the shoulder assembly.

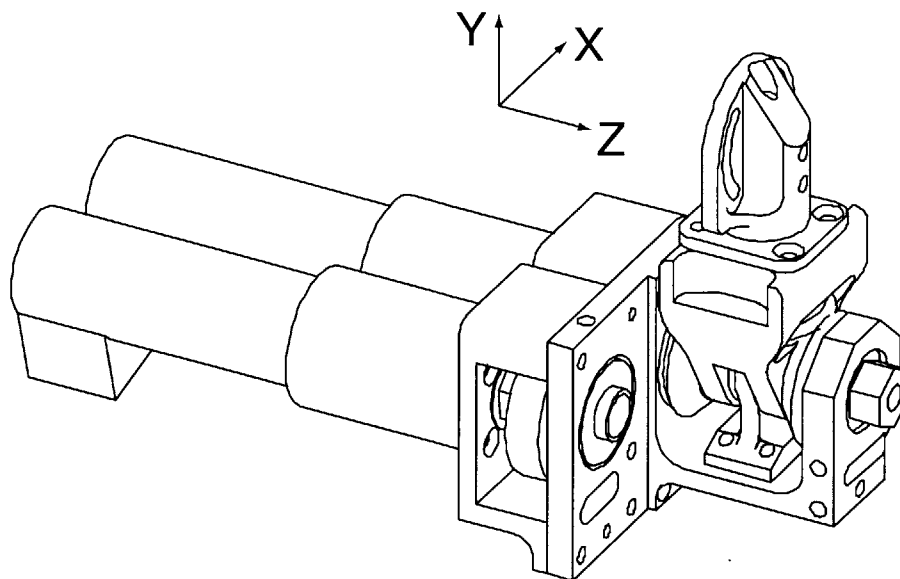
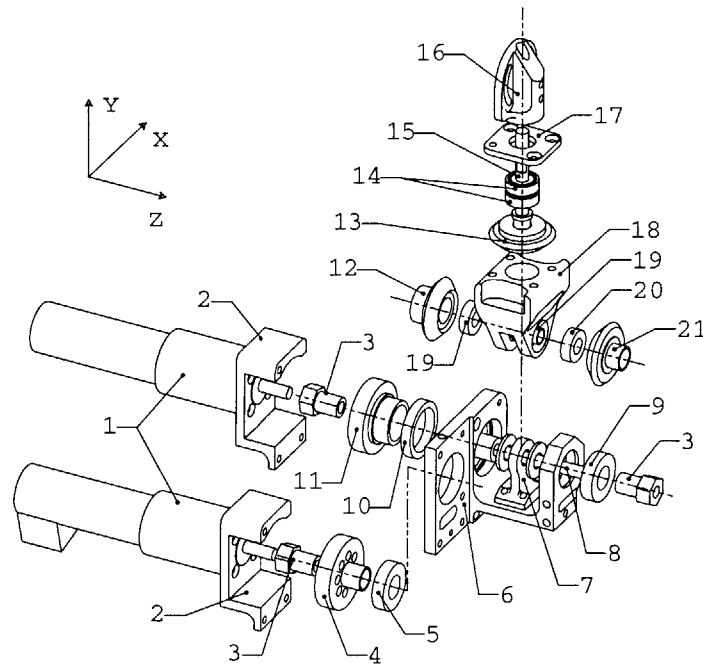


Figure 4-1: Coco's shoulder design uses a differential to allow both motors to mount vertically inside the body, lowering the center of gravity and allowing both motors to share the load.

The differential consists of three bevel gears; the two drive gears face each other on the Z [yaw] axis and actuate the output gear, which is mounted on the Y [pitch] axis. When the drive gears rotate in the same direction they cause the output to rotate around the drive gear axis. When the drives rotate in opposite directions, the output rotates around the

output gear's axis. The drive gears are connected to the motors in an unusual manner. The motor that drives the upper (closest to the head) drive gear is mounted coaxially to the drive axis. A shaft passes through clearance holes in the lower drive gear and the output mount to connect them. The lower drive gear has a spur gear mounted to its hub. A large diameter, deep-groove radial bearing and a thrust bearing support this two-gear set. The lower drive gear motor is located parallel to the upper drive gear motor and mounts an equally sized spur gear for 1:1 torque transfer. The output gear is mounted using a post and clevis arrangement. The clevis pin is a thin tube made from heat-treated tool steel, which is necessary to provide clearance for the upper drive gear's drive shaft. The output shaft is mounted using angular contact bearings oriented back-to-back (Figure 4-3-4). See Figure 4-2 for an exploded view of the shoulder.



No.	Description	No.	Description
1	Motors	12	Lower differential drive gear
2	Motor mounts	13	Differential output gear
3	Shaftloc™	14	Angular contact bearings
4	Spur gear	15	Output shaft
5	Radial bearing	16	Arm mount
6	Shoulder housing	17	Bearing retainer plate
7	Output mounting post	18	Output housing
8	Upper gear drive shaft	19	Output mounting tube
9	Radial bearing	20	Radial bearings
10	Thin deep groove bearing	21	Upper differential drive gear
11	Spur gear		

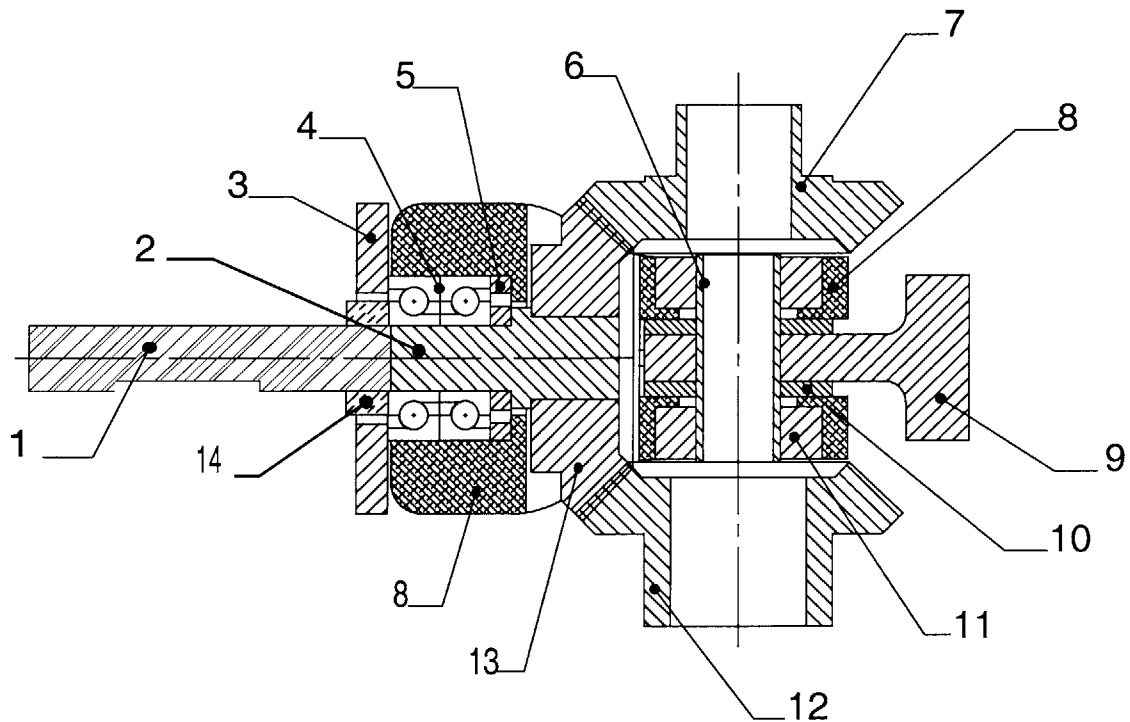
Figure 4-2: Exploded view of the shoulder

The key design constraint in mounting the output shaft was the need to keep the arm as close as possible to the yaw axis of the shoulder. In humans, the shoulder is essentially a ball and socket joint so the midline of the arm is collinear to yaw rotation. A differential arrangement precludes this orientation so the arm will necessarily be offset from its axis of rotation. A large offset would significantly diminish the natural look of the robot's gestures. The internal structure and transmission components as well as the output assembly affect the size of the offset. The size of the internal components and structure determine how close the yaw axis can come to the top-front corners of the robot's body and thus how close the arm can be to the yaw axis without interfering with the body. The output shaft must be rigidly mounted to insure proper meshing of the bevel gears. The size of this mounting must be kept small since it comes between the output gear and the arm. To minimize the space occupied by the bearing assembly, the output shaft is threaded ¼-28 UNC for a portion of its length and then transitions to a precision surface. The bearings fit over the precision surface and a locknut screws onto the threads to preload them. The arm mount is also threaded so that it can screw onto the output shaft behind the locknut. The arm mount locks using a setscrew that engages a flat on the output shaft (Figure 2-1-1). By combining the arm mount and the preloading mechanism the size of the shaft mounting assembly is minimized.

The differential gives unlimited range of motion to the pitch axis but allowing the arm to revolve multiple times could tangle and break wires running from the arm. A bar on the arm mount stops against the head of a cap screw holding the bearing retainer plate allowing rotations of +93° and -224°. The yaw axis is inside the body and so is limited by the amount of the chassis that can be removed to provide clearance and the necessary presence of the output mount. These issues limit the yaw rotation to +40° and -90°. The workspace of the arm created by these two ranges of motion does allow Coco to interfere with itself. If the yaw axis is near +40° then it is possible for the arm to strike the body if the yaw axis has an angle greater than approximately -20°. The robot can also strike the head in certain orientations. Providing hard stops to avoid these possibilities would significantly limit the arm's workspace. Therefore, software limit stops that are conditional based on the position of both axes are used to avoid collisions.

The differential's reliance on gears that are positioned by several different mating parts to transmit power raises the issue of backlash. Tolerance stack-ups can cause backlash greater than what is required for proper operation. In Coco's current configuration backlash is not a large issue because the motors are controlled directly from encoder feedback on the motor shaft. Backlash in the joints affects the final position of the limb but in current walking and gesture algorithms the tolerance for position errors is quite large. The differential assembly adds approximately 3.6° of backlash to the system. The spur gears that transmit power from the motor to the lower differential drive gear are high precision and well mounted so the backlash is no more than 0.5°. The gearheads in the servomotor contribute approximately 3.9° so the total backlash in the system is roughly 7.5-8.0°. This amount of backlash may become a problem if future configurations require more precise positioning of the limb. If, for instance, it becomes necessary to control the limb from a sensor at the output of the joint backlash would cause a dead spot that would

adversely affect the control system. In cases like this, shimming the gears in the differential to remove errors caused by the multiple mating parts could reduce the backlash. Since the differential only accounts for 50% of total, the possible reduction is only about 30-40%. The elbow joint also uses bevel gears to transmit power from the motor to the joint. In this case, there is only one part, aside from bearings and a precision shaft, responsible for locating the two gears so the backlash is only about 1.0°.



No.	Description	No.	Description
1	Threaded section of output shaft	8	Output housing
2	Bearing mount area of output shaft	9	Output mounting post
3	Bearing retainer plate	10	Thrust washer
4	Back-to-back bearing set	11	Radial bearing
5	Spacer	12	Lower differential drive gear
6	Output mounting tube	13	Differential output gear
7	Upper differential drive gear	14	Hex nut

Figure 4-3: Cross section of Coco's shoulder output assembly showing the gears of the differential, output shaft, and mounting post

The emphasis placed on minimizing space and weight lead to the breaking of a traditional rule in the design of mechanical transmission systems. The drive shafts are overconstrained. The output shaft from the motors is fully supported by internal bearings. In the case of the upper drive gear the connecting shaft should have a compliant coupling to account for misalignment. The driving spur gear for the lower drive gear can apply more radial force to the motor bearing than they can handle, so additional support is required. Ideally, the spur gear would have its own supports and the motor would be connected through a flexible coupling. In an overconstrained system the slightest misalignment can cause high loads on the bearings leading to premature failure. To combat misalignment, the mating parts were carefully toleranced for parallelism. Additionally, the motors were mounted to their drive shafts and allowed to “find” the best location by rotating the joints as the mounting screws were tightened. Provisions were made such that once the motors were located they could be permanently fixed with dowel pins.

This design maintains a low overall center of gravity for the robot. It also positions the axes of rotation very close to the outside corners of the robot, closely approximating a biological shoulder.

The design previously described is the second one implemented on Coco. The original design had the two degrees of freedom oriented in roll and pitch instead of yaw and pitch. This configuration was the result of a focus on the robot’s walking characteristics and neglecting some of the needs for gesture. Figure 4-4 shows how the original design allowed Coco to make chest beating and hugging gestures as well as large lateral movements while walking. Unfortunately, with the axes oriented to provide roll and pitch rotation the arm is unable to point to arbitrary locations in the Y-Z plane. The arm can only move one-dimensionally along the Y or Z-axes. The inability of the robot to point to objects in front it was an unacceptable drawback to the original design.

The original and final shoulder designs share the same differential system but the orientation necessarily differs. In the final shoulder the motors are parallel to the differential’s input axis which allows one motor to connect directly to the differential. The second motor is offset from the input axis so a spur gear transmits the power. In the original design (Figure 4-5) the motor’s are perpendicular to the differential’s input axis. In this case, both motors use bevel gears to transmit power to the differential.

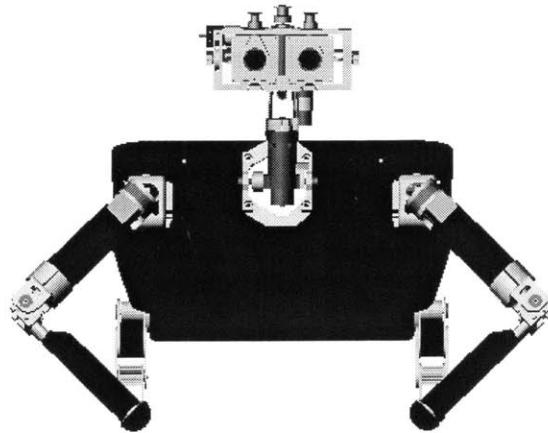


Figure 4-4: Coco with its original shoulder. With the degrees of freedom oriented in roll and pitch the arms can be oriented to hug and perform a realistic chest beating behavior.

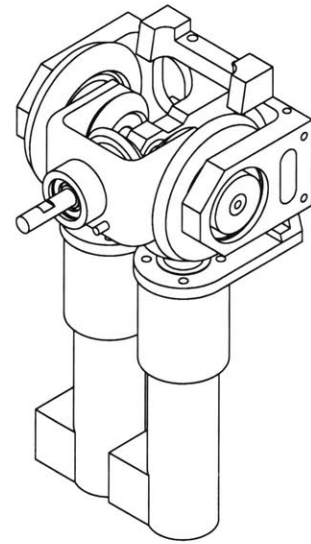


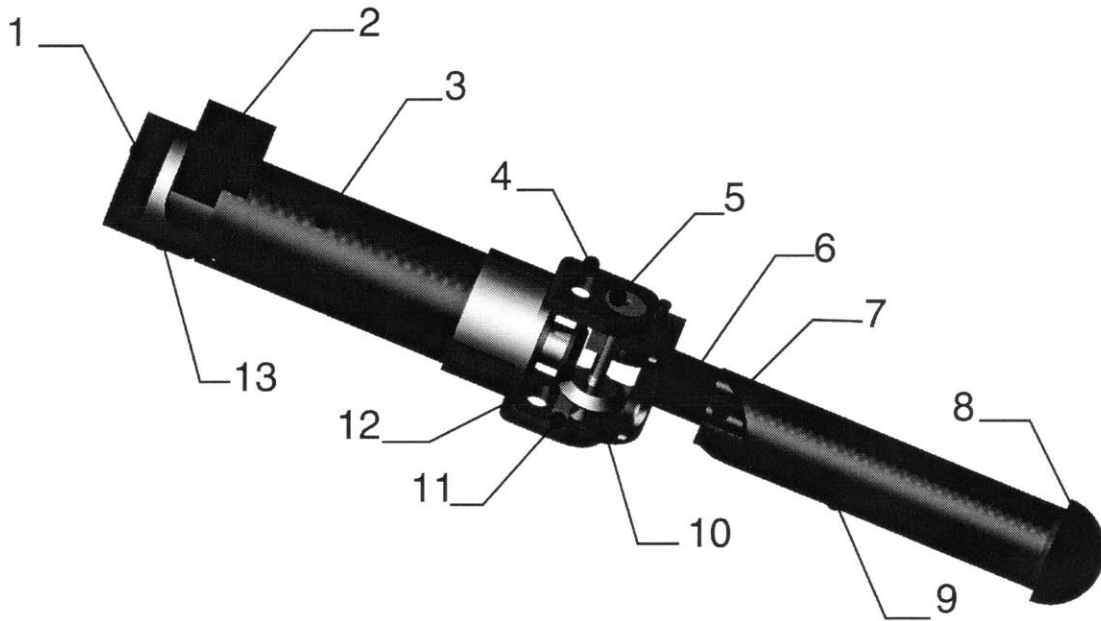
Figure 4-5: The original shoulder used the same differential arrangement as it's successor but the motors are perpendicular to the differential's input axis.

4.2 Arms

As described earlier, the arms are mobile masses that can greatly shift the robot's center of mass during walking. To minimize weight, the structure of the arms primarily consists of carbon fiber reinforced polymer (CFRP) tubes. The elbow motor resides in the upper arm and actuates the elbow through a set of bevel gears. At the top of the upper arm, an aluminum block provides an attachment point for the output of the shoulder. The mounting block (Figure 4-6-13) has a large cutout for the elbow motor's encoder. Four bolts pass through slots in the shoulder output to mount this block. The slots allow the arm to be rotated so, if necessary, the elbow axis can be adjusted relative to the body. A plastic spacer between the shoulder output and the arm block adds length to the arm. The current configuration has a 10mm spacing but this is easily changed to accommodate future modifications. This block then bolts to a CFRP tube that surrounds the elbow motor.

At the elbow, a single aluminum part glued to the end of the CFRP tube both mounts the elbow motor and the bearings for the elbow axis. Creating the entire elbow knuckle out of a single part allows there to be a tight tolerance on the distance between the motor's mounting face and the elbow axis. This is a critical dimension that defines the spacing of the bevel gears that are used to transmit force perpendicularly from the motor to the elbow axis. The forearm mounts to the elbow axis via a clamp that straddles the output bevel gear and engages the output shaft. The range of motion of the elbow is $+0^\circ$ and -135° , roughly equal to that of humans. In order to allow the forearm to bend this far it

was necessary to taper the forearm near the elbow. This was accomplished by gluing two narrow (6mm) CFRP shafts inside the forearm tube. These shafts mate to an aluminum boss that bolts onto the elbow clamp. The addition of these thin load-carrying members allows the forearm tube to be tapered to accommodate the elbow range of motion. At the end of the forearm tube, a threaded insert is glued inside the tube to allow different hand modules to be easily installed. Currently, Coco's hand is a simple rubber hemisphere. In the future, load cells, tactile sensors or grippers may be developed.



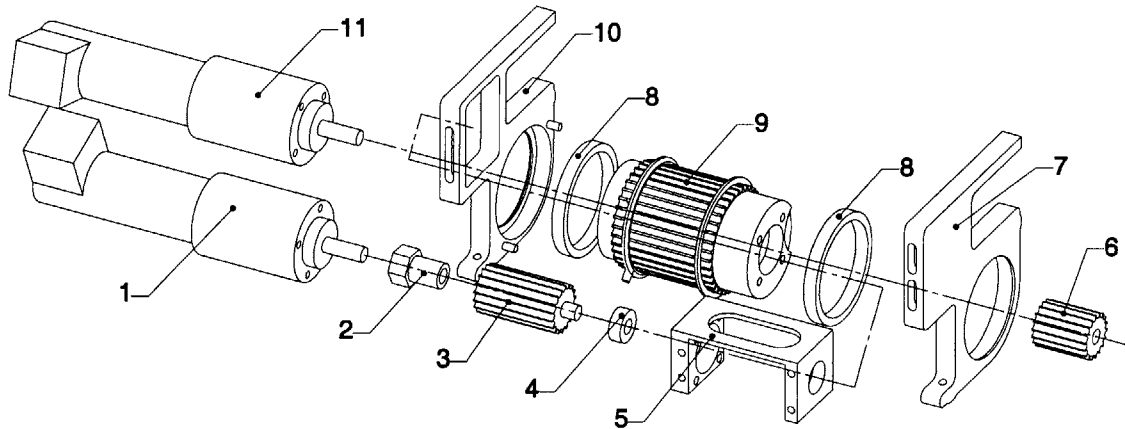
No.	Description	No.	Description
1	Spacer	8	Hand attachment
2	Elbow motor with encoder	9	CFRP tube
3	CFRP tube	10	Output mount
4	Elbow knuckle	11	Clamp
5	Angular contact bearing	12	Bevel Gears
6	Forearm mounting stud	13	Arm mounting boss
7	Thin CFRP tubes		

Figure 4-6: Coco's arm. The elbow motor is housed in the upper arm and drives the elbow via a set of bevel gears. The forearm is hollow and has a threaded end to accept various hand components

4.3 Hips and Legs

Coco's short hind legs require the knee motors to reside inside the body due to the space constraints. Additionally, the cantilever nature of the hip joint coupled with high torques (especially as the robot transitions from standing to sitting) and large shock forces

transmitted from the leg require that it be well supported. One solution, which is often seen in robotics, is to fasten both motors to the body and pass the knee torque through the hip joint. This couples the movement of the two joints by requiring moves to be coordinated between the joints, slightly complicating the motor control algorithms.



No.	Description	No.	Description
1	Hip Motor	7	Outer hip mounting plate
2	Shaftloc™	8	Bearing
3	Hip motor capstan	9	Hip capstan
4	Bearing	10	Inner hip mounting plate
5	Hip output support frame	11	Knee motor
6	Knee motor capstan		

Figure 4-7: Exploded view of Coco's hip. The hip motor (1) turns the inner leg assembly via a timing belt. The knee motor mounts inside the output capstan (9) and actuates the knee via a timing belt in the thigh (not shown) .

Coco's hip design decouples the hip and knee joints by rotating the knee motor with the hip and thigh. As shown in Figure 4-7, the knee motor is mounted coaxially to the hip inside a timing belt pulley. The thigh is mounted to the end of the pulley and a second timing belt connects the output of the knee motor to the knee joint with a 1:1 ratio. The leg-pulley-motor assembly is supported by large diameter, thin section bearings. Rotation is limited by a dowel pin protruding radially from the hip capstan. This pin interferes with dowel pins in the inner hip mounting plate (Figure 4-7-10) limiting rotation to $+0^\circ$ and -180° .

From its offset position the hip motor drives the leg, pulley, motor assembly through a timing belt with a 2:1 reduction. The additional speed reduction provided by this

reduction reduces the torque the hip motor's gearhead must endure which will increase the life of the joint. In this configuration, a cable drive would also have been a solution. However, the hip area provided more space for a thin and wide transmission, like timing belts, that can be made stronger by adding width, as opposed to cables that grow in both dimensions as strength is added. Additionally, the timing belt solution allowed placement of the tensioning mechanism away from the tight space of the leg assembly.

The 2:1 reduction in the hip transmission required that the diameter of the drive pulley be as small as possible based on the minimum required diameter of the timing belts. The radial forces induced by the necessarily small and long driving pulley are higher than what the motor output shaft can handle. As with the shoulder drive shafts, an external, overconstraining support was added. The support bolts to the mounting face of the motor and connects to a bearing mount at the end of the driving pulley through a thin web. The flexibility of this web minimizes the force induced by the overconstraint. This system then bolts onto a pocket in the frame that supports the leg assembly. The pocket allows the timing belts to be properly tensioned and then bolted into place. This design combines compact packaging of the two motors, a shock-tolerant high-load-bearing system, and a torque increasing power transmission with the added benefit of decoupling the degrees of freedom.

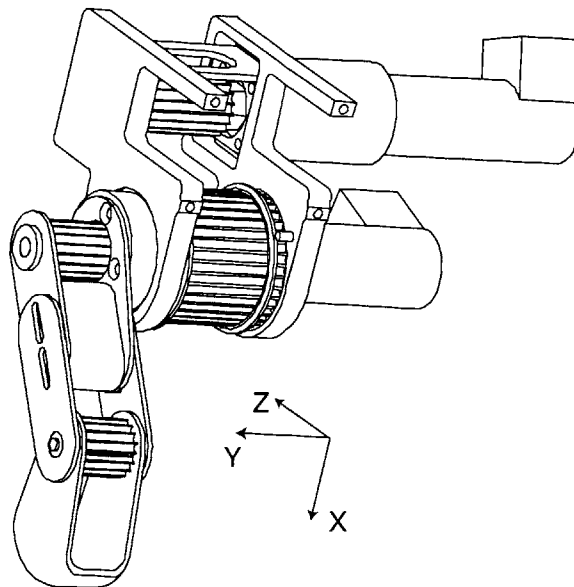


Figure 4-8: The leg bolts to the face of the hip capstan. The knee motor drives the knee via a timing belt that runs down the thigh.

Coco's thigh is made up of four plates that bolt to a central mounting block. One of the upper plates attaches to the hip capstan and the other supports the knee motor output shaft via a flange bushing. The lower pair of plates mount the shaft for the knee axis and have slotted holes for mounting to the central mounting block. This allows the knee's timing belt to be properly tensioned. The knee capstan is pinned to the foot, which is a single

aluminum part. Knee rotation is limited by the foot's (Figure 4-9-5) interference with the upper thigh plates (Figure 4-9-6&9). This occurs at $\pm 120^\circ$.

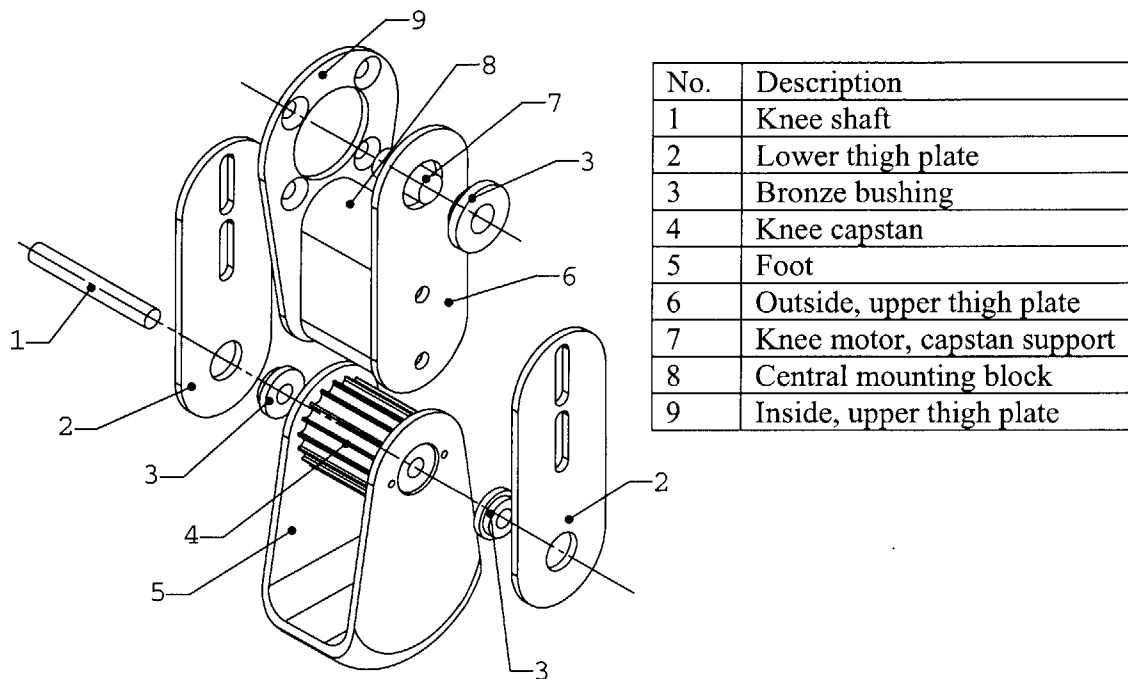


Figure 4-9: Coco's leg is comprised of a pair of plates (2) that can slide relative to another pair (6&9) providing adjustment for the timing belt running from the knee motor at the hip to the knee joint. The foot (5) is a single aluminum part.

4.4 Head

Excluding the camera and motor mounts, the frames that make up the structure of the head are all fabricated from 1.5mm thick laminated CFRP. The CFRP plates were used to create beams with great stiffness and low weight. The key advantages of the CFRP beam construction in the frames of the head are their great strength-to-weight ratio and the simple manufacturing method used. The flat CFRP laminate is cheap to manufacture and cut precisely using a water-jet. The camera roll and pitch frames are constructed using aluminum or ABS plastic inserts where shafts or screws are needed and balsa wood filler to provide additional shear area. The frames were assembled with the aid of locating jigs as shown in Figure 4-11 using high strength epoxy. An alternative to this method would be to laminate the CFRP skins, filler, and inserts together. This method is more costly due to the use of higher skilled labor, longer lead-time, and the necessity for deflashing and cleaning operations.

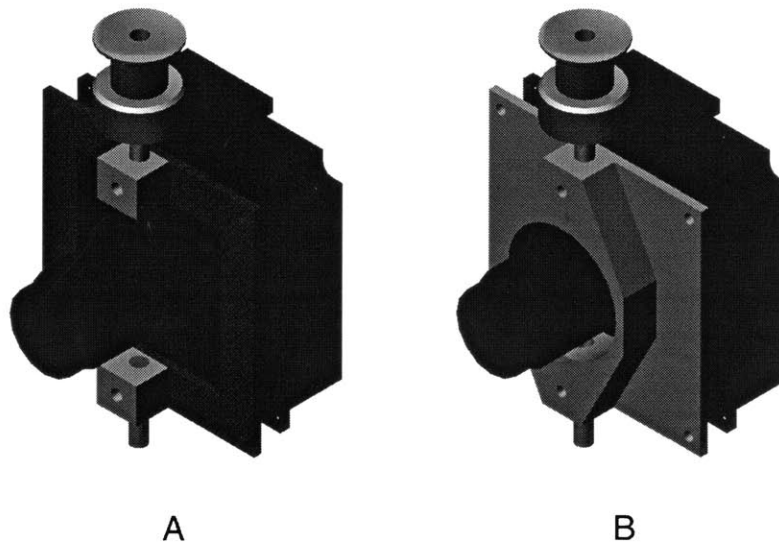
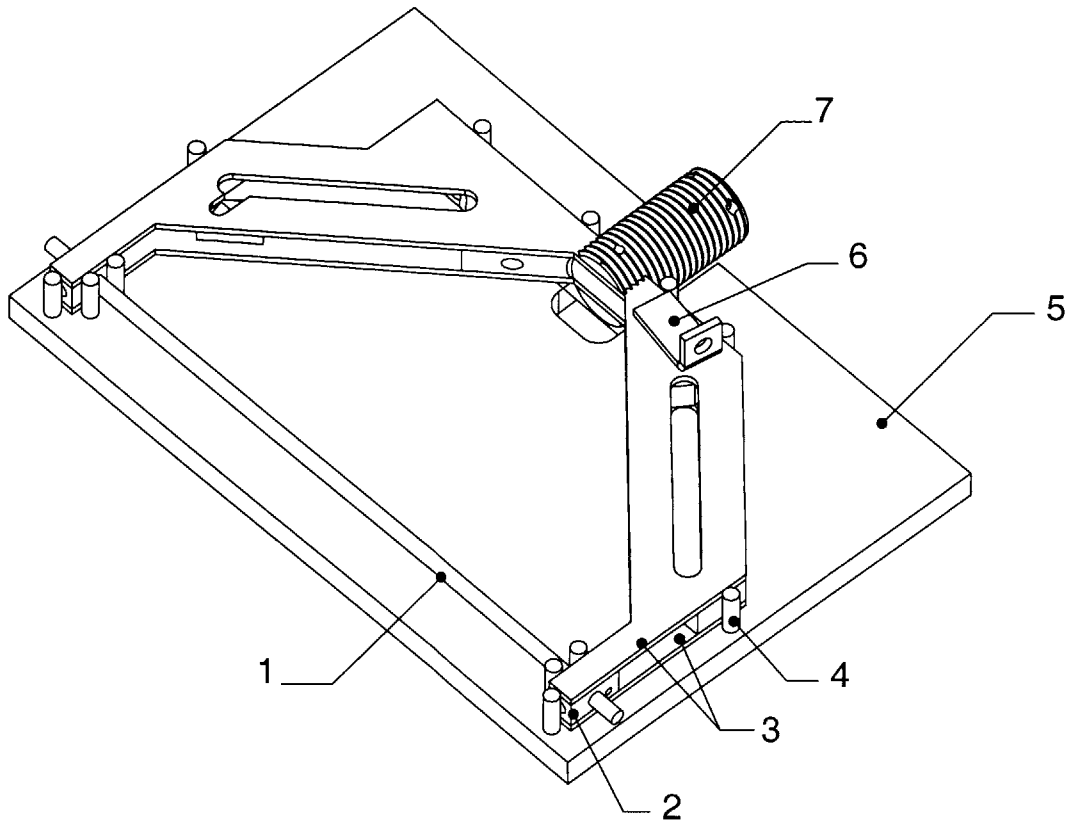


Figure 4-10: Original and redesigned camera mounts. The original mounting frame (A) used a CFRP plate with two small aluminum studs bonded on the surface to mount the yaw shaft. The minimal surface was prone to peel failure so the mount was redone with negligible weight gain as a single aluminum part (B).

The yaw frame is of a simpler design. The two aluminum bosses that connect the frame to the yaw and roll axes have locating pins that simplify assembly and add to the shear strength of the bonded joint. The taper from the yaw mount to the roll mount simultaneously reduces material in the roll mount and adds lateral stiffness.

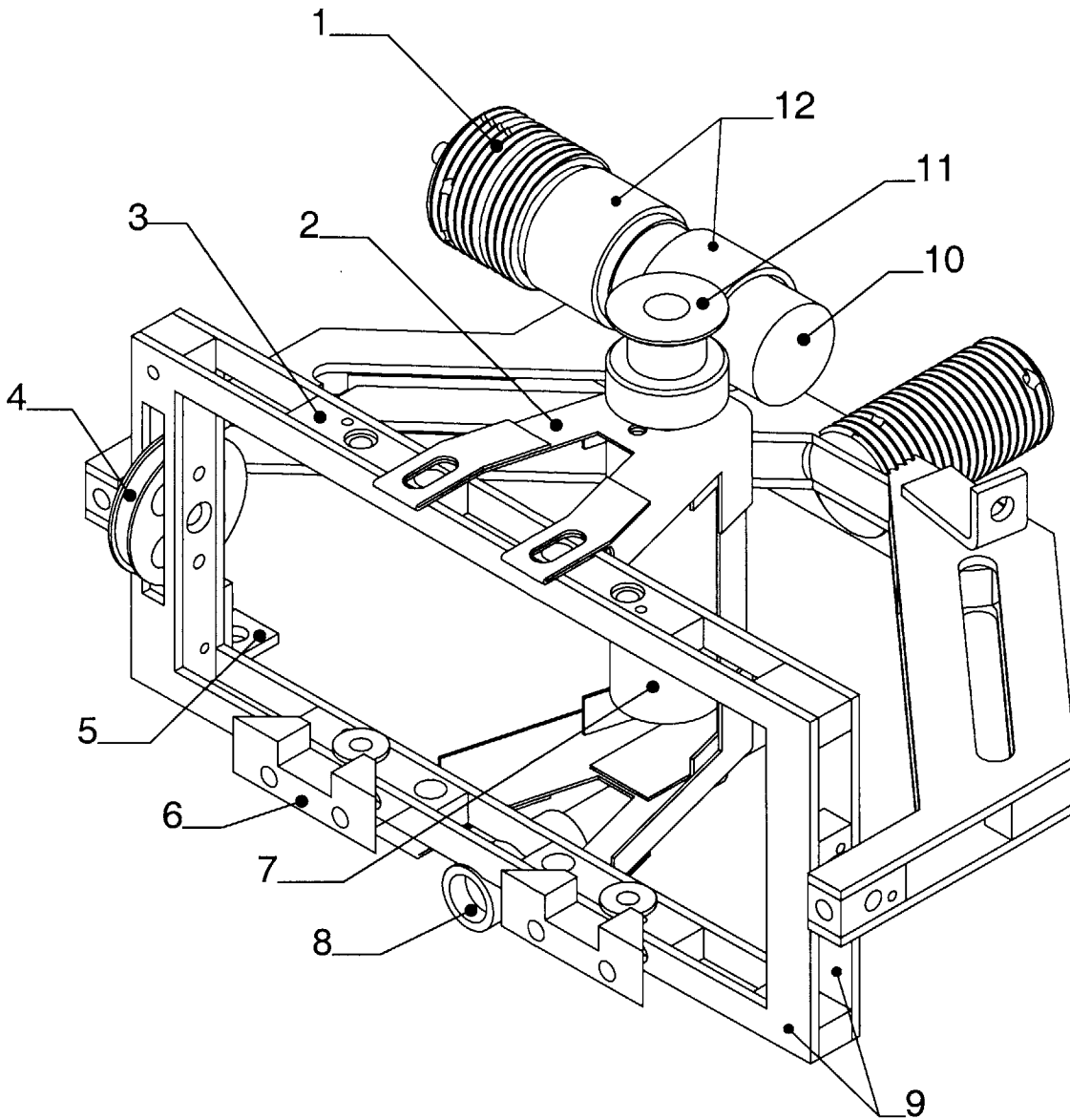
The original camera mounts were designed as CFRP plates bonded to aluminum studs (Figure 4-10A). In practice, this quickly proved to be an inferior design due to the minimal bonding area and high peel forces induced by bending. Since the overall volume of the mounts is small it was feasible, on a weight basis, to machine them out of aluminum (Figure 4-10B). Therefore, we used this solution as it traded a small amount of weight for a large savings in robustness simplicity of manufacture.

The coupled camera yaw axes are actuated with a single motor. This motor mounts to a steel weldment (Figure 4-12-2) that, in turn, mounts to the pitch frame. A timing belt provides power transfer and encircles the driving capstan and the two driven capstans. The capstans were sized appropriately to engage the recommended number of belt teeth. The four mounting holes in the weldment are slotted to provide belt adjustment. Yaw motion is limited to $\pm 45^\circ$ by a plastic limit stop (Figure 4-12-6) mounted on the front of the pitch frame.



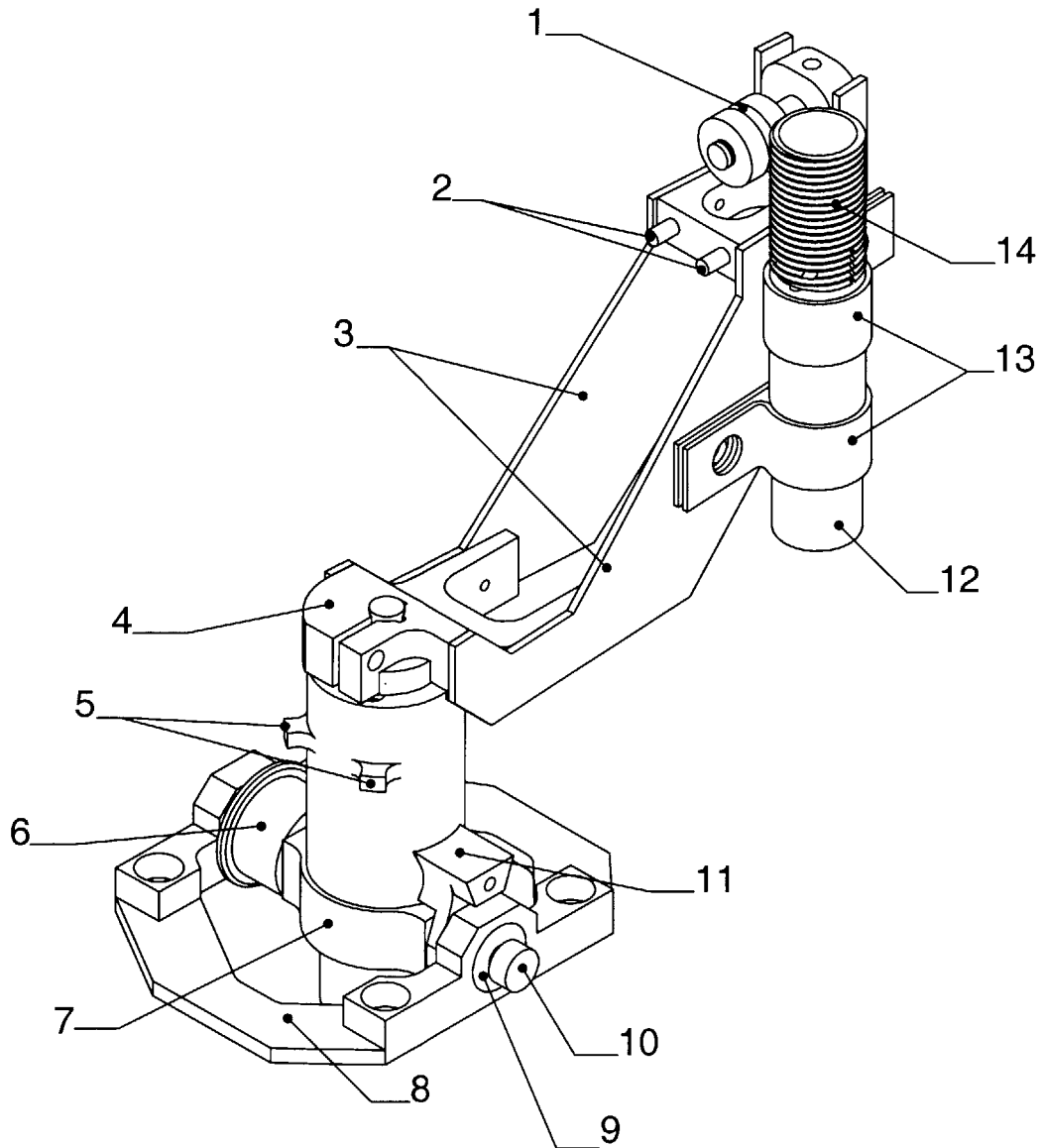
No.	Description	No.	Description
1	Locating shaft	5	Assembly jig base
2	Aluminum insert	6	Roll cable terminator
3	CFRP plates	7	Roll capstan and bearing mount
4	Locating pin		

Figure 4-11: Head roll frame shown with its assembly jig. The locating pins (4) and shaft (1) fix the assembly while the epoxy cures so that all critical geometry (IE the pitch axis mount) is properly positioned. The pitch frame used a similar jig to locate its critical geometry.



