Development of a Computer Balanced Motion Table:

A Ground Testing Facility for Microsatellite Attitude Control Systems

By

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A thesis submitted in conformity with the requirements for the Degree of Master of Applied Science in the University of Toronto

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2000
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Development of a Computer Balanced Motion Table:

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Abstract

This thesis documents the design, build, and test, of a microsatellite attitude control system ground testing facility at the University of Toronto Institute for Aerospace Studies, Space Flight Laboratory. This facility is called a three-axis motion table. The motion table provides three rotational degrees of freedom similar to those experienced by a satellite in space. The trait that complicates the design of a motion table is that it has to be mass balanced. This means that the center of mass of the platform has to be positioned as close to the center of rotation as possible. In this manner, gravity will have little effect on the platform's rotation and therefore, will not overwhelm the ability of the satellite attitude control system to hold the platform in a commanded orientation. The fine balancing is accomplished by computer controlled on-board hardware. The balancing procedure involves recording the platform's unbalanced movement and then using this data to solve rigid-body motion equations to determine the position of the mass center. Once this position is known, three linear sliding masses are moved by stepper motors to correct the mass center offset. The sliding masses are referred to as mass movement units or MMUs.

A Matlab simulation of the movement and balancing of the motion table was completed. The simulation served three important purposes: 1) to educate the author on the mathematics involved in the workings and balancing of the table, 2) to quantify how well the table could be balanced with various quality sensors and actuators that were available off-the-shelf, 3) to quantify the errors induced by introducing simplifications to the balancing algorithm. It was shown that with a suite of affordable off-the-shelf sensors the balance algorithm is able to determine the mass center position to approximately 2% of what the mass center offset is during the recording of the platform motion data.

The table design uses a 4" spherical air bearing which gives the platform near frictionless movement with ±45 degrees of roll and pitch movement and 360 degrees of yaw movement. The MMUs that were built have a step movement of 0.00635 mm and a minimum moving mass of 0.2208 kg. This means, if the total mass of the platform is 30 kg (a typical platform weight with attitude control system equipment), the mass center can be stepped in 0.000045 mm increments. Therefore the balance requirement for the platform of 0.001 mm from the mass center to the center of rotation should easily be attained. However, it was found that the ¼” thick aluminum platform was relatively flexible causing the mass center to move 0.1 mm due to gravity bending the platform as it rotates. The critical balancing element is no longer dependent on the accuracy of the sensors and actuators but is now the rigidity of the platform. The solution to this problem is to have the on-board computer move the MMUs in proportion to platform tilt to compensate for the mass center movement. There was not enough time to test this idea but it should be able to be implemented with a small amount of work and with no additional hardware needed.
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1.0 Introduction

1.1 Purpose of Thesis Work

The purpose of this thesis is to design, build, and test, a microsatellite (microsat) attitude control system (ACS) ground testing facility for the University of Toronto Institute for Aerospace Studies (UTIAS) Space Flight Laboratory (SFL). This system is called a motion table. Figure one shows the general makeup and layout of a three-axis motion table. The Motion Table has not been designed from scratch but was based on a motion table that was designed and built by the Department of Mechanical and Aerospace Engineering at Utah State University under the direction of Rees Fulmer. The two main requirements that are driving the design are a relatively small budget and the ability of the system to simulate, as close as possible, three uninhibited rotational degrees of freedom. This facility is being developed for the initial purpose of testing the ACS of a Canadian microsat mission named MOST (Microvariability and Oscillations of STars). Therefore, the motion table will be built to the requirements of testing the MOST ACS. However, this facility will also be used in testing future attitude control systems and therefore must be adaptable.

1.2 Workings of a Motion Table

A three-axis motion table is a platform that is free to rotate in three directions (three degrees of freedom) while minimizing gravitational torques incident on the table. The platform will accommodate satellite ACS hardware. The platform simulates the space environment with its ability to point in almost any orientation without gravity torques overwhelming the satellite ACS. The external torque that is of greatest concern is the gravity-induced torque produced when the mass center (MC) of the platform does not coincide with the

![Figure 1: Table Components](image-url)
rotation center (RC) of the platform (see Figure 2).

In other words, when the table is not balanced, gravity produces a pendulous torque on the platform in all orientations except where the MC is directly underneath the RC. The on-board computer system (OBC) and sensors are used to record the free pendulous motion of the table. This data is then input into an off-board computer algorithm that calculates the MC to RC offset. The Mass Movement Units (MMUs) are then adjusted to correct for the MC offset. The table is then said to be "balanced".

Another less upsetting torque is caused by aerodynamic drag. The drag is induced by either rotation of the table or by air circulation around the table due to external sources within the testing room. The rotational aerodynamic torque is dealt with by including it in the platform's mathematical model and the "air circulation" induced torque will be minimized by isolating the table within its own testing area.

1.3 System Level Requirements

The system level requirements (that were determined before the design of the table began) act as general motion table design guidelines to ensure that the final system is useful as a microsat ACS ground testing facility.

