Design of a Second Generation Articulated Leg for the GAVIA Underwater Vehicle

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SUMMARY

This report details the design of a folding leg mechanism used by the Gavia for pipeline inspection. There is a brief introduction to the Gavia and the previous leg system. A list of requirements and challenges is then presented. The theoretical design is given and described. The encoder system and wheel choice is then explained. A force analysis is completed and a virtual model of the leg, created in MatLAB, is displayed. Finally, a conclusion is given with suggestions for future work.

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DESIGN OF A SECOND GENERATION ARTICULATED LEG FOR THE GAVIA UNDERWATER VEHICLE

SR-2006-13

Steven Williams

April 2006

Table of Contents

1.0 Introduction 1

2.0 Design Challenges 3

3.0 Leg Design 4
- 3.1 Link Design 4
- 3.2 Hinge Design 5
- 3.3 Joints and Connections 6
- 3.4 Slider Mechanism 6

4.0 Wheel and Encoder 8

5.0 Force Analysis 10
- 5.1 Bending Moment Calculations 10
- 5.2 Force Analysis Calculations 12

6.0 MATLAB® Code and Analysis 15
- 6.1 Force Analysis 15
- 6.2 Virtual Reality / Simulink® Model of Articulated Leg 16

7.0 Conclusions and Future Work 21

8.0 References 22

Appendix A – CAD Drawings

Appendix B - MATLAB® Code

List of Figures

Figure 1: Gavia AUV in modular sections 1

Figure 2: Leg development in "GeoGebra" 4

Figure 3: Leg with unbalanced forces 5

Figure 4: Leg with fork that distributes force evenly 5

Figure 5: Bushing for wheel that will allow it to rotate 6

Figure 6: Leg with attached sliders and motor 7

Figure 7: Top linkage with encoder (left), Cross section of wheel and encoder (right) 8

Figure 8: Bending moment diagram using a bar supported on both ends 10

Figure 9: Geogebra model of leg and the forces at each joint 13

Figure 10: Slider level with the base (left), slider dropped down 2.5 cm (right) 14

Figure 11: Force analysis of leg as it folds down 15

Figure 12: Leg development in 'V-Realm' 17

Figure 13: System of legs to be placed on Gavia 18

Figure 14: Simulink® model of Gavia 19

Figure 15: Gavia with legs extended 20

Figure 16: Gavia with legs folded 20

List of Abbreviations and Symbols

AUV………………………….. Autonomous Underwater Vehicle
ABS…………………………Acrylonitrile Butadiene Styrene
CAD………………………...Computer Aided Design
Li……………………………Lithium
NRC-IOT…………………...National Research Council Institute for Ocean Technology
PVC…………………………Polyvinyl Chloride
VRML………………………Virtual Reality Machine Language

1.0 Introduction

The Gavia is an AUV (autonomous underwater vehicle) designed by Hafmynd Ltd., which is located in Iceland. This AUV has the ability to accept a very large variety of payloads, which extend the vehicle along its central communication bus.

It uses a variety of modules to move and navigate in the water. These modules include the nosepiece, Li-ion battery module, communications system, and a propulsion and steering module.

As the Gavia is modular, custom payloads can be created for an endless number of applications.

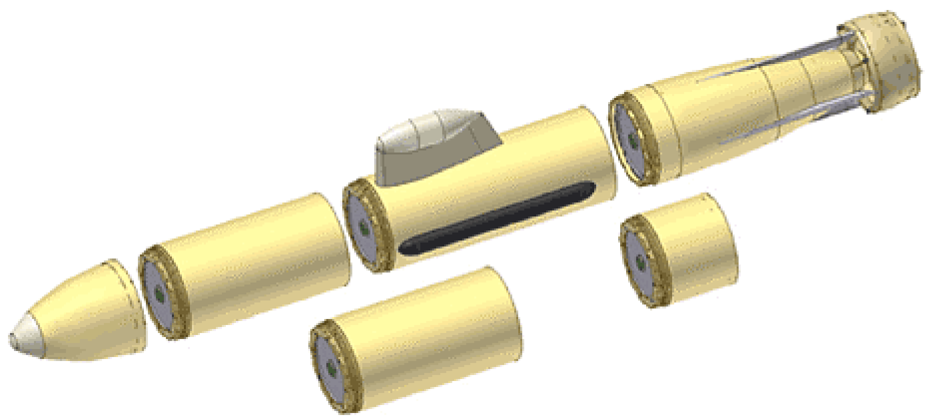

Figure 1: Gavia AUV in modular sections

The Institute for Ocean Technology and the Institute for Research in Construction are interested in using the Gavia to inspect the insides of freshwater pipelines. As the Gavia can be modified with ease, it provides the perfect test bed for new sensor and navigation systems as it applies to profiling the inside of a pipe.

It has been decided to profile the pipe using a multibeam sonar fitted to the outside of the vehicle. A system of legs will be used in order to hold the Gavia around the center of the pipe to allow for a useable sonar image.

A first generation of legs have been developed which can only provide force according to their spring coefficient. They are one solid piece made from PVC and they are mounted onto a ring that slips over the Gavia's hull.

A second generation of legs must be designed that can fold into the vehicle and apply a variable force on the walls of the pipe. As well, these legs will be outfitted with an encoder system that will allow the user to monitor the AUV's position more closely.

2.0 Design Challenges

There are a number of challenges involved in designing the legs for the Gavia. Many of them relate to the physical space we have to work with.

The legs must be able to fold into the vehicle allowing it to be placed into the pipe. As well, they must be able to support the vehicle's weight on land, as ideally the Gavia can roll on its folded legs.

The legs must be able to extend a minimum of 40 cm and support a 100 Newton force (10 times safety factor).

The wheels need to be modified to include an encoder ring and proper circuitry.

A linear slide must be found to allow the actuator to extend the leg. The slide must also be small enough to fit under the leg mechanism when it is folded down.

Tolerances for the wheel must be very exact to allow for very little lateral travel. In this way, the distance between the encoder and recorder will be less than 2 mm.

All electronics must be waterproofed without adding much to the weight or size of the system.

3.0 Leg Design

3.1 Link Design

The second-generation leg had to be able to extend to a height of 45 cm while fold into a height of about 5 cm. The required link lengths were developed using the software "GeoGebra", developed by Markus Hohenwarter. Using the dimensions developed, a model leg was developed and built using PVC.

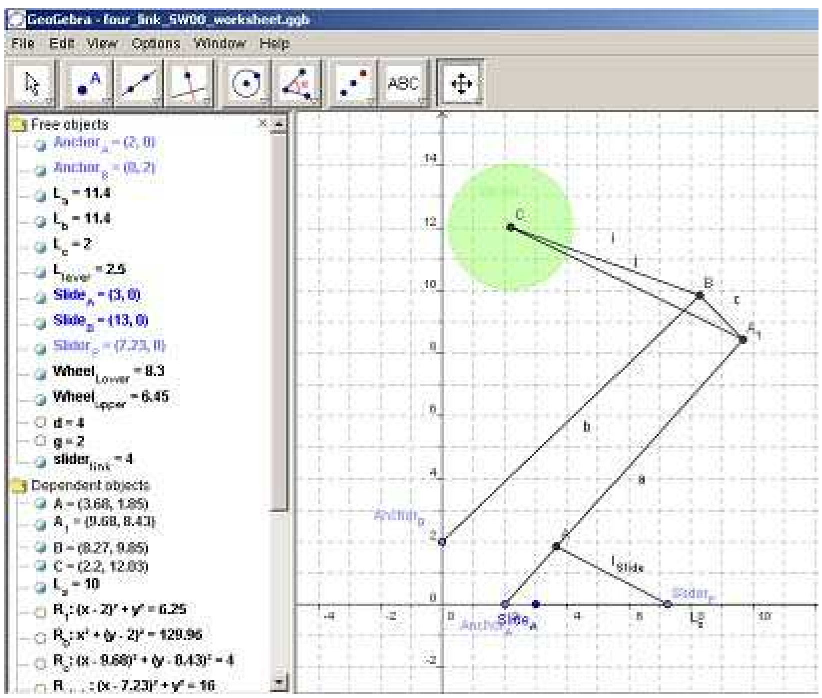

Figure 2: Leg development in "GeoGebra"

Each wheel is supported with two linkages like the one above. However, there is only one upper linkage (as seen below). Initially the upper linkage's base was just made wider to accommodate the width of the wheel. However, this led to an unequally distributed force and created a weak point.

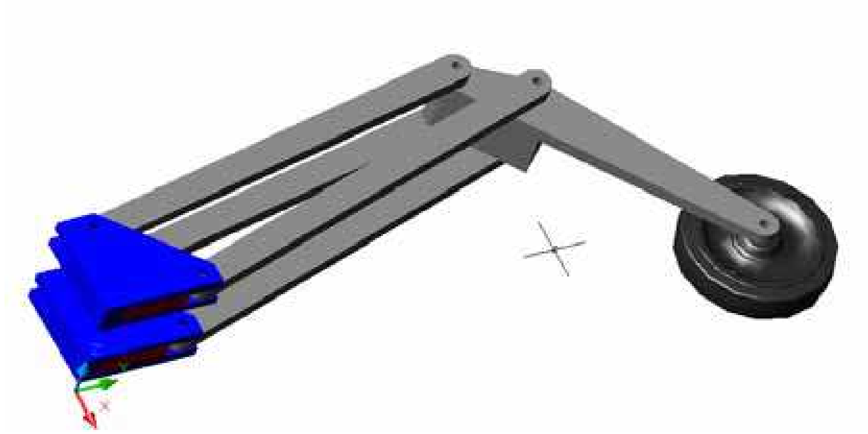

Figure 3: Leg with unbalanced forces

It was decided that using a fork design would be much more practical and would make the leg only about one cm wider, as shown in Figure 4.