No.	Description	No.	Description
1	Pitch drive capstan	7	Yaw motor
2	Yaw motor mounting weldment	8	Narrow angle camera & mount
3	Plastic insert	9	CFRP plates
4	Pitch capstan	10	Pitch motor
5	Cable tensioner	11	Yaw drive capstan
6	Yaw limit stop	12	Pitch motor mounts

Figure 4-12: The pitch frame is a CFRP beam that employs ABS plastic inserts to mount the pitch and yaw axes as well as the yaw motor mount (2).



No.	Description	No.	Description
1	Roll bearing set	8	Head mount
2	Roll limit stops	9	Pitch axis bearing
3	CFRP plates	10	Shoulder screw
4	Yaw frame motor clamp	11	Pitch limit stop
5	Yaw limit stops	12	Roll motor
6	Pitch capstan	13	Roll motor clamps
7	Pitch frame	14	Roll driving capstan

Figure 4-13: Head mount (8) , neck (7) and yaw frame (3). The neck is a tube that holds the yaw motor and has bosses to mount the pitch capstan (6), pitch limit stop (11) , and shoulder screws (10). The yaw frame clamps to the yaw motor output (4) and mounts the roll motor (12), and roll axis bearings (1).

Mounting the motors for camera pitch and roll was made easier through the use of off-the-shelf conduit clamps with an inside diameter that matched that of the motors. The camera pitch motor mounts to an aluminum boss in the back of the roll frame. A wire cable is used as the transmission medium to the pitch capstan. Pins in the pitch frame that interfere the roll frame limit the range of motion to $\pm 40^\circ$.

When designing cable drive systems, the recommended safety factor, relative to the breaking strength of the cable, is 10. Experience has shown that the safety factor can be reduced to 2 for research robots by designing capstans that conform to the best practices recommended by the manufacturer. This involves supporting the cable along its contour (Figure 4-14-C) instead of allowing it to deform, as it will when tensioned against a flat surface (Figure 4-14-B). If a cable winds onto a flat capstan it is compressed slightly by the reaction forces against the cable tension. This repeated compression of the cable weakens it over time. Even with proper support, the life of the cable will be reduced when operating with a safety factor of two but the duty cycles that the cable will see on Coco push the trade-off between life and size/weight toward shorter life.

The practical application of this best practice is to use capstans that have a helix of proper cross-section cut into them. This insures that the cable is well supported as it takes the multiple turns necessary to generate the friction force needed to transmit the driving torque. In the camera pitch transmission, only the motor capstan could be grooved according to this best practice. Since the driven capstan is part of the camera pitch frame that is enclosed by the roll frame, and the desire for facial symmetry meant that both sides of the frame should be the same width, minimizing width was critical. In this case, the distance between the flanges of the capstan was designed so that they would support the sides of the cables to minimize deformation (Figure 4-14-D).

The transmission for the roll motor also used cables. In this case, both capstans had sufficient length to fully support the cable with a helical cut. The motor was mounted transverse to the roll axis on the yaw frame. Similar to the pitch limit stop, pins in the yaw frame interfere with the roll frame to limit roll motion to $\pm 30^\circ$ (Figure 4-13-2).

The volume of the neck pitch frame is almost completely taken up by the yaw motor. A thin aluminum shell surrounds the motor to connect its mounting surface to the neck pitch axis. Bosses on the tube accept shoulder screws that run through bearings mounted in the head mounting plate to create the pitch axis. These bosses also mount a plastic limit stop (Figure 4-13-11) that constrains the pitch motion to $\pm 70^\circ$. The output shaft of the gear-motor for the yaw axis directly drives the yaw frame. A thrust bearing was added between the motor mount and the yaw frame to add stiffness to the head. A pair of tabs (Figure 4-13-5) on the tube interferes with a pin on the yaw frame to limit rotation to $\pm 130^\circ$.

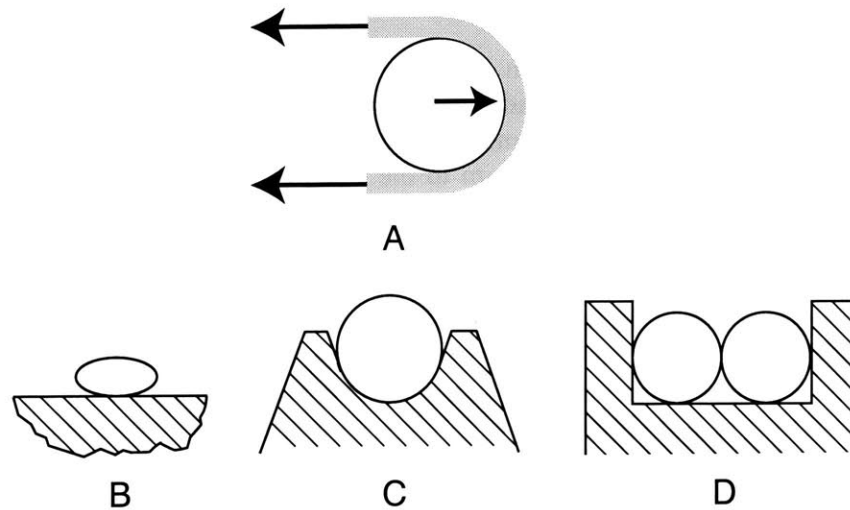


Figure 4-14: How a cable is supported on the capstan can have a dramatic effect on its life. An unsupported cable (B) cycles in and out of compression (A) as it winds on and off the capstan. If properly cradled (C), the crushing effect is minimized and life is extended. When the capstan cannot be designed to properly cradle the cable, close flanges (D) can be used to partially support the cable (The figure in D shows a capstan with two turns of cable on it).

4.5 Body

Coco's body serves as mount for all of the individual extremities and all of the onboard electronics. The body chassis is also responsible for creating the rough overall appearance of a biological being. Although animals have decidedly flexible overall structures, Coco needs to have a stiff platform to mount the various components. A stiff structure will reduce the chances of breaking the electronic components mounted inside. Additionally, control algorithms are generally complicated by the introduction of unmodelled dynamics. Body flex would be difficult to model and could result in poor performance by causing unpredicted behavior in the motor control system.

There are several approaches and materials that could have suited all of these purposes. One method would have been to create a frame connecting the head, hips, and shoulders using aluminum or CFRP tubes. A cosmetic chassis could then be fitted around the structural components. Another option would have involved creating a welded monocoque frame out of sheet aluminum or steel.

For Coco's body we used a monocoque CFRP chassis. The benefits of CFRP are the smooth contoured shapes made possible by molding and exceptional stiffness afforded by the graphite reinforcement. Additionally, the ability to create the net shape of the robot from a single part results in a better appearance and simpler design and assembly. As shown in Figure 4-15 the body has tapered sides that give the appearance of broad primate shoulders which give way to a narrower waist. The sharp narrowing at the base

simulates the pelvic-femoral interface that results in a nearly straight transition from the abdomen to the legs.

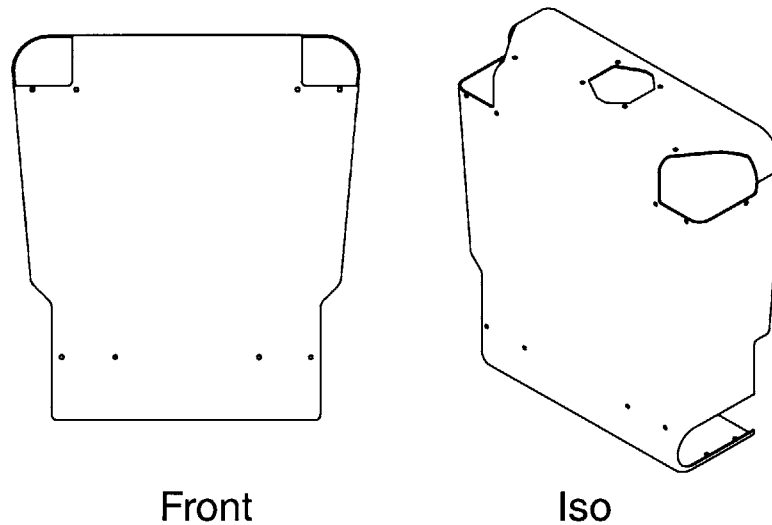


Figure 4-15: Two views of Coco's CFRP body chassis. It is molded as a single part and has cutouts for the arms, legs, and head as well as bolt holes to directly mount the various components.

The finished lay-up for the body chassis is 1.5mm thick, which affords sufficient material and local strength for press-on panel fasteners and bolts. Each extremity simply bolts on to the chassis. Similarly, the five motor control units are joined together by running threaded rod through their mounting holes. This assembly is bolted to the chest portion of the chassis via tabs fixed to the ends of the threaded rod.

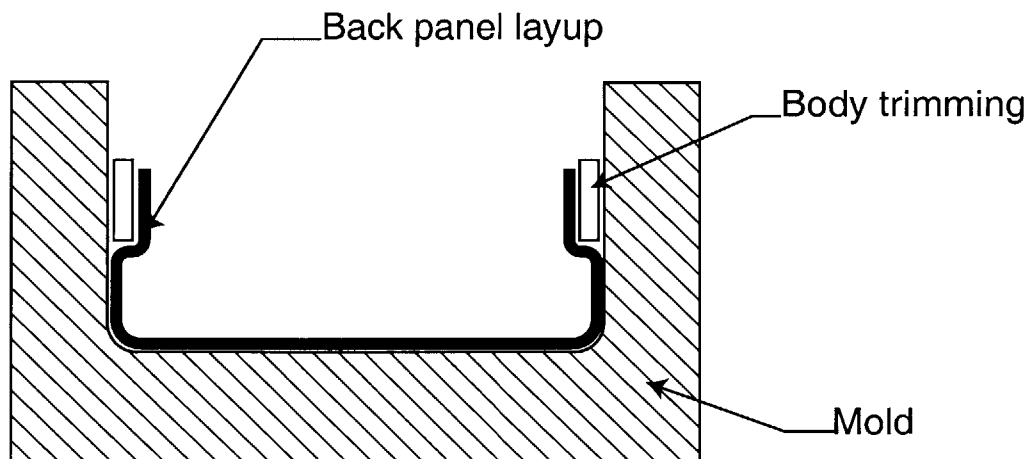


Figure 4-16: A trimming from the outer edge of the body chassis is saved and fixed inside the mold. When the back panel is laid-up and cured, it has lip that matches the body thickness so a nearly perfect lid is created.

Coco's back panel was developed in close cooperation with the CFRP vendor. They suggested a simple method that created a tight fitting lid for the body chassis. A trimming from the body chassis is saved and fixed in side the mold. The distance between the mold bottom and the scrap piece is the height of the back panel. This insert creates an inward step in the back panel lay-up that matches the thickness of the body panel. The result is that the back panel fits snugly onto the body panel like a jewelry box.

4.6 Electronics

Coco's power electronics and control system consists of five three-axis MAX2000 integrated motor amplifiers and control DSPs from Agile Systems. These boards implement PID position control based on feedback from encoders located on each motor. A serial communications line connects each board to an off-board PC that is responsible for generating joint trajectories.

The choice of a control system was driven by the need for a package small enough to fit inside the robot. The time constraints for the project limited choices to off-the-shelf solutions with supporting software. Coco is not an autonomous robot since power and computation is supplied externally via a tail but the size of this tail needed to be minimized or Coco's mobility would be compromised. If, for instance, all motor control was handled off board the number of wires running to the robot would be a major hindrance to the robot's mobility. Each motor has a minimum of four encoder wires and two motor power wires. This adds up to 90 individual wires. This is in addition to the video, sound and, attitude sensors that also run off board. By handling the motor control inside the robot, the motor system's power and signal connections are greatly condensed.

Finding a motor control system that could fit inside the robot proved difficult. Most commercial systems are designed for large stationary automation equipment and are therefore too big and overpowered for Coco's needs. It is also difficult to find systems that integrate motor controllers and power amplifiers or support multiple axes on one system. An integrated system can provide large space savings by reducing connectors, which account for a large part of a system's volume. The MAX2000 board supplied by Agile Systems was selected based on its integration of three axes of motor control and power amplification onto one board. Agile Systems also supplied software libraries and tuning software that enabled fast implementation of high-level algorithms. Although the MAX2000 boards were the best commercial solution found, they are by no means perfect. The system is designed to supply up to 400 Watts to each motor. This is 20 times what is necessary for Coco's actuators. The extra capability is wasted on the robot and a physically smaller system that matches the robot's requirements would be preferred. The system has also failed to reliably deliver some features, such as analog IO, due to system bugs.

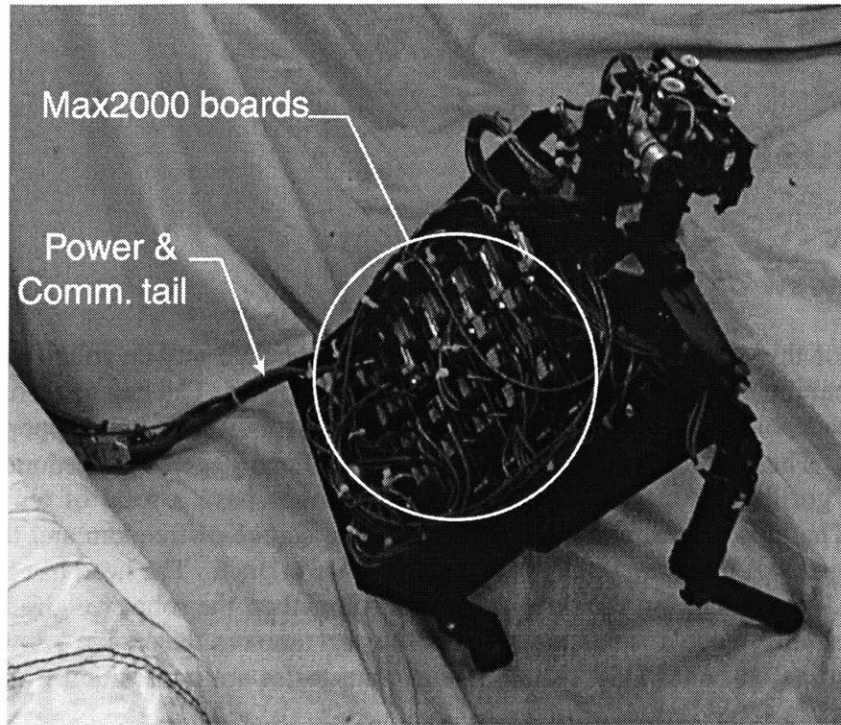


Figure 4-17: Five MAX2000 3-axis motor controllers provide PID motor control. A tail supplies power and serial communications with the controllers.

Chapter 5

Conclusions

5.1 *Review of Thesis*

The focus of this design effort was to produce an articulate mobile robot with multiple sensing capabilities to facilitate the study of social machines. The key goals of the design were approachable form, low weight, expressiveness, robustness, and support for vision processing. These goals lead to the creation of a fifteen degree-of-freedom quadruped robot with gorilla-like morphology. The robot's limbs have a total of ten degrees of freedom. The hips, knees, and elbows are each one degree-of-freedom and the shoulder has two degrees of freedom, one in yaw and the other in pitch. The head has five degrees of freedom, for positioning the three cameras. Altogether, the robot weighs 10.2 kg and stands 0.5m tall. Coco's joints are actuated by servomotors that receive low-level PID control from an on-board DSP system. Joint trajectories are transmitted from off-board computers via a serial link.

The completed robotic platform performs almost exactly as designed. Members of the Coco Team successfully implemented a static walking algorithm that allows Coco to easily walk at 3.5m/minute. The walking speed achieved is acceptable, although limited by the shortness of the hind legs. A future modification may be to lengthen them to allow Coco to walk slightly faster. The Team has also implemented several social behaviors, such as orienting to and approaching both visual and auditory stimulus. The actuators can supply sufficient power to the joints for all walking and gesture tasks attempted to date. The head performs as expected, with the exception of oscillations that occur in the neck pitch while the robot is walking. As the robot walks, the backlash in the pitch motor and compliance in the body chassis allow the neck to oscillate several degrees due to the motion of the body. The length of the head translates this into a noticeable vibration. The modular design of the robot simplifies maintenance and future modifications. After nearly a year of operation there have been few failures. Those that have occurred have been in easily replaceable, off-the-shelf-components.

There are a number of important lessons to be learned from the design of Coco. The original shoulder design was thought to provide excellent gesturing ability, but neglected a key need because of failure to completely assess all requirements. Similarly, in designing the camera mounts, weight reduction was pursued too aggressively, leading to the use of CFRP in a place where a simple aluminum part was more appropriate resulting in a faulty design.

Not all lessons were learned through mistakes however. Coco uses cable drive systems in some areas and belt drive systems in other areas according to a conscious weighing of their respective advantages. Cable drives, which are made out of steel, generally have

greater power-transmitting density than polymer belts. On the other hand, belts are often easier to use and maintain because they are continuous which can simplify mounting and tensioning. Coco's design makes efficient use of both methods. Another success was the use of molded CFRP for the body chassis. Coco's light, yet very strong body allows all hardware to simply bolt onto the appropriate place. This eased design of individual joints by reducing integration issues. The use of a differential in the shoulder allowed the two motors to share the torque of the most severely loaded joint and enabled placement of those motors in an orientation that positively affected the center of gravity.

5.2 Future Work

As research using Coco progresses there will be countless modifications desired. The Coco group has already identified several possible changes. The current on-board motor-control electronics is heavy and has several software bugs. Weighing 2.25kg the system accounts for 20% of the robot's mass. If this system were replaced by a system better tailored to Coco's needs, there could be significant weight savings. The addition of tactile and force sensors, especially to the hands and feet, are another possible upgrade. This addition would strengthen Coco's repertoire of sensory information.

Another immediately useful improvement to the robot would be the implementation of series elastic actuators¹⁰. Series elastic actuation is an innovative force control method that intentionally places a significantly compliant spring between the load and motor. The spring is servoed to the desired compression by the motor and the force is inferred from the compression in the spring according to Hooke's Law ($F=Kx$). The resulting actuator has high force fidelity, good bandwidth, shock tolerance, and extremely low output impedance.

Series elastic actuators have an advantage over traditional force control methods for two reasons. First, series elastic actuators are inherently compliant due to the spring between the environment and transmission. Inherent compliance in the system means that there will always be a level of compatibility between the environment and the drive system, even for high frequency impact loads. Second, the spring lowers the mechanical stiffness of the system, allowing for a proportional increase in the control gains of the system¹¹. Increased control gains result in better low impedance performance. Improved low impedance performance implies that the system can interact in an effective way with a wider range of environments.

Although force control can also be achieved with stiff load cells, low impedance performance will deteriorate significantly due to lack of high control gains. Furthermore, force control using stiff load cells is not inherently compliant, making it susceptible to high frequency shock loads which will be passed directly to the actuating mechanism. Low impedance behavior can be achieved with 'soft' position controllers, but control performance is seriously degraded, resulting in sloppy, unnatural motions. Soft position controllers also lack inherent compliance, making them susceptible to high frequency shock loads.

Force control would lessen wear on Coco's drive system by attenuating shocks. Instead of sharp impacts when interacting with hard objects the compliance would allow smooth transitions. For this reason, the vibration in the head that is caused by the impacts of walking would also be reduced. Coco would also more safely, and effectively interact with people. Actions such as handshaking would be safer since the force used could be regulated. Such actions would also be more lifelike with the use of force control because of the fluidity of interaction.

Coco's size would require design of a custom elastic element capable of fitting into the small spaces available near the existing joints. This upgrade was not unforeseen, however, and some space has been allocated for the purpose.

5.3 Summary

Coco successfully merges a walking platform and articulated vision head. Standing approximately one quarter the height of an adult human and weighing about the same as a large cat the robot matches the measurements of common household companions. The torso, arms, legs, head, and eyes are clearly recognizable as such. Algorithms implemented on the robot have enabled it to exhibit behaviors such as orienting to and approaching a stimulus. The robot's multi-degree-of-freedom front limbs and head provide a broad palette for expression. The design of the head was specifically tailored to ease the implementation of planned vision algorithms. Coco's modular design and broad utilization of off-the-shelf parts simplifies repairs and modifications. After nearly a year of operation there have been few failures, and those have been limited to easily replaceable third party components. Thus the robot meets all the main design criteria set forth at the inception of the project.

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Appendix A

Human Standard Anatomical Position

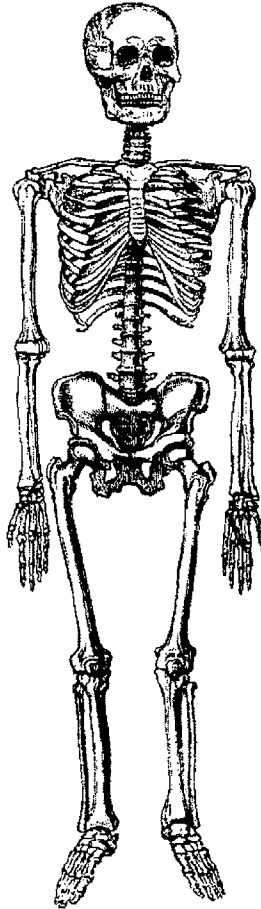


Figure A-1. Standard Anatomical Position of a human

Appendix B

Suppliers

Company Name	Contact Name	Address	City	State/ Province	Postal Code	Phone Number	Website
Prime Source	Doris	-	-	-	-	(781) 740-4422	www.elmocorp.com
Maxon Motor	Sandra Lovely	101 Wldron Rd.	Fall River	MA	02720	(508) 677-0520	www.maxonmotor.com
Alpine Bearing	Jim	298 Lincoln Street	Allston	MA	02134	(617) 254-1420	http://www.alpinebearing.com/
The Imaging Source	-	Suite 400, 1201 Greenwood Cliff	Charlotte	NC	28204	(704) 370-0110	www.theimagingsource.com
Sava	-	4 No. Corporate Dr PO Box 30	Riverdale	NJ	07457	(973) 835-0882	http://www.savacable.com/
Agile Systems	Dan Rose	575 Kumpf Dr	Waterloo	On	N2V 1K3	(519) 886-2000	www.agilesys.com
Micro-Mo	-	14881 Evergreen Avenue	Cearlwater	FL	33762	(727) 572-0131	www.micromo.com
IGUS	-	PO Box 14349	E. Providence	RI	02914	(800) 521-2747	www.igus.com
McMaster Carr	-	P.O. Box 740100	Atlanta	GA	30374	(404) 346-7000	www.mcmaster.com
W.M. Berg	-	499 Ocean Avenue	East Rockaway	NY	11518	(516) 596-1700	www.wmberg.com
Stock Drive Products	-	2101 Jericho Turnpike, Box 5416	New Hyde Park	NY	11042	(516) 328-3300	www.sdpsi.com

Table B.1: List of Suppliers

Appendix C

Stock Parts

P/N	Part Desc	Qty Rdq	Piece Price	Vendor	Location	Purpose
ssMER3SD509	3/16" x 1/2" Ang Contact Brg	4	20	Alpine Bearing	Arm	elbow shaft
118755+103935+11477	REo25 motor, 100cpt encoder, 86:1 gearhead	2	527.4	Maxon Motor	Arm	elbow drive
A 1C 4-Y32024	.75" PD Miter gear	4	81.74	Stock Drive Products	Arm	elbow drive
A 7X 1-06017	3/16" x 1.75" shafting	2	1.65	Stock Drive Products	Arm	elbow shaft
MAX2000	3 axis controller /amp	6	1900	Agile Systems	Body	Motor Control
SH-2	Rubber bumper	2	1.4	W.M. Berg	Hand	hand
ssMER3SD509	3/16" x 1/2" Ang Contact Bearing	4	20	Alpine Bearing	Head	neck pitch& eye roll
LFM-0304-05	Iglide L280 flange bushing	6		Igus	Head	Eye Saccade & Pitch
110151+134173+110778	A-Max-22, 16cpt encoder,231:1 gearhead	1	183.6	Maxon Motor	Head	Neck Pitch
94035A204	3/16" x .375" shoulder screw	1	1.37	McMaster Carr	Head	Neck Pitch
8863T6	Clamp for 16mm motor	4	0.1648	McMaster Carr	Head	roll & eye pitch
8863T6	Clamp for 22mm motor	2	0.1962	McMaster Carr	Head	Neck pitch
94035A205	3/16" x .5" shoulder screw	1	1.4	McMaster Carr	Head	Neck Pitch
91610A208	2mm x 16mm roll pin	2	0.134	McMaster Carr	Head	Neck Pitch
91610A204	2mm x 8mm roll pin	11	0.1152	McMaster Carr	Head	Neck Pitch & neck plate
91610A207	2mm x 14mm roll pin	2	0.1176	McMaster Carr	Head	Eye pitch
94100A110	M3 PEM style press nut	2	0.3485	McMaster Carr	Head	neck plate
9714K27	Wave spring for .5" OD bearing	3	0.3184	McMaster Carr	Head	Roll & Neck Pitch
1524E024SRIE2-512+16/7,66:1	1524 Motor, 512cpt encoder, 66:1 gearhead	2	230.1	Micro-Mo	Head	Eye pitch & Roll
1524E024SRIE2-512+15/5,41:1	1524 Motor, 512cpt encoder, 41:1 gearhead	1	174	Micro-Mo	Head	Eye Saccade
2224U024SRIE2-512+23/1,66:1+X0737A	2224 Motor, 512cpt encoder, 66:1 gearhead	1	286.4	Micro-Mo	Head	Neck Yaw
8920AD1	Elmo AC adapter for CCU	1	66.25	Prime Source	Head	Vision

P/N	Part Desc	Qty Rdq	Piece Price	Vendor	Location	Purpose
QN42HL	7MM dia. Elmo Camera	1	1575.4	Prime Source	Head	Vision
RA7	right angle lens adapter for Elmo camera	1	351.2	Prime Source	Head	Vision
CC421E	Elmo camera control unit	1	764.54	Prime Source	Head	Vision
9831	15mm lens for Elmo camera	1	420.25	Prime Source	Head	Vision
403B2	Ball end plug for 1032SN cable	2	0.8	Sava	Head	Eye pitch & Roll
455B0500	Threaded plug for 1032Sn cable	2	2.06	Sava	Head	Eye pitch & Roll
1032SN	.949mm OD Nylon coated low stretch cable	250	1.31	Sava	Head	Eye pitch & Roll
A 6R53M082090	3mm pitch x 246mm GT timing belt	0		Stock Drive Products	Head	Neck pitch
A6A53M020DF0906	3mm pitch x 19mm PD GT timing pulley	1		Stock Drive Products	Head	Neck pitch
A 6A52M020FA	pulley flange for 19mm PD GT timing pulley	1		Stock Drive Products	Head	Neck pitch
A 6R53M081090	3mm pitch x 243mm GT timing belt	1		Stock Drive Products	Head	Neck pitch
A7A30M060312	6mm-3mm bore reducer	1	7.98	Stock Drive Products	Head	eye saccade
A 6A51M014DF0603	2mm x 9mm PD GT pulley	2		Stock Drive Products	Head	Eye Saccade
A 6A51M017DF0606	2mm x 11mm PD GT pulley	1		Stock Drive Products	Head	Eye Saccade drive
A 6R51M080060	160mm x 2mm PL GT timing belt	1		Stock Drive Products	Head	Saccade
S40PX0MHG3M-025	3MM X 25MM hardened shafting	2		Stock Drive Products	Head	Eye Saccade
A 7X 8-C06063	3/16" X 1/4" x 1.16" shaft spacer	2		Stock Drive Products	Head	Roll & Neck Pitch
S40PX0MHG3M-025	3MM X 30MM hardened shafting	0		Stock Drive Products	Head	Eye Saccade
A 7X 1M030075	3mm x 75mm ground shafting	4		Stock Drive Products	Head	Assy jig
A 7X 1M030200	3mm x 500mm ground shafting	1		Stock Drive Products	Head	Assy jig
A 6R53M080090	3mm pitch x 240mm GT timing belt	0		Stock Drive Products	Head	Neck pitch
A 7X 1M030025	3mm x 25mm ground shafting	4		Stock Drive Products	Head	Eye Saccade & Pitch
DFM 5003/N	Board Camera	2	349	The Imaging Source	Head	Eye Saccade
BR5M-3	6mm ID thrust bearing	1	5.88	W.M. Berg	Head	Neck Yaw
s2428mc5	1.5" ID x 1.75" OD Radial Bearing	4	60	Alpine Bearing	Hip	Hip capstan
nmb1360	6mm ID Radial Bearing	2	5	Alpine Bearing	Hip	hip drive
118755+103935+11475	REo25 motor, 100cpt encoder, 66:1 gearhead	2	527.4	Maxon Motor	hip	hip drive
90805A185	Laminated Shim Spacer	2	8.14	McMaster Carr	Hip	Hip capstan
A6A52M045GT15	43mm PD pulley stock	1		Stock Drive Products	Hip	hip capstan
A6A52M020GT15	19.1mm PD pulley stock	2	42.76	Stock Drive Products	Hip	hip & knee capstans
A 6R53M067090	3mm GT timing belt 201mm X 9mm	3	6.59	Stock Drive Products	Hip	left hip

P/N	Part Desc	Qty Rdq	Piece Price	Vendor	Location	Purpose
A 6R53M063090	3mm GT timing belt 189mm X 9mm	3	6.59	Stock Drive Products	Hip	right hip
A7Z39M0610	6MM ID Shaft-Loc	2	25.25	Stock Drive Products	Hip	Hip capstan
118755+103935+11479	REo25 motor, 100cpt encoder, 111:1 gearhead	2	527.4	Maxon Motor	Leg	knee drive
A7B4MF040806	4mm ID Bronze bushing	4	0.93	Stock Drive Products	Leg	Knee capstan
A7B4MF061004	6mm ID Bronze bushing	2	4	Stock Drive Products	Leg	Knee drive
A7X1M060025	6mm x 25 shafting	2		Stock Drive Products	Leg	Knee drive
S40PX0MHG4M-030	4mm x 30 shafting	2	0.1797	Stock Drive Products	Leg	Knee capstan
MD1481MQB015X008	1.5mm x 8 Roll pin	8	4.33	Stock Drive Products	Leg	Knee capstan
A 6R53M063090	3mm GT timing belt 189mm X 9mm	4	6.59	Stock Drive Products	Leg	Knee
SmartCard	RS485 interface	2	1100	Agile Systems	Off board	Motor Control
Interface cable	RS485 cable	2	200	Agile Systems	Off board	Motor Control
Win Max	Tuning Software	1	300	Agile Systems	Off board	Motor Control
Max C++ Libs	Control Software	1	1400	Agile Systems	Off board	Motor Control
SSL-1680	8mm id radial bearing	4	7.5	Alpine Bearing	Shoulder	output mount
61901	12id X 24 Radial Bearing	2	9	Alpine Bearing	Shoulder	drive support
MER11901DL	12id X 24 Ang Contact Bearing	2	100	Alpine Bearing	Shoulder	differential support
SSRI-1878ZSD502Kc	.875" id X 1.125" OD Dp. Gr. Radial Bearing	2	40	Alpine Bearing	Shoulder	differential support
SSMER-4-SD504	1/4" x 5/8" Ang contact bearing	4	23.3	Alpine Bearing	Shoulder	Output shaft
LTM-0818-01	8mm id thrust bearing	4	0	Igus	Shoulder	Output mount
118755+103935+14471	REo25 motor, 100cpt encoder, 23:1 gearhead	4	489.95	Maxon Motor	Shoulder	shoulder drive
A 1C 4MYK10030A	30mm short hub miter gear	2	16.54	Stock Drive Products	Shoulder	differential
A 1C3MYK15036	54 mm bevel gear	4	40.53	Stock Drive Products	Shoulder	drive pinon
A 1C3MYK15018	27 mm bevel gear	4	20.04	Stock Drive Products	Shoulder	drive gear
A 1C 44MYK10030A	30mm long hub miter gear	4	17	Stock Drive Products	Shoulder	differential
A7Z39M0610	6MM ID Shaft-Loc	6	25.25	Stock Drive Products	Shoulder	motor attachment

Table C.1: List of Stock Parts

Appendix D

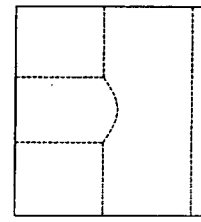
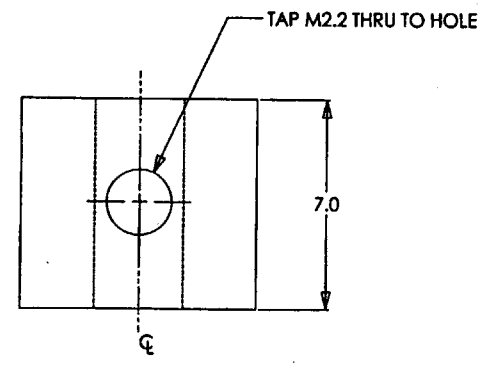
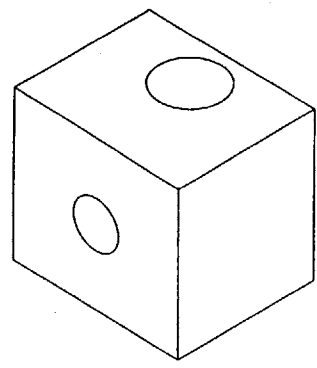
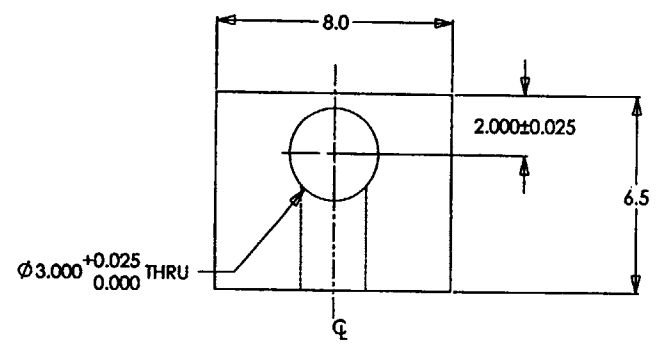
Part Drawings

This section contains the mechanical drawings for the robot's custom fabricated parts

09

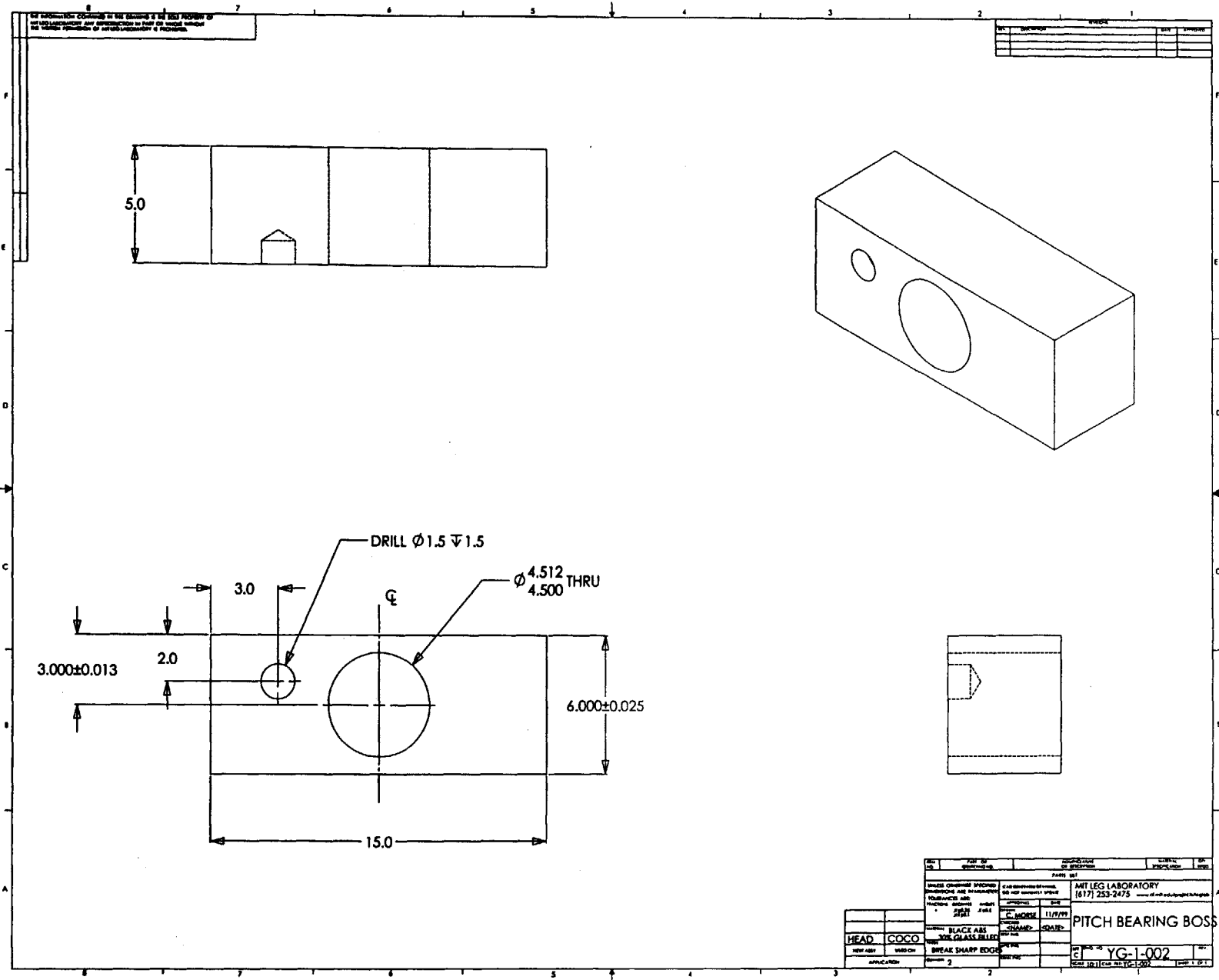
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ANT LEG LABORATORY AND SHALL BE KEPT IN STRICTLY CONFIDENTIAL
AND NOT BE REPRODUCED OR TRANSMITTED IN ANY FORM OR BY ANY MEANS
ELECTRONIC, MECHANICAL, PHOTOCOPYING, RECORDING, OR BY ANY INFORMATION STORAGE AND RETRIEVAL SYSTEM.

REV	DESCRIPTION	DATE	BY



- NOTES:
- 1: BREAK SHARP EDGES
 - 2: ALL DIMENSIONS AFTER FINISHING

HEAD	COCO	AL 6061 T6	ANT LEG LABORATORY
REV		BLACK ANODIZE	(617) 253-2475
			CAMERA SHAFT BOSS
			YG-1-001



ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED TO BE IN MILLIMETERS TO THE NEAREST 0.0125 MILLIMETER (1/1000 INCH). DIMENSIONS ARE TO BE TAKEN FROM THE UNFINISHED SURFACE UNLESS OTHERWISE SPECIFIED.

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DATE	REV	DESCRIPTION	BY	APP'D

NAME (PRINTED)	DATE	LABORATORY

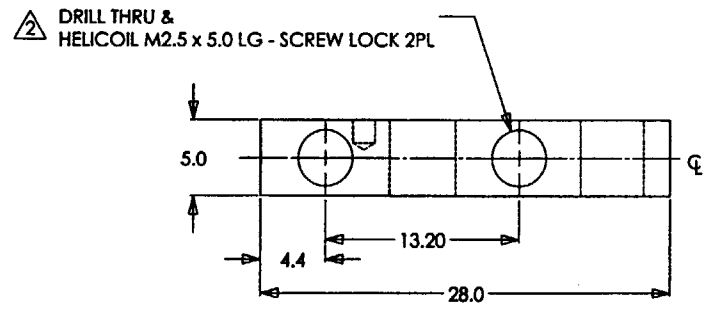
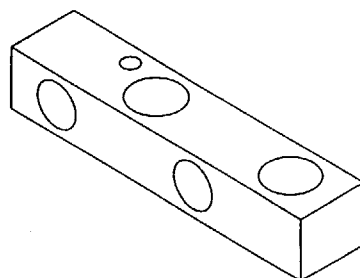
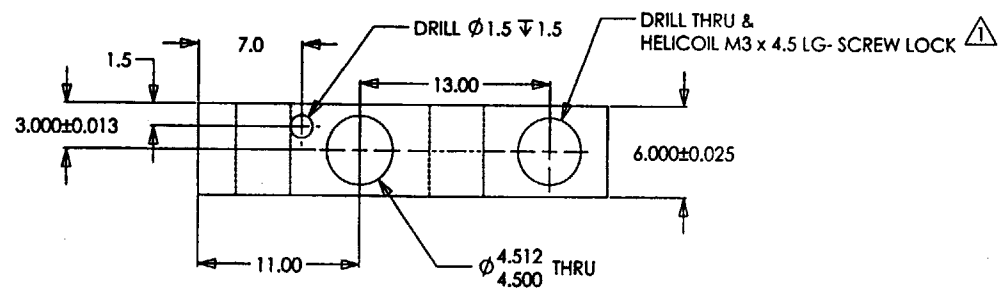
HEAD	COCO		

PITCH BEARING BOSS

YG-1-002

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED TO BE IN MILLIMETERS TO THE NEAREST DECIMAL PLACE. DIMENSIONS IN PARENTHESES ARE FOR INFORMATION ONLY AND ARE NOT TO BE USED FOR MANUFACTURING PURPOSES.