1. Environmental Torque: the satellite attitude control system being tested should be able to manage the total environmental torque that is experienced on the motion table. In the case of the MOST ACS, the ACS reaction wheels, starting at zero speed, should be able to hold any attitude for a period of at least 1000 seconds before becoming saturated. This requirement was set by the MOST ACS designers.
2. **Rigidity:** As the platform rotates the gravity vector changes direction relative to the platform axis, the platform masses are thus pulled in different directions by gravity and the platform’s MC thus changes distance relative to the RC. Therefore, in order for the platform to remain balanced in all orientations, the platform must be rigid enough that its flexure does not cause the MC to move significantly relative to the required balance distance. As well, the table base will have a fundamental excitation frequency that must be above any platform oscillation rate. In other words, the table base and RC shouldn’t be able to be excited by vibrations seen during testing and therefore start to move.

3. **Inertia:** The inertia of the fully integrated table should be as close to the inertia of MOST as possible. This would provide a preferred hardware test environment. However, the inertia should not be significantly greater than the inertia of MOST so that the reaction wheels are not overwhelmed.

4. **User Friendliness:** The table should be as “user friendly” as possible in all its workings, taking into account time and money constraints.

5. **Balancing Time:** To computer balance a fully integrated table (manual balancing and sensor calibration has already been performed) should take under one hour.

6. **Payload Weight Accommodation:** The table should be able to accommodate at least 50kg of test hardware.

7. **Table Space:** The table should be able to spatially accommodate all of the ACS components to be tested.
8. **Table Adaptability:** The motion table facility should be flexible enough to accommodate future project requirements. It should also be as easy as possible to change from one project to the next.

9. **Payload Component Alignment:** Components that are mounted to the table should be able to be easily aligned with principle axes of the table. This will help in sensor alignment and make the platform’s inertia matrix easier to calculate.

10. **Platform Locking Mechanism:** The table platform should be able to be locked in place and supported while the air bearing is not in use. The ability to lock the platform in certain known orientations will also help in calibration of the table sensors.

11. **Autonomous Operation:** The platform has to be able to perform some of its duties with no physical exterior connections. This will ensure that there are few external torques and forces on the platform that are unaccounted for in the balancing algorithm.

### 1.4 Motion Table Balancing Characteristics

This section is a discussion of the inherent motion table balance properties that are required for understanding the sections that follow.

#### 1.4.1 Table Balance Requirement

The UTIAS Motion Table requirement is to balance the table so that the maximum gravity torque cannot saturate the MOST ACS reaction wheels in less than 1000 seconds (~15 minutes). The MOST ACS reaction wheels have a momentum capacity of 0.1 N·m·s. Therefore, the wheels can withstand 0.0001 N·m of torque for 1000 seconds from zero starting speed.
It is shown in Table 1, that in order to attain the MOST ACS table balance requirement the UTIAS table will have to bring its MC within 0.001 mm of its RC.

<p>| Calculation of Platform Gravity Torque (Platform Mass = 30 kg) |
|-----------------------------|-----------------------------|-----------------------------|</p>
<table>
<thead>
<tr>
<th>MC offset (mm)</th>
<th>Platform Tilt Angle (deg)</th>
<th>Gravity Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>20</td>
<td>1.01E-03</td>
</tr>
<tr>
<td>0.01</td>
<td>30</td>
<td>1.47E-03</td>
</tr>
<tr>
<td>0.01</td>
<td>40</td>
<td>1.39E-03</td>
</tr>
<tr>
<td>0.0001</td>
<td>20</td>
<td>1.01E-04</td>
</tr>
<tr>
<td>0.001</td>
<td>30</td>
<td>1.47E-04</td>
</tr>
<tr>
<td>0.001</td>
<td>40</td>
<td>1.89E-04</td>
</tr>
</tbody>
</table>

Table 1: External Gravity Torque

At first this requirement might seem too fine for the MMUs to cope with, but if the adjustable balancing masses are 1/100 of the full weight of the table, they only have to be positioned to 100 times the total MC position. In other words, to move the table MC 0.001 mm, the balancing mass has to move 0.1 mm, which is an easily attainable adjustment distance.

1.4.2 Flexible Body Effects

The table platform is constructed from ¼ inch thick aluminum plate. In the horizontal/rest position the gravity vector is perpendicular to the plane of the platform. Since the platform is only supported in its center and the weight of the attachments are spread over the platform, the weight of the attachments will bend the platform slightly downward around its center in an umbrella fashion. As the platform tilts away from the horizontal, the gravity vector rotates away from the perpendicular position and therefore its perpendicular component decreases as the platform tilts further off horizontal. Because the perpendicular gravity component decreases, the umbrella shaped bend in the platform straightens out. This causes the MC of the platform to move relative to the RC (upwards along the platform's z-axis). Therefore, as the platform rotates the MC will be in constant movement relative to the RC. If this movement is larger than
the balance requirement (0.001 mm), the platform will become unbalanced (and probably unstable) when it is in use.