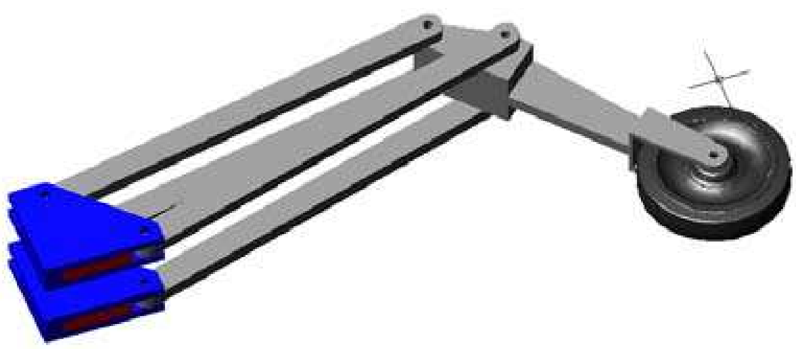

Figure 4: Leg with fork that distributes force evenly

The legs are made out of aluminum because of its strength, weight, surface finish, and its resistance to corrosion.

3.2 Hinge Design

A hinge had to be developed to hold the leg in place and mount it to the Gavia. The distance between the 2 base legs is 5 by 5 cm. The hinge is secured with two screws in its base. This piece is also machined in aluminum.

3.3 Joints and Connections

Shoulder bolts are used in between the legs for motion. Four bolts have to be made with a 5cm unthreaded surface in order to accommodate the thicker third leg.

The joint between the wheel and the fork was designed to have no clearance issues with the leg when folding. A horizontal travel of one-tenth a millimeter had to be considered in order to allow the encoder to work correctly. To do this, a bushing is press fit into the wheel. Two separate rollers are then screwed into the bushing; see Figure 5. This allows the rollers to rotate in the fork without creating any connection points outside of the fork

Figure 5: Bushing for wheel that will allow it to rotate

3.4 Slider Mechanism

To move the leg, it was decided to use a linear actuator that would move horizontally at the base, attached to the leg by a slider link; see Figure 6. The motor is fixed and the link moves up and down the slider track.

A moving model of the leg was built in “GeoGebra” that could be rotated by moving the virtual sliding link. Ideally, the slider travel needs to be less than 5 cm so the slider must be placed as close to the base of the leg as possible.

However, this will increase the force required to raise the leg. It was decided to make the slider 10 cm long and place it 63 cm up on the base leg.

The 2 slider bars will be attached to a very small slider rail found on McMaster-Carr (item #'s 6725k9 and 6725k23). The sliders will be joined together and driven by a single actuator located under the center of the leg.

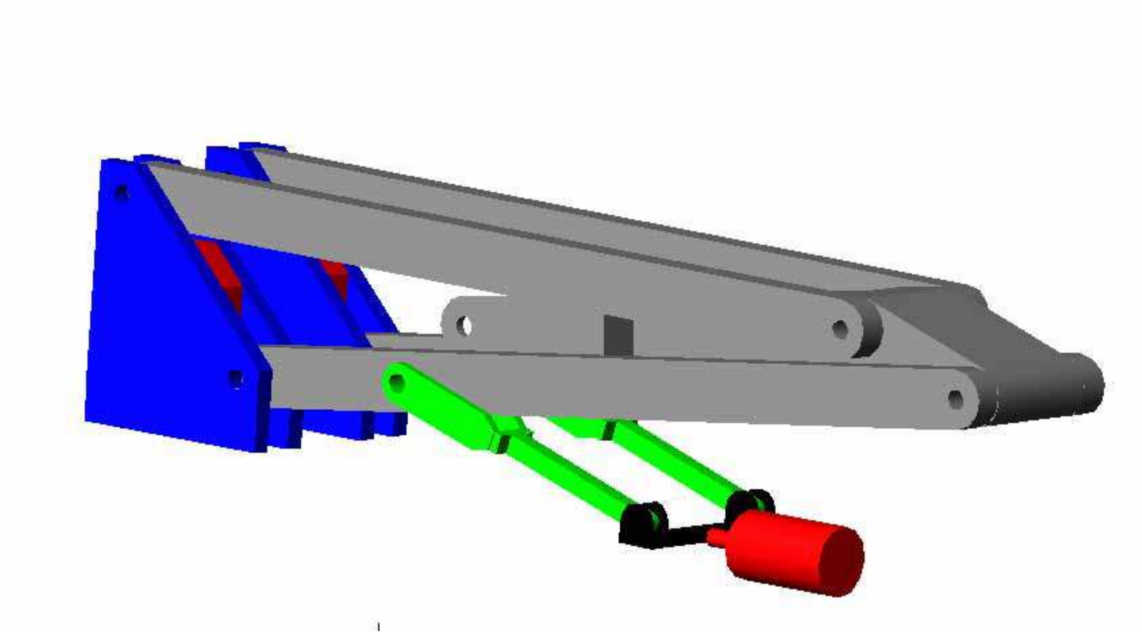

Figure 6: Leg with attached sliders and motor

4.0 Wheel and Encoder

As the previous generation wheel was made of a solid rubber, a new wheel had to be found that would provide enough frictional force in water. It was decided to use a 10 cm diameter wheel by Coloson for the application.

In order to track the AUV's position in the pipe, it was decided to use an encoder mechanism on the wheel. In this way, as the wheel rotates along the pipe, the sensor picks up signal from the magnetic strip in the encoder ring and the distance can be recorded.

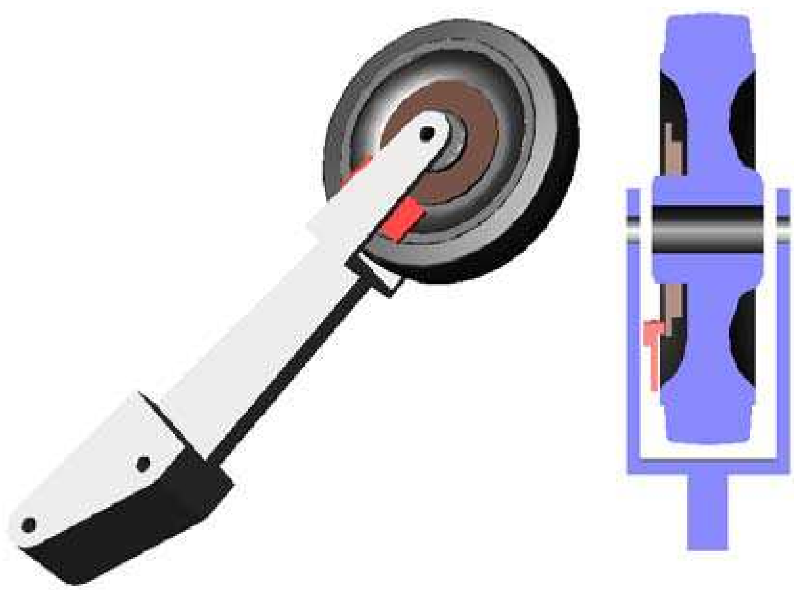

Figure 7: Top linkage with encoder (left), Cross section of wheel and encoder (right)

In order for the sensor and encoder ring to work, there must be a maximum distance of 2 mm between them. For our application, it was desired to bring this distance to a maximum of 0.5 mm. To accommodate this, the lateral travel of the wheel was machined to a tenth of a millimeter.

CAD diagrams were developed in order to decide on a mounting mechanism for the encoder. It was decided to mount the encoder circuit on the inside of the top leg. The wheel was then put onto a lathe and machined so that the encoder ring would fit in over the wheel. The encoder is held in place using four M4 screws tapped into the wheel.

5.0 Force Analysis

5.1 Bending Moment Calculations

In order to calculate the size of actuator to power the leg, a force analysis was completed. The strength of the material was calculated as well as the bending moment. In order to simplify the system, the leg will be considered as a 29 cm bar with two fixed ends and a 100 N force pushing down at 75 mm from one end.

The tensile strength of a common aluminum (6060) was found to be 45 000 psi using a reference book.

Since:
1 Mpa = 145 psi

45 000 psi = 310 MPa

Therefore, 310 MPa is the maximum force we can apply on the beam.

To calculate the bending moment we will need to find the moment created on the beam:

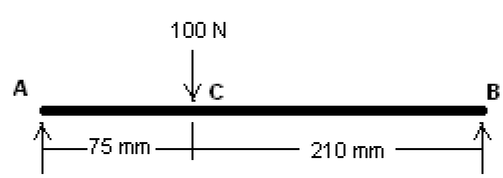

Figure 8: Bending moment diagram using a bar supported on both ends

Moment about A = -(100)(75) + (210)(Rb)
7500 = 210Rb

Rb = 26.54 N

Ra + Rb = 100 N

Ra = 73.46 N

The maximum bending moment is calculated by taking the moment around the point at which the 100 N force is applied. That is:

Mc = 73.46 N * 75 mm

Mc = 5597.7 N mm

The maximum bending stress is calculated using the formula:

$$\sigma \max = \frac{M}{Z}$$

where:

M = bending moment

Z = I/C = section modulus

C = distance from the neutral axis to the outer surface where maximum stress occurs

I = moment of inertia

The neutral axis is located at the geometric center of the bar and as the force is located on the outer surface of the bar, C = 9.525 mm.

The moment of inertia is calculated using the equation:

$$I = \frac{b \cdot h^3}{12}$$

where:

b = thickness of bar (mm)

h = width of bar (mm)

$$I = \frac{(9.1875)(18.375)^3}{12}$$

I = 4750.04 mm^4

Therefore:

$$\sigma \max = \frac{(5597.7N \cdot mm)(9.525mm)}{4750.04mm\text{^}4}$$

$\sigma \max$ = 11.223 MPa

According to the tables provided by “Russel Metals Inc”, the stress required for breakage is 45 MPa. This will give us a safety factor of four, which is acceptable for this application as the maximum force applied to the leg will be about 10 Newton.