REV	DESCRIPTION	DATE	BY



NOTES:

- ⚠ HELICOIL PART #: 4184-3CN045
- ⚠ HELICOIL PART #: 4184-2.5CN050

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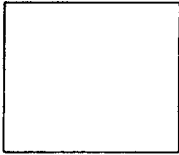
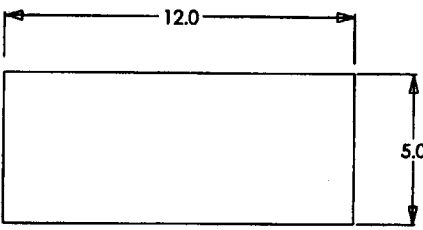
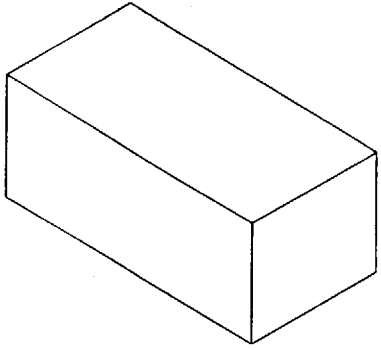
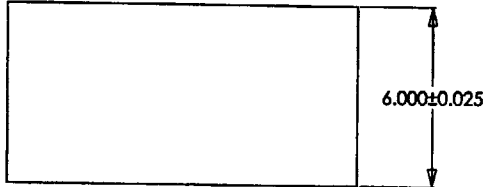
DATE	11/19/99
BY	

LAB	LEG. LABORATORY
	(617) 253 7475

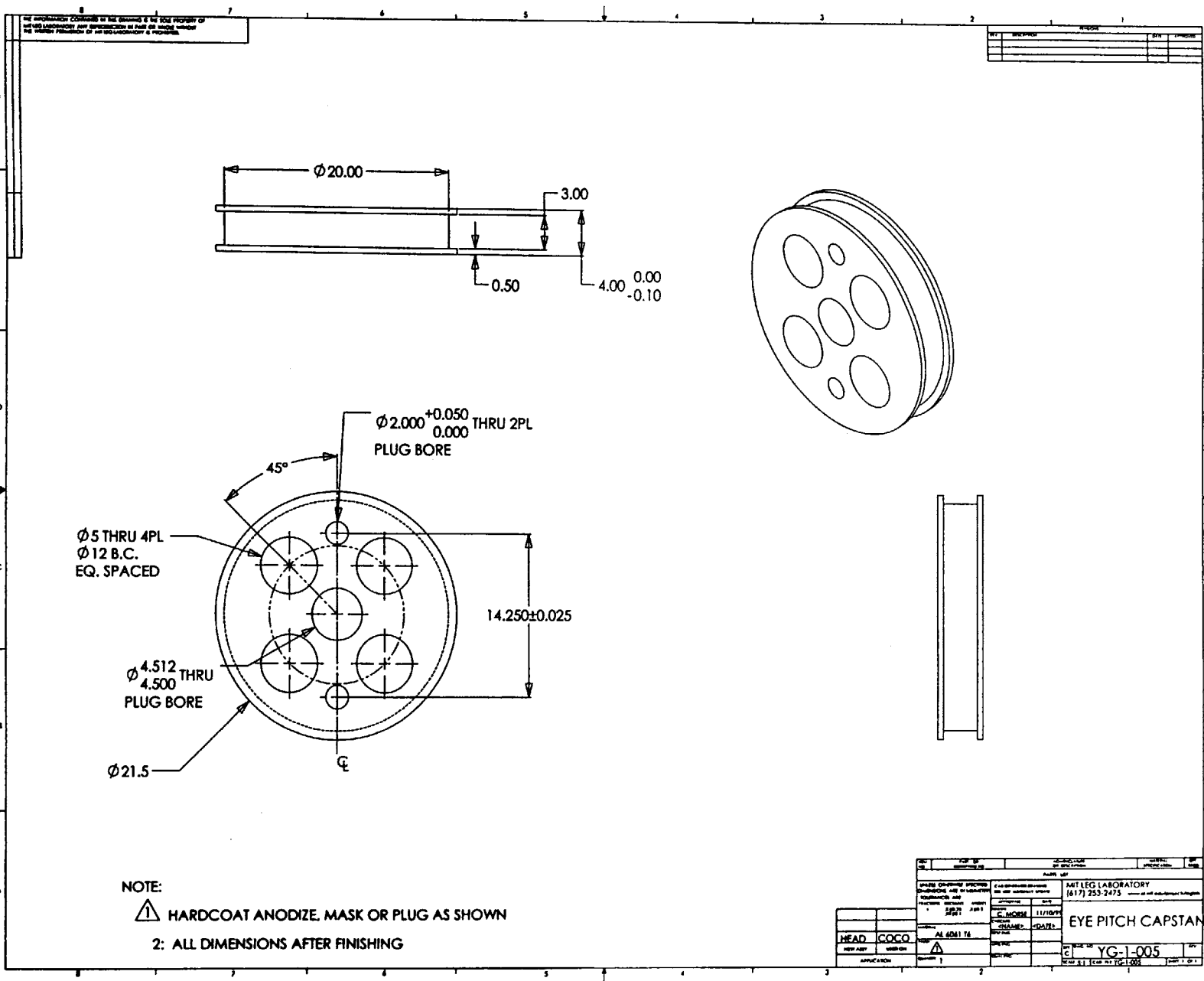
SACCADE BEARING BOSS	
E YG-1-003	

ALL DIMENSIONS CORRESPOND TO THE DIMENSIONS OF THE PARTS OF THE LABORATORY AND DIMENSIONS IN THIS DRAWING ARE THE DIMENSIONS OF THE PARTS OF THE LABORATORY.

REV.	DESCRIPTION	DATE	APPROVED



HEAD		COCO		LOPE		BREAK SHARP EDGES		APPROXIMATION	
MFG LAB				MFG LABORATORY				(417) 253-2425	
EYE MOUNT SPACER				YG-1-004					



ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES AND DECIMALS THEREOF.

REV	DESCRIPTION	DATE	BY

NOTE:
 1: HARDCOAT ANODIZE. MASK OR PLUG AS SHOWN
 2: ALL DIMENSIONS AFTER FINISHING

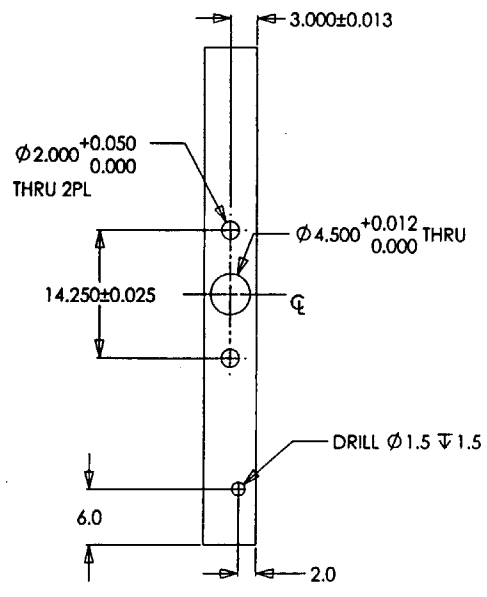
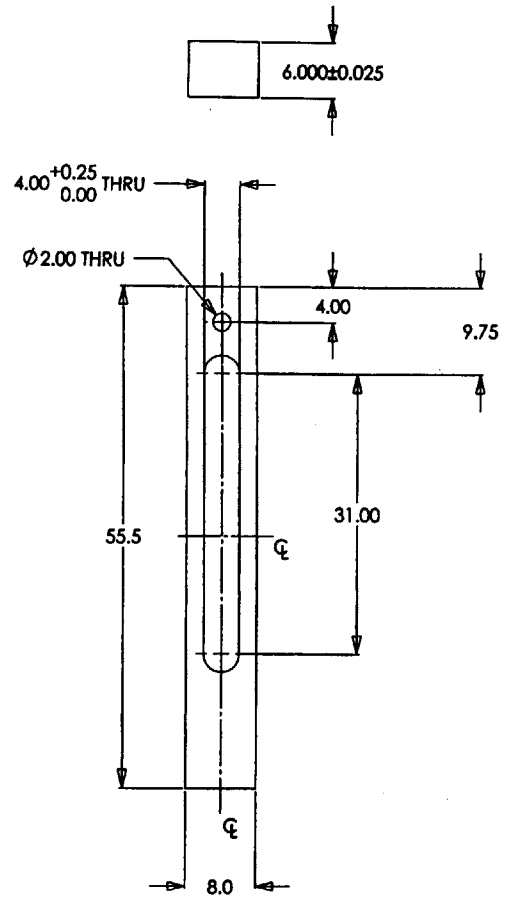
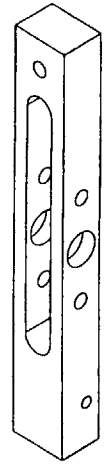
HEAD		COCO		AL 4041 T6	
REV	APP	DATE	BY	DATE	BY
APPLICATOR			DATE		

PART NO YG-1-005 REV. 1	QTY 100	DATE 11/15/99	BY J. J. COOPER
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AMTEC LABORATORY (617) 253-2475	EYE PITCH CAPSTAN
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REV	DESCRIPTION	DATE	BY



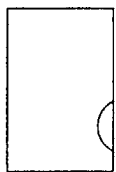
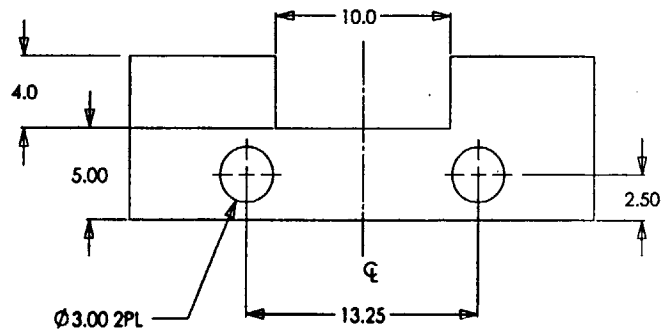
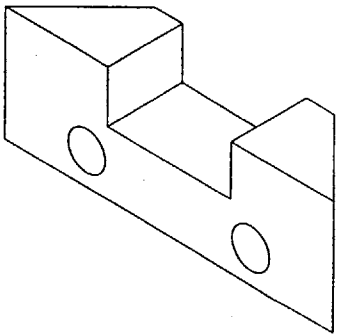
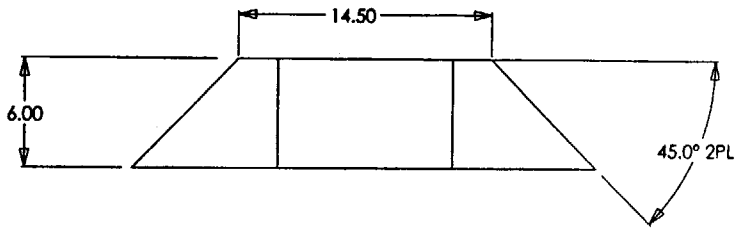
DATE	REV	DESCRIPTION	DATE	BY

DESIGNED BY	MIT IFC LABORATORY
DRAWN BY	(617) 253-7475
CHECKED BY	
DATE	
SCALE	
TITLE	EYE CAPSTAN MOUNT
PROJECT	YG-1-006
APPV	
DATE	
BY	
DATE	

HEAD	COCO
DATE	
APPV	
DATE	
BY	
DATE	
BY	
DATE	

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MILLIFEG LABORATORY AND SHALL BE KEPT AS SECRETS UNLESS
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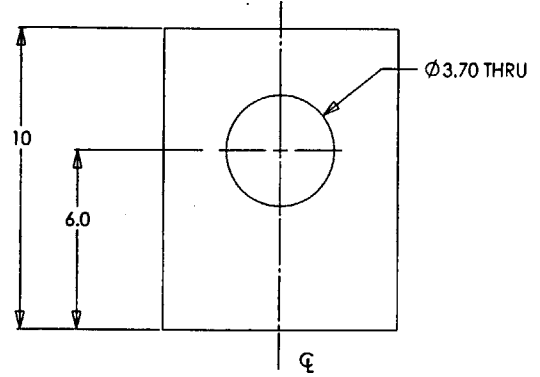
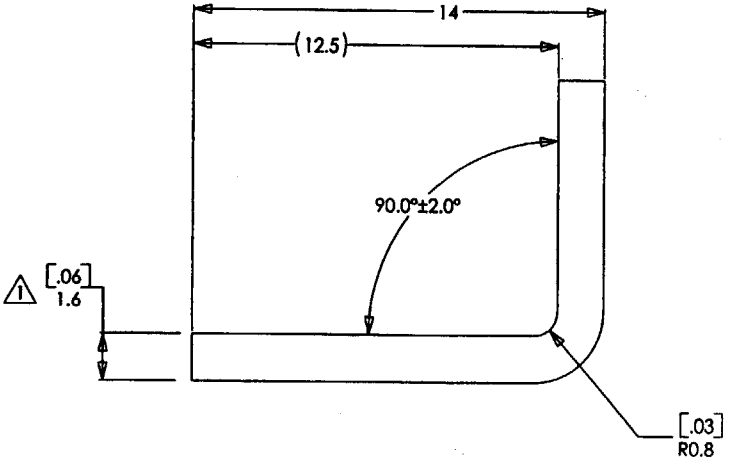
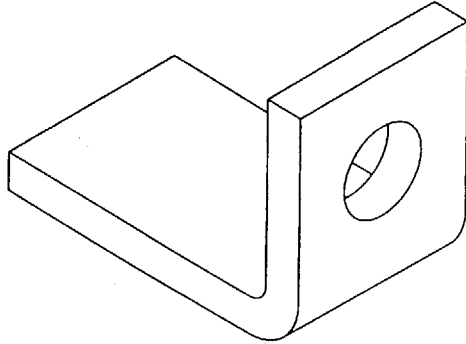
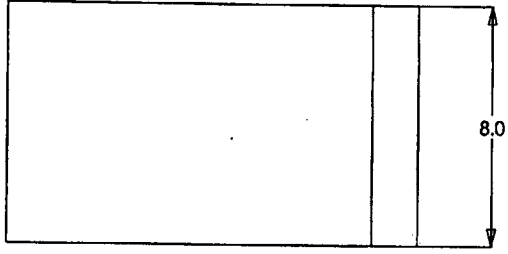
REVISION		DATE	



DATE		DRAWN BY		CHECKED BY		DATE	
MATERIAL				PART NO.			
MILLIFEG LABORATORY				MILLIFEG LABORATORY			
(617) 253 2475				(617) 253 2475			
PROJECT				PROJECT			
SACCADE				SACCADE			
LIMIT STOP				LIMIT STOP			
YG-1-007				YG-1-007			
REV. 1				REV. 1			

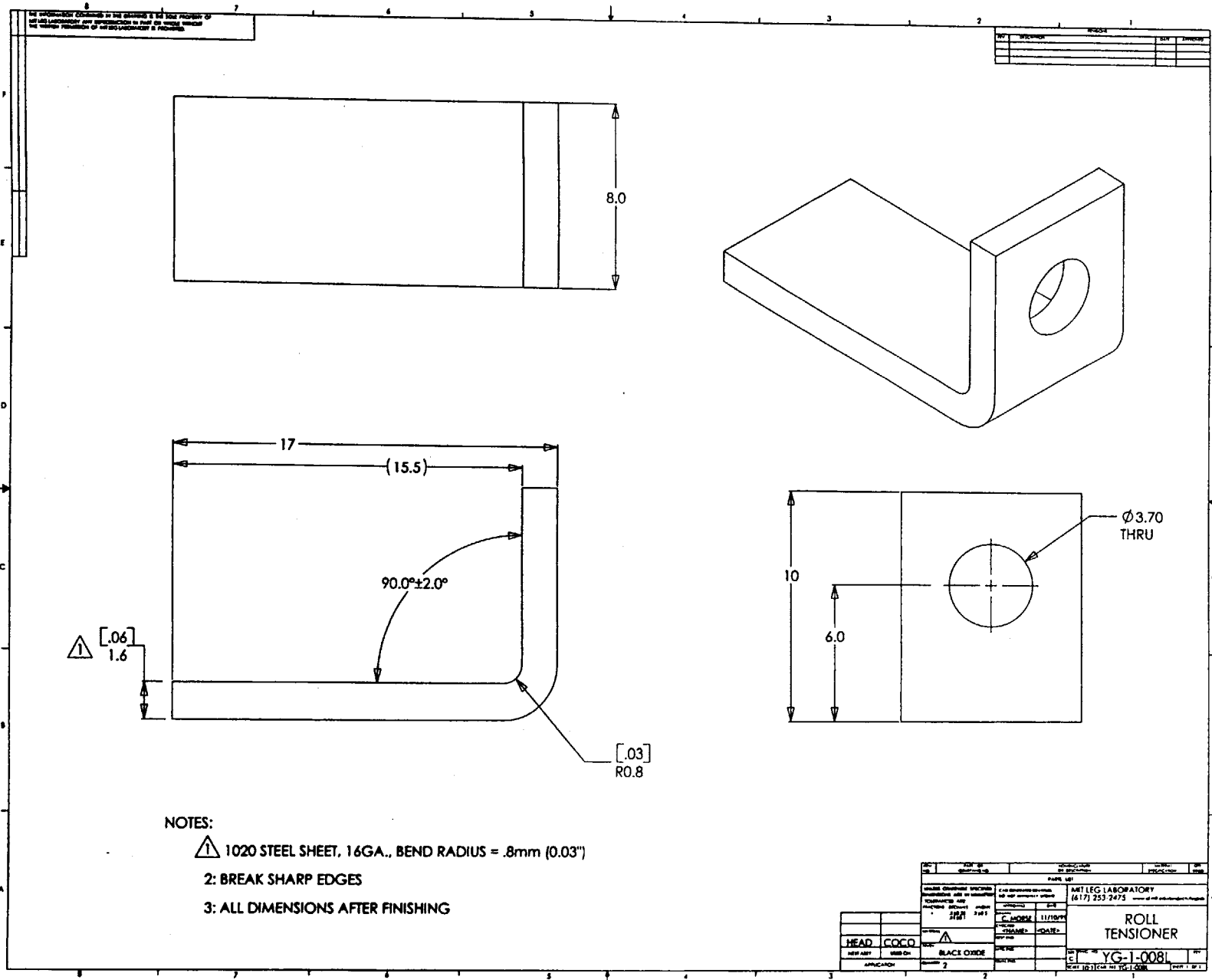
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REV	DESCRIPTION	BY	DATE



- NOTES:
- 1: 1020 STEEL SHEET, 16 GA., BEND RADIUS = .8mm [.03"]
 - 2: BREAK SHARP EDGES
 - 3: ALL DIMENSIONS AFTER FINISHING

HEAD	COCO	BLACK OXIDE	2
AME LFG LABORATORY (617) 251-2475 EYE PITCH TENSIONER YG-1-008		DATE: 10/1/08 REV: 1 OF 1	

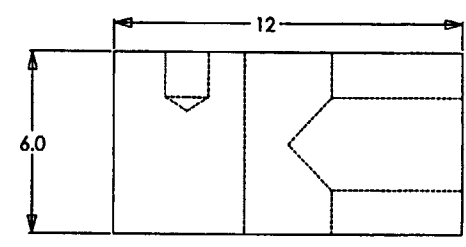
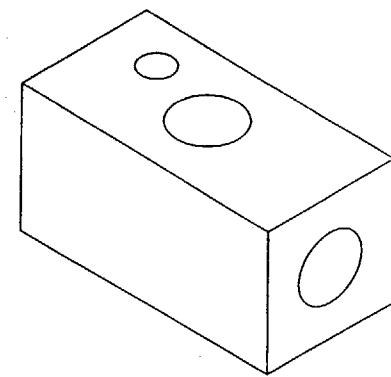
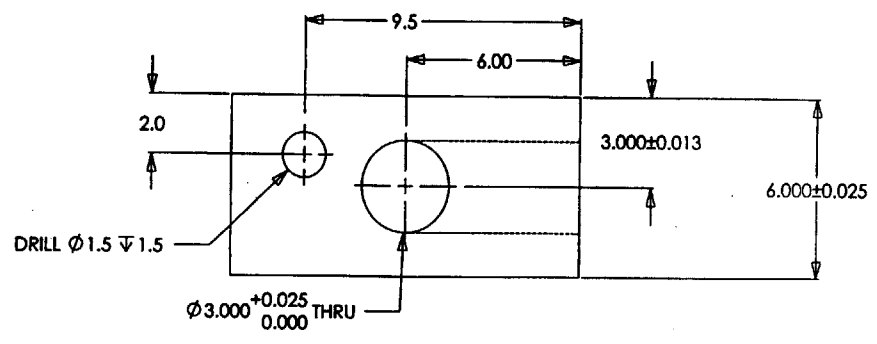


- NOTES:
- 1: 1020 STEEL SHEET, 16GA., BEND RADIUS = .8mm (0.03")
 - 2: BREAK SHARP EDGES
 - 3: ALL DIMENSIONS AFTER FINISHING

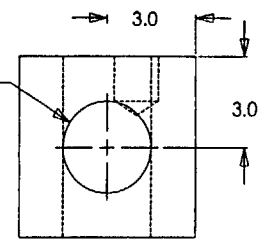
HEAD	COCO	BLACK OXIDE	ART LEG LABORATORY (617) 253-2475
			ROLL TENSIONER
			YG-1-0081

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REV	DESCRIPTION	DATE	BY



① HELICOIL M2.2x3.3 - SCREW LOCK THRU TO HOLE



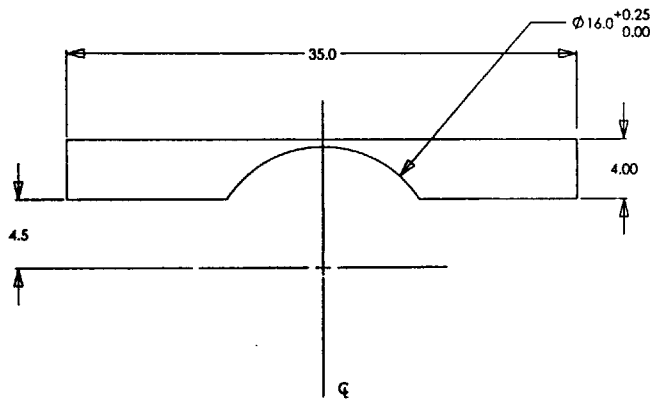
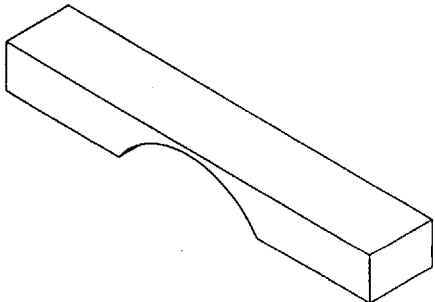
- NOTES:
- ① HELICOIL PART #: 4184-2.2CN033
 - 2: BREAK SHARP EDGES
 - 3: ALL DIMENSIONS AFTER FINISHING

HEAD	COCO	AL 6061 T6	DATE	11/10/11
REV	3	BLACK ANODI	DATE	
APPROVAL				

MILITARY LABORATORY	16171 253-2478
EYE PITCH SHAFT BOSS	
YG-1-009	

ALL DIMENSIONS GIVEN IN MILLIMETERS UNLESS OTHERWISE SPECIFIED
 ALL DIMENSIONS ARE APPROXIMATE TO THAT OF MODEL NUMBER
 THE VENDOR'S DRAWING IS TO BE USED

REV	DESCRIPTION	DATE



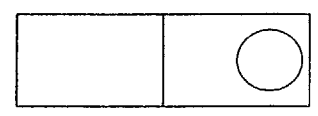
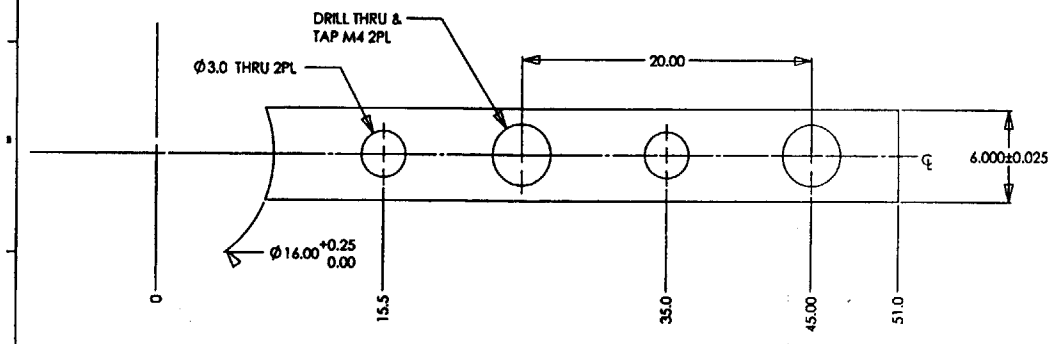
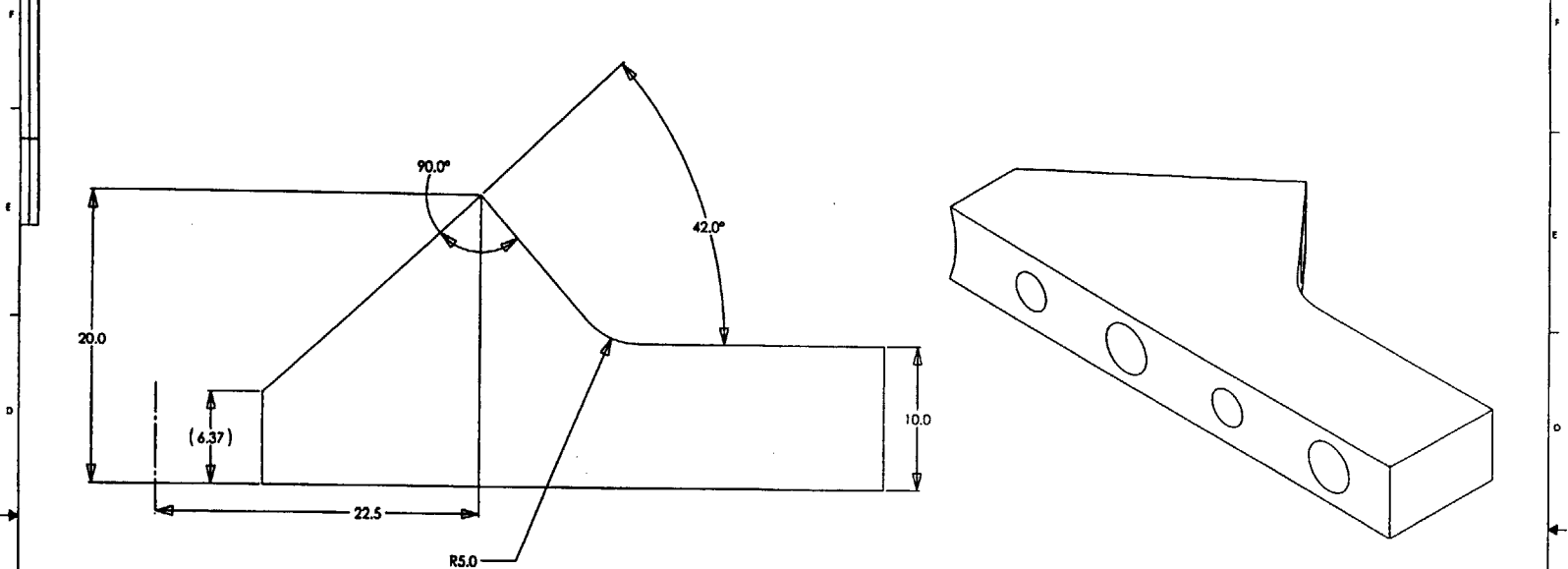
70

HEAD		COCO		BLACK LDPE		BREAK SHARP EDGE		APPLICATION	

MILLIG LABORATORY	
16171 253 2475	
ROLL LIMIT STOP	
YG-1-010	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS AND UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE TO BE HIDDEN EDGES UNLESS OTHERWISE SPECIFIED.

REV	DESCRIPTION	BY	DATE



NOTE:
 1: BREAK SHARP EDGES
 2: ALL DIMENSIONS AFTER FINISHING

REV	DESCRIPTION	DATE	BY

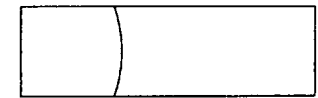
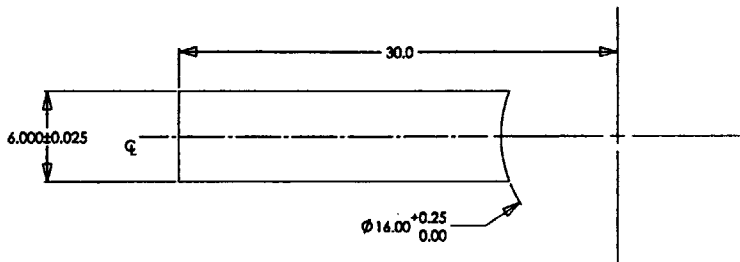
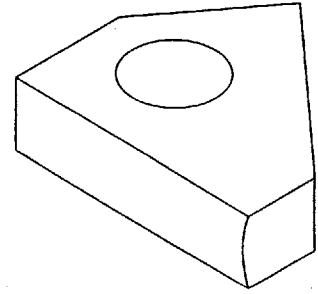
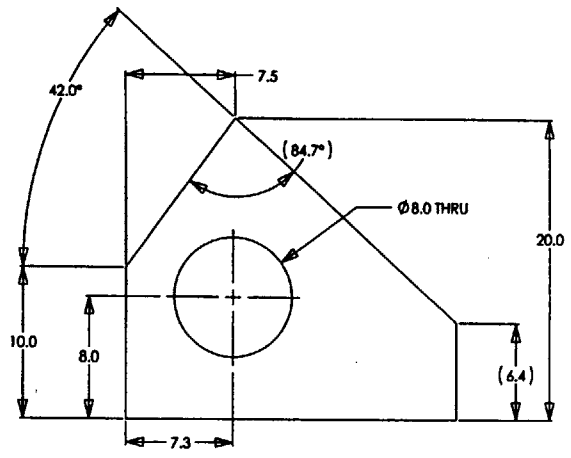
DATE	11/11/97
DESIGNED BY	E. MOORE
CHECKED BY	
DATE	
DESIGNED BY	
CHECKED BY	

MIT LEG LABORATORY	(617) 253-2475
PITCH MOTOR MOUNT	
CI YG-1-011	

HEAD	COCO
MATERIAL	AL 6061 T6
FINISH	BLACK ANODIZE

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 THE MANUFACTURER AND DIMENSIONS TO PART OF WHICH WITHOUT
 THE NECESSARY PRESENCE OF SURFACE FINISHING IS REQUIRED.

REV.	DESCRIPTION	BY	DATE

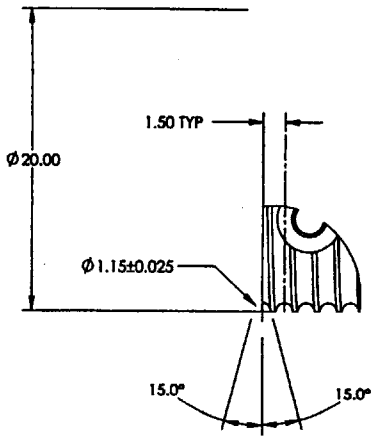


NOTES:
 1: ALL DIMENSIONS AFTER FINISHING

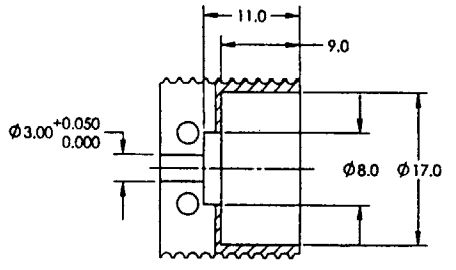
HEAD		COCO		BLACK ANODIZE		YG-1-012	

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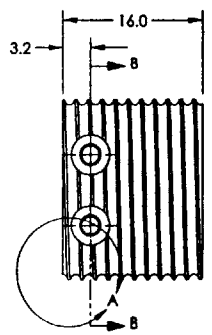
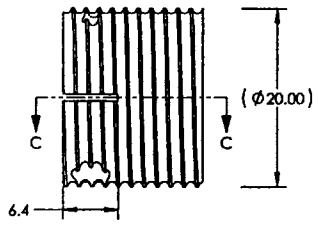
REV	DESCRIPTION	DATE	BY
1	ISSUE		



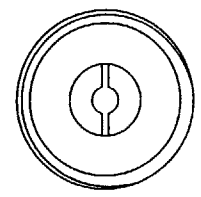
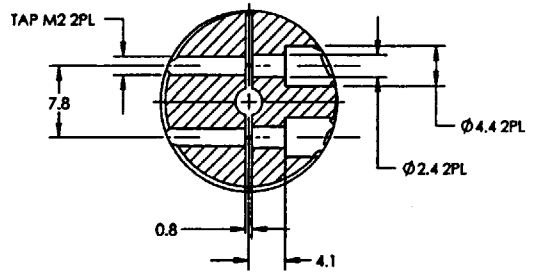
DETAIL A
 SCALE 5:1



SECTION C-C



SECTION B-B

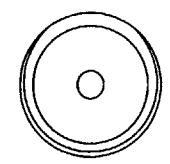
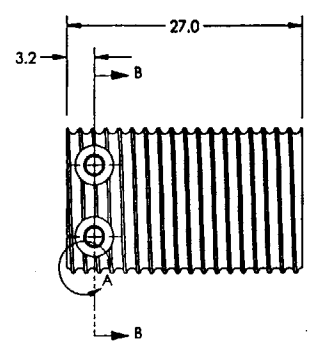
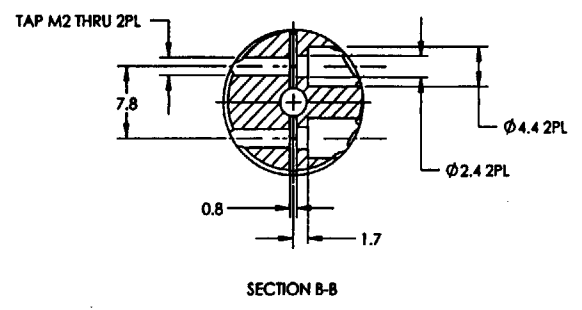
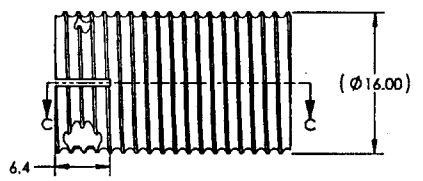
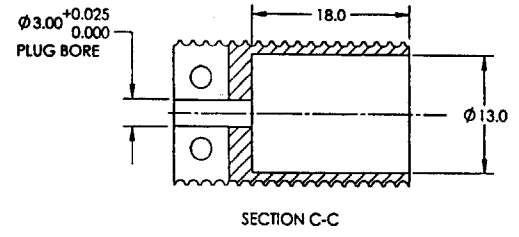
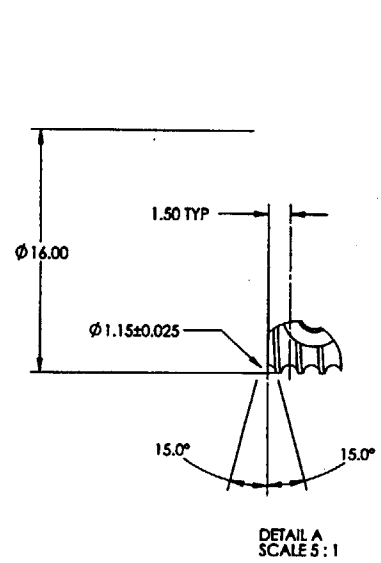


- NOTE:
 1: BREAK SHARP EDGES
 2: RIGHT HAND THREAD

MIT	ARTIFICIAL INTELLIGENCE LAB	PAPER 101
DATE	11/22/75	MIT Artificial Intelligence Lab
DESIGNED BY	ALFRED W. ALM	
CHECKED BY	ALFRED W. ALM	
DATE	11/22/75	
PROJECT	BLACK ANOODE	
APPRECIATION		
HEAD	COCO	
DATE	11/22/75	
PROJECT	BLACK ANOODE	
APPRECIATION		
MIT	ARTIFICIAL INTELLIGENCE LAB	
DATE	11/22/75	
PROJECT	BLACK ANOODE	
APPRECIATION		
MIT	ARTIFICIAL INTELLIGENCE LAB	
DATE	11/22/75	
PROJECT	BLACK ANOODE	
APPRECIATION		

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REV	DESCRIPTION	DATE	BY	APPVED
1	ISSUE			



NOTE:
1: RIGHT HAND THREAD
2: BREAK SHARP EDGES

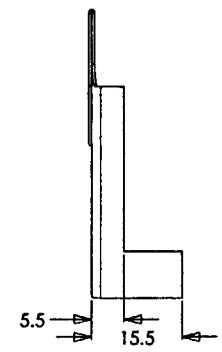
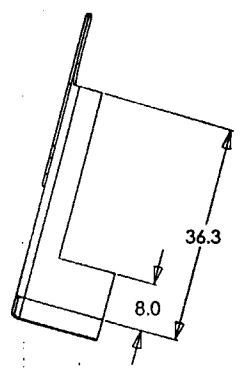
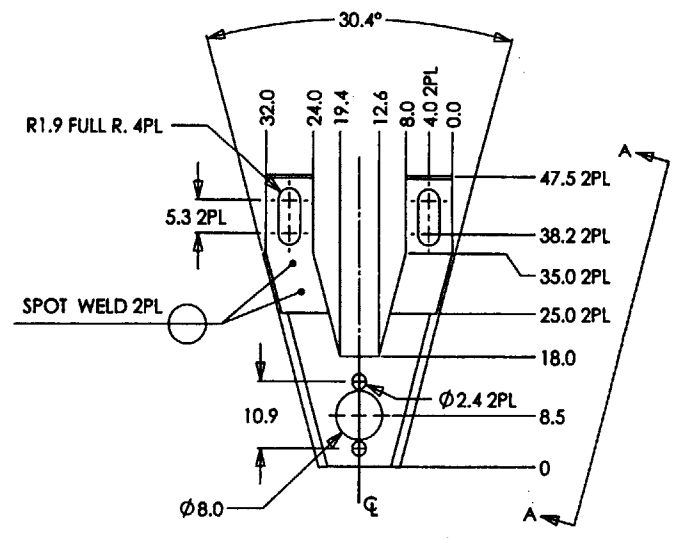
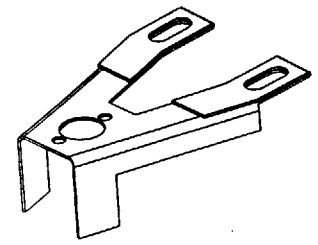
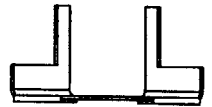
DESIGNED BY	DESIGNED BY	DATE	DATE
HECKENROTH	HECKENROTH	11/14/82	11/22/82
PROJECT	PROJECT	PROJECT	PROJECT
MIT Artificial Intelligence Lab	MIT Artificial Intelligence Lab	MIT Artificial Intelligence Lab	MIT Artificial Intelligence Lab
ROLL DRIVE CAPSTAN	ROLL DRIVE CAPSTAN	ROLL DRIVE CAPSTAN	ROLL DRIVE CAPSTAN
YG-1-015	YG-1-015	YG-1-015	YG-1-015

75

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REV.	DESCRIPTION	DATE	BY	APP'D.