**Approximate Bending Calculation**

A coarse calculation was performed to uncover the order of magnitude of the bending that occurs between the platform being in a horizontal position and a 45-degree tilt. This calculation is not meant to be accurate but is presented only to reveal whether the platform bending will have a significant effect on the movement of the MC, and therefore, the balance of the platform.

The Platform will have a total approx weight of 30kg (including the MOST hardware being tested). Therefore, in the horizontal position the gravity vector applies a 300 N force on the platform. When the platform is tilted 45 degrees from the horizontal, the perpendicular component of the gravity vector applies a force of $300 \cdot \cos(45) = 212$ N.

The formula for bending of a centrally supported circular plate with an equally distributed normal force around the plate perimeter is [Cook 1985]:

$$w = \frac{0.0505Pa^2}{D}$$

(1)

where:

$$D = \frac{Et^3}{12(1-\nu^2)}$$

(2)

Here, $w$ is the distance of downward bend of the outer edge of the plate, $P$ is the normal force placed around the edge of the plate, $a$ is the radius of the plate (0.4m), $E$ is the modulus of elasticity of the aluminum (72 GPa), $t$ is the thickness of the plate (0.00635m), and $\nu$ is poisson's ratio for aluminum (0.32).
Using this formula, in the horizontal position, the edge of the plate/platform bends 1.39 mm. In the tilt position the plate bends 1.00 mm. Therefore the movement of the edge between the two positions is 0.39 mm (Δw). Since all the mass is not concentrated on the edge and instead is spread over the platform, the bending stress will not be as great and therefore the bend will not be as great. Therefore, as an approximation this number is halved (Δw=0.20 mm). And again, since the Δw (vertical displacement) of the platform diminishes as you go in from the edge, and the mass is spread over the platform, the summation of the movement of the platform mass will be less than the movement at the edge. The movement of the MC of the platform is therefore approximated by halving the 0.20mm displacement (Δw=0.10mm).

As can be seen, the maximum movement of the MC is approximately on the order of 100 times the balance requirement. Therefore, the bending of the platform will have a significant effect on the balance of the table. Solutions to this problem are discussed in Section 3.8.
2.0 Table Sensor / Algorithm Simulation

A simulation of the motion table was performed in Matlab. This computer simulation represents the fundamental design work of the motion table. The Matlab code simulates the motion table movement, the sensors and sensor errors that track this movement, the errors in calculation of the platform inertia matrix and aerodynamic coefficients, and the algorithm that calculates the MC to RC offset of the platform. These simulations enabled the motion table hardware and software candidates to be evaluated before any hardware was actually purchased or built. On the hardware side, different levels of sensor noise and combinations of sensors were simulated. The results of these simulations showed which combination of sensors provides the motion table balance required at the lowest cost. On the software side, different complexities of rigid body motion equations and numerical solving methods were compared to determine the amount of balance accuracy lost with the simplification of the balancing algorithm.

The simulations were performed early in the project before the author was aware of the relatively large magnitude of the flexible body effects. Therefore, these effects were not simulated in the tests. The simulation results, however, are still helpful and the relevant data is now discussed.

2.1 Simulation Code Outline

Figure 3 shows a flow chart of the computer simulation code. The oval boxes show the input, the rectangular boxes show the program code, and the triangular boxes show the output. The “Inertia Matrix, Initial State, MC Offsets” input plus the “Full Motion Equations” code simulates the physical motion of the platform and outputs angle and rate data. Random error is then added to the data (Gaussian and uniformly distributed errors of various magnitudes were simulated) to simulate angle and rate sensor errors. This is representative of the platform motion data that the table sensors will output. This motion data is then filtered using a low-pass filter to minimize sensor noise. The data is filtered in forward time and then reverse to minimize the movement of the signal phase caused by low-pass filters. A Kalman filter was suggested by Rees Fulmer but was beyond the scope of this thesis and was not tried. The filtered data is compared to the original “Simulated Table Motion” data (without errors) to determine the best filtering
techniques. The "Inertia Matrix with Calculation Errors" is used in the balance algorithm and is formed by increasing the magnitude of the original "Inertia Matrix" terms by a chosen amount (i.e. add 10% to each term). The filtered data is input into the "Balance Algorithm", the heart of our balance code, which calculates the MC offsets of the platform. The "Calculated MC Offset" can then be compared to the original "MC Offset" numbers to reveal the calculation errors that occurred.

The sensor error magnitudes were determined from noise specifications of the off-the-shelf sensors that were being considered for use on the table. The platform inertia matrix errors were chosen from the errors expected from various methods, used by industry, for determining the rotational inertia of a rigid body [Crookston, 1992]. The errors were simulated one at a time so that their effect could be measured separately.