5.2 Force Analysis Calculations

As the aluminum legs should not bend, we can treat each leg as a rigid body and calculate the forces on the leg by summing the forces at each joint. This will allow us to calculate the force required by the linear actuator to lift the leg from its closed position with 100N of force on the wheel.

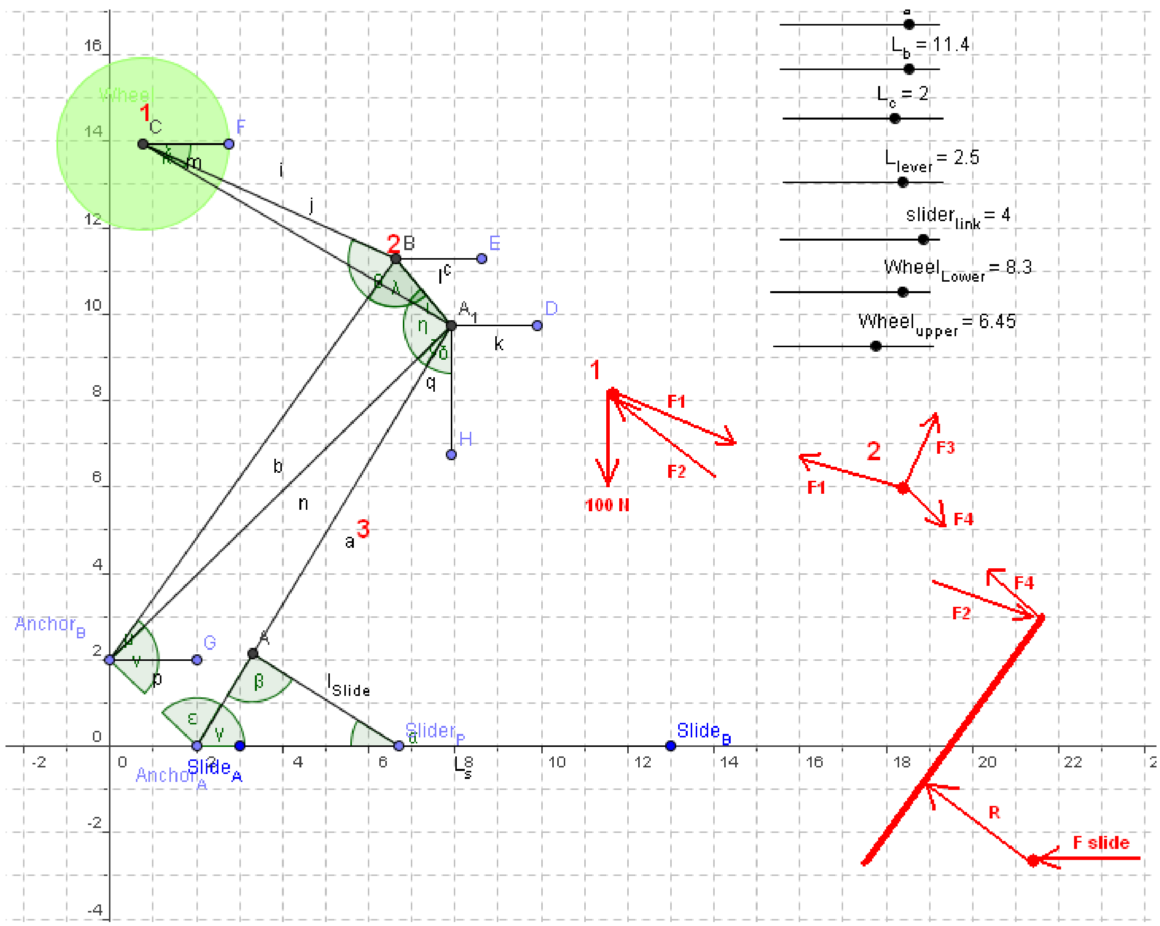

Figure 9: Geogebra model of leg and the forces at each joint

As seen in Figure 9, points 1 and 2 can be used to calculate F1, F2, F3 and F4. At point 1 there are two equations and two unknowns. F1 and F2 must be found using the equations for the sum of the forces in the x and y directions. From there we can now do the same at point 2, as F1 is known.

At link 3, a point analysis cannot be used as R is acting on the bar. This force creates a moment on the leg. As F2 and F4 are known, we can find R by summing the moments around the base. In turn, 'F slide' is simply the x component of R.

In order to calculate 'F slide' as the leg is extended, this calculation must be completed again and again as the leg changes position. In order to do this, a

MATLAB® code was written that could do this and graph the results (see Section 6.0).

It was also desirable to look at the force required if the sliding base was moved down 2.5 cm to allow for a smaller “F slide” force when the leg was closed. This is a result of R having a smaller x component when the slider is lowered; see Figure 10.

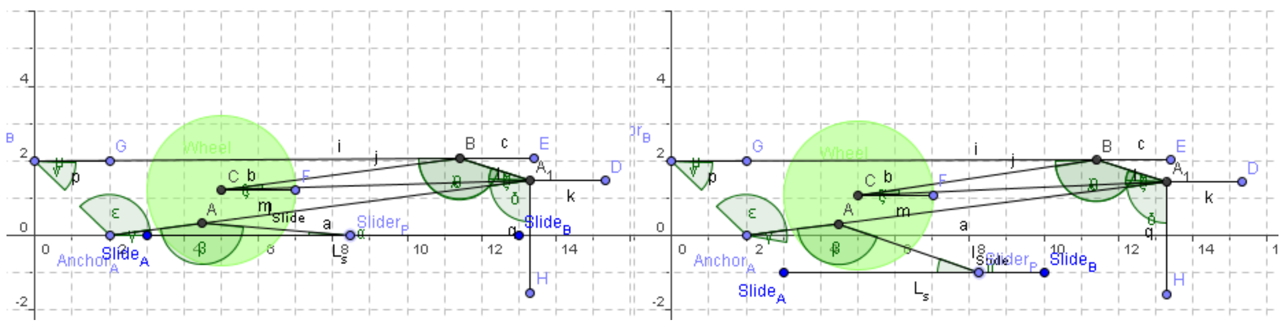

Figure 10: Slider level with the base (left), slider dropped down 2.5 cm (right)

6.0 MATLAB® Code and Analysis

6.1 Force Analysis

MATLAB® was used to graph the changes in force while the leg was folded. As the leg is moved, the instantaneous forces are calculated at each joint and related to the overall force on the system in order to keep it static in that position.

In order to calculate these forces, it was required to find the angles between the linkages at each joint. All of these angles must be related back to one initial angle, which was chosen as the angle between the slider path and slider bar. All of these angles are then stored in a data structure and called on when needed in the force analysis. All calculated forces are stored in a separate structure where they can be compared and analyzed.

A set of simple graphs was generated to compare the forces on the motor when the slider was moved; see Figure 11.

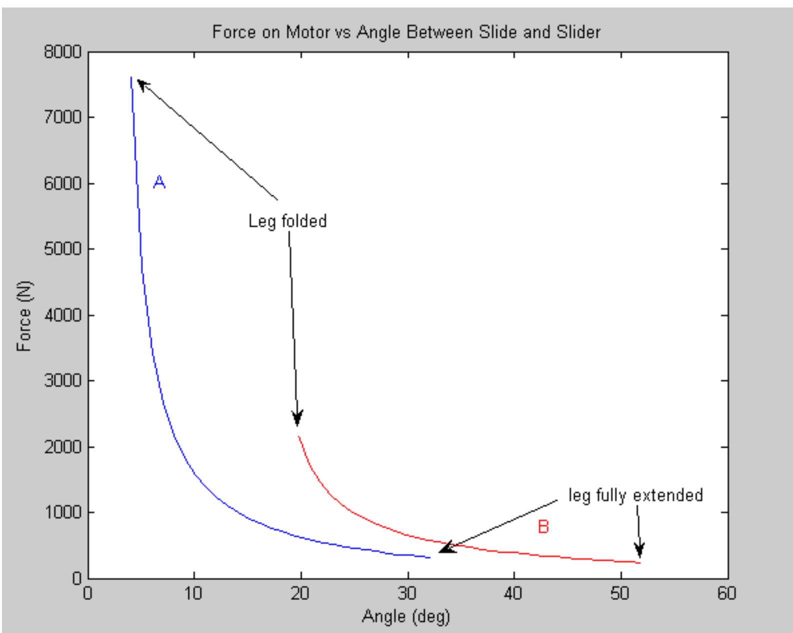

Figure 11: Force analysis of leg as it folds down

Force ‘A’ is found when the slider is level with the base of the leg and Force ‘B’ is defined as the motor force when the slider is lowered to allow for a larger folded angle.

It can be seen that there is a large difference in the maximum force when then leg is closed. As well, when the slider is lowered there is a much more continuous force with a smaller slope.

As this test is accommodating a 100 N force at the wheel and the real world force will be around 10 N, position ‘B’ will provide the best control of the leg and a smaller motor will be needed. Moving the slider down 2.5 cm will only increase the motor travel by about 20 mm. This will put the actuator travel at about 63 mm, which can easily be obtained in a small motor.

6.2 Virtual Reality / Simulink® Model of Articulated Leg

It was desired to develop a virtual model of the leg for visual representation of how the final leg would fold into the vehicle. This was done in MATLAB® using the virtual reality toolbar in Simulink®.

Initially, the AutoCAD drawing file of the leg had to be converted into a vrml file. This was done using a trial of the tool “VrmlExport for AutoCAD” by Xanadu.