NOTES:
 1: 1020 STEEL SHEET 0.5mm (.02") THK (25 OR 26 GA. OK)
 2: BEND RADIUS = 0.8mm (.03")

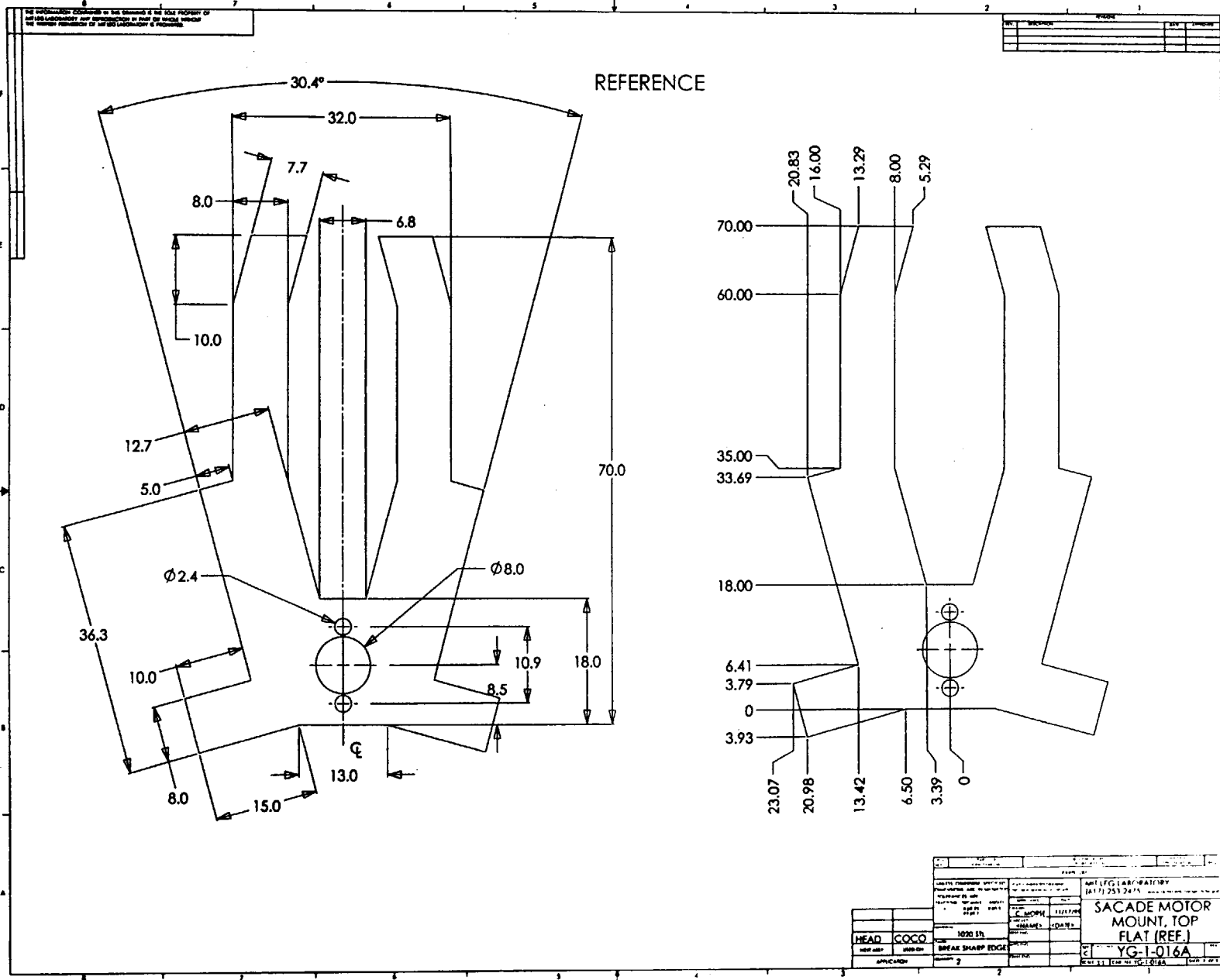


77

DATE CHANGED		REVISION		DATE		BY		APP'D.	

HEAD	COCO	DATE	11/22/95	BY		APP'D.	

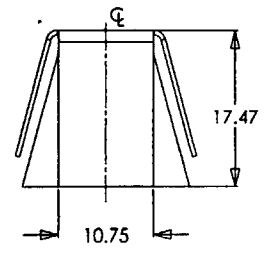
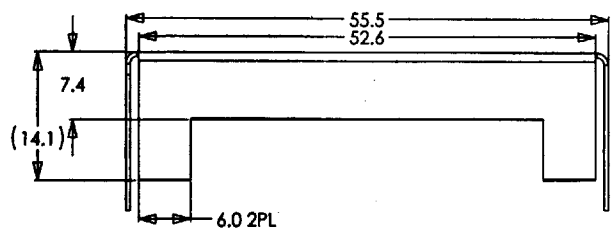
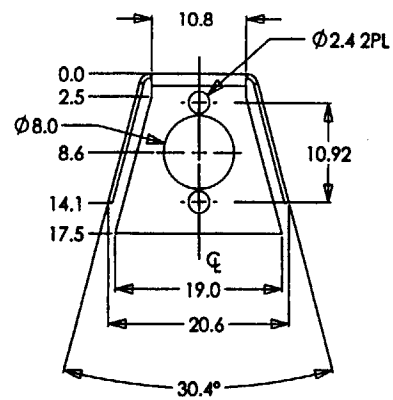
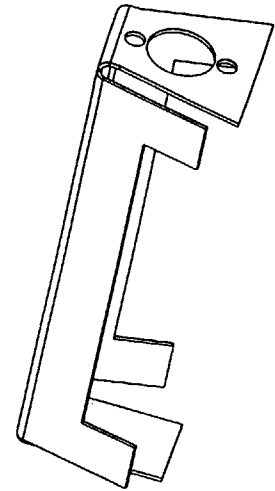
MIT LEG LABORATORY	
(617) 253-2475	
SACCADE MOTOR MOUNT TOP	



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REV	DESCRIPTION	DATE	APPROVED

NOTES:
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 (25 OR 26 GA. OK)
 2: BEND RADIUS = 0.8mm (.03")



79

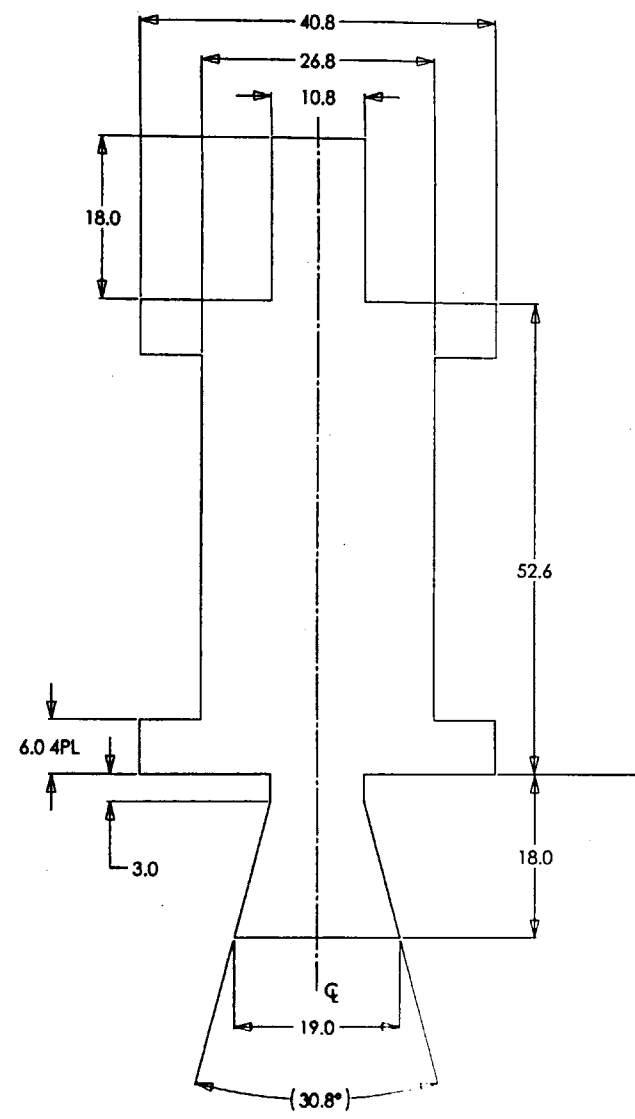
DATE OF		QUANTITY		APPROVED	
REV	DESCRIPTION	DATE	QUANTITY	APPROVED	DATE

MIT LEG LABORATORY 617-253-7475	SACCADE MOTOR MOUNT MAIN
DATE: 11/17/94	
DATE: 11/22/94	
HEAD COCO	
BREAK SHARP EDGES	
APPROACH	

MIT LEG LABORATORY	617-253-7475
DATE: 11/17/94	
DATE: 11/22/94	
HEAD COCO	
BREAK SHARP EDGES	
APPROACH	

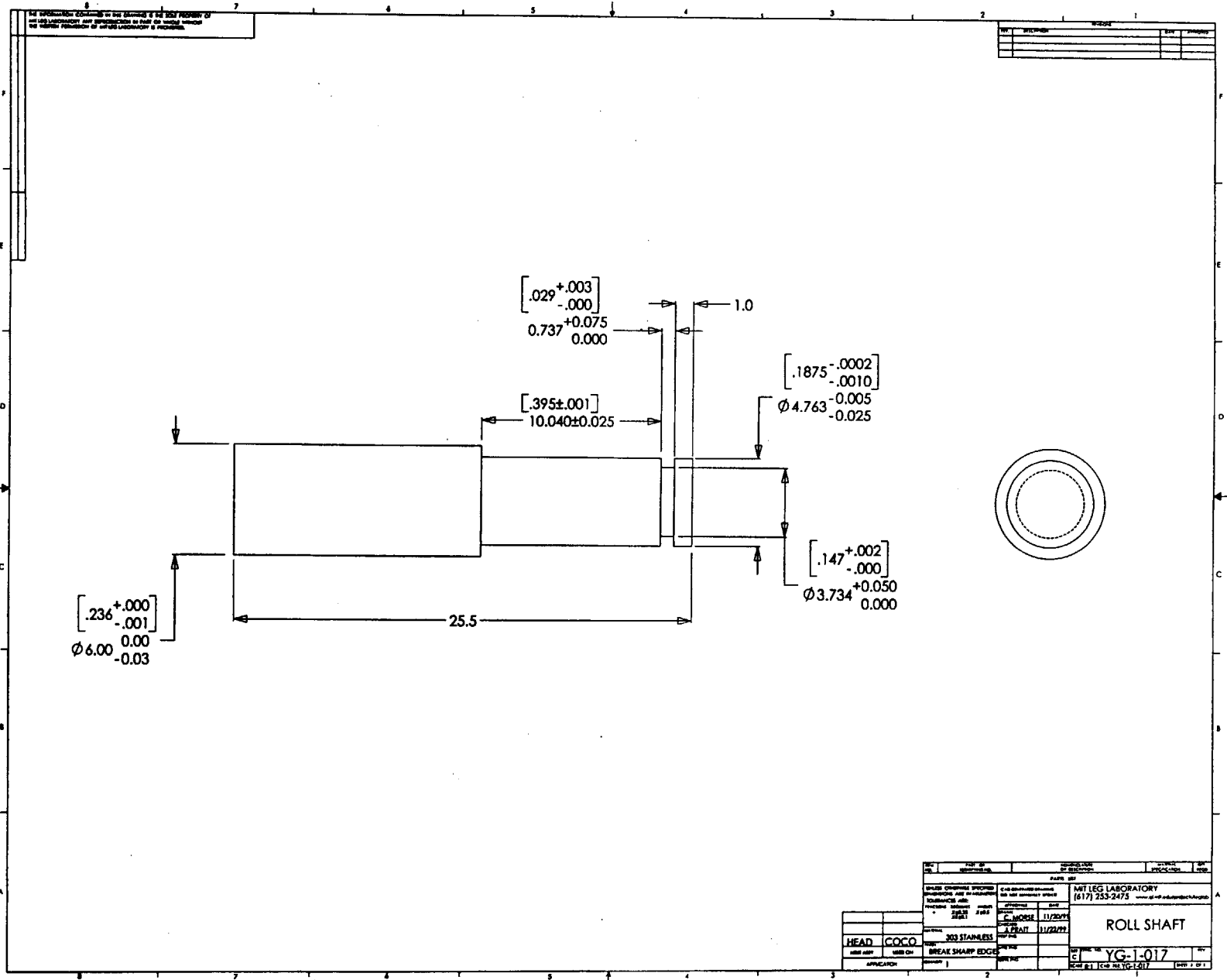
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REV.	DESCRIPTION	DATE	BY



REFERENCE

HEAD	COCO	SR 1020	11/17/78	AMT LEG LABORATORY 1617 253 7475
		BREAK SHARP EDGE		SACADE MOTOR MOUNT MAIN FLAT (REF)
				YG-1-016B



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REV	DESCRIPTION	BY	DATE

HEAD NAME: COCO TITLE: HEAD OF DEPARTMENT:	MATERIAL: 303 STAINLESS FINISH: BREAK SHARP EDGES QUANTITY: 1	DATE: 11/20/95 TIME: 11:22:27 BY:	MIT LEG LABORATORY (617) 253-2475 www.mit.edu/leglab/
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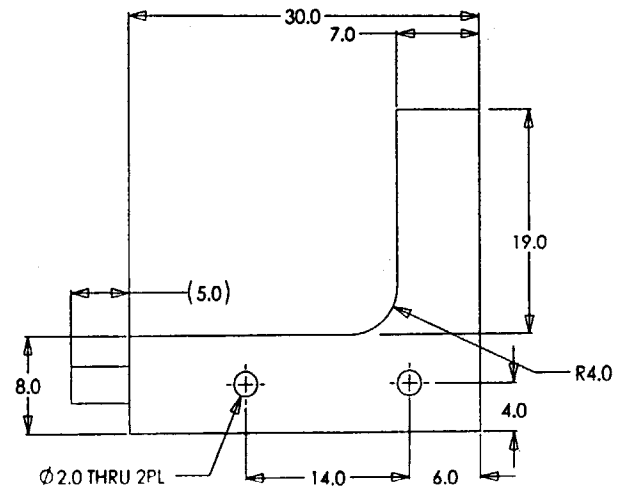
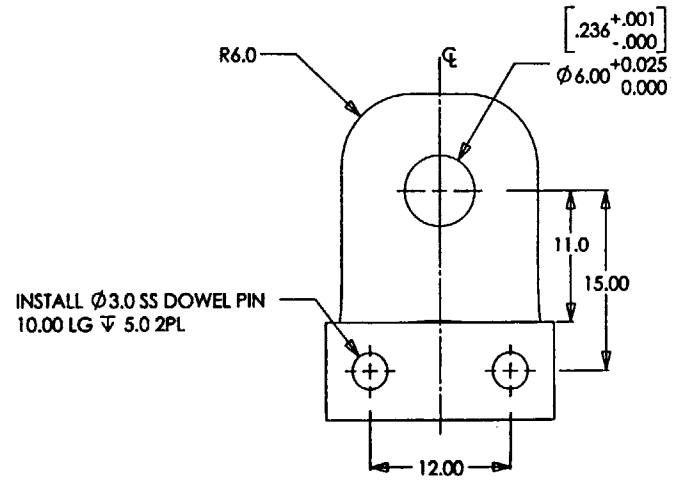
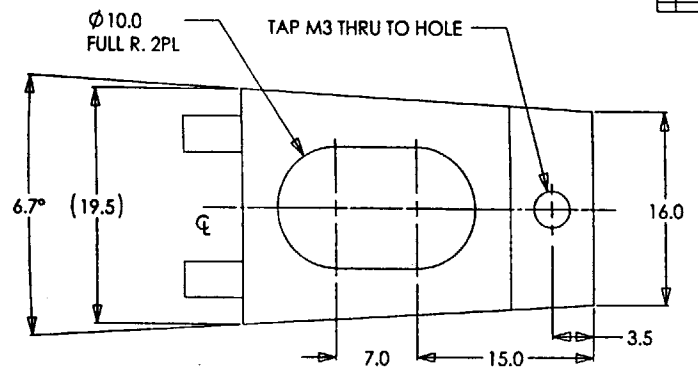
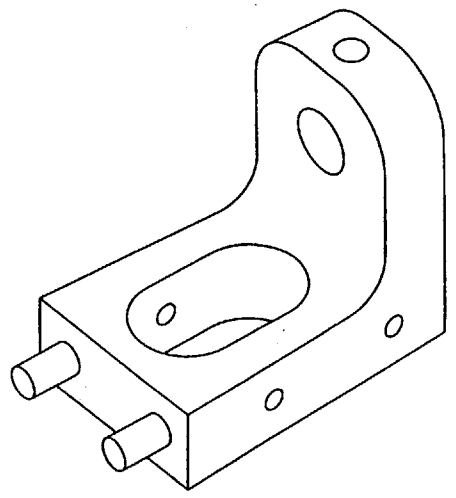
ROLL SHAFT

YG-1-017

REV: 1

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REV	DESCRIPTION	DATE	BY

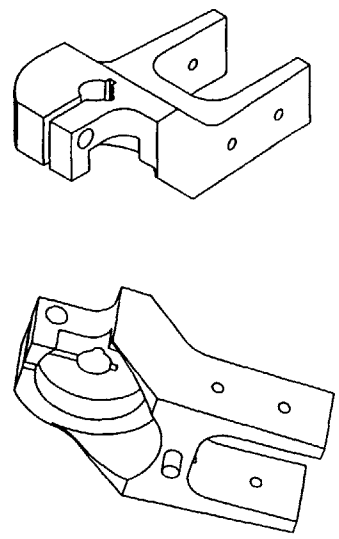
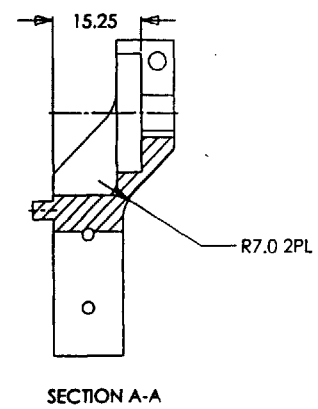
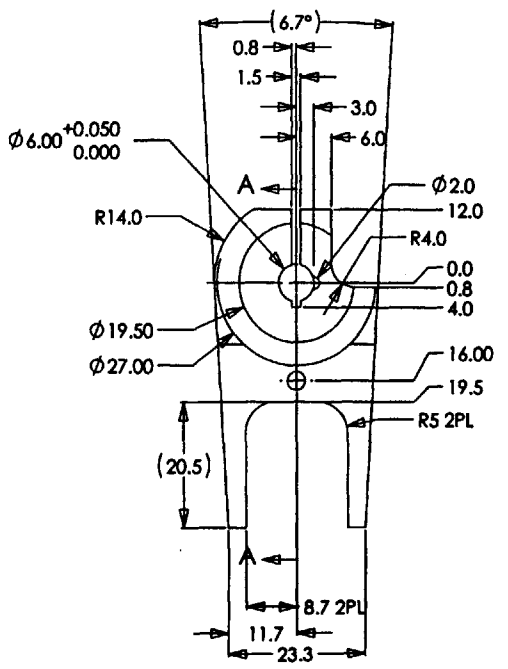
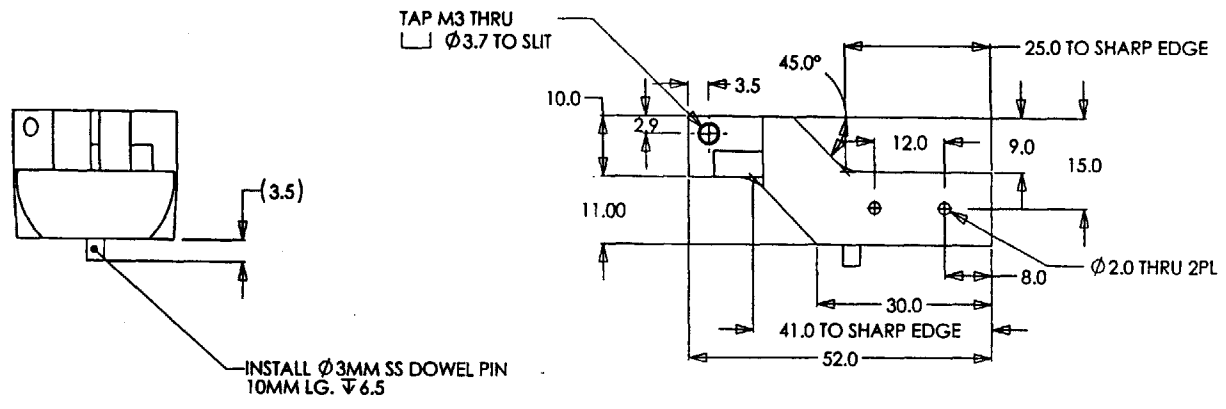


NOTES:
1: BREAK SHARP EDGES

HEAD	COCO	AL POTS 16	DATE	11/20/95
APPLICATOR	BLACK ANODIE	REVISION	BY	11/27/95
MATERIALS LABORATORY			ROLL MOUNT	
PART NO. YG-1-018			REV. 1	

ALL INFORMATION CONTAINED ON THIS DRAWING IS THE SOLE PROPERTY OF
 THE LABORATORY AND IS NOT TO BE REPRODUCED OR TRANSMITTED IN ANY FORM OR BY ANY MEANS
 WITHOUT THE WRITTEN PERMISSION OF THE LABORATORY OF FORENSICS

REV.	DESCRIPTION	DATE	BY

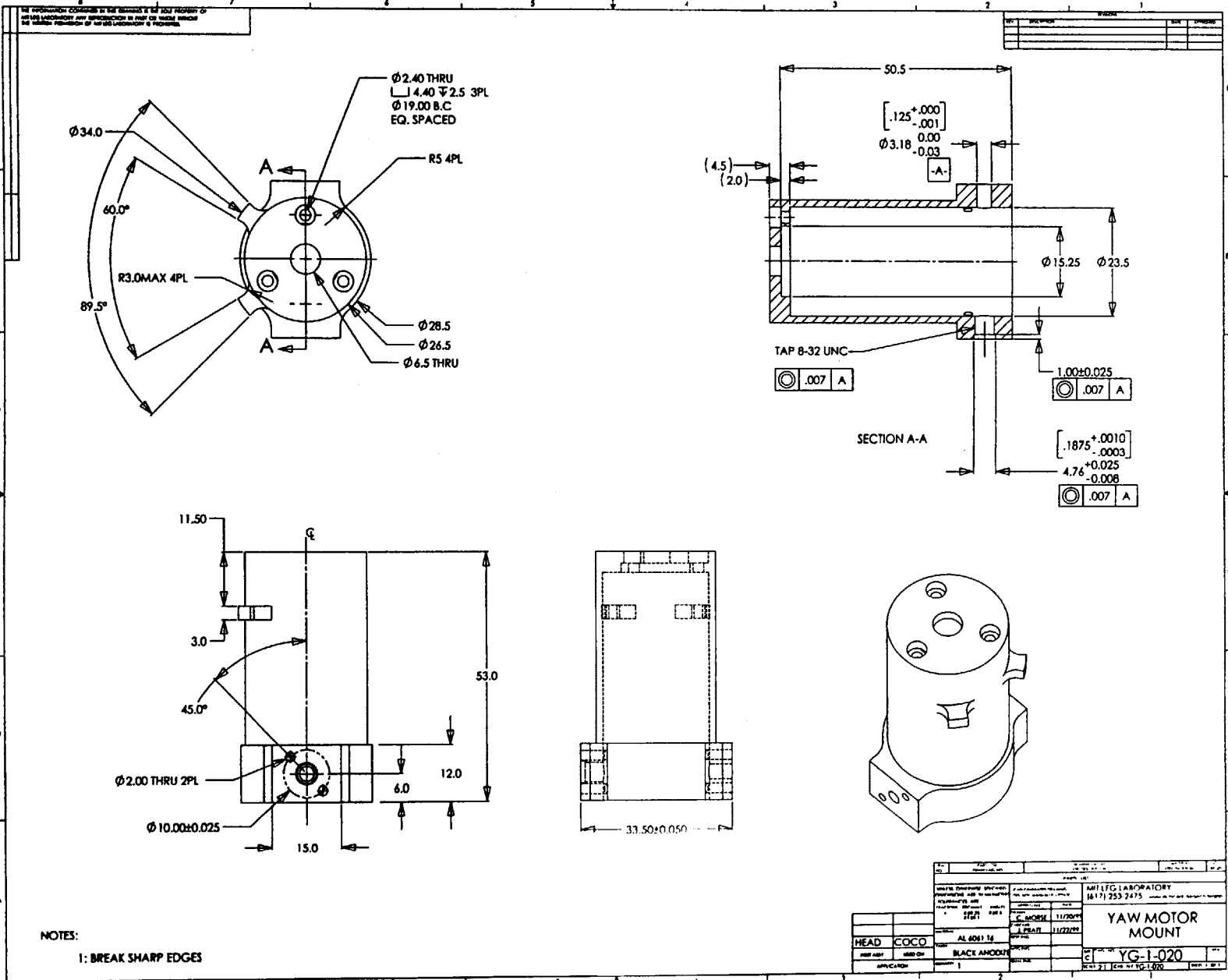


NOTES:
 1: BREAK SHARP EDGES

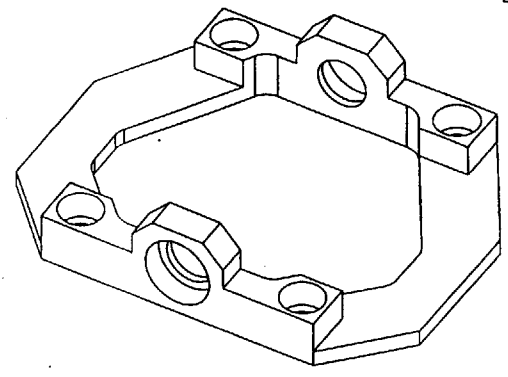
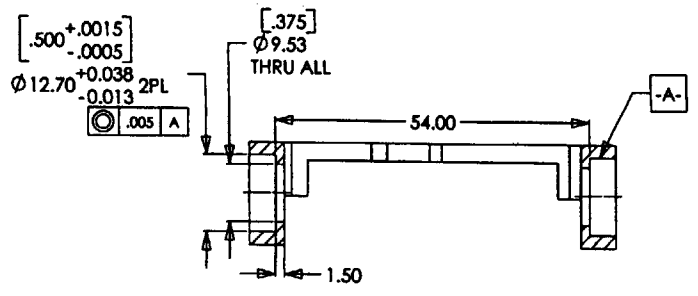
DATE	11/20/95	BY	C. MORSE
DESIGNED BY	11/22/95	CHECKED BY	J. PRATT
APPROVED BY	AL 7025 16	DATE	11/22/95
BLACK ANODIZE			
HEAD	COCO		
REV			

MILLEG LABORATORY	
(617) 253-2475	
YAW MOTOR CLAMP	
CT	YG-1-019
REV	1

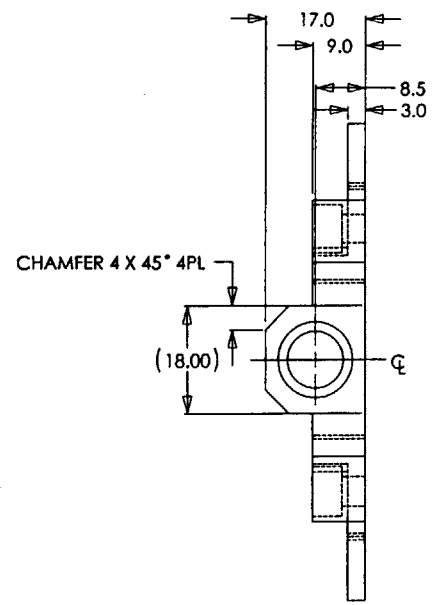
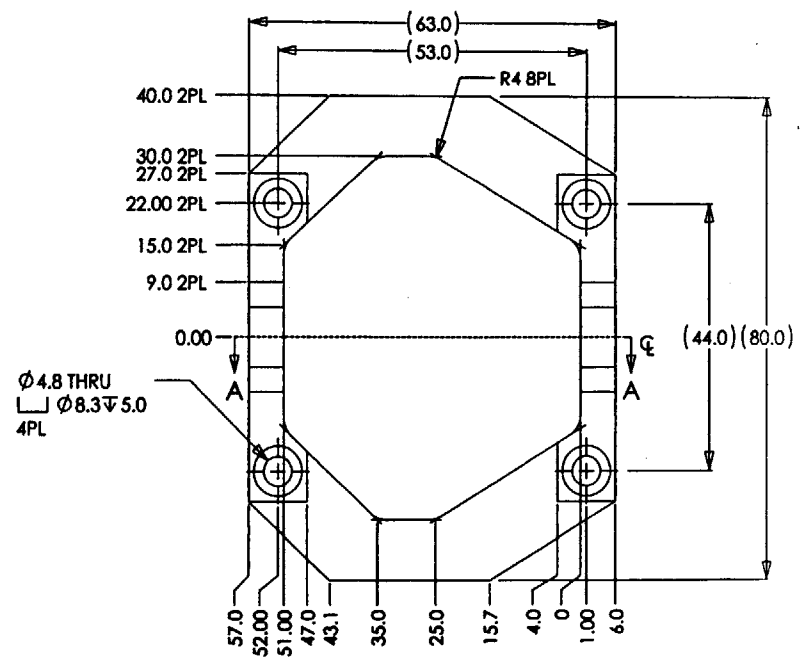
83



MIL IFCG LABORATORY 16171 253 2475		MIL IFCG LABORATORY 16171 253 2475	
AL 4041 14		BLACK ANODIZ	
HEAD COCO		YG-1-020	
MFG DATE		MFG DATE	
APPROVAL		APPROVAL	

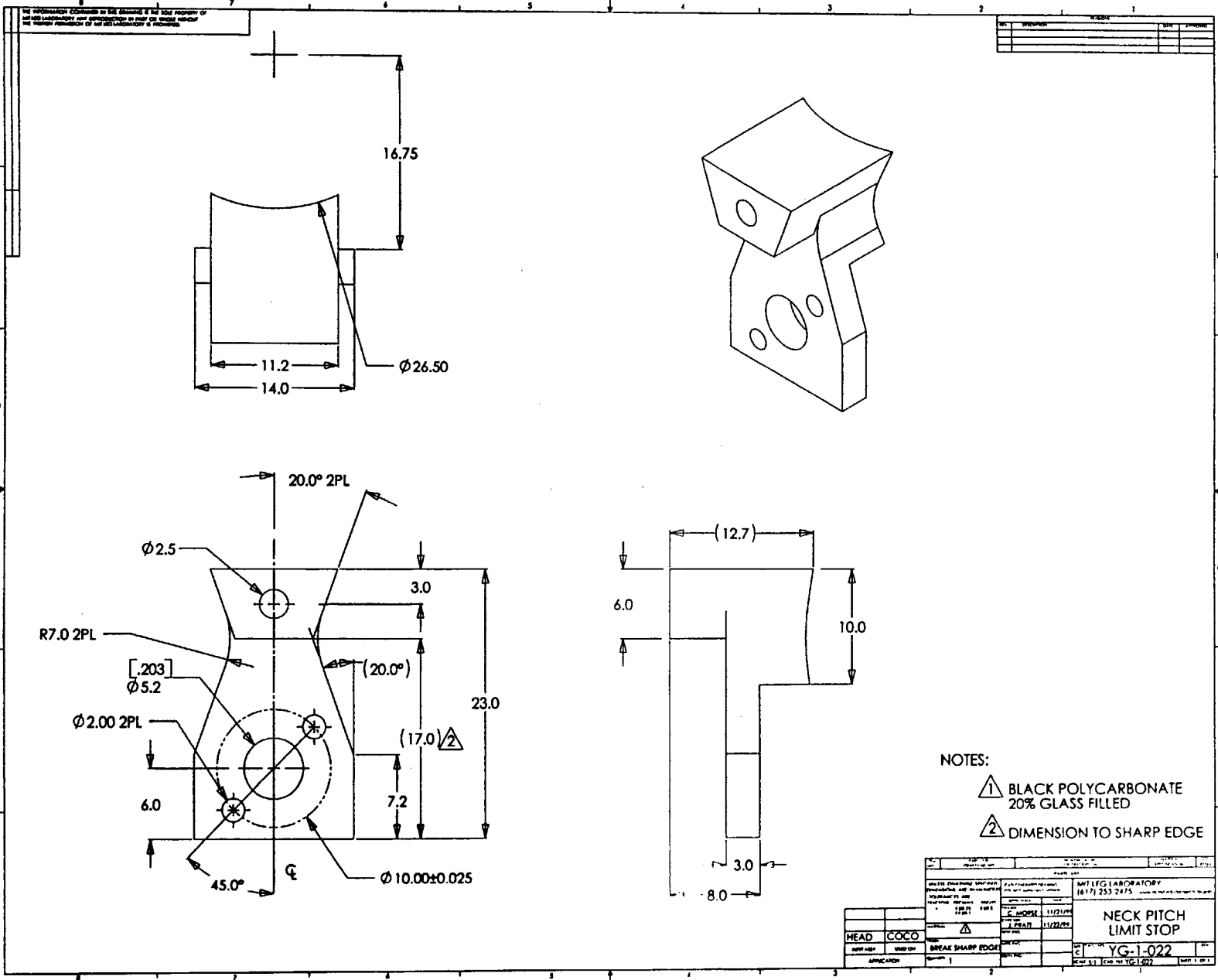


SECTION A-A



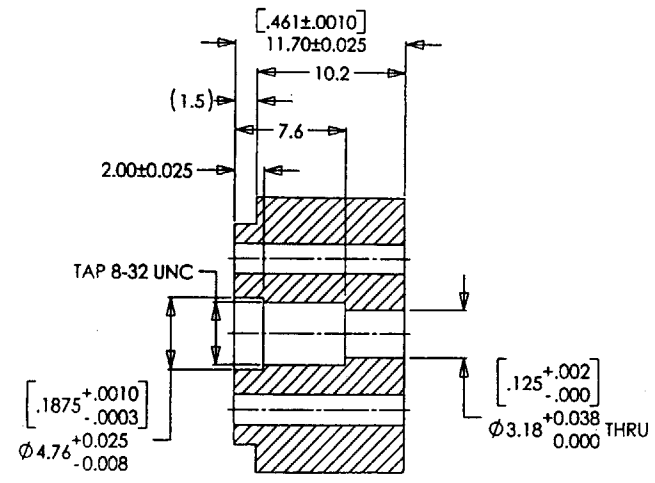
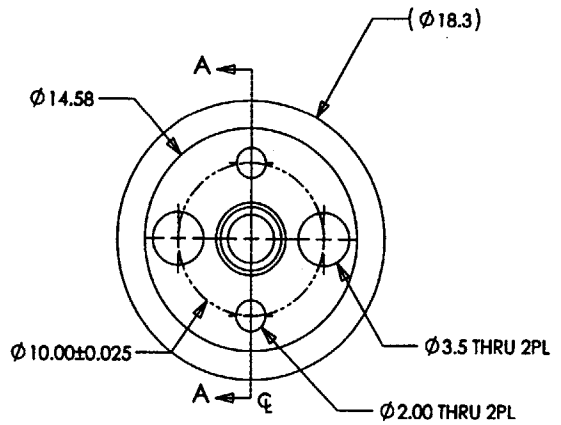
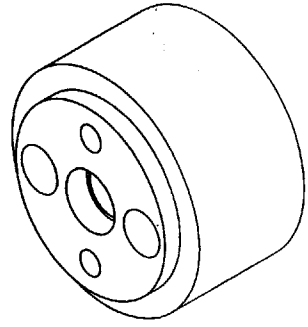
- NOTES:
- 1: ALL DIMENSIONS TO SHARP EDGE
 - 2: BREAK SHARP EDGES

MIT LEG LABORATORY (617) 253-2475	NECK MOUNT
YG-1-021	1 of 1



ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS AND DECIMALS THEREOF. DIMENSIONS IN PARENT BRACKETS ARE IN INCHES AND DECIMALS THEREOF. THE FINISH REQUIREMENT OF ALL DIMENSIONS IS F250.