2.2 Simulation Test Results

The MC offset determination errors shown in the next four sections are averaged over a range of initial conditions and initial MC offset values. The data from which the average errors were calculated are contained in Appendix 1.
2.2.1 Balance Algorithm error

The following percent errors are MC offset determination errors, as determined by three different balance algorithms. The errors are calculated as a percentage of the initial MC offset and are an average of the error in each axis and over a range of initial conditions. The errors are due only to numerical approximations in the algorithm formulas. The simplified motion equations are the equations used by Utah State to balance their motion table. Utah assumes that the rotation rates, products of inertia, and the aerodynamic torques are small compared to the other terms and therefore are set to zero. This leaves simple equations that can be integrated to leave variables of Euler angles and rotational rates. When using the full motion equations as described in Section 4.1 either the rotation rates have to be numerically differentiated for substitution into the angular acceleration terms (as done in the second balance algorithm) or the motion equation acceleration terms have to be numerically integrated into rotational rate terms (as done in the third balance algorithm).

- Closed solution to simplified motion equations (Utah State Method) = 0.5%
- Using full motion equations & numerical differentiation of rate data = 0.006%
- Using full motion equations & numerical integration of acceleration terms = 0.002%

All these errors are relatively low, but the algorithm with the lowest error value is the obvious one to use since there are no concerns about the computing power needed to solve these equations.

2.2.2 Inertia Matrix Error

The inertia matrix errors are caused by inexact determination methods for the table platform inertia matrix. The products of inertia and moments of inertia terms were increased by the amounts shown below to simulate the inertia matrix determination errors. The CM offset determination errors caused by the errors in products of inertia and moments of inertia were calculated separately because different determination methods can be employed to measure the two types of inertia. So the different methods’ impact on MC offset error is viewed separately.
+10% increase in products of inertia terms = 0.2% MC offset error
+20% increase in products of inertia terms = 0.5% MC offset error
+10% increase in moments of inertia terms = 10% MC offset error
+20% increase in moments of inertia terms = 20% MC offset error

The error in the platform's moments inertia terms cause significant error in the determination of the MC offset. Therefore, the most accurate method for calculating these values should be used and special care should be taken by the motion table operator to ensure that these values are accurate. The products of inertia, on the other hand, have a much smaller effect on MC offset error. Therefore, accurate determination of these values is less important than the determination of the moments of inertia.

2.2.3 Aerodynamic Drag Coefficient Error

An aerodynamic drag coefficient of 0.1 was used by Utah State in a similar motion table simulation [Young 1998]. Since the UTIAS motion table design is similar 0.1 was thought to be a good initial estimation of the aerodynamic drag coefficient. To simulate the error in the determination of the aerodynamic drag coefficient, a value of 0.1 was used in the algorithm that generates the table motion data then different values for the coefficient were used in the balancing algorithm.

- Original coefficient = 0.1
- Solver coefficient of 0.2, error = 1.4% MC offset error
- Solver coefficient of 0.3, error = 2.7% MC offset error
- Solver coefficient of 0.4, error = 4.1% MC offset error

The MC offset errors are relatively small for relatively large drag coefficient error. Therefore, a relatively simple method for determining this coefficient was used. This method is discussed in Section 6.3.
2.2.4 Rate & Angle Sensor Error

In the computer balancing procedure the motion table platform has an initial, unknown, MC offset that causes the platform to move in a pendulous manner. It is the recording and analysis of this movement that gives the user the position of the MC offset (for which he can then correct).

The MC offset determination error is calculated as a percentage of the MC offset magnitude that the platform has during the recording of its movement. The results of the sensor error simulations showed that, the MC offset error stays relatively constant while varying the initial MC offset value (Other simulation parameters are constant). Therefore, as the initial MC offset gets smaller, the calculation of the MC position became more precise. In other words, if the initial MC offset is 1.0 mm and the MC offset determination error is ±10% then the MC position can be determined to an accuracy of ±0.1 mm. However, if initial MC offset is 0.1 mm, the MC position can be determined to an accuracy of ±0.01 mm. Therefore, the most accurate MC position can be found by gathering platform motion information using the smallest practical initial MC offset. Since the platform was found to exhibit non-negligible bending as a function of platform tilt, if the initial MC offset is too small, tilting of the platform will cause it to go unstable rendering the recording of the pendulous movement of the table impossible. Therefore, to calculate the most accurate MC position the initial MC offset must not be set too large or too small. In Section 1.4.2 the flexible platform bending was determined to cause the MC to move 0.1 mm from 0 to 45 degree tilt (with the approx. MOST ACS weight). It was decided that smallest practical MC offset that can be used during a balancing run is one that would set the stable/unstable tilt limit at 15 degrees. Using the “bending” spreadsheet (reference), this offset was determined to be approximately 0.01 mm. If a smaller offset is used the tilting range for stable platform movement becomes too small to work with.

The following table shows the MC calculation errors with respect to different sensor errors. The levels of sensor error were chosen to correspond to output errors found in off-the-shelf sensors that were designated as possible design picks (the zero magnitude sensor noise is simulated for comparison purposes and is not meant to represent an actual sensor).
As seen in Table 2, the rise in error of the rate sensor seems to have more of an effect on the MC calculation error than the rise in the angle errors. This can be attributed to the slow platform rotation rate and relatively large rate sensor noise. Therefore, an alternative approach was pursued.