Once a vrml file was created, it could be edited in “V Realm Builder” from the MATLAB® package.

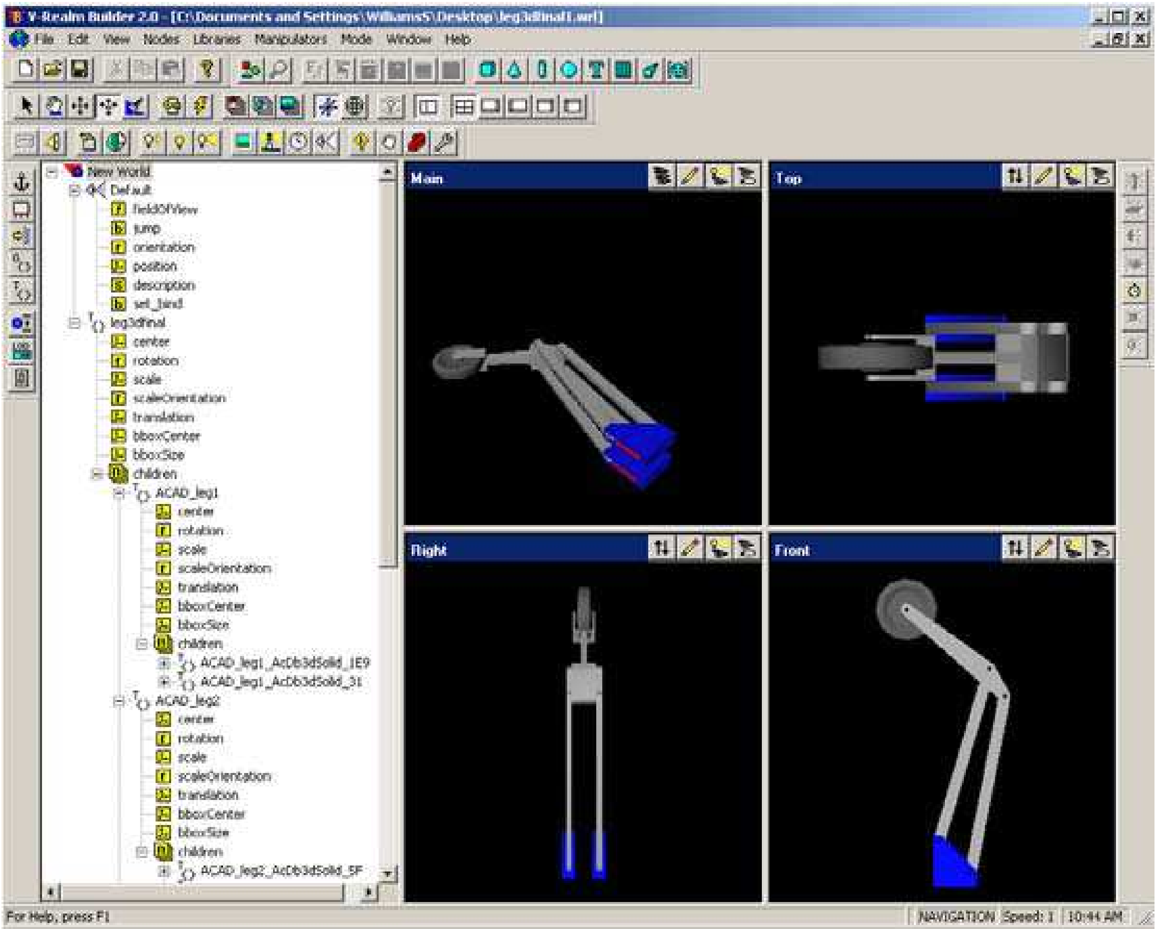

Figure 12: Leg development in 'V-Realm'

In "V Realm Builder", all objects are located on the left hand side with sub-objects labeled as children; see Figure 12. For our application the center of gravity was relocated to the rotation point on each link. This allows the linkages to rotate around the proper joint when a signal is applied though Simulink®.

In order to rotate the link that holds the wheel, translation and rotation had to be accommodated for. In order to do this, the wheel and fork were given a center point at the end of that linkage as sub-systems, or children. The global system was then given a common center point to the entire leg located at the base of the system. In this way, the upper linkage can rotate around two points simultaneously.

Once the signals were developed in Simulink® to control one leg, a more advanced model was developed that could control multiple legs at once. A code was developed to rotate four legs that would be placed on the Gavia; see Figure 13.

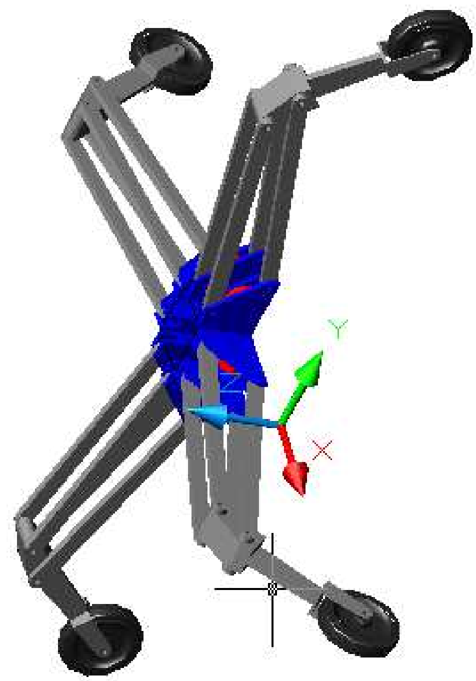

Figure 13: System of legs to be placed on Gavia

Finally a complete model was developed that included the Gavia vehicle with two sets of legs and the multibeam sonar that will profile the inner wall of the pipeline.

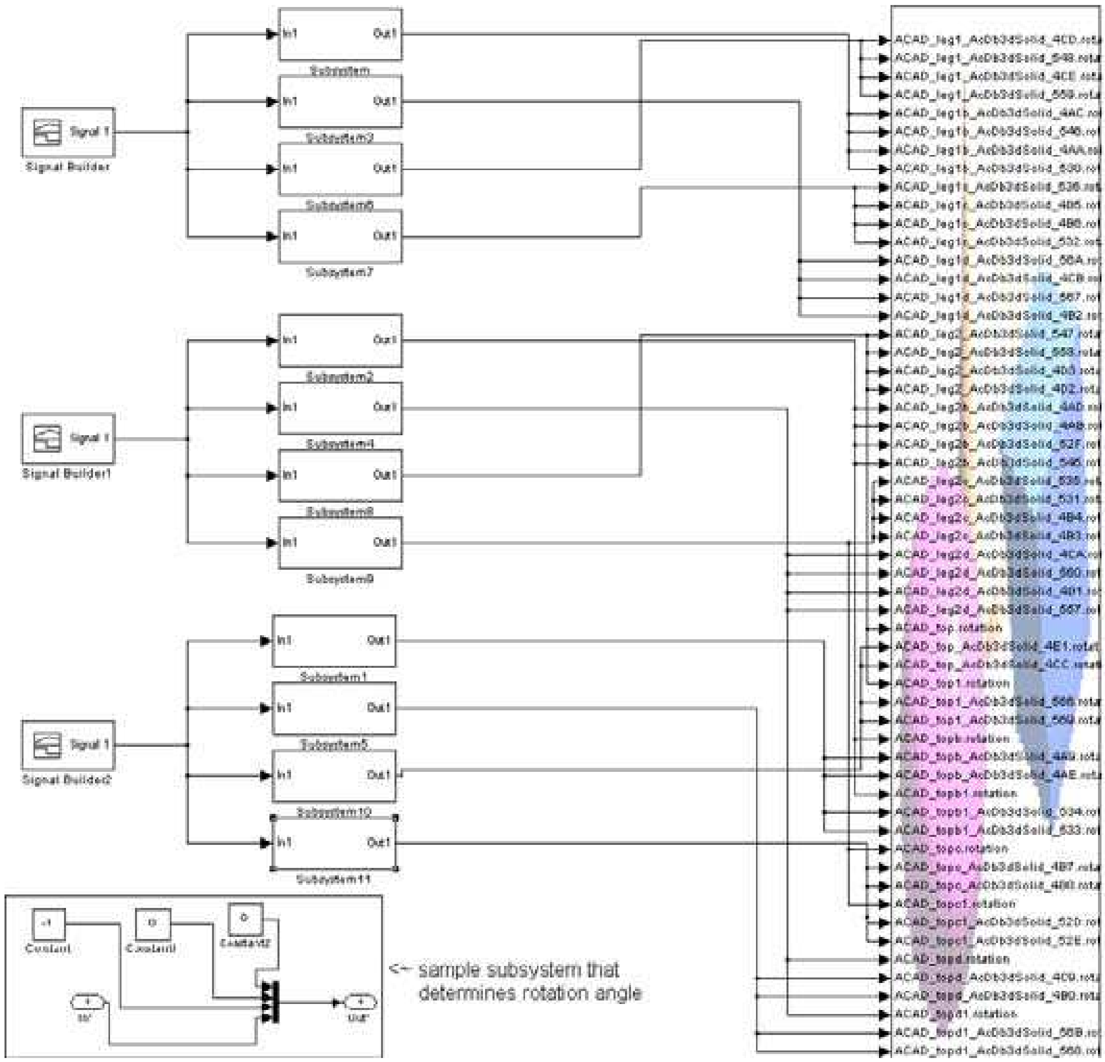

Figure 14: Simulink® model of Gavia

In the Simulink® code, each signal controls a joint on the leg. The subsystems break up the coordinate system and tell the model which axis it should use in rotation. The signal is then fed into the appropriate input on the model; see Figure 14.