REV	DESCRIPTION	DATE	BY	CHKD



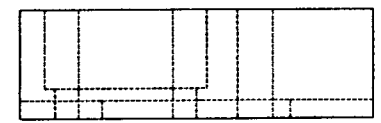
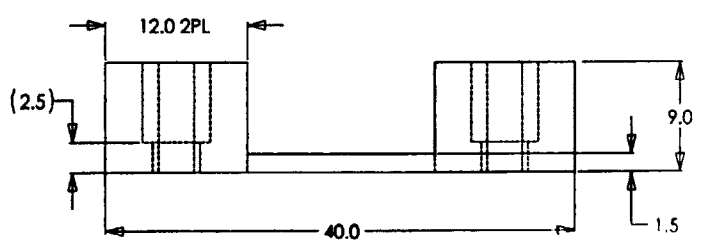
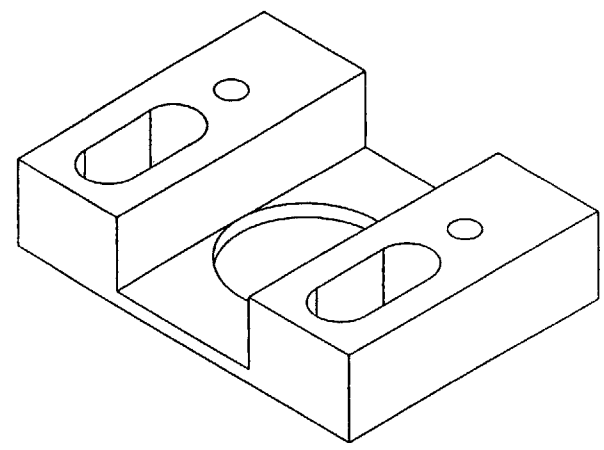
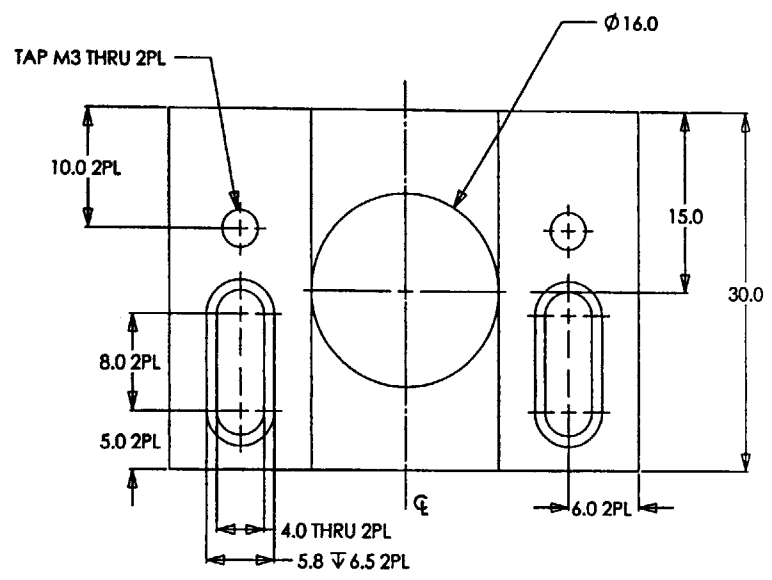
SECTION A-A

NOTES:
 1. 3MM PITCH X 19.1MM PD GT PULLEY STOCK
 STOCK DRIVE P/N: A 6A52M020GT15
 2: BREAK SHARP EDGES

DATE: 11/21/99	BY: E. MOORE	CHKD: J. ALBERT	DATE: 11/22/99
HEAD COCO	BLACK ANODIZE	MIT LEG LABORATORY (617) 253-2475	
PART: NECK PITCH CAPSTAN		PART: YG-1-023	

ALL INFORMATION CONTAINED HEREIN IS UNCLASSIFIED EXCEPT WHERE SHOWN OTHERWISE

REV	DESCRIPTION	DATE	BY

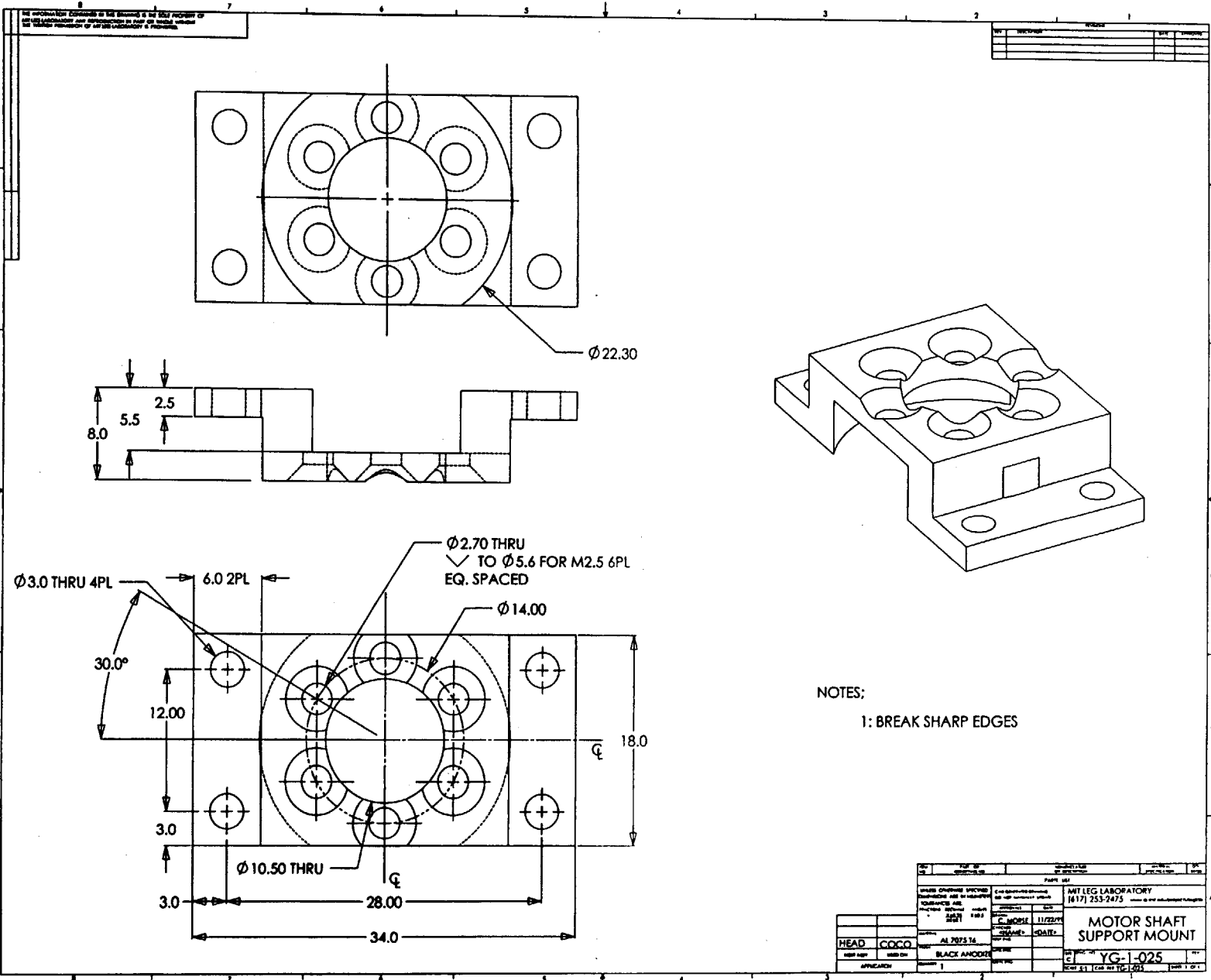


NOTES:
 BLACK POLYCARBONATE 20% GLASS FILLED

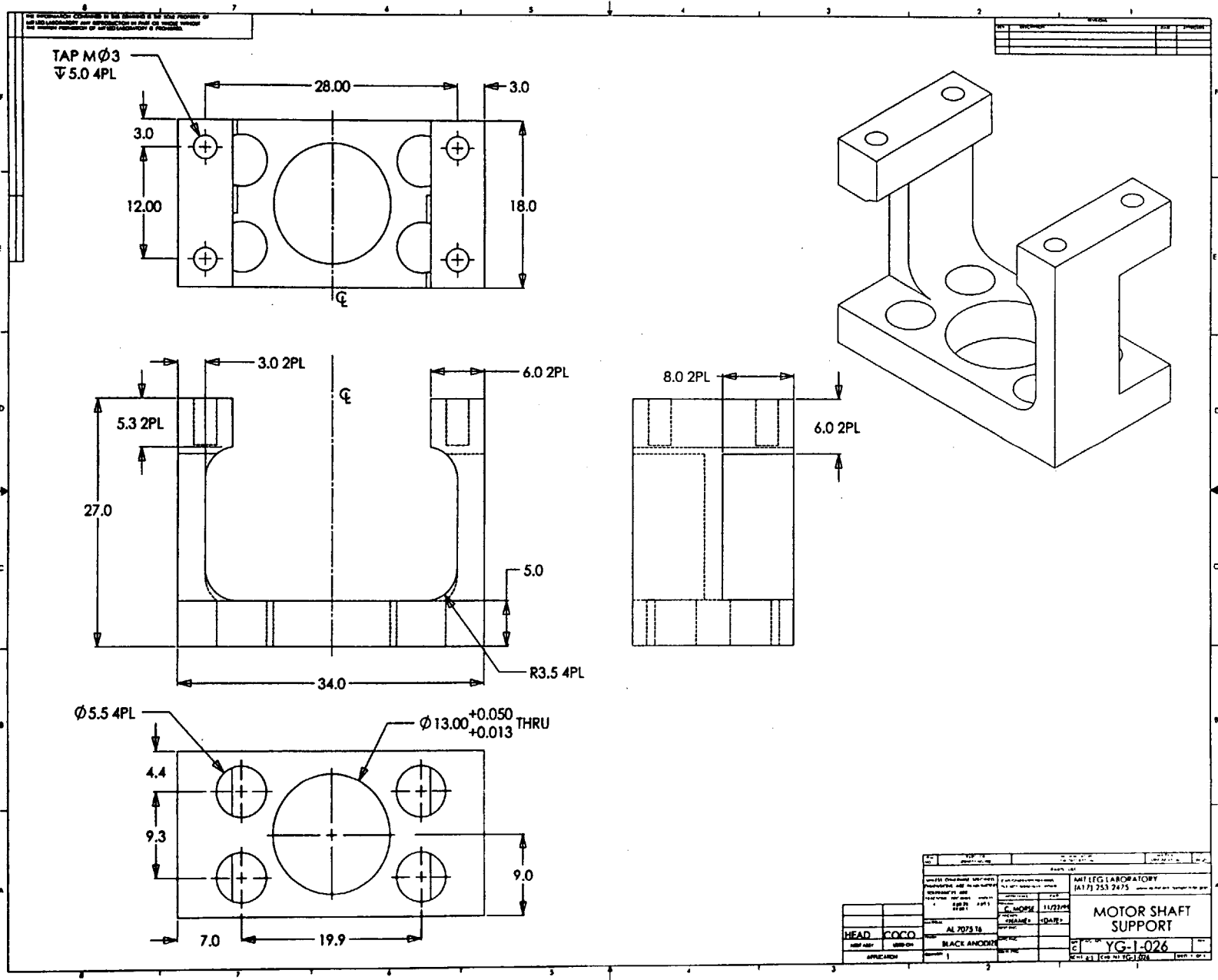
HEAD		COCO		BREAK SHARP EDGE		APPLICATION	

DATE	11/23/98
BY	
CHECKED	
APPROVED	

MIT IFC LABORATORY
1071 253 2415
NECK PITCH MOTOR MOUNT
YG-1-024



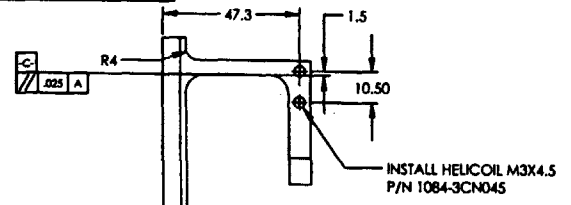
06



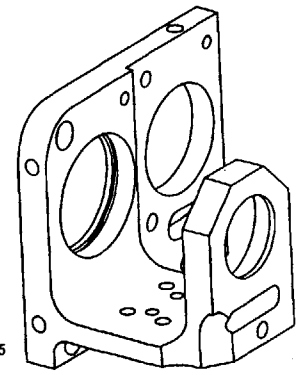
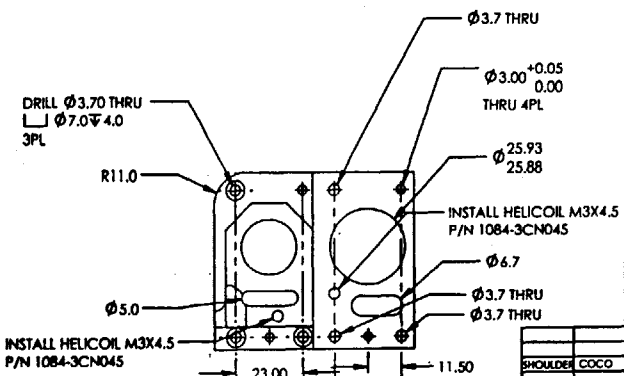
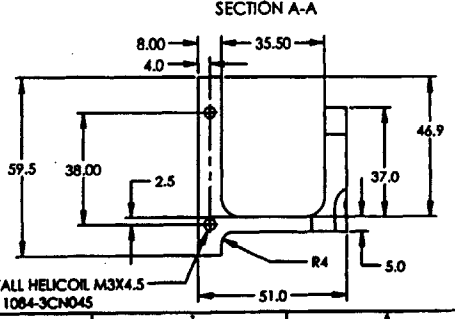
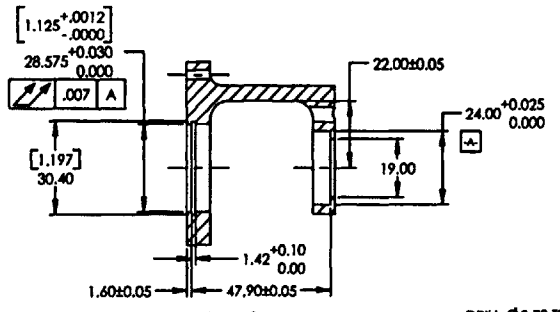
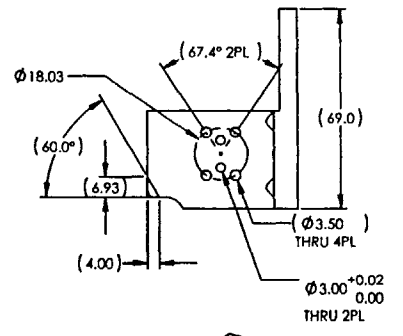
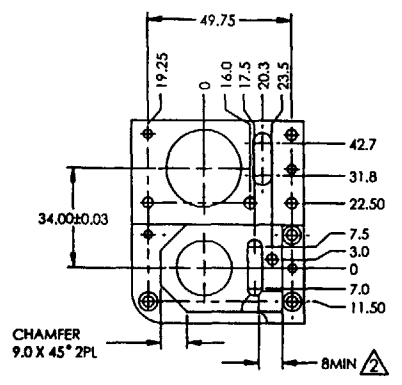
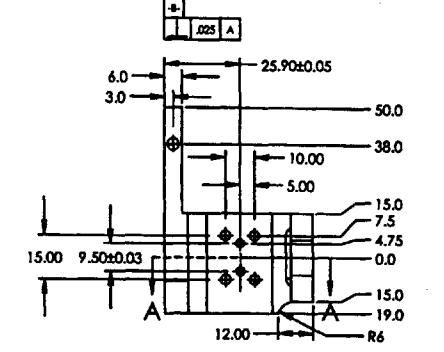
HEAD		COCO		AL 7075 T6		BLACK ANODING		1	
APPLICATION		1		1		1		1	
DATE		11/22/94		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
DRAWN BY		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
CHECKED BY		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
APPROVED BY		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
MATERIAL		AL 7075 T6		BLACK ANODING		1		MOTOR SHAFT SUPPORT	
PART NO.		YG-1-026		1		1		MOTOR SHAFT SUPPORT	
REV.		1		1		1		MOTOR SHAFT SUPPORT	
DATE		11/22/94		11/22/94		11/22/94		MOTOR SHAFT SUPPORT	
BY		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
CHECKED		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
APPROVED		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
MATERIAL		AL 7075 T6		BLACK ANODING		1		MOTOR SHAFT SUPPORT	
PART NO.		YG-1-026		1		1		MOTOR SHAFT SUPPORT	
REV.		1		1		1		MOTOR SHAFT SUPPORT	
DATE		11/22/94		11/22/94		11/22/94		MOTOR SHAFT SUPPORT	
BY		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
CHECKED		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	
APPROVED		D. DAVIS		C. MOORE		D. DAVIS		MOTOR SHAFT SUPPORT	

THE DIMENSIONS CONTAINED IN THIS DRAWING ARE THE BEST PROVIDED BY THE LABORATORY AND NO ASSURANCE IS MADE OF THE ACCURACY THEREOF AND NO LIABILITY IS ASSUMED BY THE LABORATORY FOR ANY DAMAGE TO PROPERTY OR PERSONS.

REV	DESCRIPTION	DATE
1	INITIAL RELEASE	11/22/00
2	CHANGE HOLE PATTERN	7/17/00



NOTE:
 1. BREAK SHARP EDGES
 △ CHAMFER END CONDITION NOT CRITICAL



DATE	BY	CHKD	APP'D
11/22/00	ALBERT	DAVE	
SHOULDER COCO		BLACK ANODISE	

DATE	BY	CHKD	APP'D
11/22/00	ALBERT	DAVE	

DATE	BY	CHKD	APP'D
11/22/00	ALBERT	DAVE	

DATE	BY	CHKD	APP'D
11/22/00	ALBERT	DAVE	

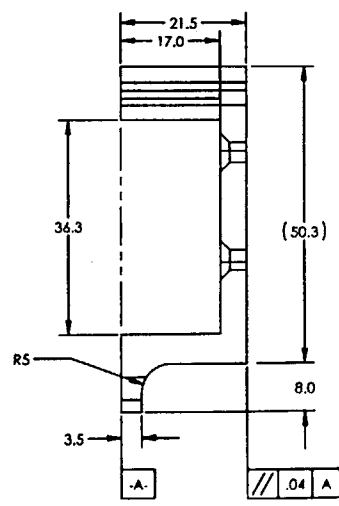
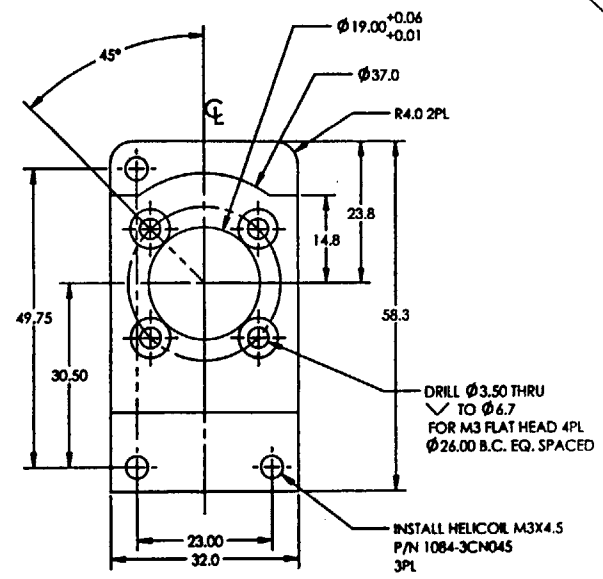
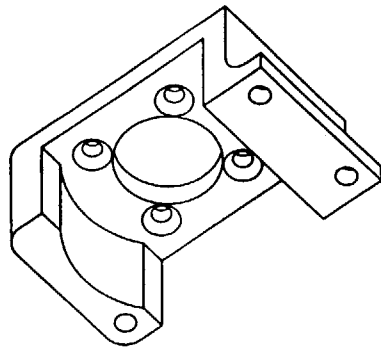
DIFFERENTIAL MOUNT RIGHT
 YG-2-101R

ALL DIMENSIONS CONTAINED IN THE DRAWING ARE THE FINAL DIMENSIONS OF THE PART UNLESS OTHERWISE SPECIFIED. ALL DIMENSIONS ARE TO BE TAKEN FROM THE UNMOUNTED PART UNLESS OTHERWISE SPECIFIED.

REV	DESCRIPTION	DATE	BY
1	ISSUE RELEASE		ALBERT

NOTES:

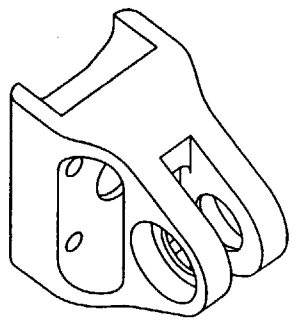
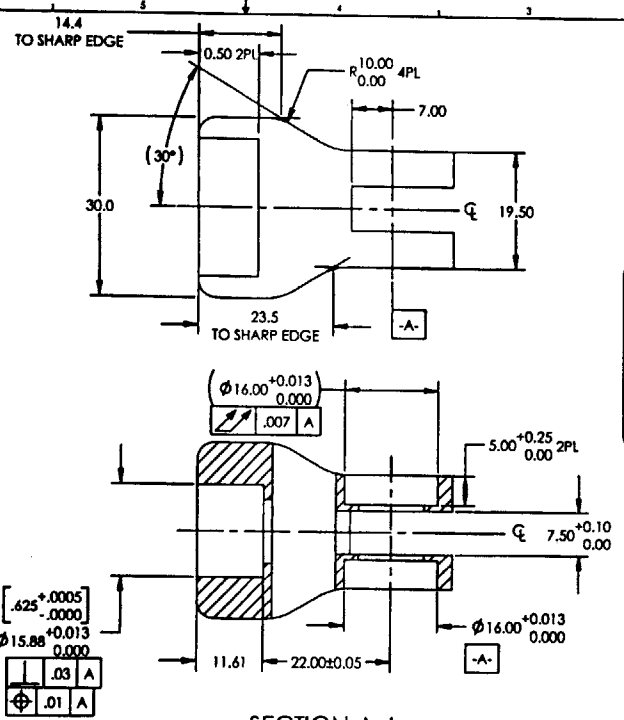
1. BREAK SHARP EDGES



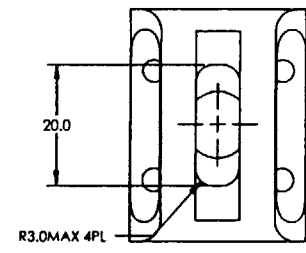
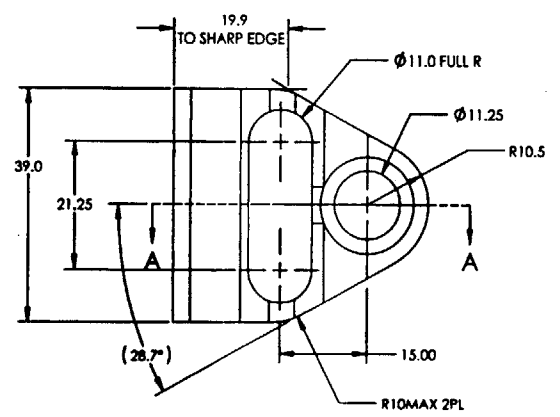
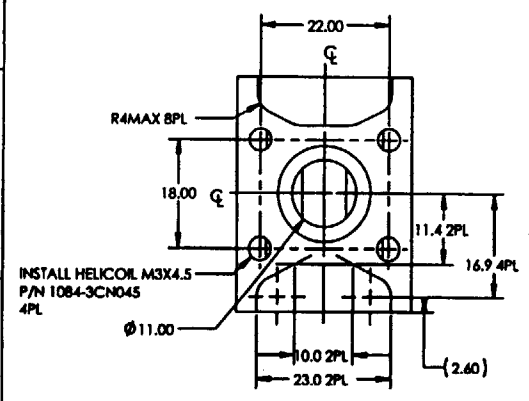
SHOULDER		COCO	ALBON 1/2	MOTOR MOUNT	
BLACK ANODIZE				E YG-2-102	
APPLICATOR				REV 2.11 (REV 10/2/02)	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS AND DECIMALS THEREOF. DIMENSIONS IN PARENTHESES ARE FOR INFORMATION ONLY AND SHALL NOT BE USED FOR FABRICATION.

REV	DESCRIPTION	DATE	BY
1	INITIAL RELEASE	11/20/04	CM
2	REVISIONS FOR BLACK ANODIZING	11/20/04	CM
3	REVISIONS FOR BLACK ANODIZING	11/20/04	CM



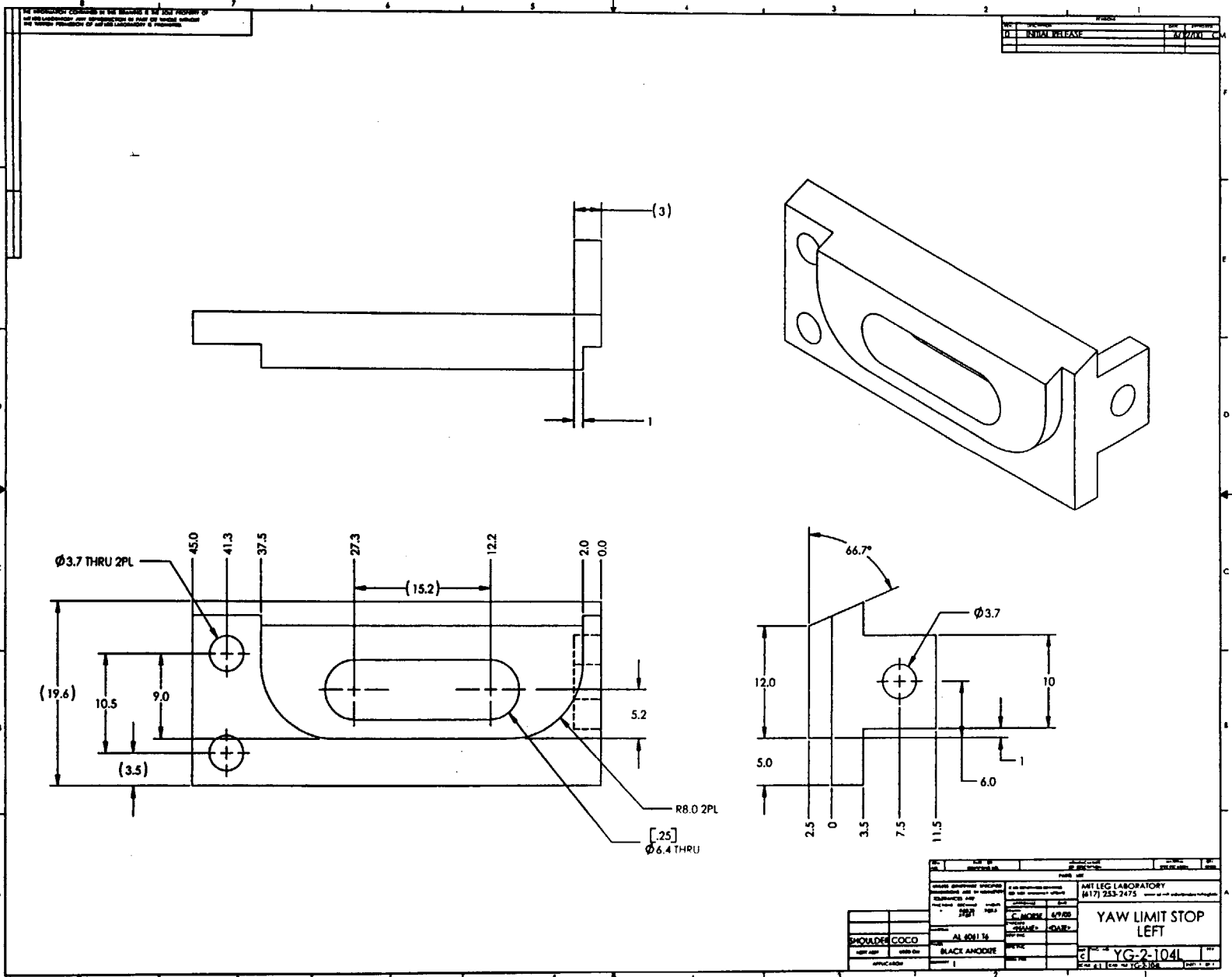
SECTION A-A



REV	DESCRIPTION	DATE	BY
1	INITIAL RELEASE	11/20/04	CM
2	REVISIONS FOR BLACK ANODIZING	11/20/04	CM
3	REVISIONS FOR BLACK ANODIZING	11/20/04	CM

APPROVED	DATE	BY	DATE	BY
SHOULDER COCO		AL 06/11/04		
		BLACK ANODIZE		

MIT LEG LABORATORY	
6171 253-2475	
BEARING YOKE	
YG-2-103	



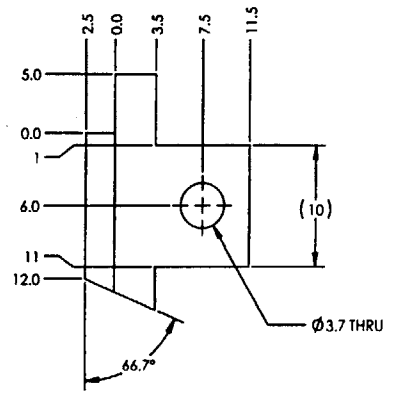
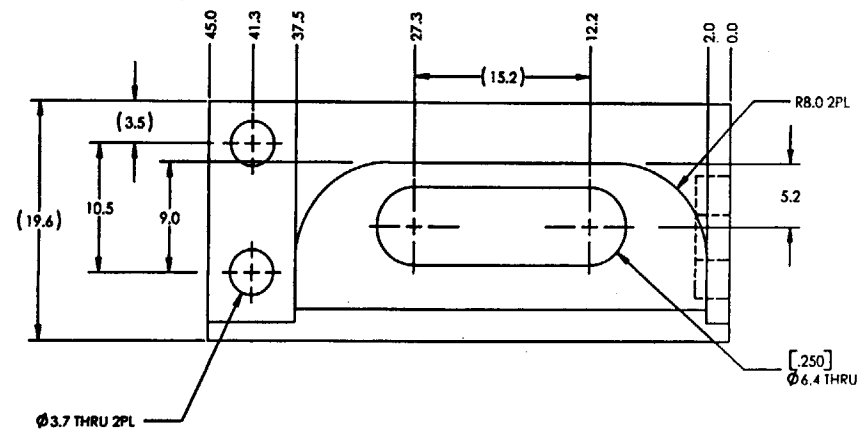
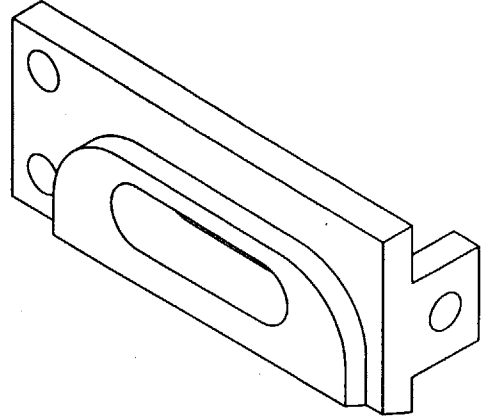
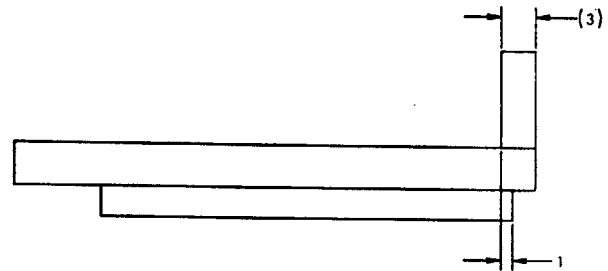
ALL INFORMATION CONTAINED HEREIN IS UNCLASSIFIED EXCEPT WHERE SHOWN OTHERWISE
 ALL INFORMATION CONTAINED HEREIN IS UNCLASSIFIED EXCEPT WHERE SHOWN OTHERWISE

REV	DESCRIPTION	DATE	APPROVED
1	INITIAL RELEASE	01/27/01	

DRAWN BY: SHOULDER CHECKED BY: COCCO DATE: 01/27/01		PART NAME: YAW LIMIT STOP LEFT PART NUMBER: YG-2-1041 QUANTITY: 1	
MATERIAL: AL 6061 T6 FINISH: BLACK ANODIZE		MANUFACTURED BY: ART LEG LABORATORY ADDRESS: 6171 253-2475	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS AND DECIMALS THEREOF. DIMENSIONS IN PARENTHESES ARE IN INCHES AND DECIMALS THEREOF.

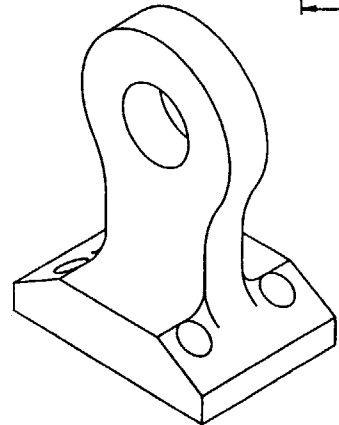
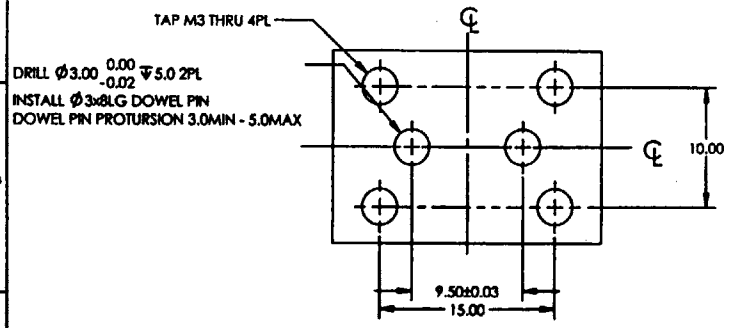
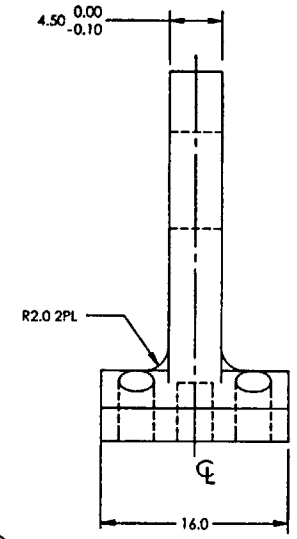
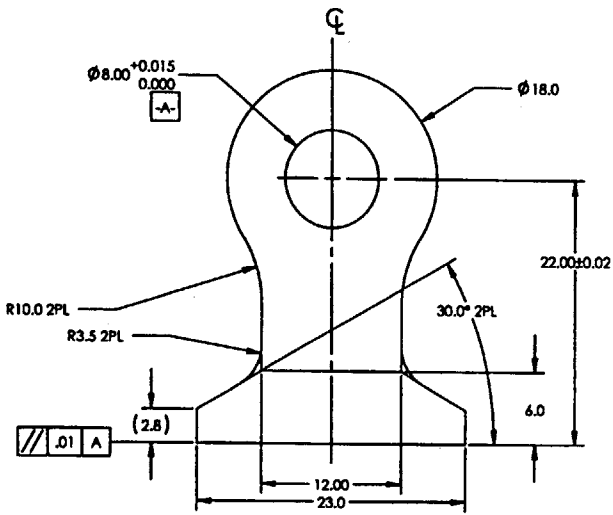
REV.	DESCRIPTION	DATE	BY
1	INITIAL RELEASE		



DATE: 11/11/88 DRAWN BY: [REDACTED] CHECKED BY: [REDACTED]		PART: 111 QUANTITY: 1000 MATERIAL: ALUMINUM FINISH: BLACK ANODITE		AMI LEG LABORATORY (617) 253-2475 YAW LIMIT STOP RIGHT YG-2-104R	
SHOLDER COGO NEW USE: [REDACTED] APPROVAL: [REDACTED]	ALUMINUM BLACK ANODITE	C. W. [REDACTED] [REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE TO BE THE BEST PRACTICE OF THE MANUFACTURER AND OPERATIONS TO MEET THE INTENT OF THE DESIGN. THE MANUFACTURER OF THE PART IS RESPONSIBLE FOR THE CORRECT INTERPRETATION OF THE DRAWING.

REV	DESCRIPTION	DATE	BY
01	ORIGINAL RELEASE	11/20/00	CJM
02	CHANGE DOWEL PIN LENGTH	4/12/01	CJM



REV	DESCRIPTION	DATE	BY
01	ORIGINAL RELEASE	11/20/00	CJM
02	CHANGE DOWEL PIN LENGTH	4/12/01	CJM

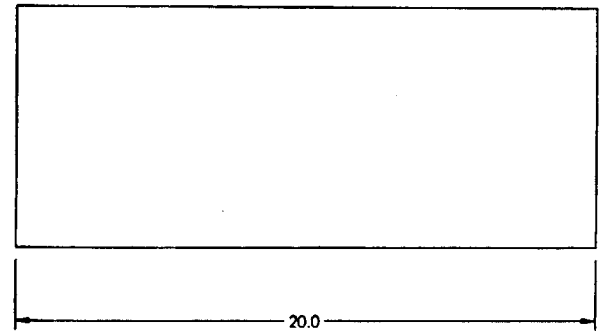
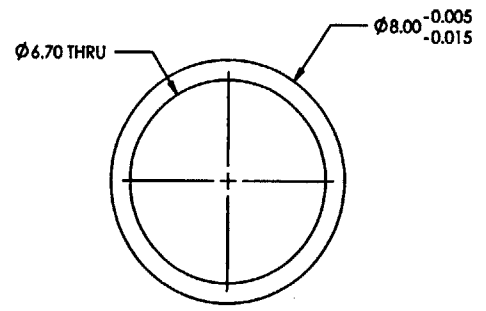
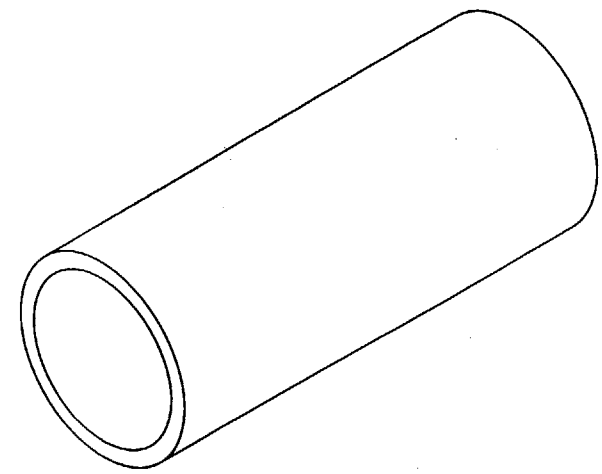
ORDER NO.	QUANTITY	DATE	BY
ORDER NO.	QUANTITY	DATE	BY

MIT LEG LABORATORY	16171 253 2475
DIFFERENTIAL CENTER POST	
YG-2-105	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS. DIMENSIONS IN PARENTHESIS ARE FOR INFORMATION ONLY AND ARE NOT TO BE USED FOR FABRICATION.

REV	DESCRIPTION	DATE	BY
1	INITIAL RELEASE		

- NOTES:
1. ALL DIMENSIONS AFTER HEAT TREATING
 2. BREAK SHARP EDGES



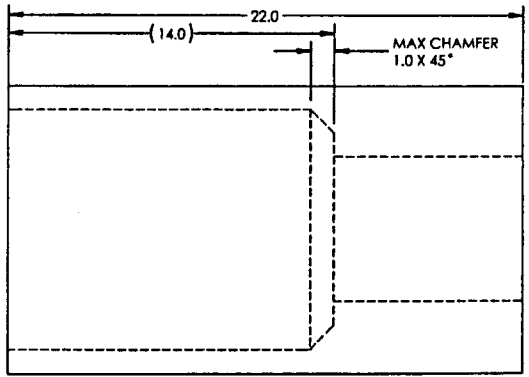
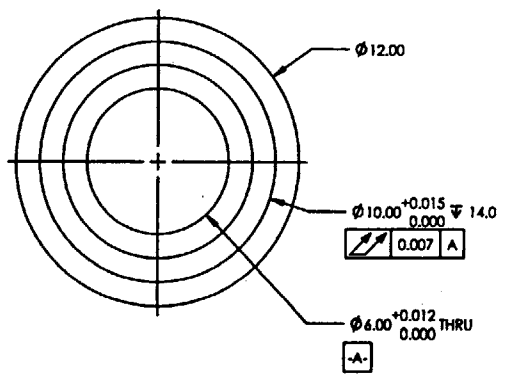
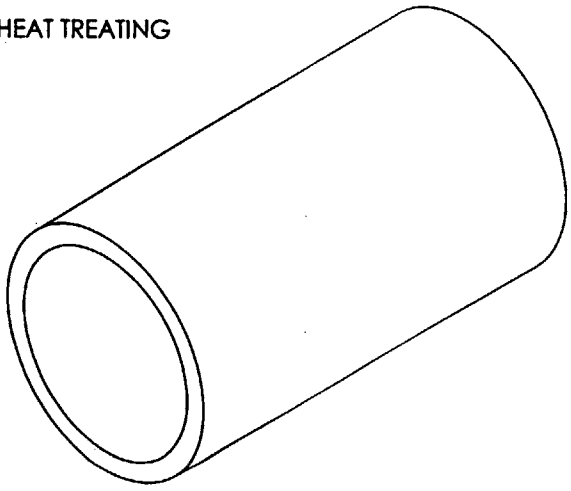
SHOULDER COCO		DIFFERENTIAL BEARING MOUNT	
HEAT TREATED		YIG LABORATORY	
BREAK SHARP EDGES		[A17] 253-2475	
		DIFFERENTIAL BEARING MOUNT	
		YG-2-106	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS AND DECIMALS THEREOF. ALL DIMENSIONS ARE TO BE TAKEN UNLESS OTHERWISE SPECIFIED TO THE NEAREST 0.01 MILLIMETER.

REV	DESCRIPTION	DATE	BY
01	INITIAL RELEASE	01/28/00	C. MA

NOTES:

1. ALL DIMENSIONS AFTER HEAT TREATING
2. BREAK SHARP EDGES

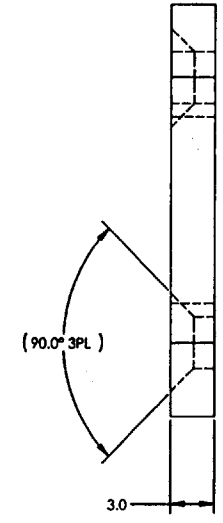
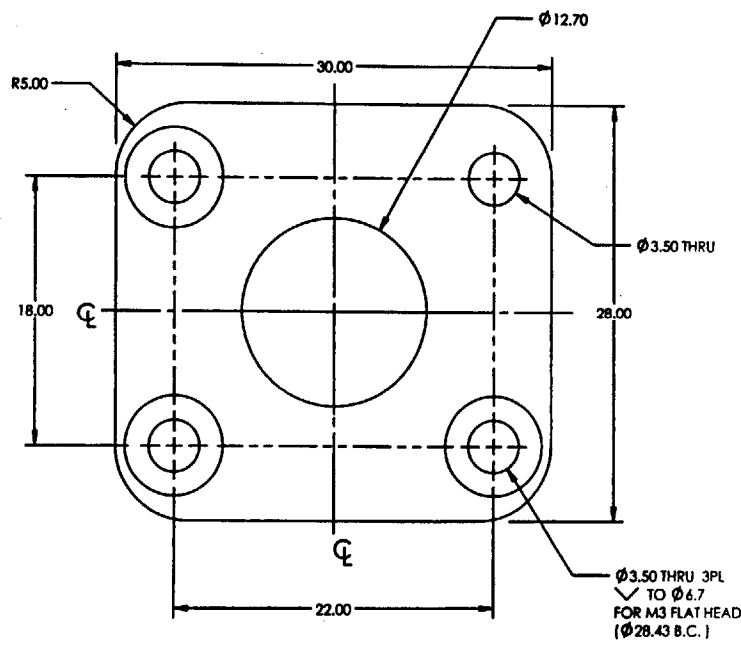


MATERIAL		PART NO.		REV.	
SHOULDER COCO		YG-2-107		01	
MATERIAL		PART NO.		REV.	
ST 1000 STEEL		YG-2-107		01	
HEAT TREATED		YG-2-107		01	
BREAK SHARP EDGES		YG-2-107		01	
MATERIAL		PART NO.		REV.	
SHOULDER COCO		YG-2-107		01	
MATERIAL		PART NO.		REV.	
SHOULDER COCO		YG-2-107		01	

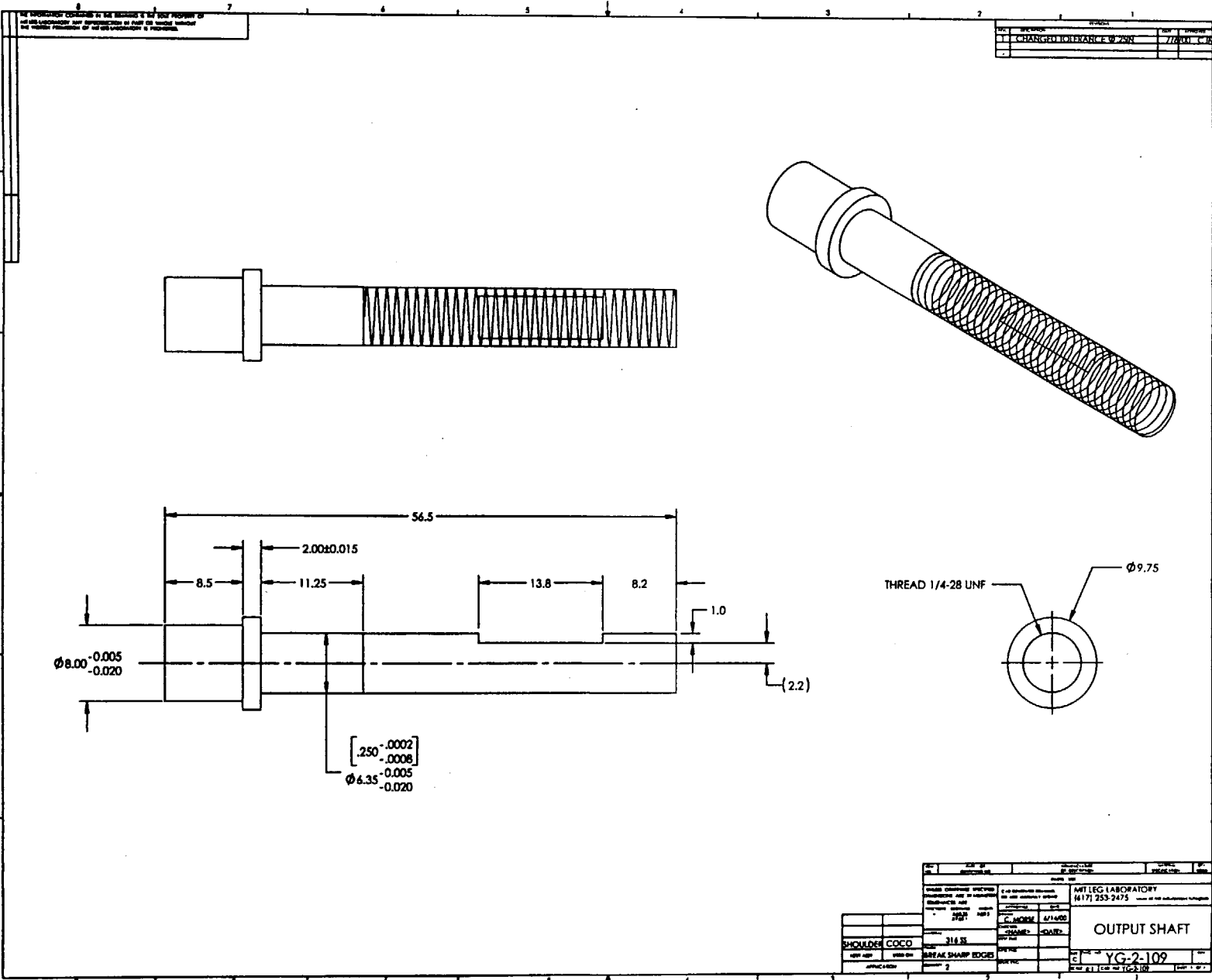
MITLEG LABORATORY
 (617) 253-2475
SHAFT COUPLING
 YG-2-107
 Rev. 1.1 (See also YG-2-107)

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS AND DECIMALS THEREOF. DIMENSIONS IN PARENTHESES ARE IN INCHES AND DECIMALS THEREOF. UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE TO BE HIDDEN SURFACES.