### 2.2.5 Angle Sensor Error

A second sensor error simulation was performed that only used angle data as input into the balance algorithm. Angular rate and angular acceleration were then determined through two numerical differentiations.

<table>
<thead>
<tr>
<th>Rate Error</th>
<th>Angle Error</th>
<th>MC Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°/sec</td>
<td>±0.5°</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>±0.01°/sec</td>
<td>-</td>
<td>0.21%</td>
</tr>
<tr>
<td>±0.3°/sec</td>
<td>7.99%</td>
<td>7.48%</td>
</tr>
</tbody>
</table>

Table 3: Average MC offset error calculated at a 0.01mm CM offset

As seen in Table 3, the results are very favorable. It shows the MC offset errors are far below the errors found in the last row of Table 2 while only using angle sensors. This is a favorable design solution since the overall motion table cost drops because it can do its job without the use of rate sensors.

### 2.2.6 Test of Simulation

Finally, a test of the simulation itself was done. Using the Utah State balance algorithm and actual balance test data from the Utah State table [Young 1998] a simulation of that test was performed. The data from the Utah State test gave the inputs and initial conditions that were used in the simulation, and the smallest MC offset that could be calculated by the balance algorithm (approx. 0.02 mm). Therefore, if the
simulation is accurate, it will show that the MC offset error goes above 100% when the actual MC offset goes below 0.02mm.

<table>
<thead>
<tr>
<th>Actual CM offset</th>
<th>0.2mm</th>
<th>0.02mm</th>
<th>0.002mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated CM offset error</td>
<td>6%</td>
<td>9%</td>
<td>244%</td>
</tr>
</tbody>
</table>

Table 4: Utah State CM offset error

As seen in Table 4, our conjecture was true, and the simulations seem to have some validity in the real world.
3.0 Table Design

There are certain key design features that went into the design of the UTIAS/SFL motion table that are discussed in the following sections.

3.1 User-friendliness

The system user-friendliness is determined by every part of the table design. Therefore, the “ease of use” philosophy was kept in mind throughout the entire development and design of the motion table to try and make the motion table as easy to use as possible given the money and time constraints. For example, as much automation as possible was built into the table software without compromising its flexibility. There are a few parts of the table software that were partially developed but not fully implemented due to lack of time (and scope of a master’s thesis). These unfinished software components are discussed in Section 8.0.

3.2 Platform Space & Layout Flexibility

The platform consists of a circular plate. Platform space is obviously dictated by the diameter of the table platform. The current platform being used is 800mm in diameter. This large diameter ensures that the platform is able to accommodate all the hardware, since the exact dimensions of the hardware to be tested will not be known until the testing starts. However, in the future, platforms specific to the hardware under test could be manufactured. This would help by minimizing unwanted environmental aerodynamic torque and flexible body bending.

Several aspects of the platform/balance hardware design enable flexibility in the use of the platform space. The table platform is designed with a grid of 8-32 threads, with 50mm spacing, that is used as a standard bolt pattern for attaching hardware. The balancing hardware, which includes the OBC, battery, sensors, and MMUs are self-contained units with the same attachment pattern. In this way, these units can be easily positioned and aligned almost anywhere on the table. This allows for flexible placement of the balance hardware, making it easier for the operator to accommodate different hardware and pre-balance the
platform by specific placement of the platform hardware (less need for manual balance weights). As well, the magnetometer, which has to be mounted away from the other components on the platform (see Section 3.9), has two types of mounting options. One option is a tripod-type mount and the other a pillar-type mount (see Figures 4 and 5). The tripod mount frees up space in the middle of the platform while the pillar mount frees up space around the perimeter of the platform. The operator then has this option for better accommodation of ACS hardware.

![Figure 4: Tripod Magnetometer Mount](image1)

![Figure 5: Pillar Magnetometer Mount](image2)

### 3.3 Platform Inertia

The inertia of the fully integrated platform can be controlled by the placement of the balance and ACS hardware on the table platform. If the inertia of the fully integrated platform is too small, extra manual balance weight can be added to increase the inertia. The fully integrated table is not expected to have a larger inertia than the fully integrated MOST satellite, and therefore, the platform inertias could be tuned to simulate the MOST satellite if required. MOST is expected to have moments of inertia of approximately 1.3, 2.2, and 2.2 kg·m². The expected moments of inertia of the motion table platform with the MOST ACS hardware is 1.4, 1.4, and 2.3 kg·m² (see Appendix 2 for the Calculation Spreadsheet).
3.4 Table Vibration Isolation

The table stand was designed to minimize the conduction of vibrations from the floor into the motion table. This was achieved by using a 100 lb concrete base (see Figure 6) that sits on four rubber vibration isolation pads. The weight of the concrete at least doubles the mass of the motion table, which works together with the isolations pads to lessen the excitation of the system from external vibrations.