The animation was captured to a movie file that shows the legs folding down from an open position; see Figures 15 and 16 which are snapshots from this movie.

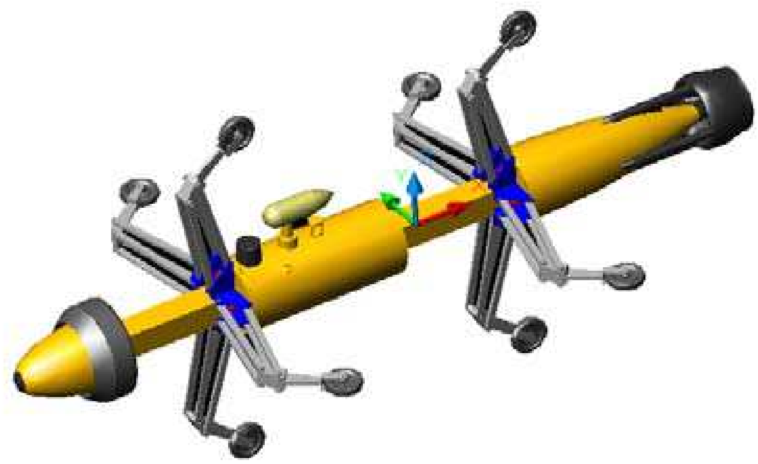

Figure 15: Gavia with legs extended

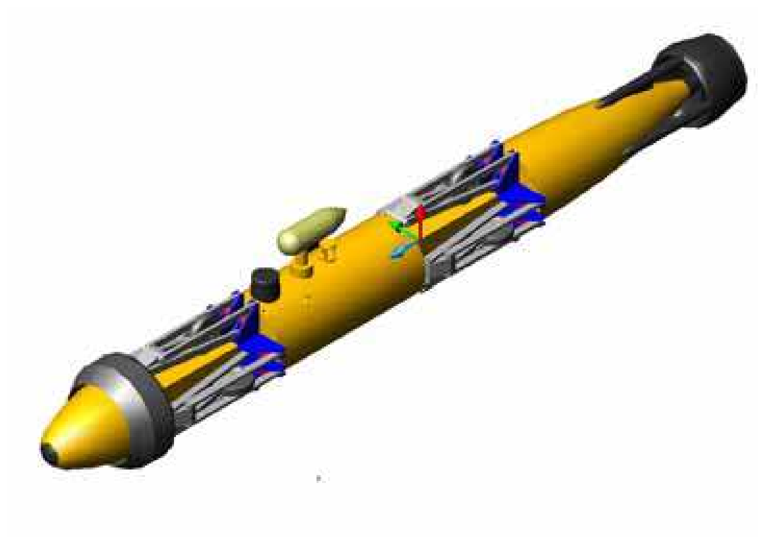

Figure 16: Gavia with legs folded

It should be noted that when the Gavia is used for the pipeline inspection the communications tower will be removed and possibly the acoustic modem as well.

7.0 Conclusions and Future Work

The goal of this project is to develop a set of new modules for the Gavia vehicle that will allow it to inspect the inside of freshwater pipelines. It will use a system of legs and wheels with integrated encoders and brakes to control its position to allow for accurate profiling of the inner wall of the pipeline.

Currently, a prototype leg has been submitted to the design team and is awaiting fabrication. Once this model is completed it will be valuable to use the existing actuator we own for the 'Flexfin' to test the leg movement as well as the force required.

A mounting mechanism must be developed for the Gavia vehicle to accommodate the folded wheels and the actuators that will drive each leg. As well, waterproofing the encoder and actuator will be a concern.

Finally, a wheel with a built in inverted motor by Maxon will be used as a brake system to allow the vehicle to hold its position in the pipe. These motors were obtained this semester but need to be tested and implemented into three of the wheels.

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Appendix A

Cad Drawings

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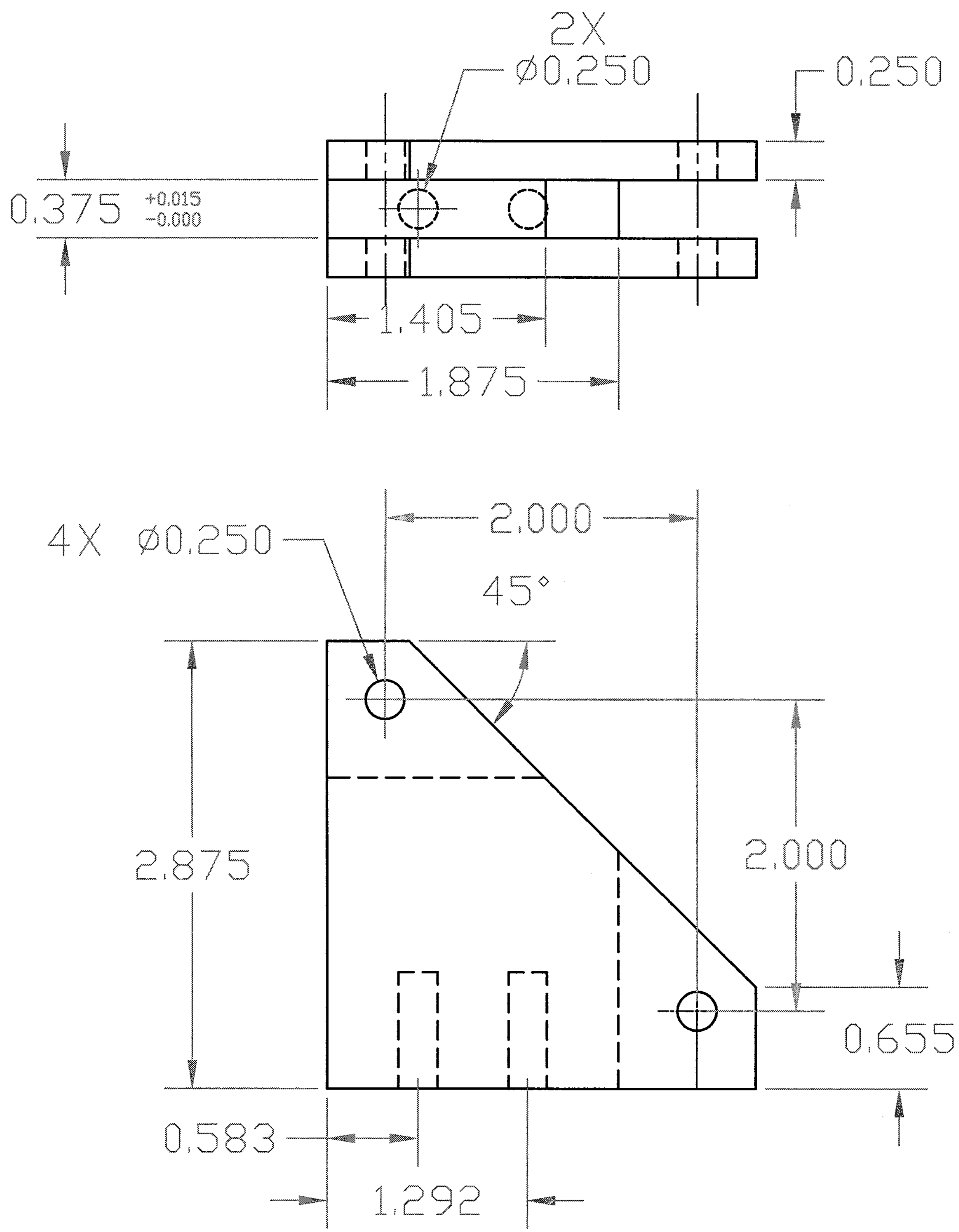

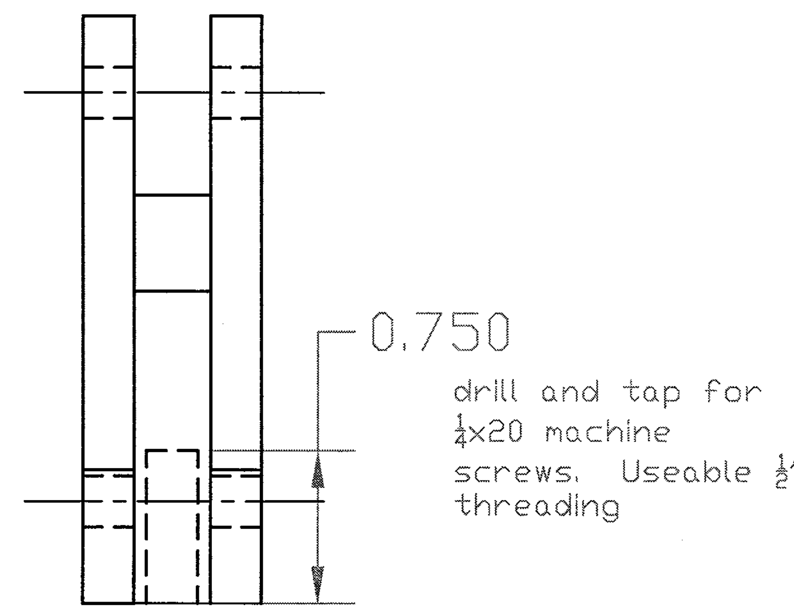

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TOLERANCES (unless specified)	
0. X	± 0.03
0. XX	± 0.015
0. XXX	± 0.005
Angle	± 0.5 deg.
Fabrication	± 0.04
Fraction < 6 Inch	± 1/64
Fraction > 6 Inch	± 1/32