REV	DESCRIPTION	DATE	BY
01	INITIAL RELEASE	11/24/81	CRJ



SHOULDER COCO		AL 7073 T4		MIT FFG LABORATORY	
BLACK ANODIZE		3		(617) 253-2475	
APPROVAL		3		BEARING RETAINER	
				YG-2-108	



REV	DESCRIPTION	DATE	BY	CHKD
1	ASSEMBLY			
2	CHARGED TO: REFERENCE W-29N	7/7/01	C-10	

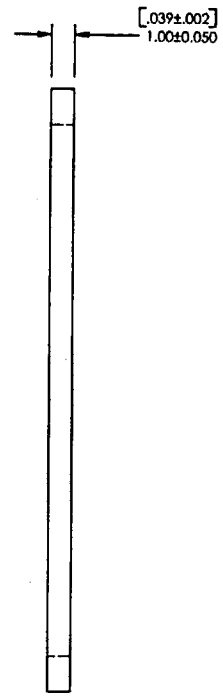
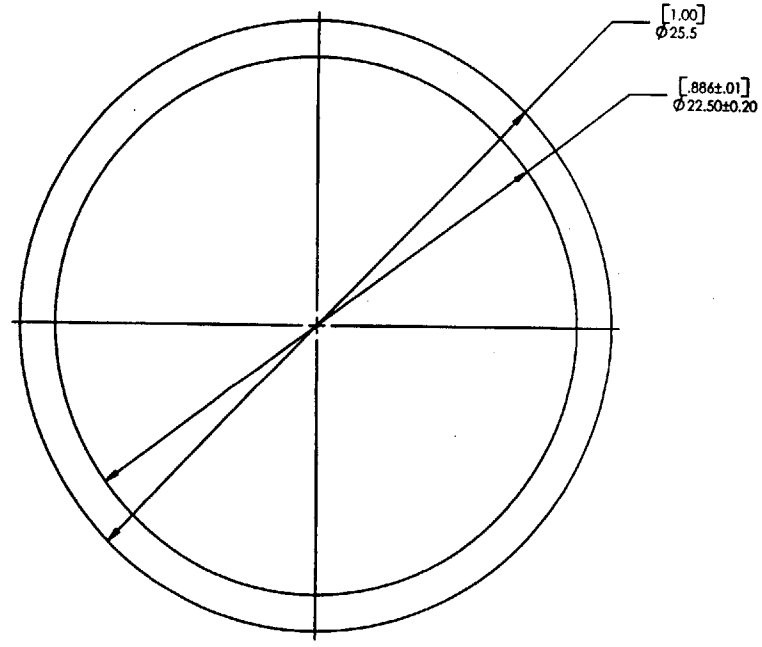
QUANTITY: 1 PART: 318 SS FINISH: BURN POLISH TOLERANCES: UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS DECIMALS ARE IN MILLIMETERS FRACTIONS ARE IN MILLIMETERS ANGLES ARE IN DEGREES	ART LEG LABORATORY (417) 253-2475 1000 S. UNIVERSITY AVENUE COLUMBIA, MISSOURI 65201
---	---

SHOULDERS: COCO SURF: SHARP EDGES	PART: 318 SS FINISH: BURN POLISH TOLERANCES: UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS DECIMALS ARE IN MILLIMETERS FRACTIONS ARE IN MILLIMETERS ANGLES ARE IN DEGREES
--------------------------------------	--

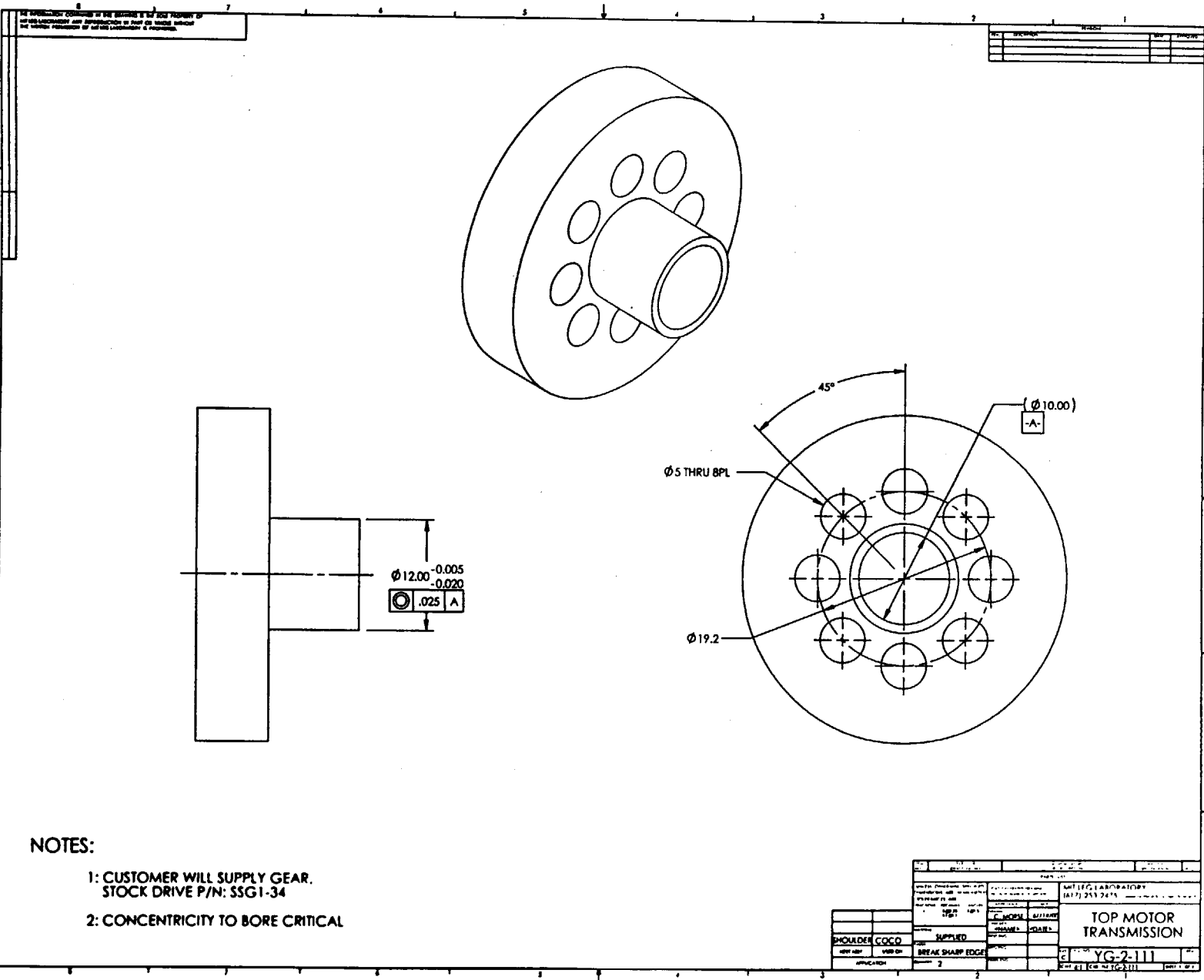
TITLE: OUTPUT SHAFT PART NO: YG-2-109 DRAWN BY: C-10 DATE: 7/7/01
--

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REV	DESCRIPTION	DATE	BY	CHKD



MIT LEG LABORATORY		PART LAB	
6171 253-2475		6/14/00	
SHAFT SPACER		MIT LEG LABORATORY	
AL 6061 T6		MIT LEG LABORATORY	
SHOULDER COCO		MIT LEG LABORATORY	
BREAK SHARP EDGES		MIT LEG LABORATORY	
REV 3		MIT LEG LABORATORY	
MIT LEG LABORATORY		MIT LEG LABORATORY	



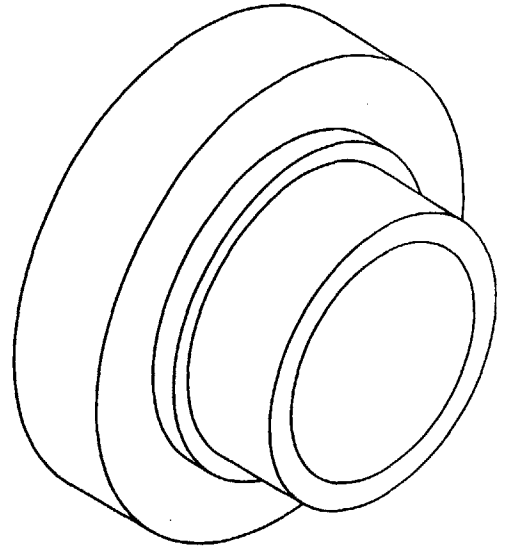
NOTES:

- 1: CUSTOMER WILL SUPPLY GEAR.
STOCK DRIVE P/N: SSG1-34
- 2: CONCENTRICITY TO BORE CRITICAL

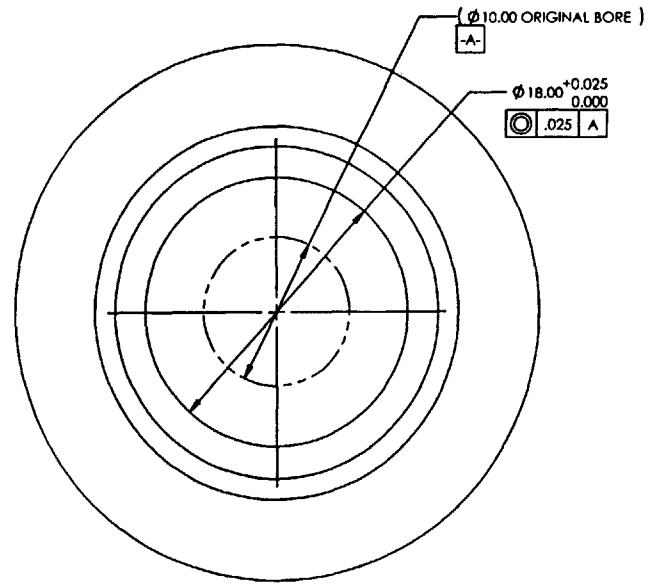
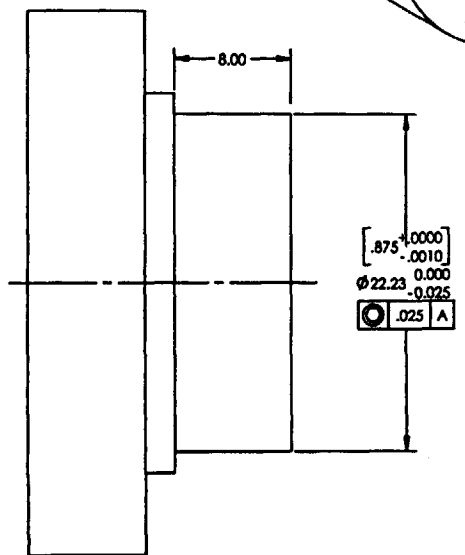
DATE: _____ DRAWN BY: _____ CHECKED BY: _____ APPROVED BY: _____		PART NO.: _____ REV: _____
MATERIAL: _____ QUANTITY: _____ UNIT: _____		MFG. LAB: _____ DATE: _____
SHARPER COGO 1000 1000	SUPPLIED BREAK SHARP EDGE APPLICATION: 2	MTEG LABORATORY (817) 251-7415 TOP MOTOR TRANSMISSION YG-2-111 REV: 01 (REV 01/03/11)

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES AND DECIMALS THEREOF. DIMENSIONS IN PARENTHESES ARE FOR INFORMATION ONLY AND ARE NOT TO BE USED FOR MANUFACTURING PURPOSES.

REV	DESCRIPTION	DATE	BY	CHKD



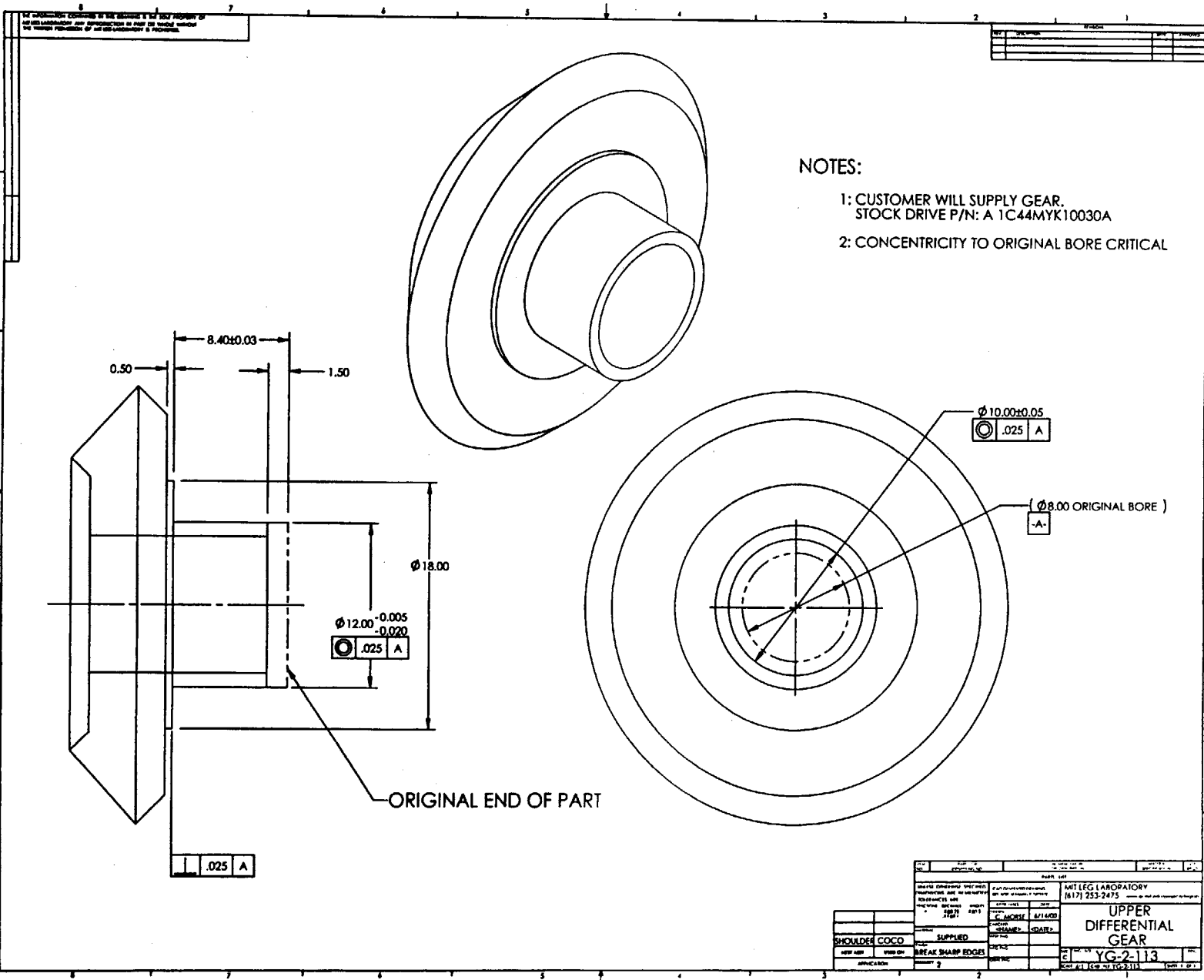
- NOTES:
- 1: CUSTOMER WILL SUPPLY GEAR.
STOCK DRIVE P/N: SSG1-34
 - 2: CONCENTRICITY TO ORIGINAL BORE CRITICAL



REV	DESCRIPTION	DATE	BY	CHKD

SHOULDER	COCO	SUPPLIED	
		BREAK SHARP EDGE	

AMT LFC LABORATORY	
18171 253-2475	
DRIVE GEAR	
YG-2-112	



NOTES:
 1: CUSTOMER WILL SUPPLY GEAR.
 STOCK DRIVE P/N: A 1C44MYK10030A
 2: CONCENTRICITY TO ORIGINAL BORE CRITICAL

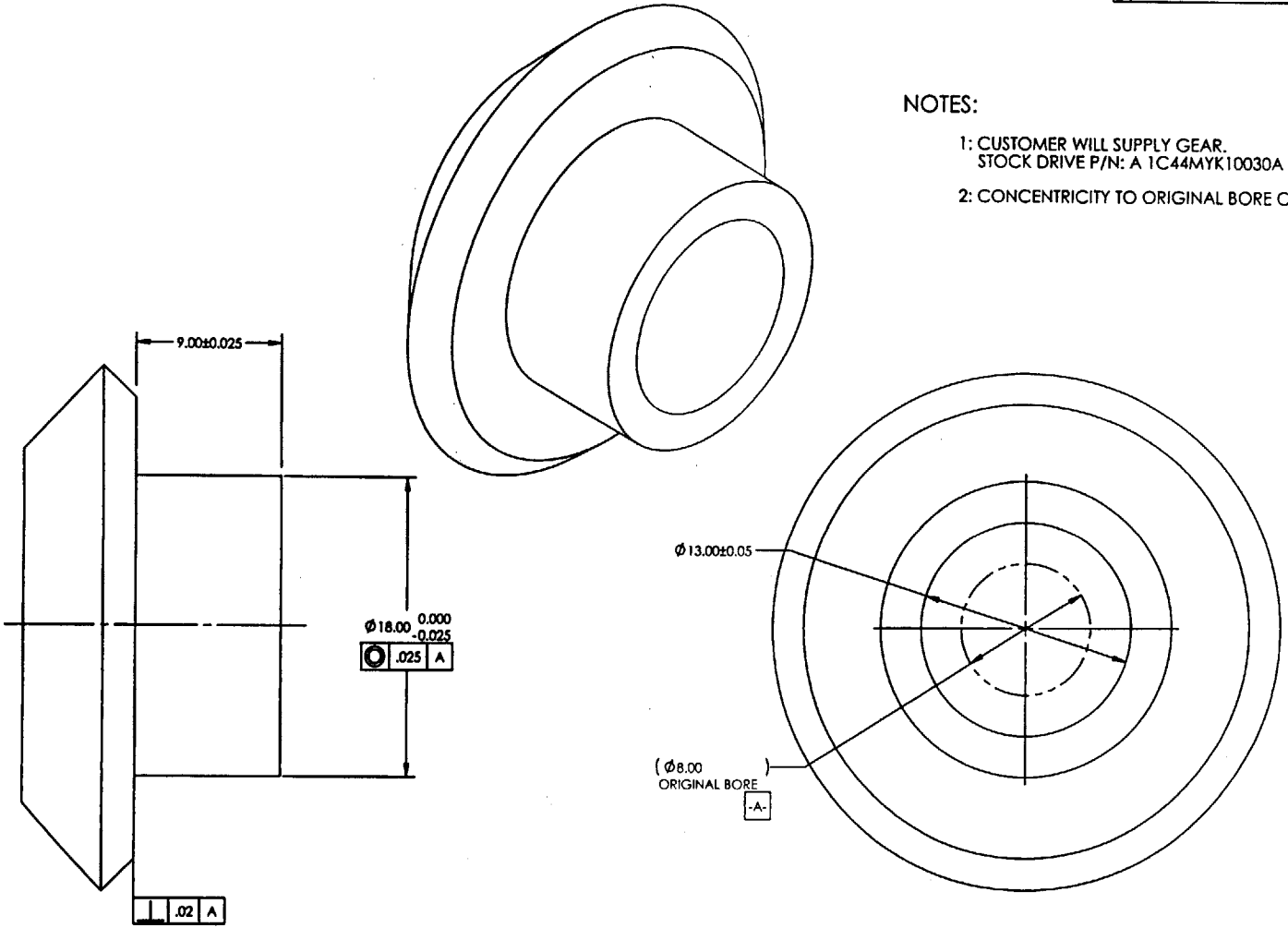
104

SHOULDER COCO		SUPPLIED		MIT LEG LABORATORY	
NEW APP		BREAK SHARP EDGES		8171 233-2475	
APPLICATION		2		UPPER DIFFERENTIAL GEAR	
				YG-2-113	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES AND DECIMALS THEREOF. DIMENSIONS IN PARENTHESIS ARE FOR INFORMATION ONLY AND ARE NOT TO BE USED FOR MANUFACTURE OF THIS COMPONENT OR FOR ANY OTHER PURPOSE.

REV	DESCRIPTION	DATE	BY	APP'D

- NOTES:
- 1: CUSTOMER WILL SUPPLY GEAR.
STOCK DRIVE P/N: A 1C44MYK10030A
 - 2: CONCENTRICITY TO ORIGINAL BORE CRITICAL

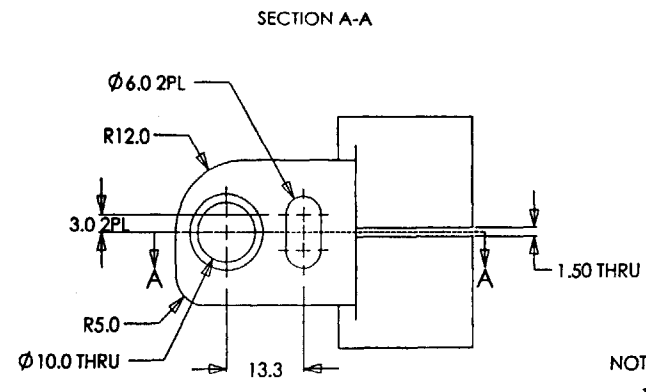
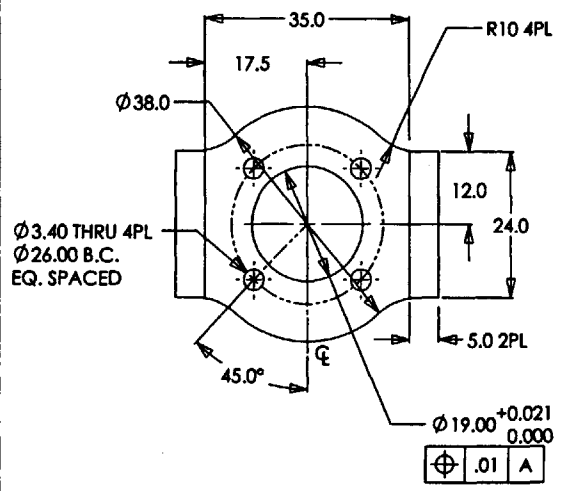
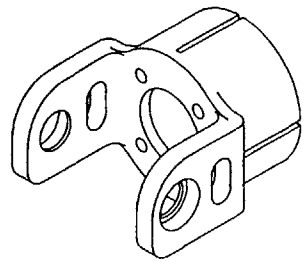
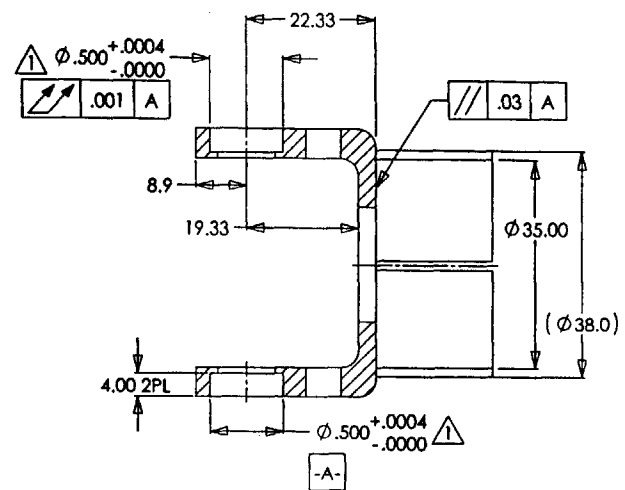
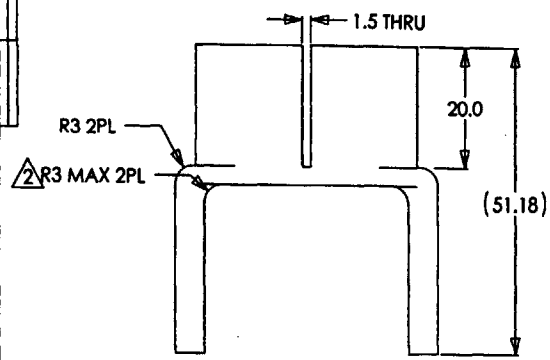


DATE	REV	DESCRIPTION	DATE	BY	APP'D

MAKE CHANGES PERMITTED DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED	ALL DIMENSIONS PERMITTED UNLESS OTHERWISE SPECIFIED	MIT LEG LABORATORY (617) 253-2475
SHARPER COGO PART NO. 100-01	SUPPLIED SPECIAL SHARP EDGES	LOWER DIFFERENTIAL GEAR YG-2-114 REV. 4.1 100-01-114

For information regarding the drawing & for the purpose of
 the manufacturer's use, dimensions in this drawing
 are not intended to be used as a basis for
 the manufacturer's use of tolerances in any other
 dimension of the drawing.

REV	DESCRIPTION	DATE	BY
1	REWORKED FOR COLLECTOR #33MM	11/27/97	CM



NOTES:
 1: THIS DIMENSION IN INCHES
 2: FILLET NOT NECESSARY,
 MACHINIST'S CHOICE

DATE	REV	DESCRIPTION	DATE	BY
11/27/97	1	REWORKED FOR COLLECTOR #33MM	11/27/97	CM

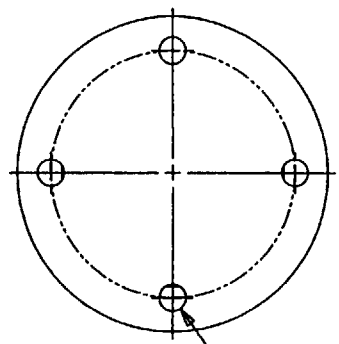
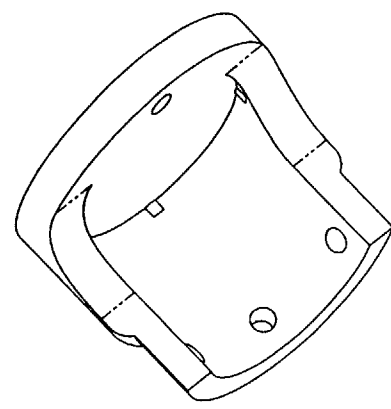
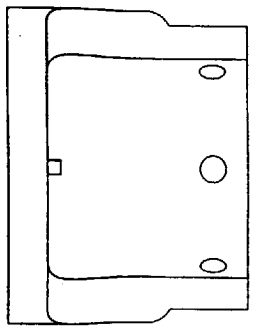
DESIGN	DATE	BY	DATE	BY
AL 4081 14	9/26/97	C. MORSE	9/26/97	CM
BLACK ANODIZE	9/27/97	D. PALMBERG	9/27/97	CM

ARM	COCCO	AL 4081 14	BLACK ANODIZE
REV	APP	9880 CH	REV
APPROVAL	DATE	2	2

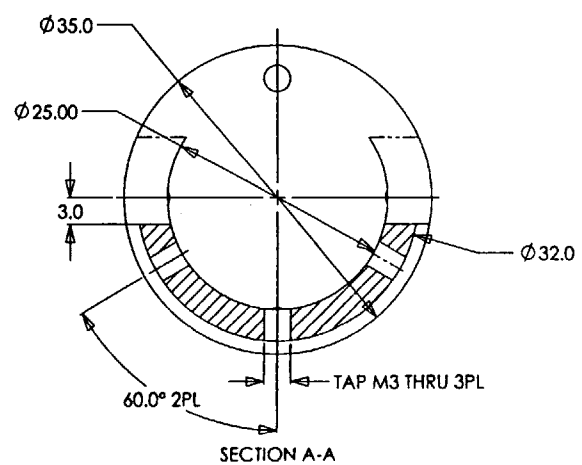
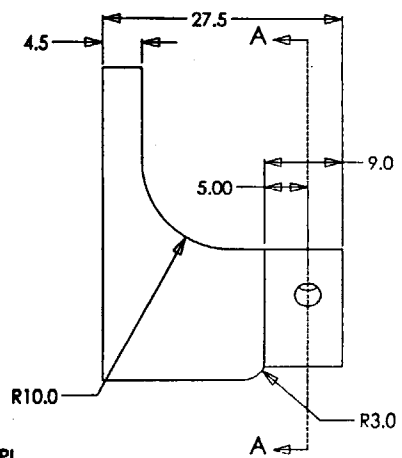
LABORATORY	LABORATORY
LAB LEG LABORATORY	LAB LEG LABORATORY
(617) 253-2475	(617) 253-2475
ELBOW KNUCKLE	ELBOW KNUCKLE
YG-3-001	YG-3-001

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS
 ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS
 ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS

REV	DESCRIPTION	DATE	BY



TAP M3 ∇ 6.0 4PL
 \varnothing 27.50 B.C. EQ. SPACED



NOTES:
 BREAK SHARP EDGES

REV	DESCRIPTION	DATE	BY

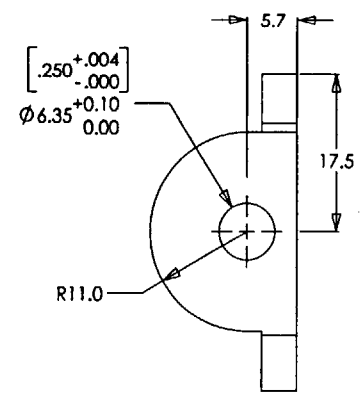
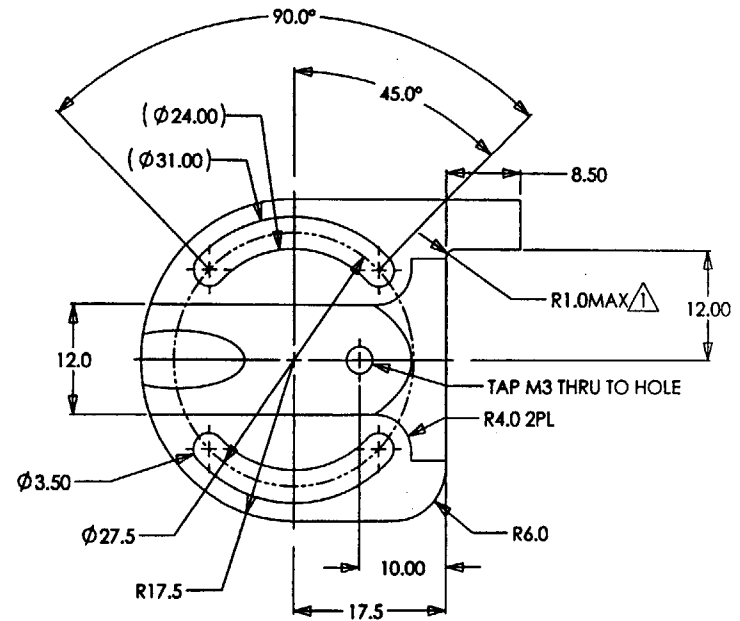
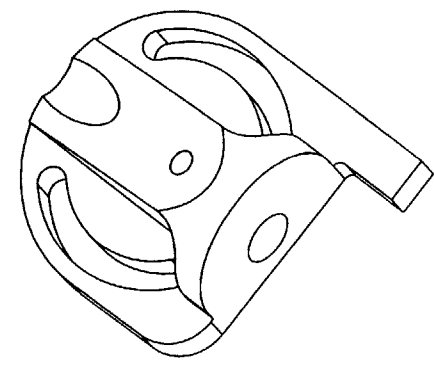
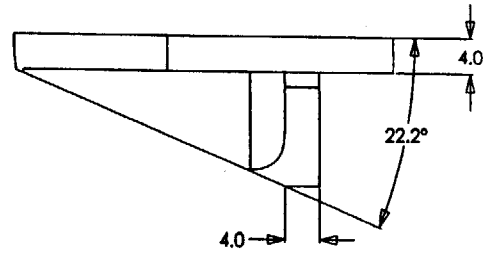
APR	COCO	AL 6061 T6	BLACK ANODIZE

AMT LEG LABORATORY	1617 253 2475
ARM ENCODER FAIRING	
YG-3-004	

110

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REV	DESCRIPTION	DATE



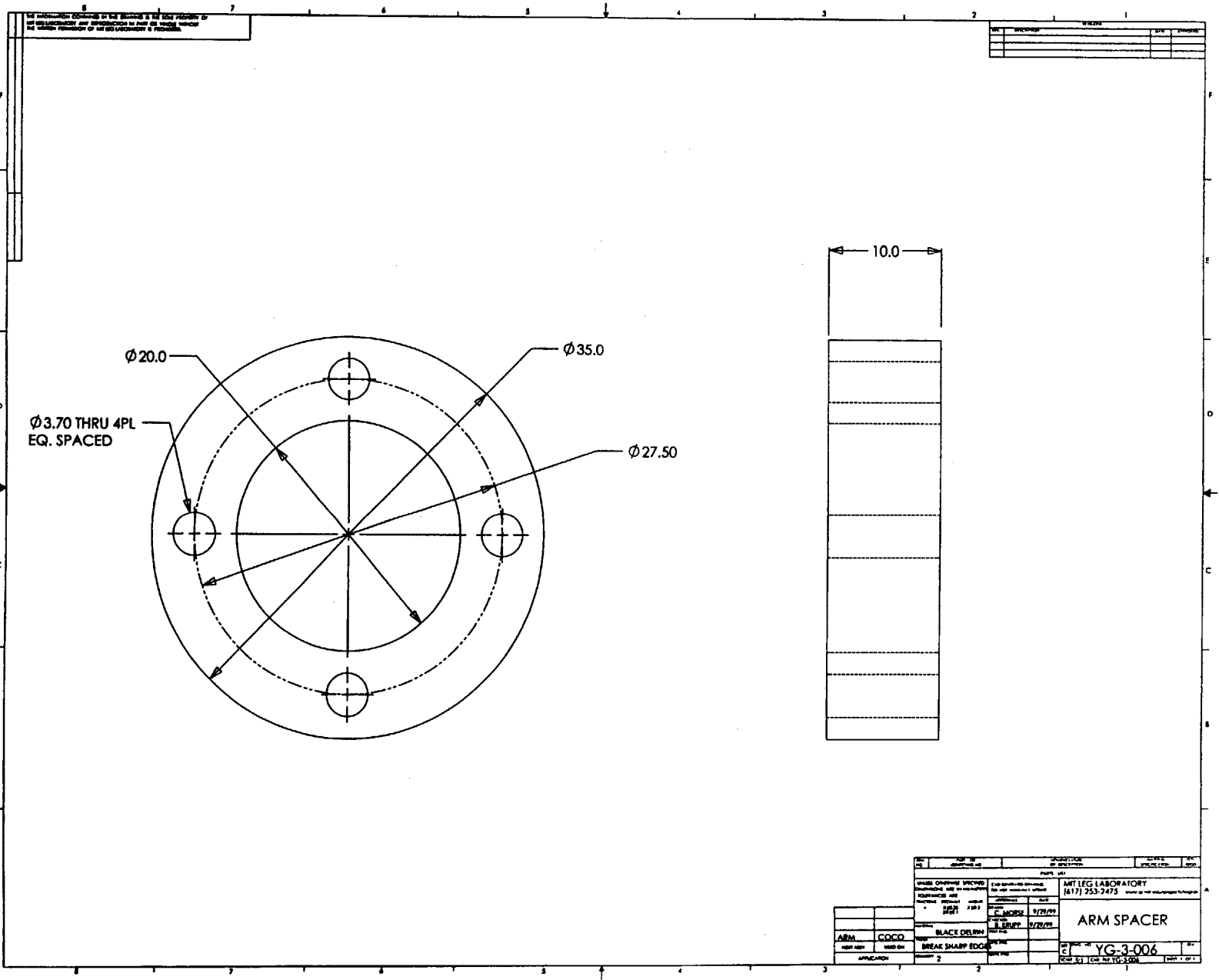
NOTES:
 BREAK SHARP EDGES
 HAND FILE OKAY

DATE	REV	DESCRIPTION	DATE	REV	DESCRIPTION

MIT LEG LABORATORY	617 253-2475	www.mit.edu/lab/leg
ARM	COCO	AL 8041 T6
BLACK ANODIZE		

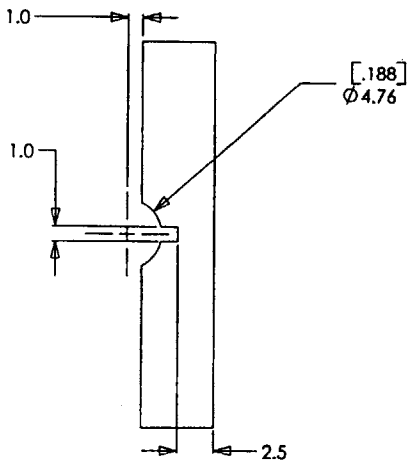
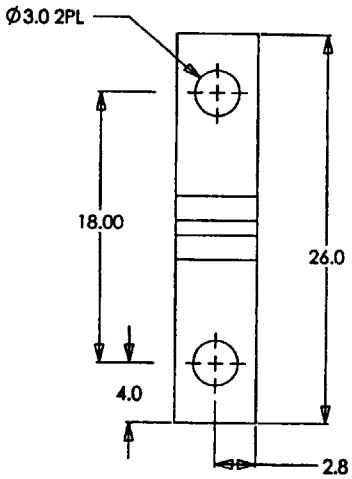
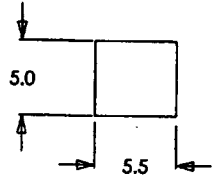
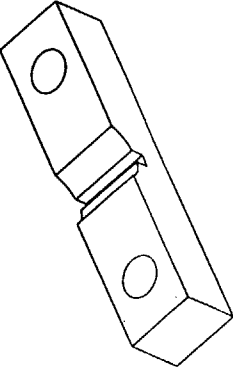
MIT LEG LABORATORY	617 253-2475	www.mit.edu/lab/leg
ARM MOUNT LEFT		
YG-3-005L		

111



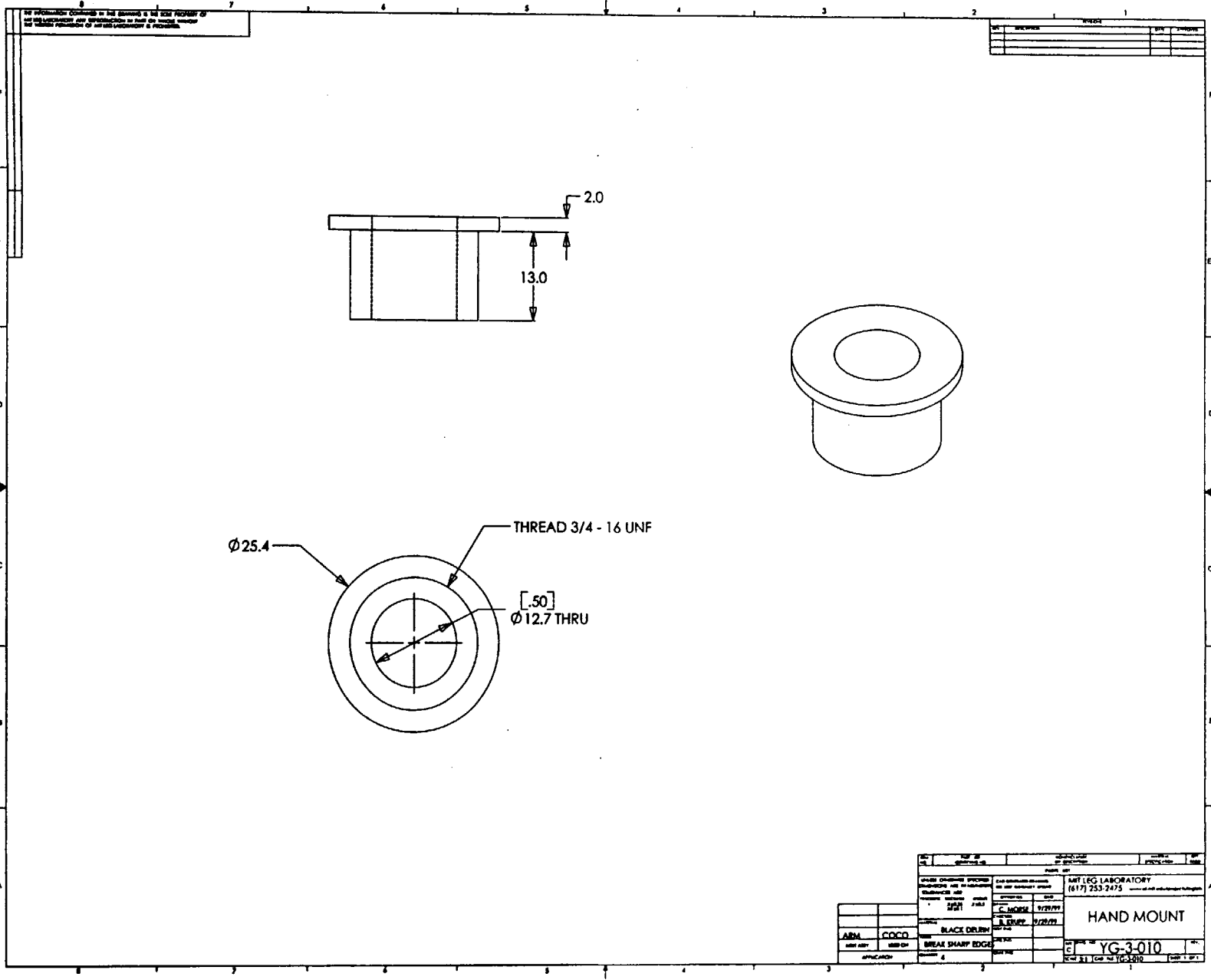
ALL DIMENSIONS EXCEPT IN THE DENOMINATOR OF THE FRACTION OF AN INCH SHALL BE IN DECIMALS OF AN INCH. DIMENSIONS SHALL BE TO UNLESS OTHERWISE SPECIFIED.