A basic vibration analysis was also performed on the stand design to ensure that the fundamental excitation frequency of the stand was greater than the highest expected rocking (pendulous) frequency of the platform movement. The highest expected rocking frequency (pendulous platform motion) of the platform is about 5 Hz, this occurs when the CM offset is about 1 mm. Using a closed-form solution of a beam with a mass at one end and fixed at the other, the fundamental frequency of the stand was determined to be between 50 and 70 Hz depending on the weight of the platform [Inman 1994]. This is much higher than the low platform motion and therefore does not present a problem. See Appendix 3 for the frequency calculation.

3.5 Air Bearing System

The air bearing system consists of air supply hardware and a spherical air bearing. The spherical air bearing is a precision-machined piece that provides almost frictionless, precise rotational movement. Therefore, the air bearing itself must be properly cared for. It must not be scratched and the pressurized air provider must supply clean filtered air.

3.5.1 Air Bearing

One of the design features that was fixed at the very beginning of this project was to use a Nelson Air 4” spherical air bearing. This is the same bearing that the Utah State University motion table uses (see
Appendix 4 for details). This air bearing fits all the requirements for the UTIAS/SFL motion table. The following table calculates the maximum bearing load capacity using the projected bearing cup area and the input pressure of the bearing (together with a Safety Factor of 1.4).

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Load Capacity (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>153</td>
</tr>
<tr>
<td>80</td>
<td>122</td>
</tr>
<tr>
<td>60</td>
<td>92</td>
</tr>
<tr>
<td>40</td>
<td>61</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5: Load Capacity vs. Air Pressure

We expect the total platform weight to not exceed 50kg for MOST. The manufacture of the air bearing specifies a maximum air pressure of 100 psi. Therefore, as seen in table 5, the bearing can easily accommodate the type of loading expected with moderate air supply pressures. The air pressure should be kept to a minimum while being extremely careful not to let the two bearing surfaces rub against each other. This will establish the lowest airflow rate, extending the life of the air cylinder.

3.5.2 Air Supply

The main components used in the Air supply system are shown in Figure 7. A compressed dry air cylinder with a two-stage pressure regulator provides the pressurized air. As a precaution, the air is run through a filter. The filtered air pressure is then lowered to the required bearing pressure with the use of a variable pressure regulator. Both the filter and regulator are mounted on the Table Base (See Figure 1). The air filter blocks particles that could either clog some parts of the air bearing or get in
between the two bearing surfaces and scratch/damage the bearing surfaces. See Appendix 4 for data sheets on these components.

3.6 Manual Balance Weight System

3.6.1 Manual Balance Weights

A set of standard weights were designed and machined from non-magnetic materials (Stainless Steel and Bronze). Each weight is a circular disk with a ¼ inch mounting hole drilled through its center. A balance weight requirement was set to cope with test equipment with a maximum weight of 20 kg and a MC 100 mm above the platform (since most of the test hardware will be mounted on the top side of the platform).

Therefore, a total of 20 kg of balance mass was machined with an attachment system capable of placing the MC of the weight 100 mm below the platform. The weights were broken into a system of half sizes so that any weight between 0 and 20 kg (in increments of 38 g) can be produced. There are four pieces for each weight size which matches the four quadrant mounting system. Manual balancing in the horizontal directions can be performed by varying the amount of weight that is attached in opposing quadrants of the platform. Table 6 shows the dimensions and masses of the manual weights that were made.

<table>
<thead>
<tr>
<th>Total Mass Increments (g)</th>
<th>Mass of Each of 4 Balance Weights (g)</th>
<th>3.5&quot; dia. Bronze Rod</th>
<th>3&quot; dia. Stainless Steel Rod</th>
<th>2.5&quot; dia. Stainless Steel Rod</th>
<th>4.8 mm thick Stainless Steel Plate</th>
<th>2.76 mm thick Stainless Steel Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000.0</td>
<td>2500.0</td>
<td>1.743</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5000.0</td>
<td>1250.0</td>
<td>0.872</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2500.0</td>
<td>625.0</td>
<td>-</td>
<td>0.689</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1250.0</td>
<td>312.5</td>
<td>-</td>
<td>-</td>
<td>0.495</td>
<td>-</td>
<td>72.68</td>
</tr>
<tr>
<td>625.0</td>
<td>156.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>72.68</td>
<td>67.76</td>
</tr>
<tr>
<td>312.5</td>
<td>78.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>67.76</td>
</tr>
<tr>
<td>156.3</td>
<td>39.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>47.86</td>
</tr>
</tbody>
</table>

Table 6: Manual Balance Weight Specifics
3.6.2 Weight Placement System

A system for simple yet flexible placement of the manual balance weights was devised. It consists of a set of 12, ¼-20 threaded holes machined into the platform in four quadrants, 3 threads to a quadrant. See Appendix 5 for thread placement on the platform CAD drawing. Threaded rods mount in these threaded holes and a combination of weights can be mounted on each of these rods. ½ inch aluminum tubing is machined to a specified length (determined during the manual balancing process and therefore specific to the hardware being balanced) and is used as a spacer between the platform and the weights. These tubes greatly stiffen the mounts to ensure rigidity. See Figure 8 for configuration of the weight attachment system.