Material: Aluminium

Heat Treatment: — — —

FINISH: 125 u-inch rms

DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐

THIRD ANGLE

TRAX

DRAWN: S. Williams

APPROVED

Quantity: 1

TITLE: **Gavia Leg Hinge**

SCALE: 1:1

NUMBER

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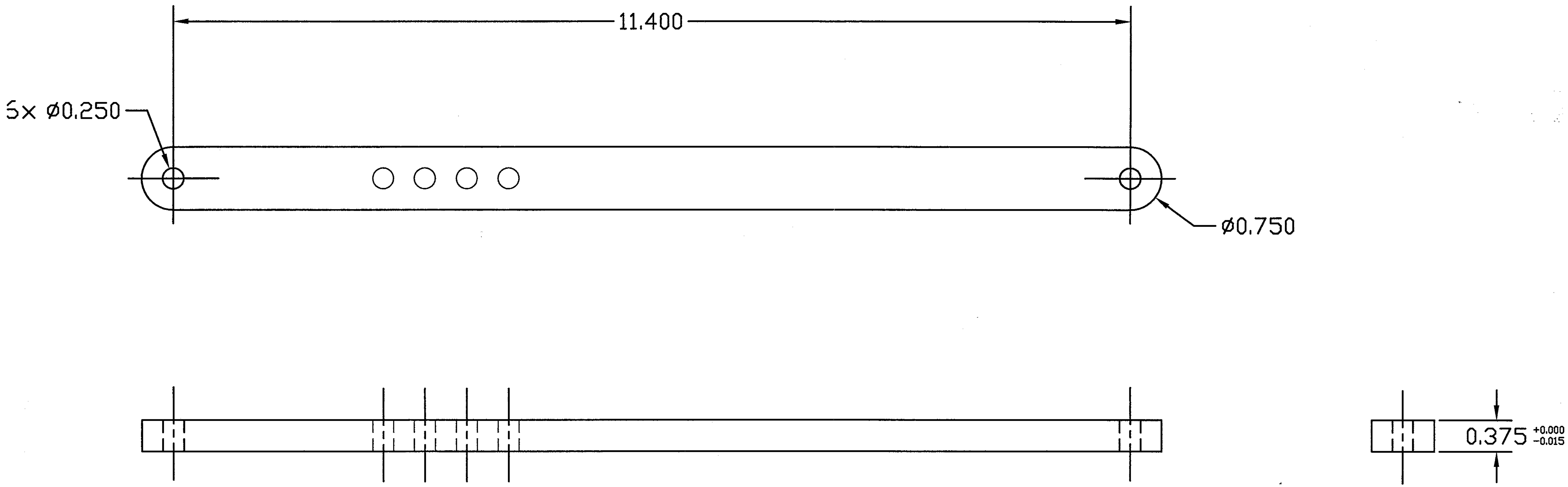

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Fabrication ± 0.04
Fraction < 6 inch ± 1/64
> 6 inch ± 1/32

Material: Aluminium
Heat Treatment: — — —
FINISH 125 u-inch rms
DIMENSIONS IN INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

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TRAX
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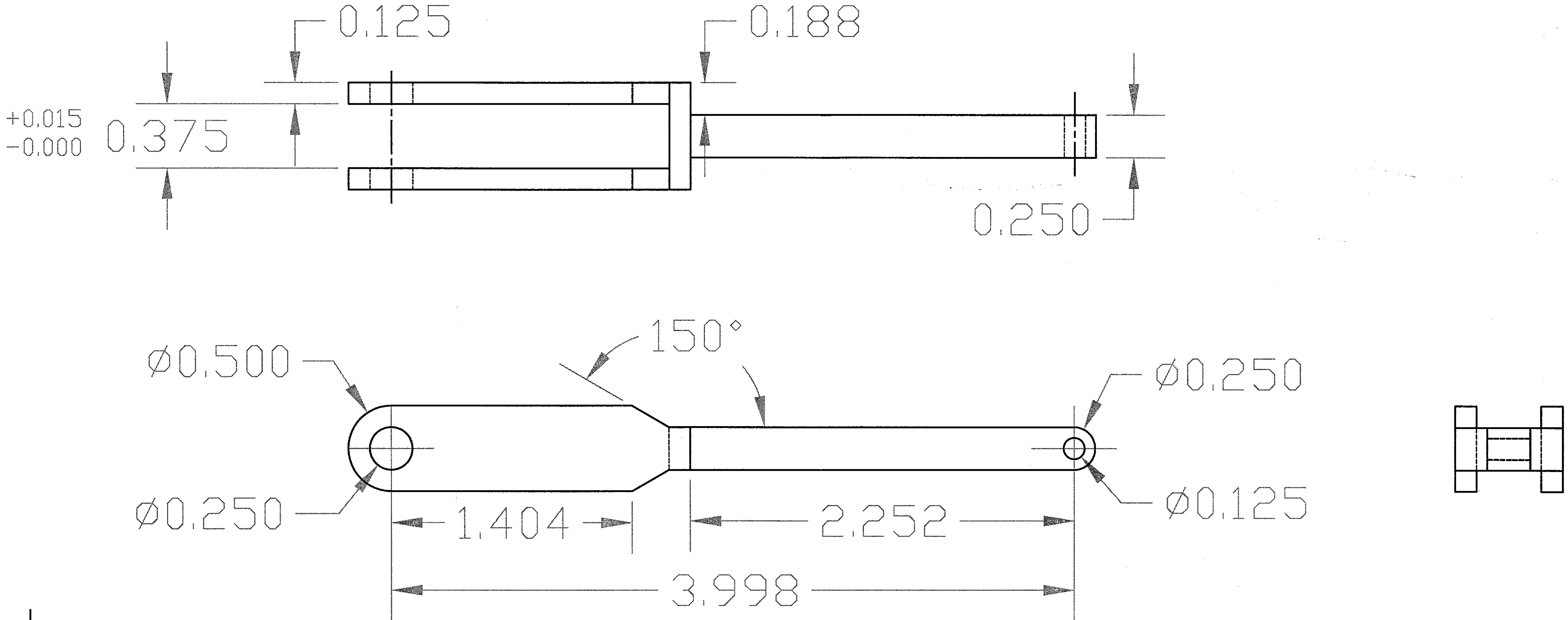

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0. XX	± 0.015
0. XXX	± 0.005
Angle	± 0.5 deg.
Fabrication	± 0.04
Fraction < 6 inch	± 1/64
> 6 inch	± 1/32

Material: Aluminium
Heat Treatment: — — —
FINISH: 125 u-inch rms
DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

Institute for Ocean Technology
Arctic Avenue, P.O. Box 12093
St. John's NL A1B 3T5

TRAX
DRAWN S.Williams
APPROVED
Quantity 1

TITLE: Slider Leg

SCALE 3:2 | NUMBER | REV 1

A2 | DATE March 28, 2006 | SHEET 1 OF 1

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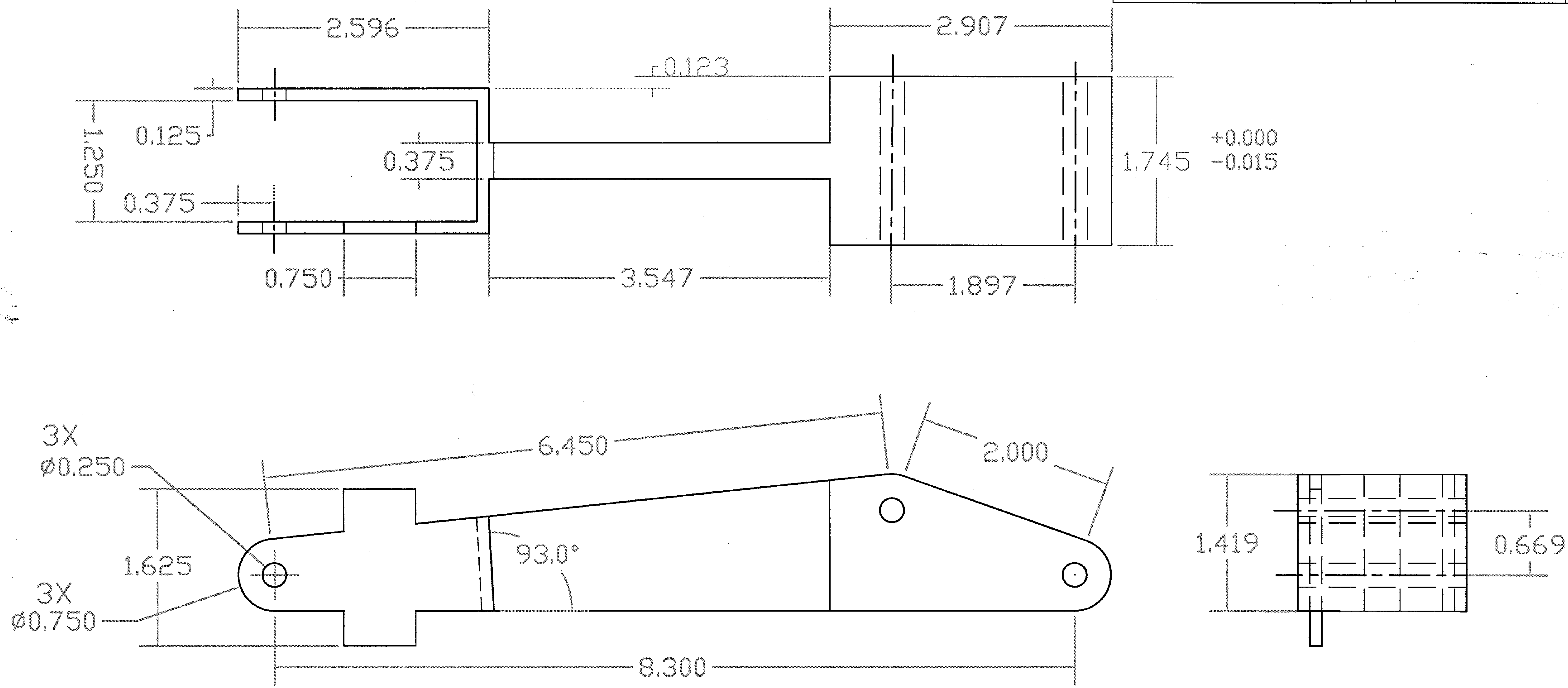
REVISIONS

NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	—	Issued For Comments	3.10.2006	
2				
3				



NUMBER 42_2088_10GH03

National Research Council Canada
Conseil national de recherches Canada
NRC-CNRC

TOLERANCES
(unless specified)
0. X ± 0.03
0. XX ± 0.015
0. XXX ± 0.005
Angle ± 0.5 deg.
Fabrication ± 0.04
Fraction < 6 inch ± 1/64
> 6 inch ± 1/32

Material: Al
Heat Treatment: ———
FINISH: -
DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

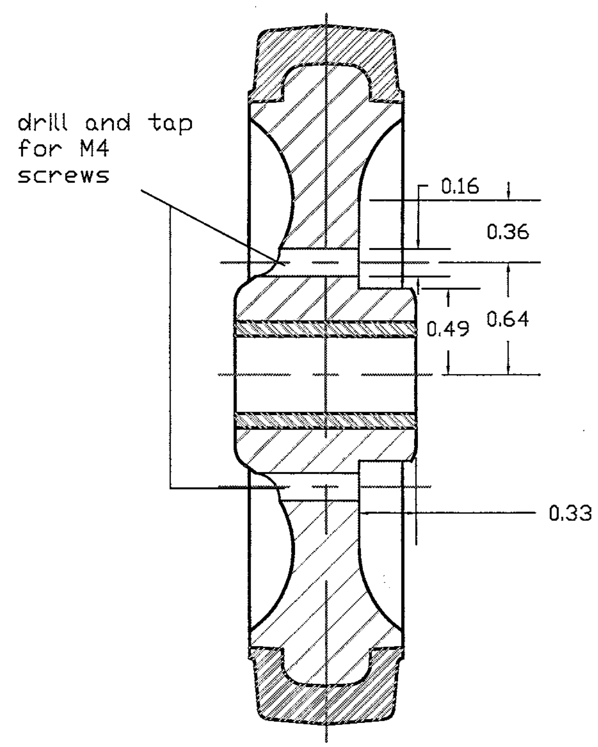
Institute for Ocean Technology
Arctic Avenue, P.O. Box 12093
St. John's NL A1B 3T5

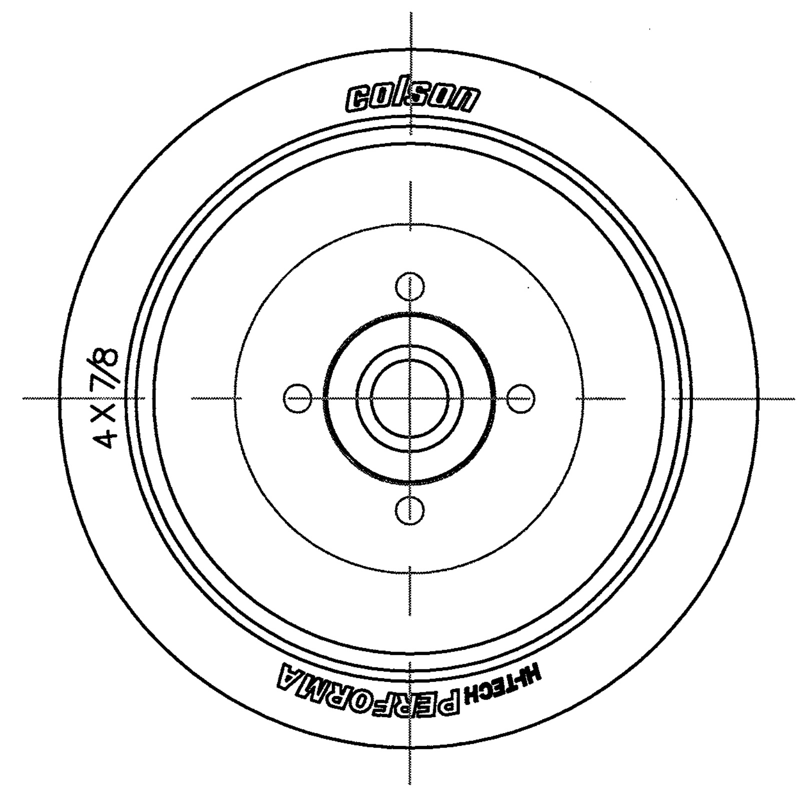
TRAX
DRAWN S.Williams
APPROVED
Quantity 1

TITLE **Top Leg**

SCALE 1:1
NUMBER
REV 1
A2
DATE Jan. 11, 2006
SHEET 1 OF 1

		REVISIONS		
NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	—	Issued For Comments	12.01.2005	
2				
3				





NUMBER 42_2088_10GH03

National Research Council Canada | Conseil national de recherches Canada | NRC-CNRC

TOLERANCES (unless specified) 0. X ± 0.03 0. XX ± 0.015 0. XXX ± 0.005 Angle ± 0.5 deg. Fabrication ± 0.04 Fraction < 6 Inch ± 1/64 > 6 Inch ± 1/32	Material Monprene 1500 Heat Treatment — — — FINISH - DIMENSIONS IN INCHES ☒ MILLIMETERS ☐ THIRD ANGLE	Institute for Ocean Technology Arctic Avenue, P.O. Box 12093 St. John's NL A1B 3T5 TRAX DRAWN S.Williams APPROVED Quantity 1	TITLE **Modified Wheel** SCALE 1:1 · NUMBER · REV 1 A2 · DATE Jan. 11, 2006 · SHEET 1 OF 1

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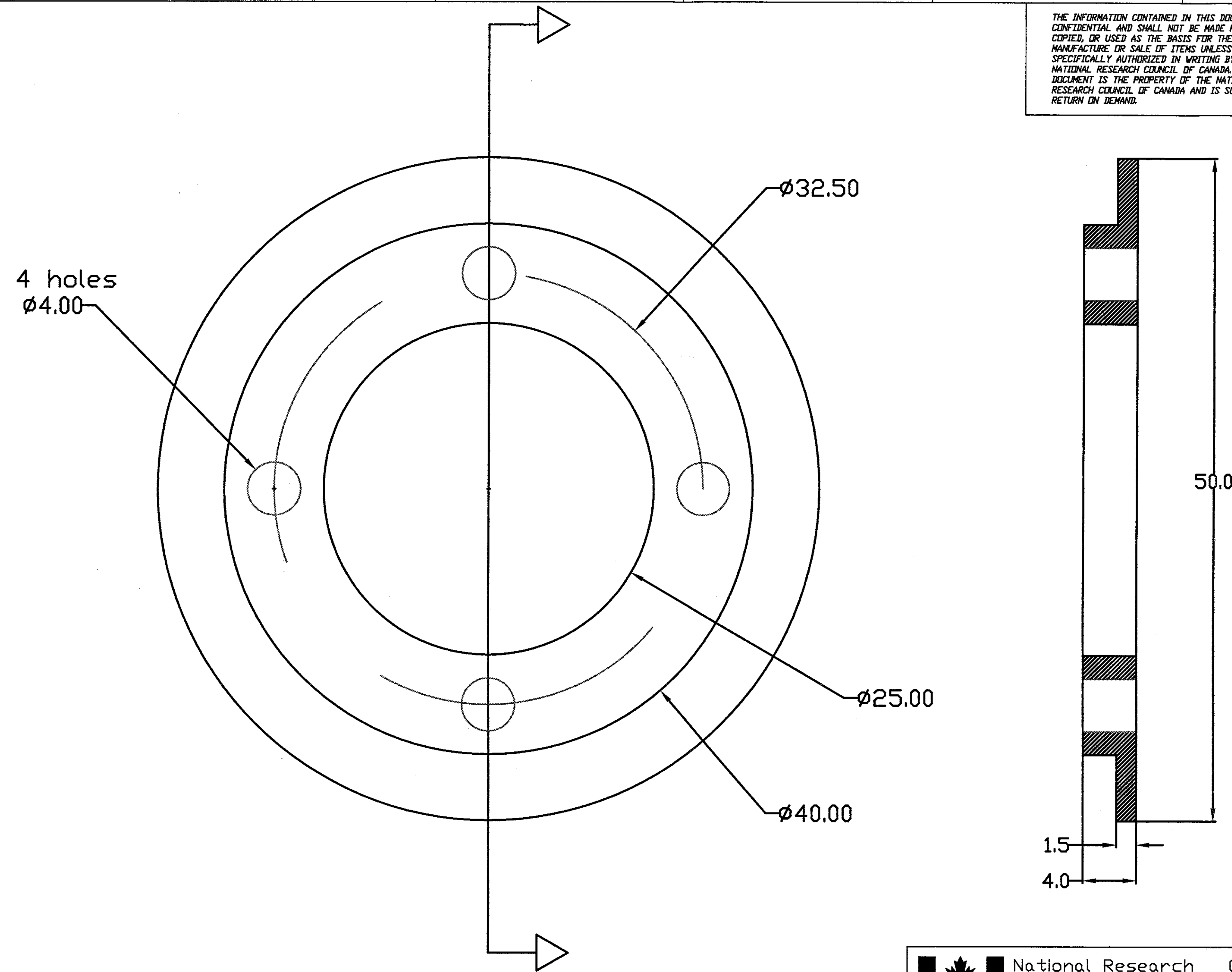
REVISIONS				
NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	---	Issued For Comments	12.01.2005	
2				
3				