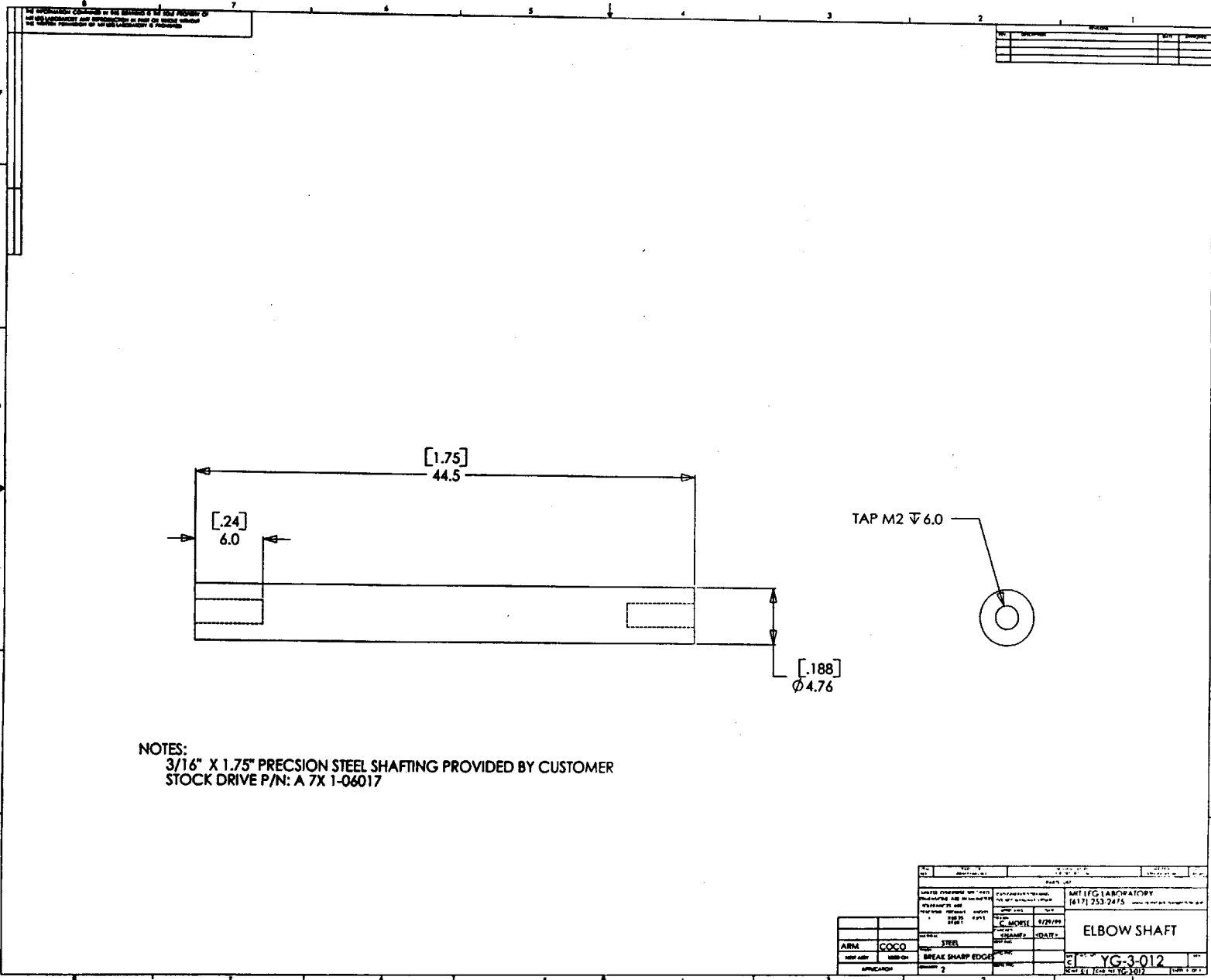
NO.	REVISION	DATE	BY	CHKD



NOTES:
BREAK SHARP EDGES

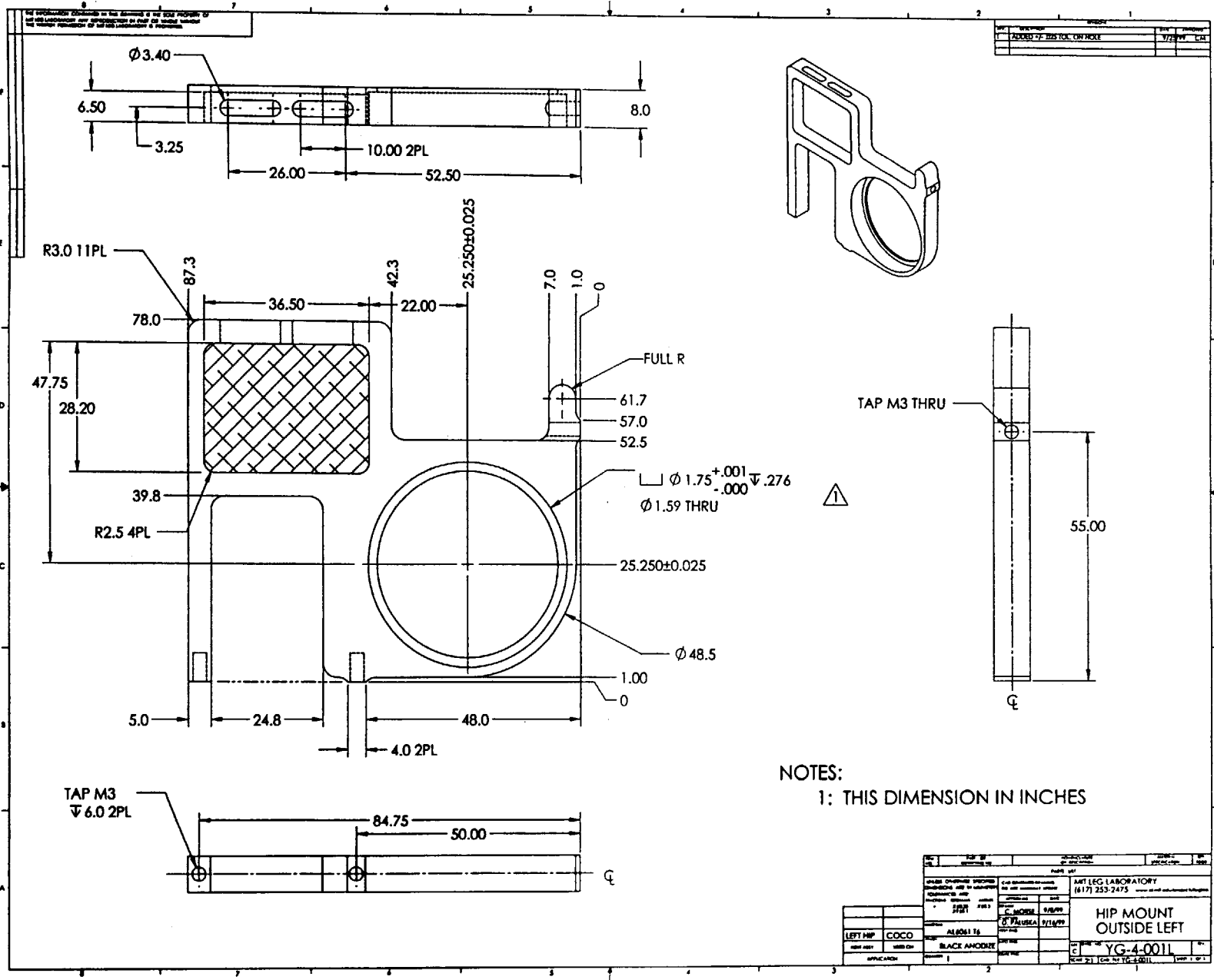
DATE	BY	CHKD	APP'D	REV	DATE	BY	CHKD	APP'D	REV
PART NAME ELBOW CLAMP		PART NUMBER YG-3-007		QUANTITY 1		UNIT EA		DRAWN BY COCO	
MATERIAL AL 6061 T6		FINISH BLACK ANODIZE		DATE 1/28/99		CHECKED BY 		DATE 	
MANUFACTURER 		SOURCE 		QUANTITY 		UNIT 		DATE 	





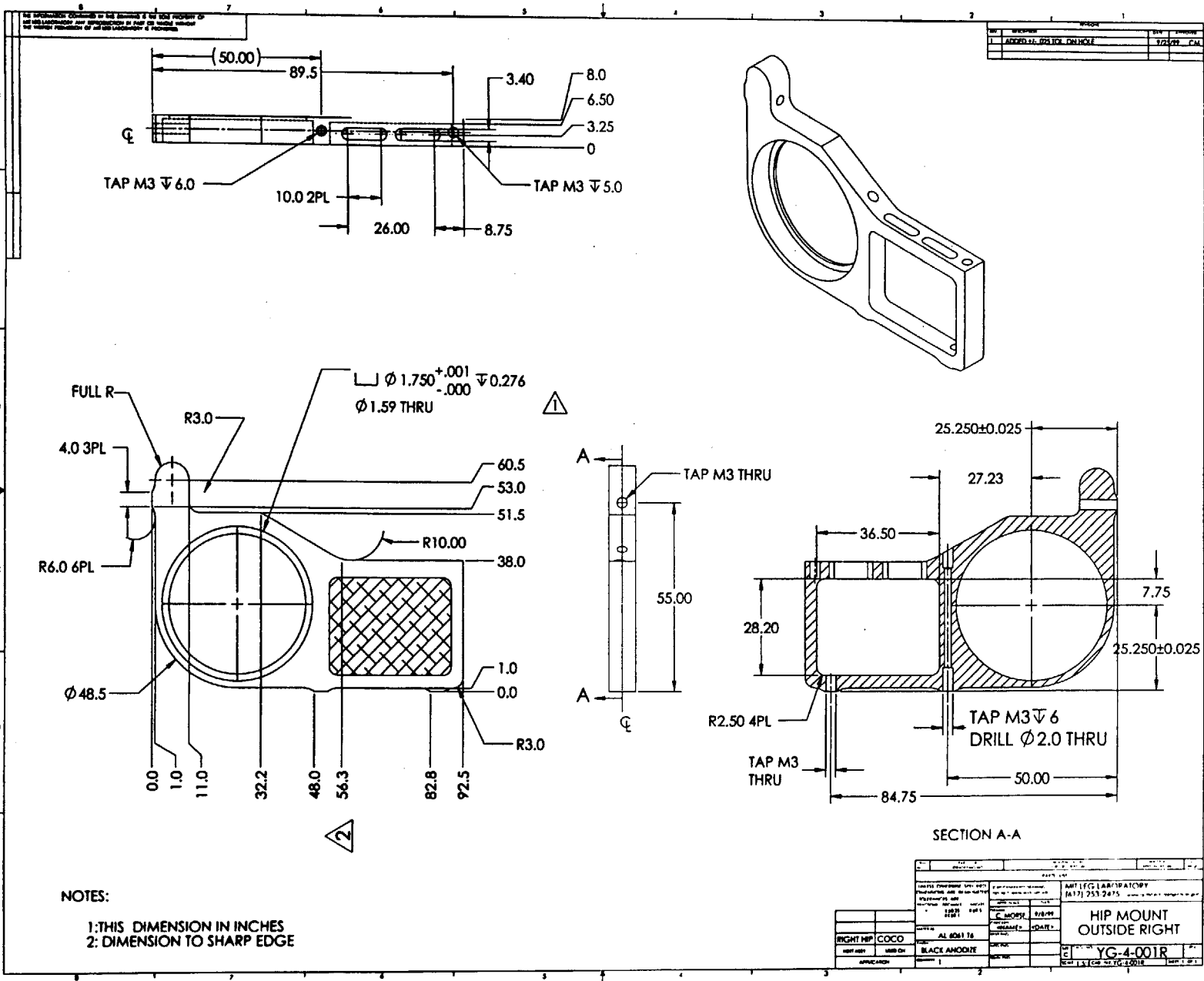
NOTES:
3/16" X 1.75" PRECISION STEEL SHAFTING PROVIDED BY CUSTOMER
STOCK DRIVE P/N: A 7X 1-06017

MILIFG LABORATORY (617) 253-2475	
ELBOW SHAFT	
DATE: 8/29/99	BY: C. MOSE
CHKD: []	DATE: []
ARM: COCO	MATERIAL: STEEL
FINISH: []	TREATMENT: []
APPROVAL: []	REVISION: 2
PART NO: YG-3-012	



NOTES:
1: THIS DIMENSION IN INCHES

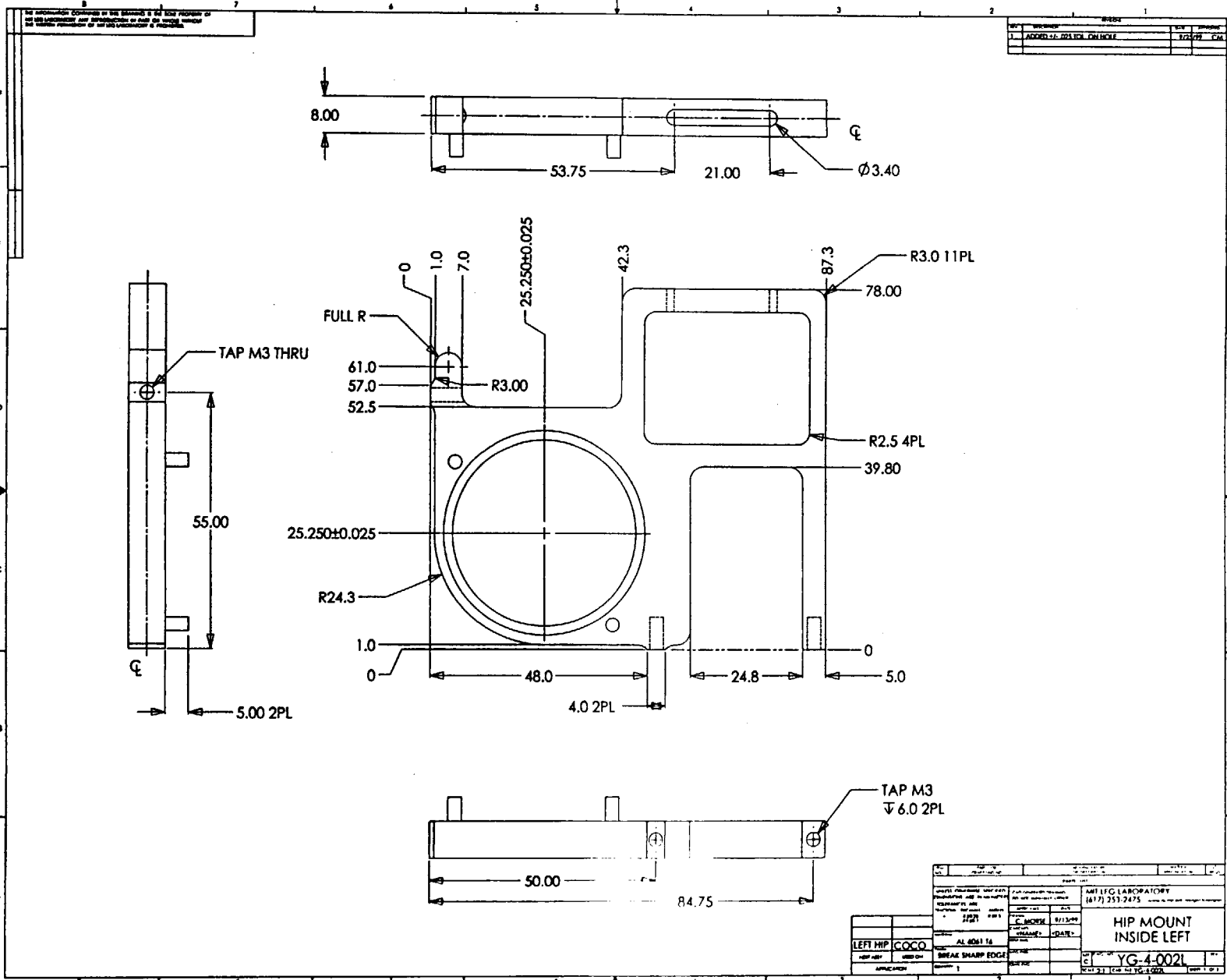
TITLE: HIP MOUNT PART NO: YG-4001L		DATE: 11/11/11 DRAWN BY: J. MOORE	
CHECKED BY: J. MOORE APPROVED BY: J. MOORE		MATERIAL: AL6061 T6 FINISH: BLACK ANODIZE	
LEFT HIP COCO		RIGHT HIP COCO	
APPLICATION:		PART NO: YG-4001L	



REV	DESCRIPTION	DATE	BY	CHKD
1	APPROX. 1.025 X 1.025 ON HOLE	12/2/99	CAK	

NOTES:
 1: THIS DIMENSION IN INCHES
 2: DIMENSION TO SHARP EDGE

RIGHT HIP COCO AL 6061 T6 BLACK ANODITE	AMTFC LABORATORY 1617 251 2475 HIP MOUNT OUTSIDE RIGHT YG-4-001R
---	--



REV	DESCRIPTION	DATE
1	ADDED 1/2" DIST. ON HOLE	12/22/99

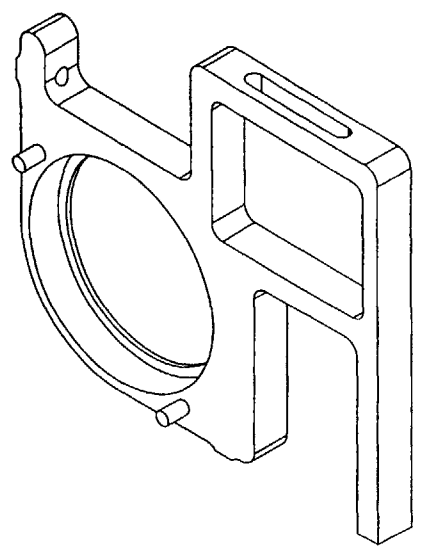
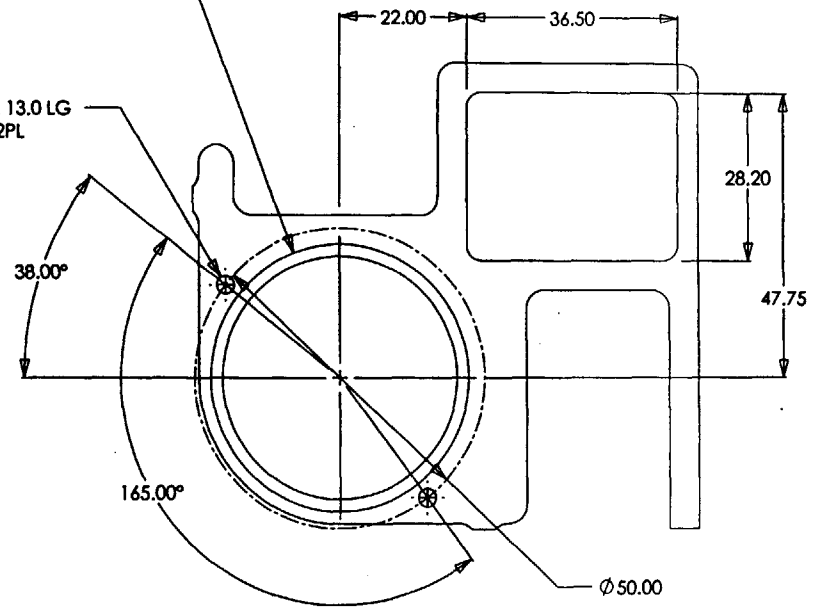
PART NAME: HIP MOUNT INSIDE LEFT PART NUMBER: YG-4-002L MANUFACTURER: ALCO		DATE: 12/22/99 DRAWN BY: [blank] CHECKED BY: [blank]
LEFT HIP RIGHT HIP APPLICATION: [blank]	COCO BREAK SHARP EDGE FINISH: [blank]	HIP MOUNT INSIDE LEFT YG-4-002L YG-4-002L

ALL DIMENSIONS CONTAINED IN THE DRAWING IS THE EXACT POSITION OF
 AN INSTRUMENT AND DIMENSIONS AS SHOWN ON THIS DRAWING UNLESS
 OTHERWISE SPECIFIED BY ANOTHER DIMENSION OR NOTE.

REV	DESCRIPTION	DATE	BY

⚠ $\perp \phi 1.750^{+.001}_{-.000} \nabla .276$
 $\phi 1.59$ THRU

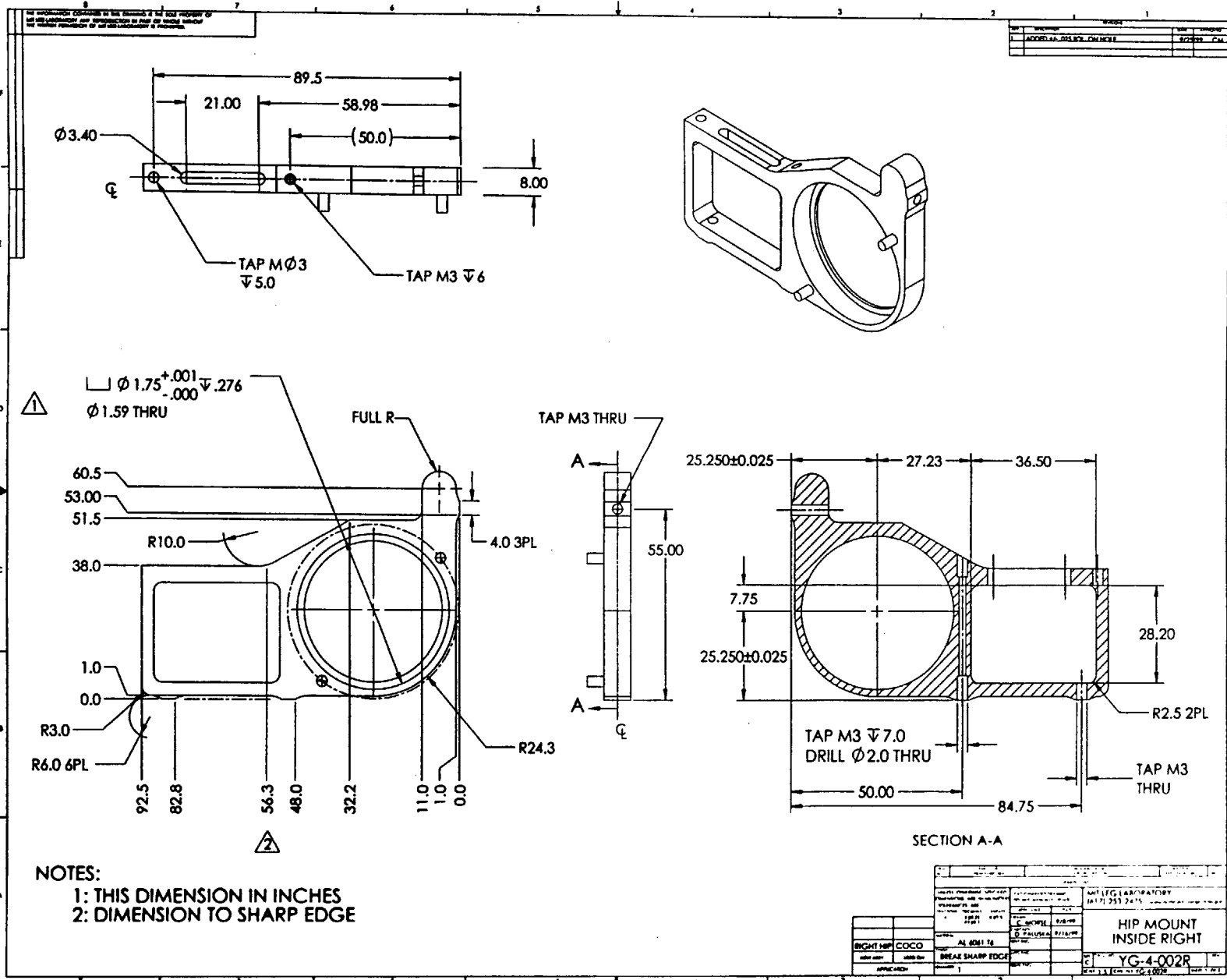
INSTALL $\phi 3.00 \times 13.0$ LG
 SS DOWEL PIN 2PL



NOTES:
 1: THIS DIMENSION IN INCHES

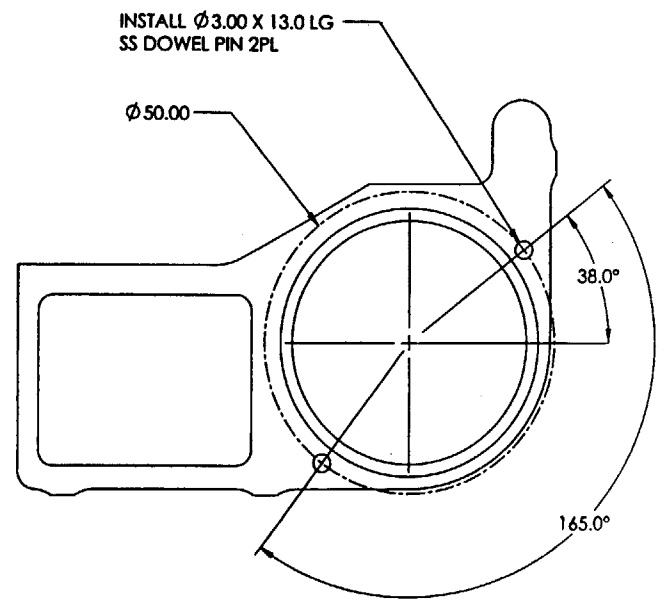
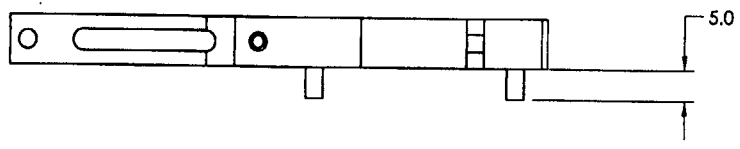
LEFT HIP COCO		AL 4041 TA		C. MORSE 9/13/09		D. PALUSKA 9/18/09		MET LEG LABORATORY (617) 253-2475	
BREAK SHARP EDGES				YG-4-002L		REV 51		REV 51	

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 WITHOUT THE WRITTEN PERMISSION OF THE LABORATORY'S PROPERTY.

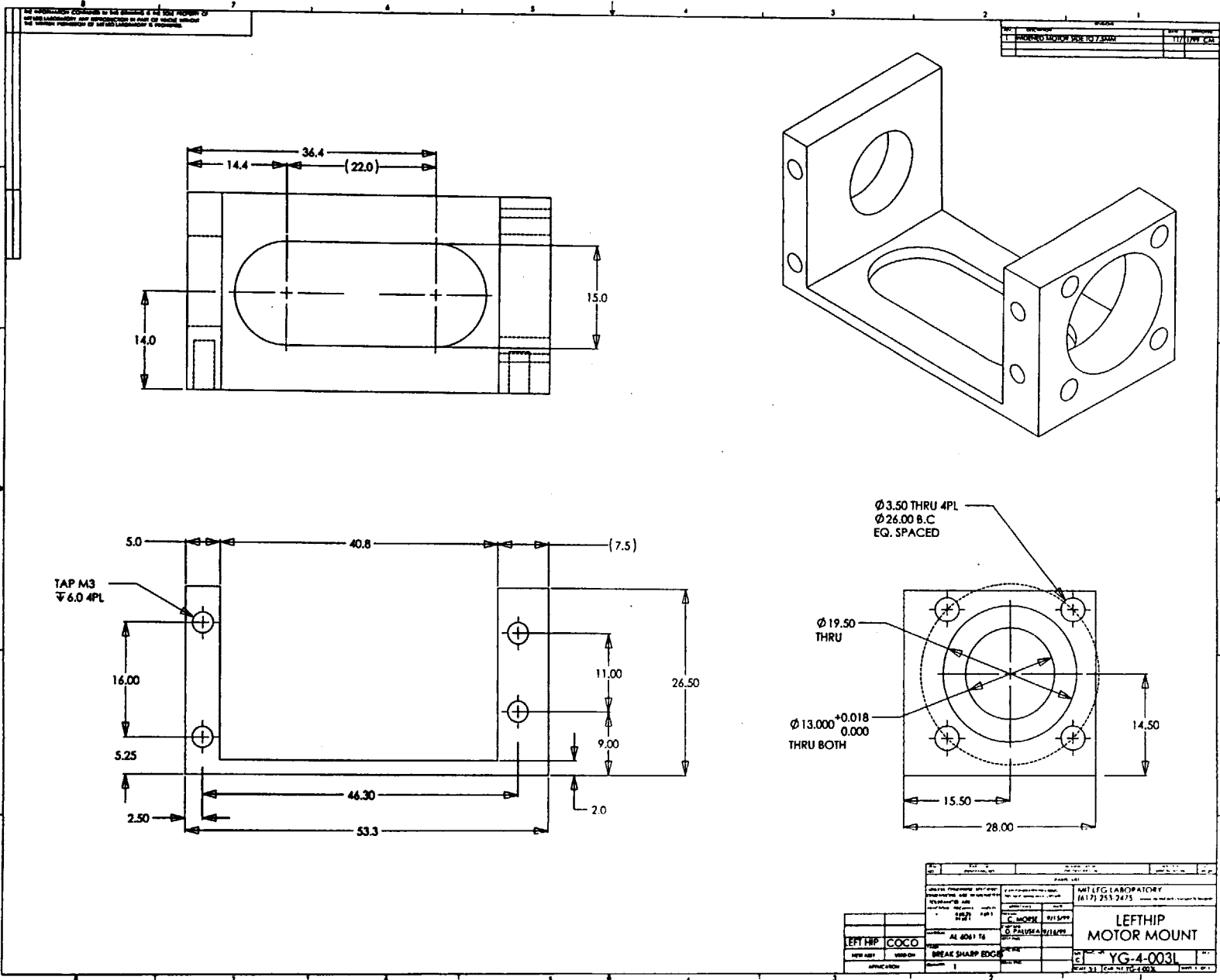
DATE	BY	APPROVED



DATE	BY	APPROVED

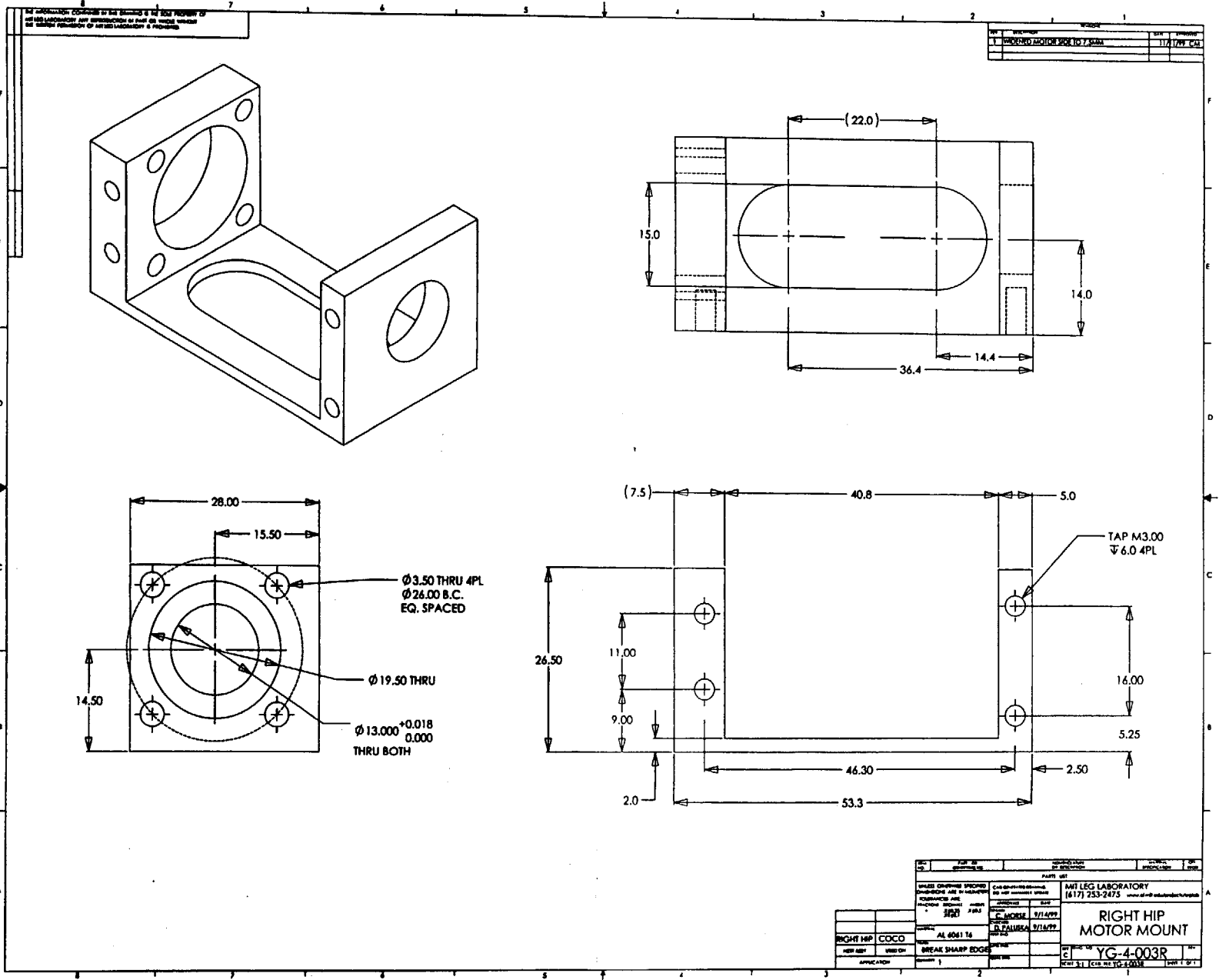
RIGHT HIP	COCO	AL 8061 16	BREAK SHARP EDGE

MILITARY CHINA LABORATORY (617) 233-2475	HIP MOUNT INSIDE RIGHT YG-4-002R
--	--



REV	DESCRIPTION	DATE	BY
1	WORKED DRAWING MADE TO 7.5MM	11/11/77	YFW/424

LEFT HIP COCO		AL 4061 TA		LEFT LEG LABORATORY (617) 253 2475	
BROKE SHARP EDGES		C. MOORE		LEFT HIP MOTOR MOUNT	
YG-4-003L					

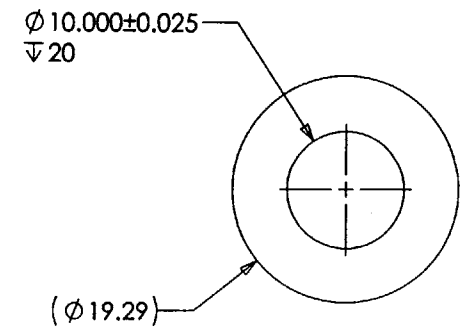
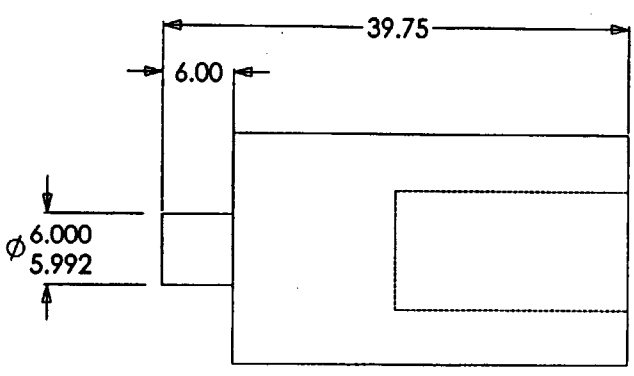


PART NO.		REV.		DATE		BY		CHKD.	
RIGHT HIP		COCO		AL 6061 T6		D. PALMISA		9/14/09	
MATERIAL		AL 6061 T6		FINISH		D. PALMISA		9/14/09	
TOLERANCES		BREAK SHARP EDGES		SURFACE		D. PALMISA		9/14/09	
APPROVAL		DATE		BY		CHKD.		DATE	

MATERIAL SPECIFICATIONS		AMT LEG LABORATORY	
MATERIAL SPECIFICATIONS		[617] 253-2475	
MATERIAL SPECIFICATIONS		www.amileg.com	
MATERIAL SPECIFICATIONS		RIGHT HIP MOTOR MOUNT	
MATERIAL SPECIFICATIONS		YG-4-003R	
MATERIAL SPECIFICATIONS		REV. 1.1	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED TO BE IN MILLIMETERS TO THE NEAREST 0.1mm UNLESS INDICATED OTHERWISE.
 ALL DIMENSIONS ARE TO BE TAKEN TO THE CENTER UNLESS OTHERWISE SPECIFIED.
 ALL DIMENSIONS ARE TO BE TAKEN TO THE CENTER UNLESS OTHERWISE SPECIFIED.

REV.	DESCRIPTION	DATE	BY



NOTES:

1: GT TIMING BELT PULLEY STOCK
 MTL: ALUMINUM; PITCH: 3mm P.D.:19.1mm;
 STOCK DRIVE PART #: A6A52M020GT15

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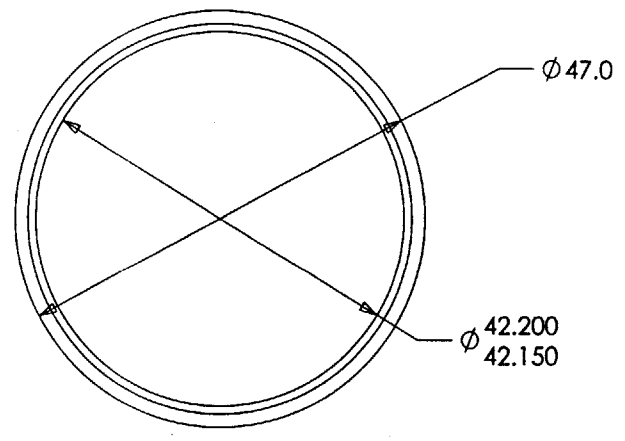
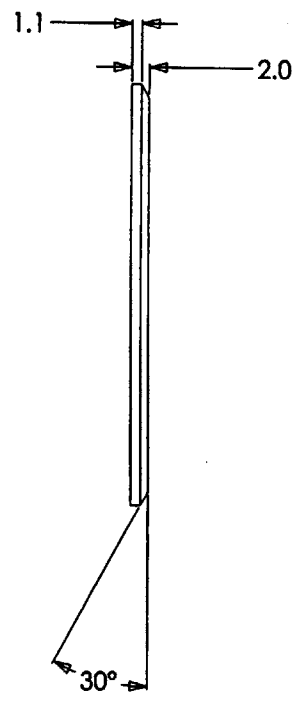
RIGHT HIP	LEFT HIP	NEW APP	APPROVAL
	COCO		

HIP DRIVE
 CAPSTAN

YG-4-004

THE DIMENSIONS SPECIFIED IN THE DRAWING IS THE BEST PRACTICE OF
 THE MANUFACTURER AND NOT NECESSARILY THE BEST PRACTICE OF
 THE USER. THE USER SHALL BE RESPONSIBLE FOR THE PROPER
 SELECTION OF THE DIMENSIONS OF THE MANUFACTURER.