3.7 Mass Movement Unit

3.7.1 Design Explanation

Design of the Mass Moving Units (MMUs) had to be carefully considered to maximize the precision of the balancing system and still keep it flexible enough to handle varying payload weights while also keeping the total MMU system cost down. After comprehensive analysis, a system of off-the-self parts with a custom structure was determined to have the best "bang for the buck". All of the off-the-shelf linear stage systems were either too expensive or too imprecise for the balance requirement. A custom MMU design would also be too expensive and impractical. The final design consists of a simple aluminum plate structure holding a small 1.8 deg. stepper motor. The stepper motor is directly connected, via a coupling, to a 25 thread per inch linear screw with an anti-backlash nut. The linear screw nut is connected to the platform of a small precision linear slide, the base of which is attached to the aluminum structure. The platform of the linear slide acts as the moving weight. If more weight is required, the extra weight can be attached to the slide platform. See Figures 9 and 10 for pictures of the horizontal and vertical MMUs.
3.7.2 MMU / MC Movement

Since a stepper motor is used to control the movement of the MMU mass, this mass will only move in increments and therefore the MC offset can only be corrected to a limited accuracy. This accuracy (MC increment distance) is determined by the MMU step distance, total stroke, balance weight mass, and total mass of the platform. Since the MMU step distance and total stroke are specified by the MMU design, these parameters had to be carefully decided upon before anything was built. Since the balancing accuracy is specified to be 0.001 mm (in the case of the MOST satellite, 30 kg platform), the z-axis MC increment distance has to be at least half of that (0.0005 mm, with a 30 kg platform). The horizontal MC increment distance (x-axis and y-axis) must be 1/10 of the z-axis increment (0.00005 mm, with a 30 kg platform). This ensures that the horizontal MC offset components are much less than the vertical component. This enables the system to keep most of the MC offset in the vertical axis, causing the platform to be horizontally stable. The MMU step distance must be accordingly small enough to accommodate the MC movement.

The ability to manually balance the platform is anticipated to translate into a maximum vertical MC offset of 0.4 mm and horizontal offset of ±0.2 mm (See Figure 2 for reference frame axes). Therefore, the MMU
for each axis must have enough stroke to correct this offset. A spreadsheet was produced to calculate the mass of the MMU's given the platform mass and the variables discussed above.

<table>
<thead>
<tr>
<th>MMU Type</th>
<th>Total Mass of Platform (Kg)</th>
<th>Mass of MMU (Kg)</th>
<th>MMU Increment Distance (mm)</th>
<th>MC Increment Distance (mm)</th>
<th>MMU Stroke (mm)</th>
<th>Total MC Movement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>30</td>
<td>0.2208</td>
<td>0.00635</td>
<td>0.0000449208</td>
<td>108</td>
<td>0.764</td>
</tr>
<tr>
<td>Vertical</td>
<td>30</td>
<td>0.1578</td>
<td>0.00635</td>
<td>0.0000321037</td>
<td>75</td>
<td>0.379</td>
</tr>
</tbody>
</table>

Table 7: Calculation of MMU Parameters

In the above spreadsheet the total move of the MMUs (stroke of the linear slide), the incremental movement of the MMUs (motor step and linear screw pitch), the mass of the MMUs (mass of linear slide with no weight), and the total mass of the system (expected MOST test weight) were fixed. This calculation gives the minimum MC increment distance and the minimum MC total move (since the minimum MMU weight is used). The horizontal MMUs are within our above specifications but the MC total move for the vertical MMU is slightly less than needed. This is corrected by adding weight to the vertical MMU.
3.8  Flexible Body Effects

As discussed in Section 1.4.2, the motion table platform bends as it rotates, causing the MC to move up to 0.1 mm (in the case of MOST ACS testing). This effect makes the static balance of the platform, to the 0.001 mm specification impossible. The following are two inexpensive, simple solutions to this flexible body problem.

Static Solution

By positioning the MMUs, the MC is deliberately placed far enough below the RC so that the MC can never move above the RC in any table orientation. In consequence, the platform will never become unstable but the gravity induced torques become much greater than the requirement. A graph of the gravity moment vs. the tilt angle for the MOST testing case is shown in Figure 11. For this example, the attitude control hardware being tested will experience torques ranging from 0 to 0.008 N-m. At the maximum torque value the MOST reaction wheels would saturate in 12.5 seconds. If this torque curve is acceptable for the ACS testing then this solution is the simplest.

![Graph of gravity torque vs. tilt angle](image)

Figure 11: Gravity Torque Vs. Tilt Angle
Dynamic Solution

Another possible solution is to use the z-axis MMU to compensate for the z-axis movement of the MC.