NUMBER 42_2088_10GH03

National Research Council Canada
Conseil national de recherches Canada
NRC-CNRC

TOLERANCES (unless specified)	Material 7256-001	Institute for Ocean Technology Arctic Avenue, P.O. Box 12093 St. John's NL A1B 3T5
0.X ± 0.03	Heat Treatment — — —	
0.XX ± 0.015	FINISH -	TRAX
0.XXX ± 0.005	DIMENSIONS IN INCHES ☐ MILLIMETERS ☐	DRAWN S.Williams
Angle ± 0.5 deg.	THIRD ANGLE	APPROVED
Fabrication ± 0.04		Quantity 1
Fraction < 6 Inch ± 1/64 > 6 Inch ± 1/32		

TITLE **Modified Encoder**

SCALE	NUMBER	REV
1:3	42_2088_10GH03	1

A2 DATE Jan. 11, 2006 SHEET 1 OF 1

Appendix B

MATLAB Code

```
%---------------------------NRC-IOT-------------------------------------
% Name: force_REV.m
% Author: Steven Williams
% Date: March 8 2006
%----------Discription-------------------------------------------------
%   Calculates the force required by a motor to hold the gavia leg static
%   with a 100 N load on the wheel.  It is calculated every degree as the
%   leg folds down.  See report (appendix A) for diagram of leg and angle
%   locations.
%---------------------------------------------------------------------
clear
clc

% create a structure to hold all angles and forces
data = struct ('A1',[],'A2',[],'A11',[],'x1',[],'G',[],'g',[],'Z',[],'H',[],'E',[],'F',
[],'D',[],'I',[],'J',[],'K',[],'x3',[]);
force = struct ('F1',[],'F2',[],'F3',[],'F4',[],'F4y',[],'F2y',[],'R',[],'F',[]);
%----------------------------------------------------------------------

m = 1; %count variable

for i = 32.08:-0.5:4.08

% angle calculation - see report for location of all angles.

A1 = i;

A1 = (A1 * pi) / 180;

A11 = asin((4*(sin(A1))) / 2.5);
A2 = pi - A1 - A11;

x1 = ((180*pi)/180) - ((90*pi)/180) - A11;

G = ((45*pi)/180) + (((90*pi)/180) - A11);

g = sqrt( (2.8284*2.8284) + (11.4*11.4) - (2*2.8284*11.4*cos(G)));

Z = asin((2.8284*(sin(G))) / g);

H = acos( (-(11.4*11.4) + (g*g) + (2*2))/(2*g*2));

E = acos( (-(8.3*8.3) + (6.45*6.45) + (2*2))/(2*6.45*2));
F = acos( (-(6.45*6.45) + (8.3*8.3) + (2*2))/(2*8.3*2));
D = pi - E - F;

I = acos( (-(g*g) + (11.4*11.4) + (2*2))/(2*11.4*2));

J = pi - I - H;
K = pi - G - Z;

x2 = K - ((45*pi)/180) + J;
```

```
x3 = x1 + H - F + Z - ((90*pi)/180);
%-------------------------------------------------------------------

%stores angle information into a structure
data(m).A1 = A1;
data(m).A2 = A2;
data(m).A11 = A11;
data(m).x1 = x1;
data(m).G = G;
data(m).g = g;
data(m).Z = Z;
data(m).H = H;
data(m).E = E;
data(m).F = F;
data(m).D = D;
data(m).I = I;
data(m).J = J;
data(m).K = K;
data(m).x3 = x3;
%-------------------------------------------------------------------

%Calculates the forces at the wheel point

matrx = [-sin(x3-D), sin(x3); -cos(x3-D), cos(x3)];
sol = [100;0];
Fin = matrx\sol;

force(m).F1 = Fin(1);
force(m).F2 = Fin(2);
%-------------------------------------------------------------------

%Calculates the forces at pin 1

x4 = K+J-((45*pi)/180);
matrx = [sin(x4), -sin(((180*pi)/180)-(x4+I)); cos(x4), cos(((180*pi)/180)-(x4+I))];
sol = [-force(m).F1*sin(E-(x4+I)) ; force(m).F1*cos(E-(x4+I))];
Fin = matrx\sol;

force(m).F3 = Fin(1);
force(m).F4 = Fin(2);
%-------------------------------------------------------------------

%ang_rev 1 and 2 change the coordinate system so that the x axis is along
%leg 1
ang_rev1 = (Z+H);
ang_rev2 = (Z+H)-F;

if ang_rev1 >= ((90*pi)/180) %makes sure angle being calculated is less than 90
    ang_rev1 = ((180*pi)/180) - ang_rev1;
end
```

```
force(m).F4y = force(m).F4 * sin(ang_rev1); %calculates the forces perpinduclar to leg 1
force(m).F2y = force(m).F2 * sin(ang_rev2);

ang_rev3 = A2;
if ang_rev3 >= ((90*pi)/180)
    ang_rev3 = ((180*pi)/180) - ang_rev3;
end

%moment calculation on leg 1
force(m).R = ((-force(m).F4y * 11.4) + (force(m).F2y * 11.4))/((2.5)*sin(ang_rev3));

%force required my motor
force(m).F = force(m).R * cos(A1);


m = m + 1;
end

for i = 1:(m-1)
    xref(i) = (data(i).A1*180)/pi; %these are used to plot the force vs angle
    yref(i) = force(i).F;
end
```

```
%----------------------------NRC-IOT--------------------------------------
% Name: force_REV.m
% Author: Steven Williams
% Date: March 8 2006
%----------Discription-----------------------------------------------
%   Calculates the force required by a motor to hold the gavia leg static
%   with a 100 N load on the wheel.  It is calculated every degree as the
%   leg folds down.  This calculates the forces when the slider is droped
%   below the x axis by 2.5 cm.
%-------------------------------------------------------------------------
%clear
%clc

% create a structure to hold all angles and forces
data = struct ('A1',[],'A2',[],'A11',[],'x1',[],'G',[],'g',[],'Z',[],'H',[],'E',[],'F',
[],'D',[],'I',[],'J',[],'K',[],'x3',[],'yy1',[]);
force = struct ('F1',[],'F2',[],'F3',[],'F4',[],'F4y',[],'F2y',[],'R',[],'F',[]);
%-------------------------------------------------------------------------

m = 1; %count variable

for i = 51.8:-1:19.12

% angle calculation - see report for location of all angles.

A1 = i;

A1 = (A1 * pi) / 180;

yy1 = sin(A1)*4;
yy1 = yy1 - 1;

A11 = asin(yy1/2.5);

A2 = pi - A1 - A11;

x1 = ((180*pi)/180) - ((90*pi)/180) - A11;

G = ((45*pi)/180) + (((90*pi)/180) - A11);

g = sqrt( (2.8284*2.8284) + (11.4*11.4) - (2*2.8284*11.4*cos(G)));

Z = asin((2.8284*(sin(G))) / g);

H = acos( (-(11.4*11.4) + (g*g) + (2*2))/(2*g*2));

E = acos( (-(8.3*8.3) + (6.45*6.45) + (2*2))/(2*6.45*2));
F = acos( (-(6.45*6.45) + (8.3*8.3) + (2*2))/(2*8.3*2));
D = pi - E - F;

I = acos( (-(g*g) + (11.4*11.4) + (2*2))/(2*11.4*2));
```

```
J = pi - I - H;
K = pi - G - Z;

x2 = K - ((45*pi)/180) + J;

x3 = x1 + H - F + Z - ((90*pi)/180);
%-----------------------------------------------------------------

%stores angle information into a structure
data(m).A1 = A1;
data(m).A2 = A2;
data(m).A11 = A11;
data(m).x1 = x1;
data(m).G = G;
data(m).g = g;
data(m).Z = Z;
data(m).H = H;
data(m).E = E;
data(m).F = F;
data(m).D = D;
data(m).I = I;
data(m).J = J;
data(m).K = K;
data(m).x3 = x3;
%-----------------------------------------------------------------

%Calculates the forces at the wheel point

matrx = [-sin(x3-D), sin(x3); -cos(x3-D), cos(x3)];
sol = [100;0];
Fin = matrx\sol;

force(m).F1 = Fin(1);
force(m).F2 = Fin(2);
%-----------------------------------------------------------------

%Calculates the forces at pin 1

x4 = K+J-((45*pi)/180);
matrx = [sin(x4), -sin(((180*pi)/180)-(x4+I)); cos(x4), cos(((180*pi)/180)-(x4+I))];
sol = [-force(m).F1*sin(E-(x4+I)) ; force(m).F1*cos(E-(x4+I))];
Fin = matrx\sol;

force(m).F3 = Fin(1);
force(m).F4 = Fin(2);
%-----------------------------------------------------------------

%ang_rev 1 and 2 change the coordinate system so that the x axis is along
%leg 1
ang_rev1 = (Z+H);
ang_rev2 = (Z+H)-F;
```

```
if ang_rev1 >= ((90*pi)/180) %makes sure angle being calculated is less than 90
    ang_rev1 = ((180*pi)/180) - ang_rev1;
end

force(m).F4y = force(m).F4 * sin(ang_rev1); %calculates the forces perpinduclar to leg 1
force(m).F2y = force(m).F2 * sin(ang_rev2);

ang_rev3 = A2;
if ang_rev3 >= ((90*pi)/180)
    ang_rev3 = ((180*pi)/180) - ang_rev3;
end

%moment calculation on leg 1
force(m).R = ((-force(m).F4y * 11.4) + (force(m).F2y * 11.4))/((2.5)*sin(ang_rev3));

%force required my motor
force(m).F = force(m).R * cos(A1);


m = m + 1;
end

for i = 1:(m-1)
    xref(i) = (data(i).A1*180)/pi; %these are used to plot the force vs angle
    yref(i) = force(i).F;
    R(i) = force(i).R;
end
```