REV	DESCRIPTION	DATE	BY



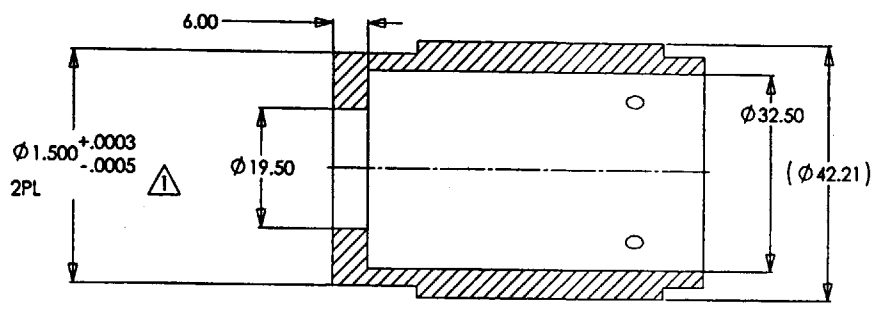
REV	DESCRIPTION	DATE	BY

RIGHT HSP			
LEFT HSP	COCO	AL 8041 76	
RIGHT HSP		BREAK SHARP EDGE	
APPLICATOR			

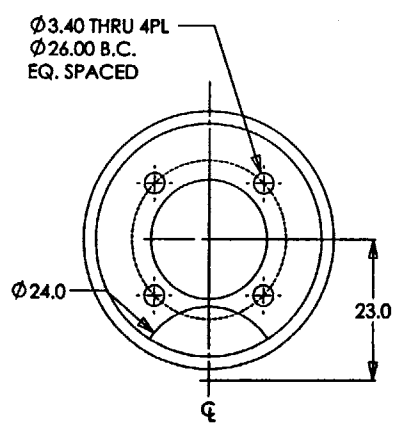
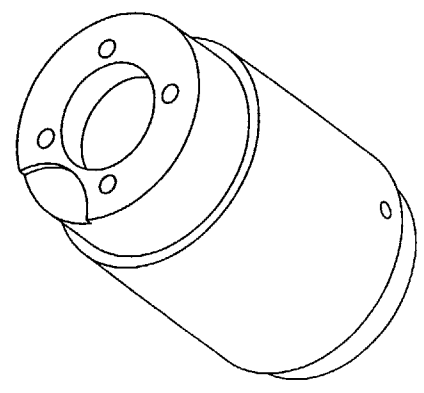
MIT LEG LABORATORY (617) 253-2475	PULLEY FLANGE
YG-4-005	

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES AND DECIMALS THEREOF.
 UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE TO BE MAINTAINED AS SHOWN ON DRAWING.
 UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE TO BE MAINTAINED AS SHOWN ON DRAWING.

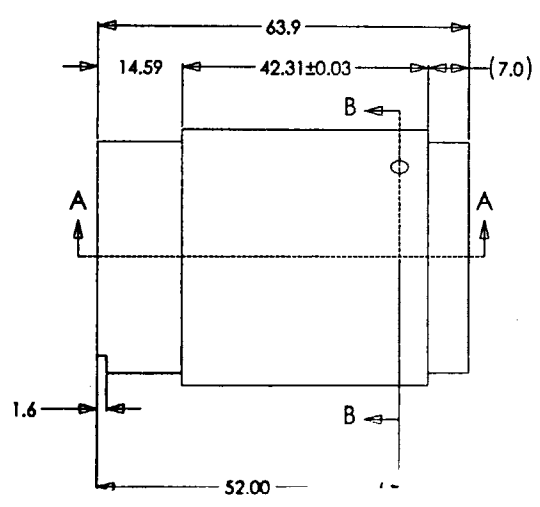
REV	DESCRIPTION	DATE	BY



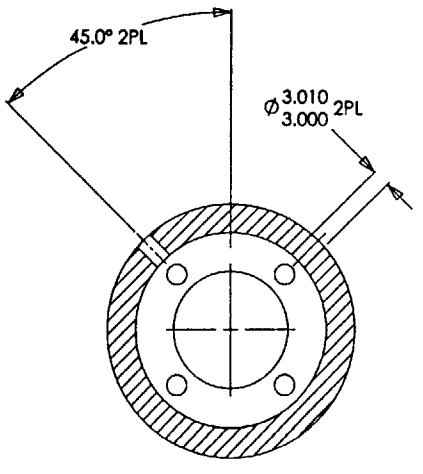
SECTION A-A



Ø 3.40 THRU 4PL
 Ø 26.00 B.C.
 EQ. SPACED



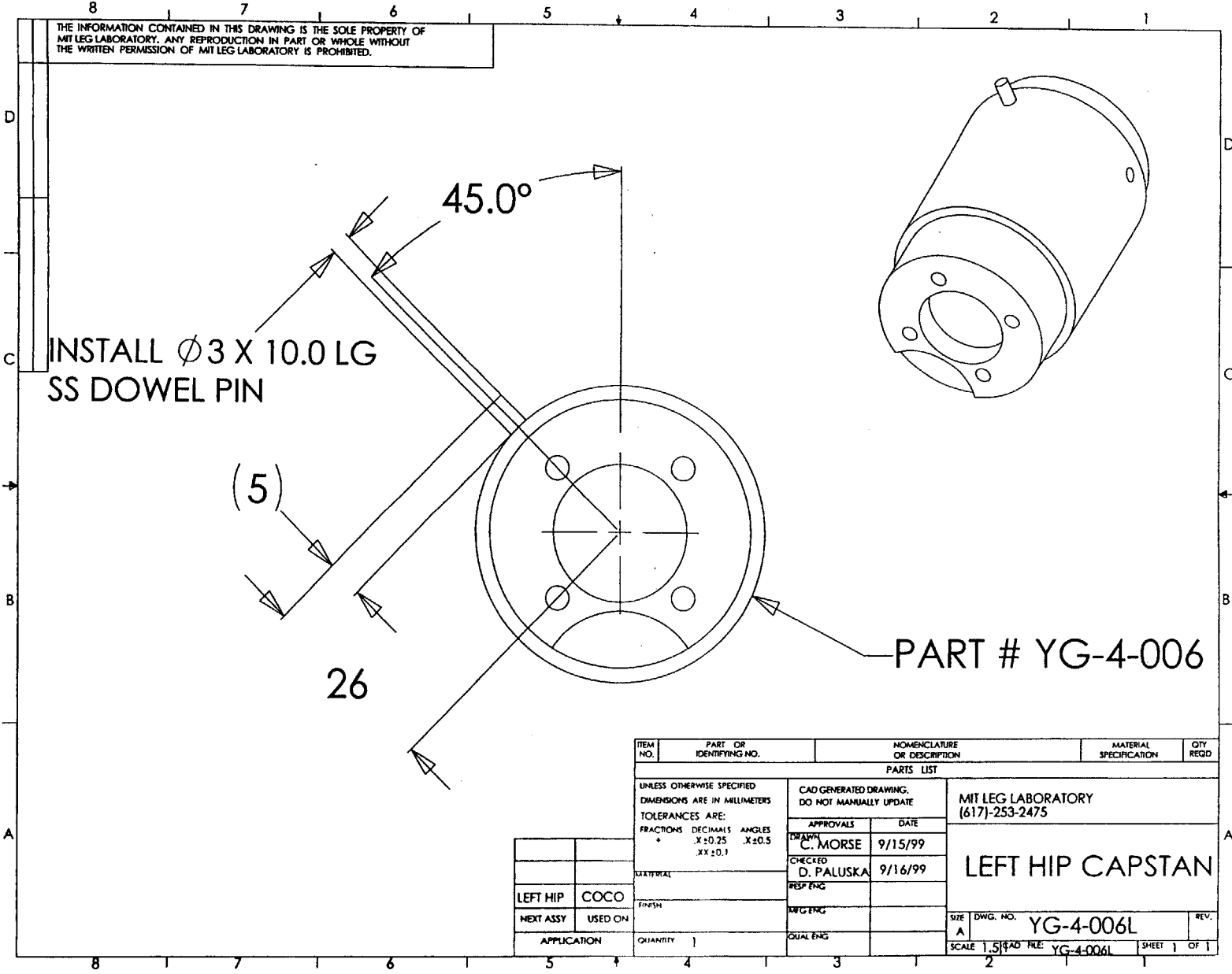
SECTION B-B



NOTES:
 1: DIMENSION IN INCHES
 2: GT TIMING BELT PULLEY STOCK
 MTL: ALUMINUM; PITCH: 3mm P.D.: 43mm;
 STOCK DRIVE PART #: A6A52M045GT20

YG-4-004R	COCO	BLACK ANODIZE	HIP CAPSTAN
YG-4-006	COCO	BLACK ANODIZE	YG-4-006

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INSTALL $\varnothing 3 \times 10.0$ LG
SS DOWEL PIN

45.0°

(5)

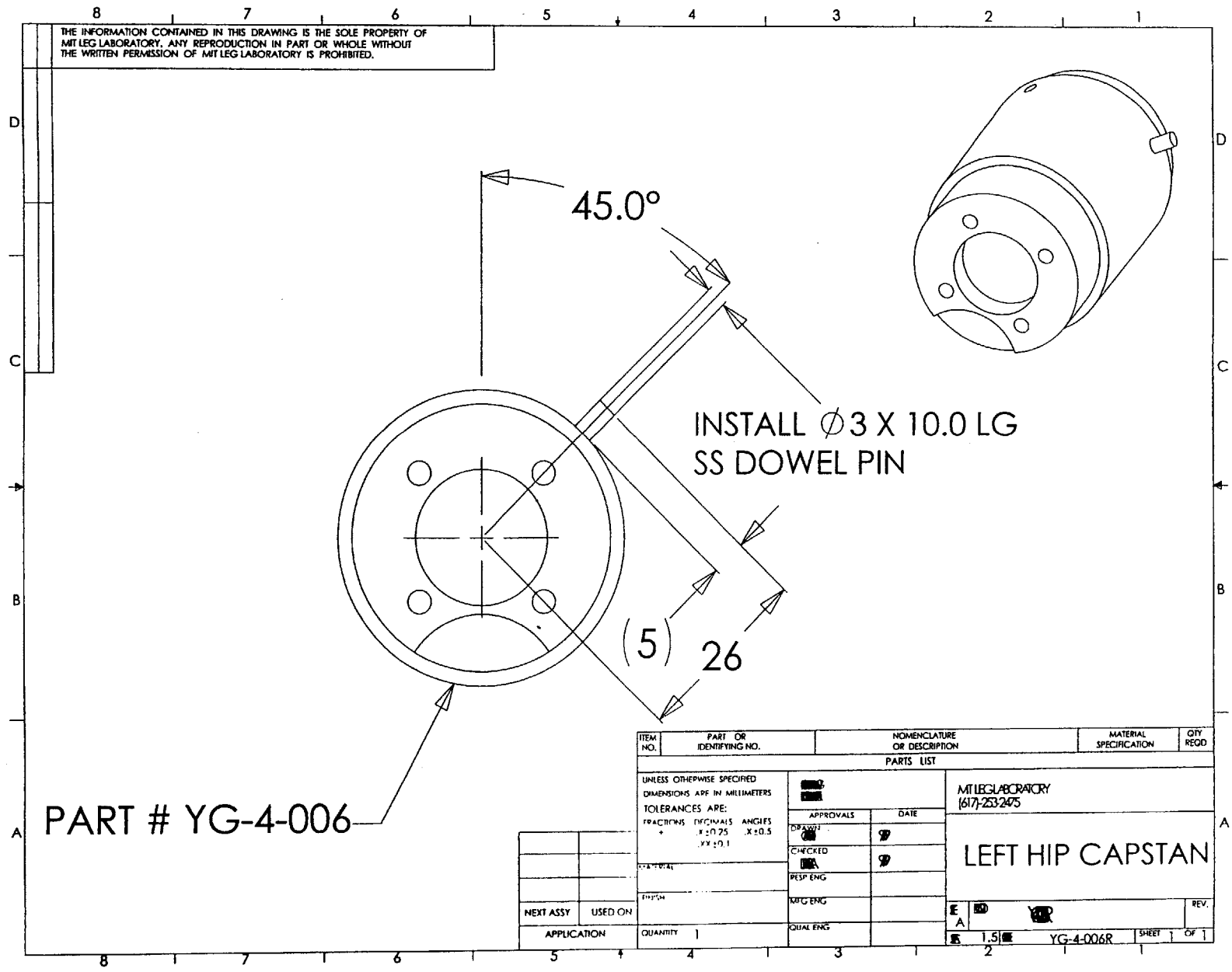
26

PART # YG-4-006

134

ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	QTY REQD
PARTS LIST				
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS TOLERANCES ARE: FRACTIONS DECIMALS ANGLES + X±0.25 X±0.5 XX±0.1		CAD GENERATED DRAWING. DO NOT MANUALLY UPDATE	MIT LEG LABORATORY (617)-253-2475	
APPROVALS		DATE	LEFT HIP CAPSTAN	
DRAWN C. MORSE		9/15/99		
CHECKED D. PALUSKA		9/16/99		
MATERIAL		RESP ENG	SIZE DWG. NO. YG-4-006L	
FINISH		DWG ENG	A	
APPLICATION		QUAL ENG	SCALE 1.5:1 (RAD FILE: YG-4-006L) SHEET 1 OF 1	
LEFT HIP	COCO			
NEXT ASSY	USED ON			
QUANTITY				

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PART # YG-4-006

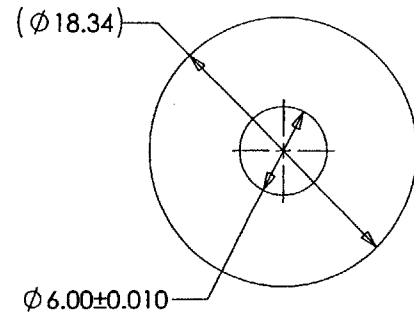
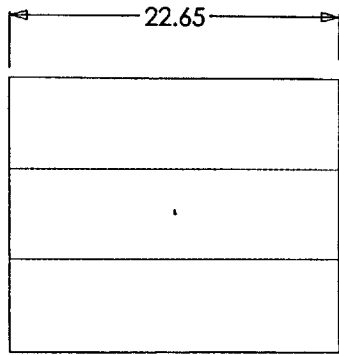
ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	QTY RECD
PARTS LIST				
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS		MIT LEG LABORATORY (617-253-2475)		
TOLERANCES ARE: FRACTIONS DECIMALS ANGLES + .025 .X±0.5 .XX±0.1		APPROVALS	DATE	
DRAWN		<input checked="" type="checkbox"/>	9	
CHECKED		<input checked="" type="checkbox"/>	9	
MAT'L		RESP' ENG		
FINISH		MFG ENG		
APPLICATION		QUAL ENG		
NEXT ASSY	USED ON	QUANTITY	REV.	
		1	E A	
			1.5	
			YG-4-006R	SHEET 1 OF 1

RIGHT HIP COCO

135

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REV	DESCRIPTION	DATE	BY



NOTES:

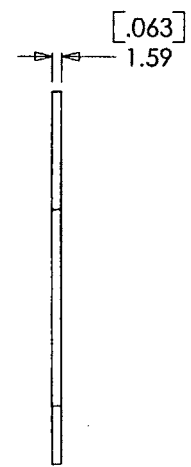
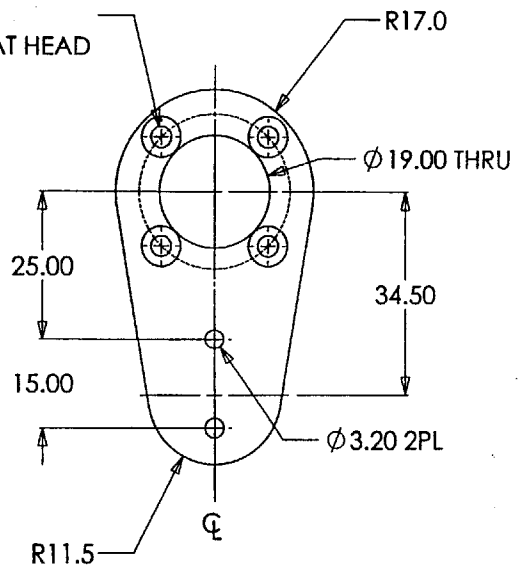
1: GT TIMING BELT PULLEY STOCK
 MTL: ALUMINUM; PITCH: 3MM; P.D.:19.1MM
 STOCK DRIVE PART #: A6A52M020GT15

MIT LEG LABORATORY		PART ID		PART NAME		DATE	
MIT LEG LABORATORY (617) 253-2475 www.mit.edu/leglab		PART ID		PART NAME		DATE	
DESIGN SPECIFICATIONS		MATERIAL SPECIFICATIONS		DATE		REV	
DESIGNER: [blank]		MATERIAL: ALUMINUM		DATE: 9/18/99		REV: 1	
CHECKER: [blank]		MATERIAL: ALUMINUM		DATE: 9/17/99		REV: 2	
APPROVER: [blank]		MATERIAL: ALUMINUM		DATE: 9/17/99		REV: 3	
LEG		COCO		BLACK ANODIZE		MIT LEG LAB YG-5-001	
NEXT ASST		ISSUED ON		DATE		REV 1 OF 1	
APPLICATION		REV 2		REV 3		REV 4	

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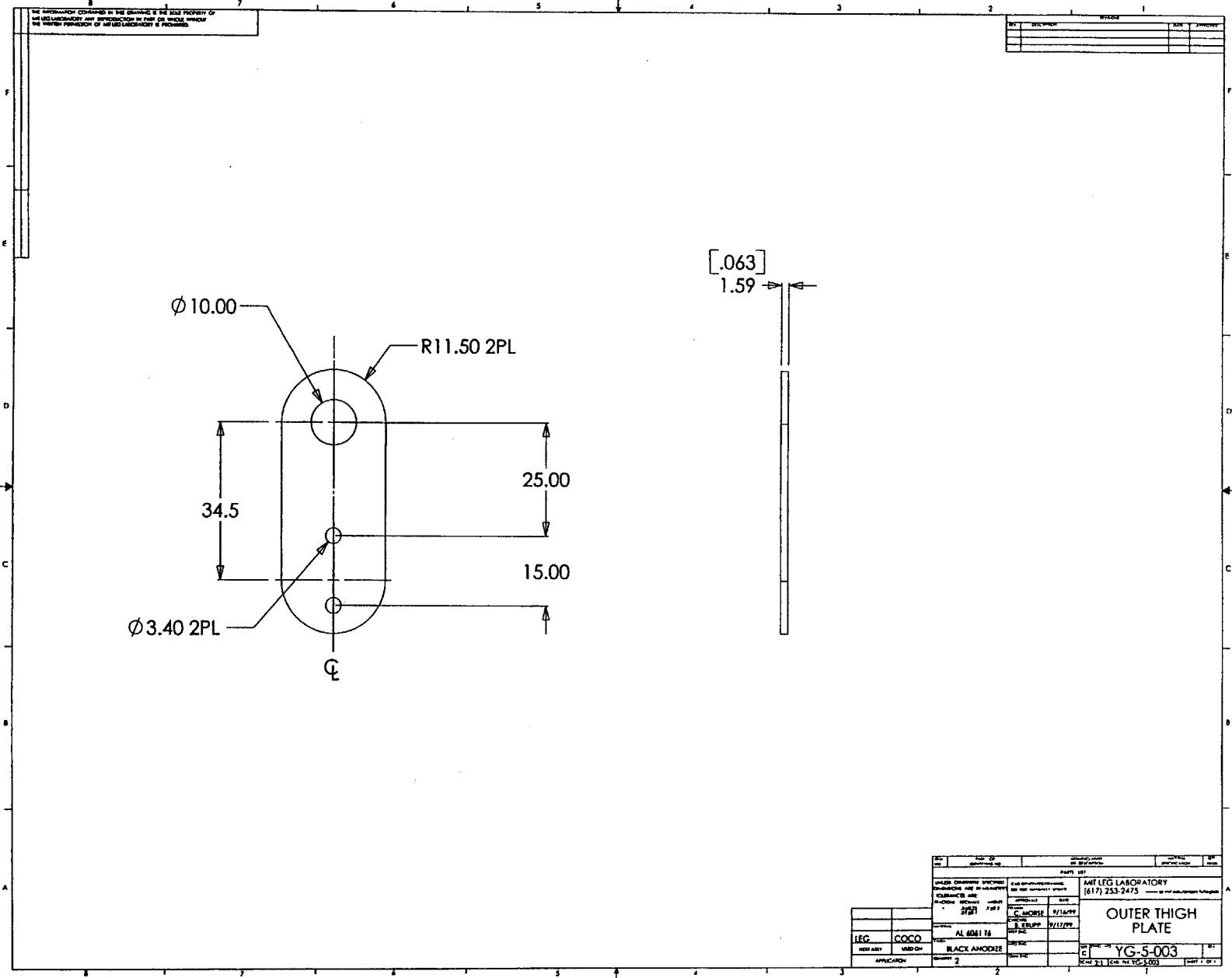
REV	DESCRIPTION	DATE	BY	CHKD

$\phi 3.20$ THRU 4PL
 ✓ FOR M3 FLAT HEAD
 $\phi 26.00$ B.C.
 EQ. SPACED



137

LEG		COCO	UNSD ON	BLACK ANODITE	APPROVAL	2
THIGH MAIN PLATE		YG-5-002		REV 2 16-3-002		



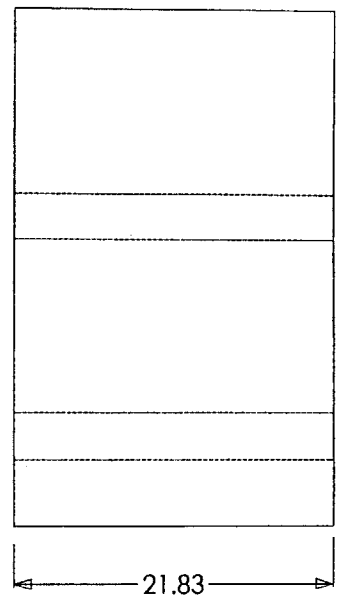
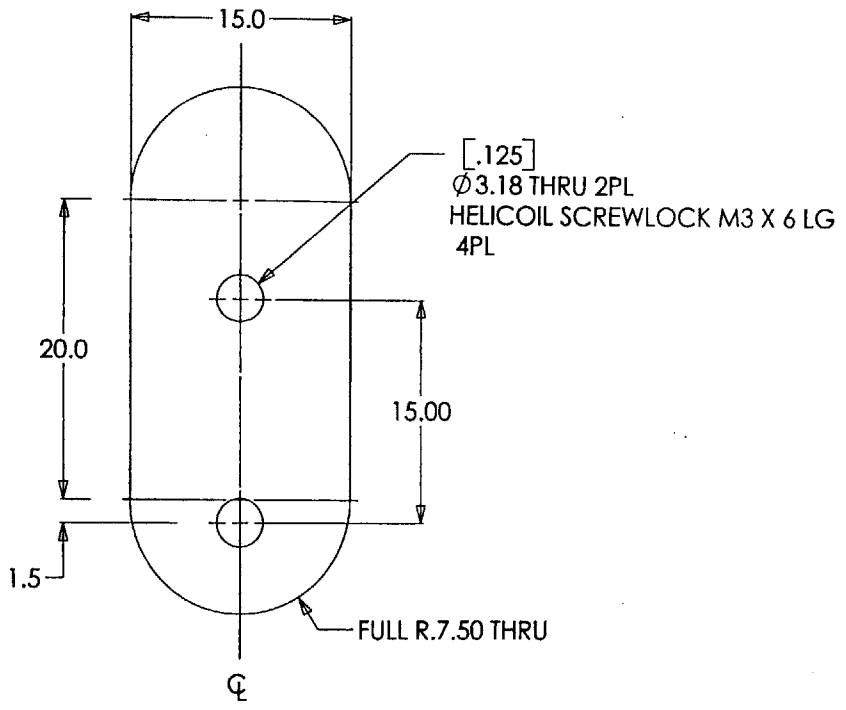
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NO.	REVISION	DATE	APPROVED

MIT LEG LABORATORY (617) 253-2475	
OUTER THIGH PLATE	
YG-5-003	
LEG: COCO MFG: MIT	AL 6061 T6 BLACK ANODIZE
QUANTITY: 2 PART NO: 2	DATE: 9/16/99 BY: 9/17/99

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 WITHOUT THE WRITTEN PERMISSION OF MIT LEG LABORATORY & PROGRAMS.

REV.	DESCRIPTION	DATE	BY



NOTES:
 1: HELICOIL PART # 4184-3CN060

REV.	DESCRIPTION	DATE	BY

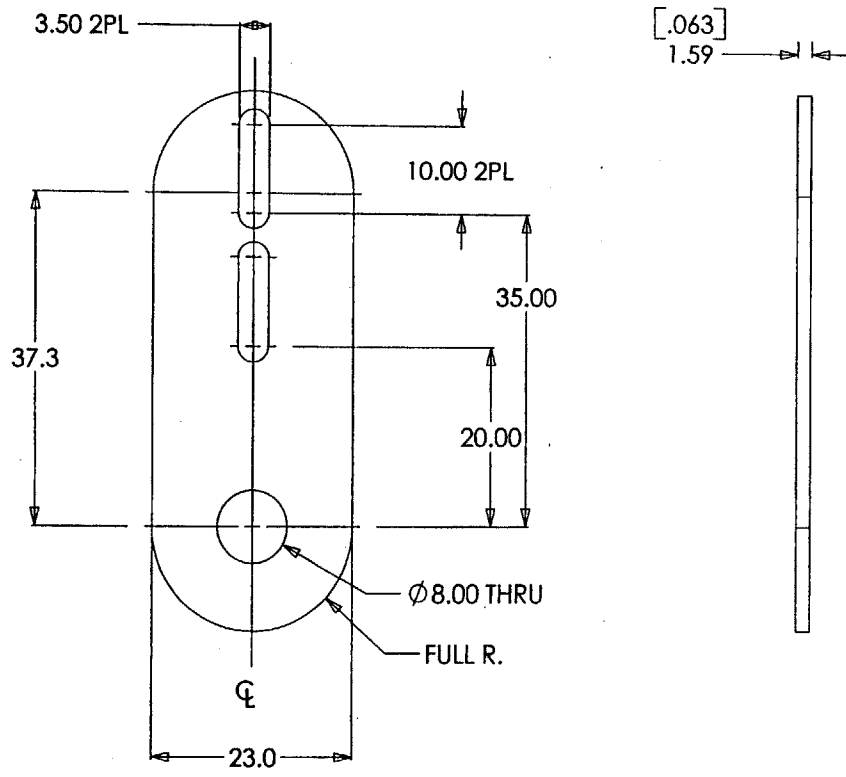
LEG	COCO	BLACK DELRIN
REF. ALL	INR. ON	BREAK SHARP EDGE
APPLICATOR	DATE	

MIT LEG LABORATORY	(617) 253-2475
THIGH SPACER	

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REV	DESCRIPTION	DATE	APPROVED

140

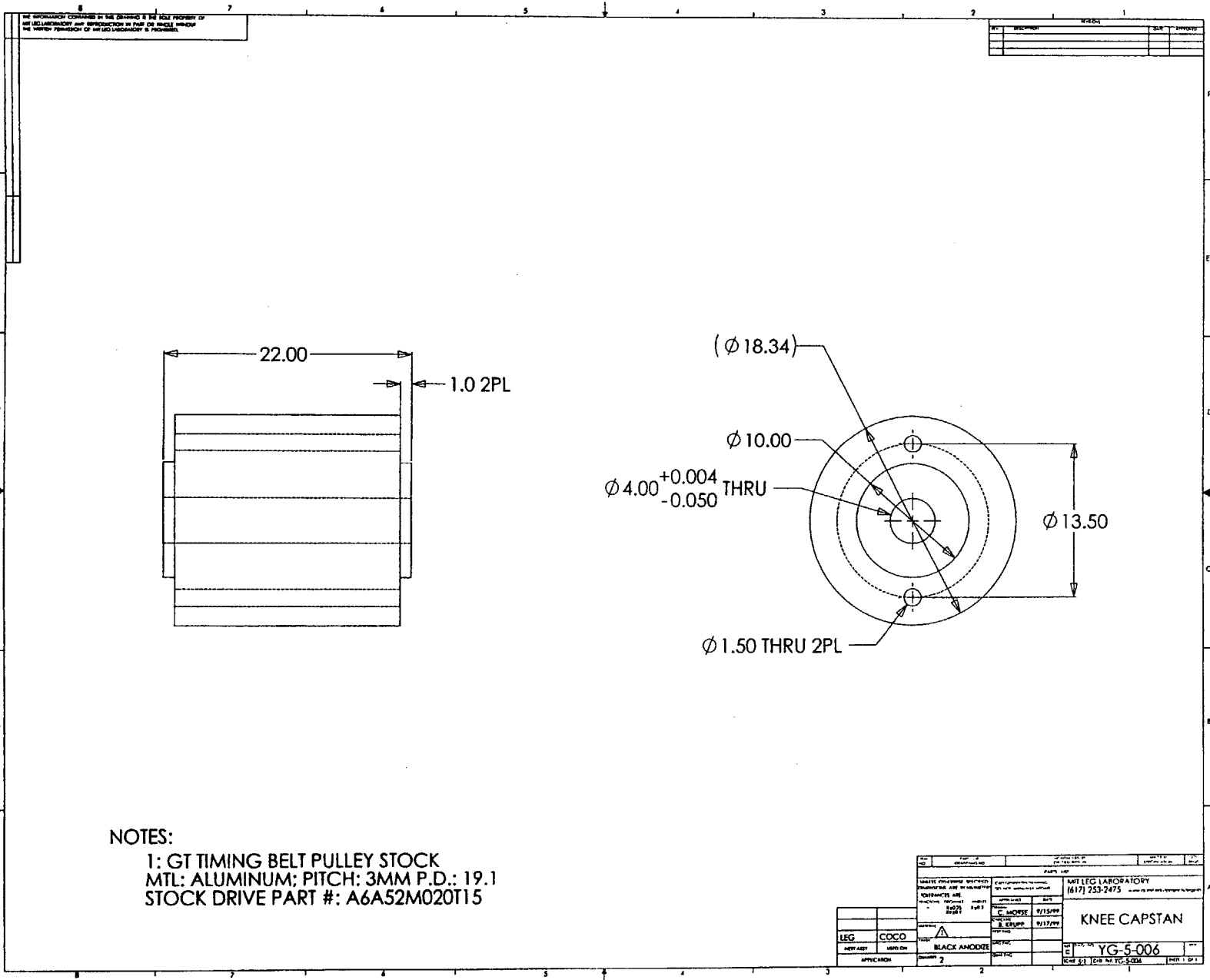


REV	DATE	DESCRIPTION	APPROVED

UNITS: DIMENSIONS SPECIFIED	DATE: 08/15/99	MET LEG LABORATORY
CONSTRUCTION: AS SHOWN	BY: J. ENY	(617) 253-2475
REVISIONS:	DATE:	
1. 08/15/99	08/15/99	
2. 08/15/99	08/15/99	
3. 08/15/99	08/15/99	
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LOWER THIGH

YG-5-005

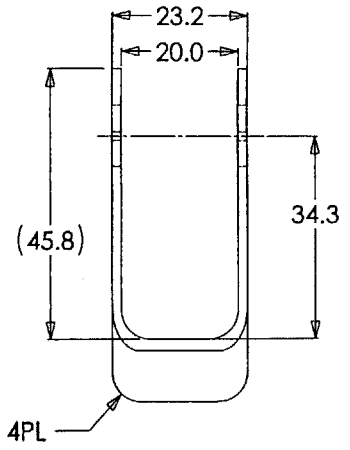
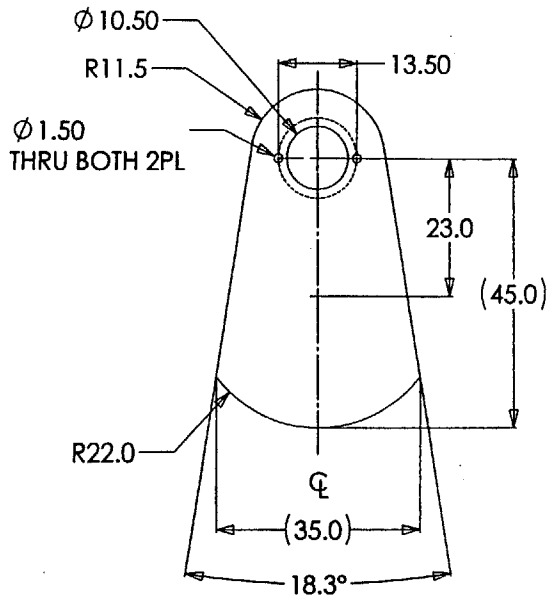
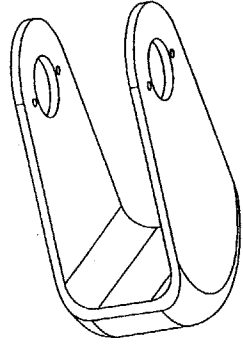
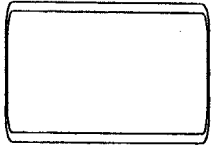


NOTES:
 1: GT TIMING BELT PULLEY STOCK
 MTL: ALUMINUM; PITCH: 3MM P.D.: 19.1
 STOCK DRIVE PART #: A6A52M020T15

LEG		COCO		BLACK ANODIZE		2	
APPROVAL		DATE		DATE		DATE	
C. MOORE		9/25/99		B. EQUIP		9/27/99	
MIL LEG LABORATORY				16171 253-2475			
KNEE CAPSTAN				YG-5-006			

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REV.	DESCRIPTION	DATE	BY	CHKD.



142

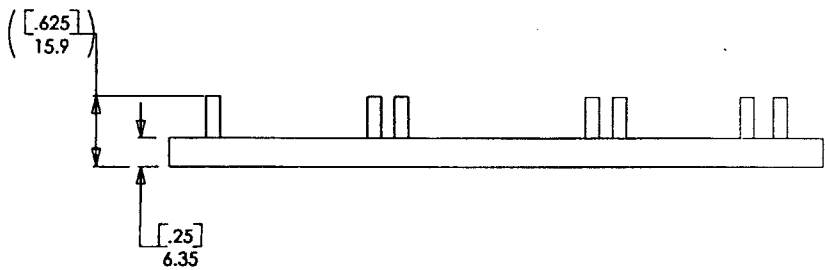
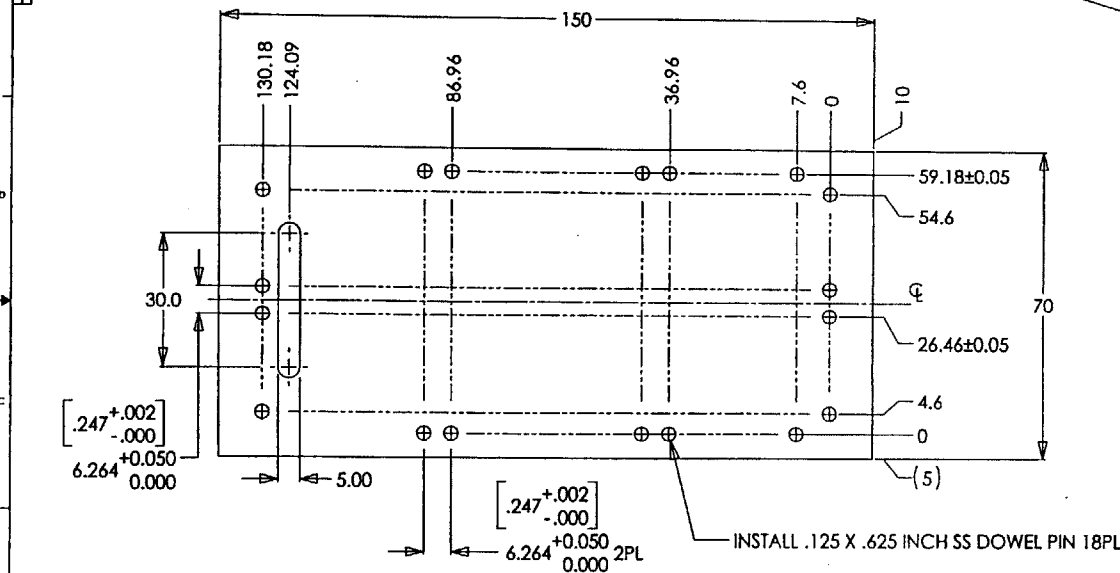
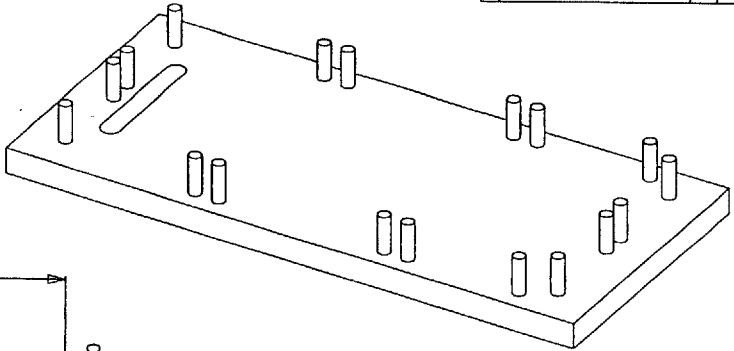
REV.	DESCRIPTION	DATE	BY	CHKD.

AMT LEG LABORATORY (617) 253-2475 1000 WASHINGTON ST BOSTON, MA 02111	PARTS LIST DATE: 11/15/99 BY: J. SMYTH CHECKED: 11/17/99	FOOT YG-5-007 REV. C SCALE: 1:1 (SEE FIG. 10-1002)
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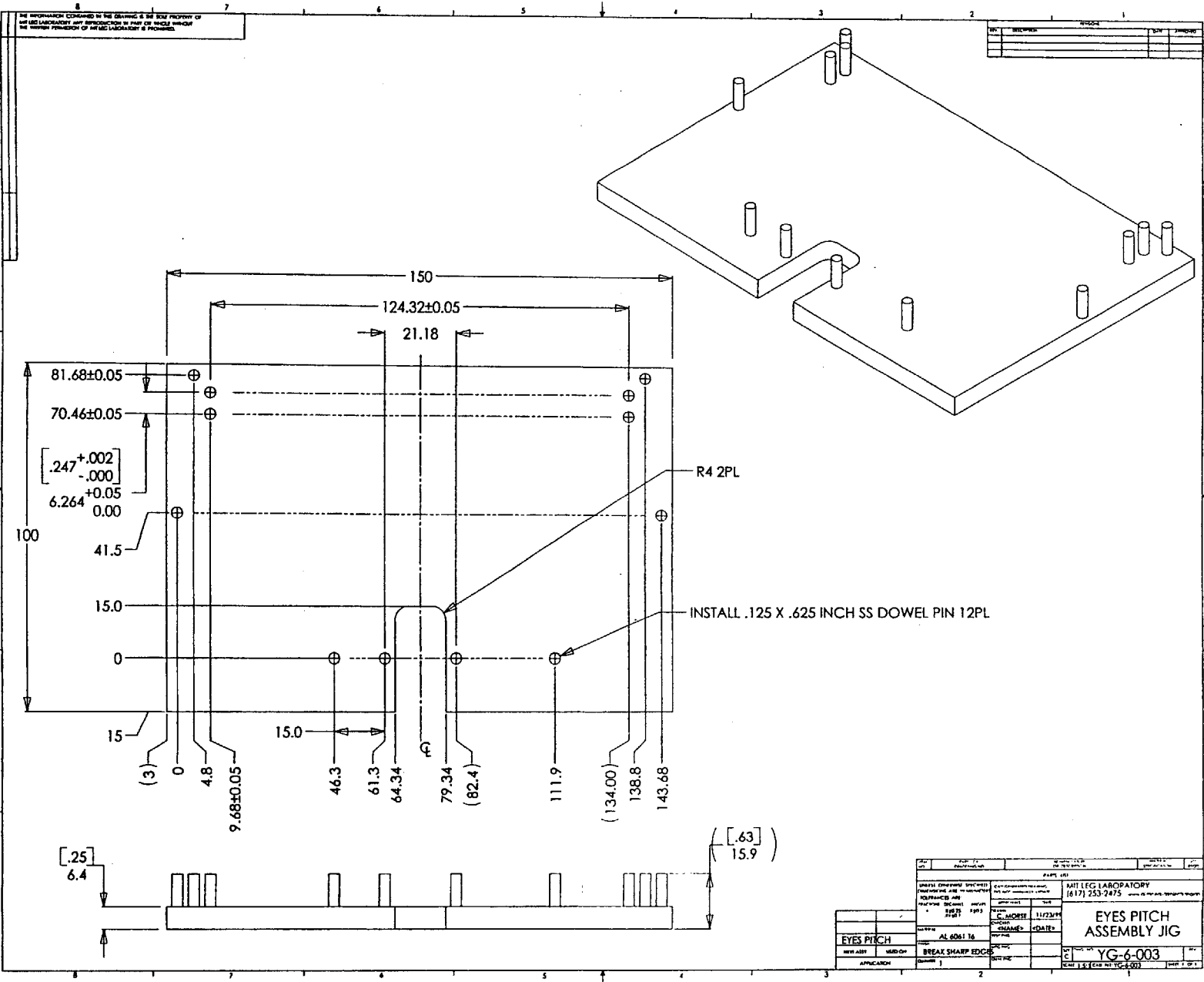
LEG	COCO	AL 6061 T4	DATE	
MATERIAL	USED ON	BLACK ANODIZED	DATE	
APPROVAL				

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NO.	DESCRIPTION	DATE	BY



PART NO.		REVISED		DATE		BY	
NITELAB LABORATORY				NITELAB LABORATORY			
(617) 253-2475				(617) 253-2475			
EYES MOUNT				EYES MOUNT ASSEMBLY JIG			



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REV.	DESCRIPTION	DATE	BY

145

EYES PITCH		AL 6061 T6		11/23/94		C. MORSE		YG-6-003	
BREAK SHARP EDGES								1 of 1	