Since the bending of the table and therefore the movement of the MC is proportional to the magnitude of the perpendicular gravity component, a simple linear formula can be used to calculate where the MMU weight should be positioned, using the absolute tilt of the table as the input. The z-axis MMU, therefore, would have to be actively moving while the table is in use. The formula for the determination of the MC position in the z-axis is:

\[
r_z = r'_z + C \cos \eta
\]

where:

\[
\eta = \arccos\left(\frac{1}{2} (\cos \theta + \cos \phi + \cos \theta \cos \phi - 1)\right)
\]

Here, \( r_z \) is the z component of the RC to MC vector (expressed in the body frame), \( r'_z \) is the z component of the RC to MC vector when there is no gravity force bending the table (expressed in the body frame), \( C \) is the absolute change of the MC z component from no gravity to full gravity, \( \eta \) is the absolute off-horizontal tilt of the table (expressed in the inertial frame), \( \theta \) is the platform pitch, and \( \phi \) is the platform roll.

This dynamic solution is accomplished using the same hardware that is used to balance the table. The OBC calculates the position of the MC using Eq. 3 and then moves the z MMU to compensate for MC movement. This computation and MMU movement should be able to be done at a maximum rate of ten times a second. This code has not been implemented due to time constraints. However, it should be a simple process to do so and it would greatly improve the balance capability of the motion table over a simple static balance.

In the same manner, slight movement of the x and y components of the MC offset can also be characterized and compensated for using the x and y axes MMUs. The MC horizontal component movement is
proportional to the sine of the off-horizontal tilt angle in each of the x and y axes. Bending equations for these axes are as follows:

\[ r_x = r'_x + A \sin \lambda \]  \hspace{1cm} (5)

\[ r_y = r'_y - B \sin \theta \]  \hspace{1cm} (6)

Here, \( r_x \) is the x component of the RC to MC vector (expressed in the body frame), \( r'_x \) is the x component of the RC to MC vector when there is no gravity force bending the table (expressed in the body frame), \( A \) is the absolute change of the MC x component from no gravity to full gravity, \( \lambda \) is the angle, perpendicular to the inertial horizontal, between the body x axis and the horizontal (x-axis tilt sensor reading), \( r_y \) is the y component of the RC to MC vector (expressed in the body frame), \( r'_y \) is the y component of the RC to MC vector when there is no gravity force bending the table (expressed in the body frame), \( B \) is the absolute change of the MC y component from no gravity to full gravity, and \( \theta \) is the platform pitch.

### 3.9 Sensor Optimization

The table design had to take into account the type of sensors being used in order to optimize the sensor working conditions and their ability to be calibrated. The following sections address these concerns.

#### 3.9.1 Sensor placement

The tilt sensor or inclinometer uses micro-machined cantilevered bars with strain gages. Gravity puts strain on the bars in proportion to the cosine of the angle between the bar axis and the gravity vector. Rotation of the table will incur acceleration forces on the bars that will add unwanted errors to the sensor reading. The further the sensor is positioned from the RC the greater these errors will be. Therefore, the tilt sensor is located directly over the air bearing in order to minimize the acceleration force errors.

The magnetometer outputs the vector components of Earth's magnetic field. Since the earth's magnetic field is weak, other artificially generated magnetic fields (e.g. from on-table motor magnets) as well as
passive metal shielding (ferrous metal table components) can easily distort the earth's magnetic field, creating large magnetometer errors [Liu 1990]. Therefore, the magnetometer is placed on a platform (connected to the table) located approximately a meter above the table (see Section 3.2, Figures 4 and 5). This minimizes gravity field distortions at the sensor position (caused by the hardware being tested) while still allowing the sensor to be a part of and move with the motion table platform.

3.9.2 Table construction materials

As mentioned above, ferrous metal components that are part of the motion table platform will distort Earth's magnetic field and produce magnetometer errors. Therefore, as much as possible non-ferrous materials were used to construct the table. These materials included aluminum, brass, and stainless steel.

3.9.3 Sensor Calibration

The tilt sensor is a relatively accurate, low noise sensor that does not require an elaborate calibration algorithm. Therefore, linear equations are used to both convert and calibrate the digital output of the sensor into radians. The sensor outputs two 8-bit numbers per tilt axis that are converted into a 16-bit number using the following equation:

\[
16 \text{ bit Integer} = 256 \cdot \text{MSB} + \text{LSB}
\]  

Figure 12: Example of a Tilt Sensor Calibration Graph

The 16-bit number corresponds to a tilt angle as shown in Figure 12. The zero offset and the slope of the two lines in Figure 12 are determined for both pitch and roll by collecting tilt data for certain predetermined tilts and inputting this data into a simple Matlab calibration program (see Appendix 6). The constants that
are output by the calibration program are then used in the platform balance algorithm. See section 6.3 for a detailed explanation of the tilt sensor calibration procedure.

The magnetometer output, on the other hand, is affected by electro-magnetic interference from surroundings and the table hardware. Therefore, a relatively advanced calibration algorithm is used and has to be updated with any change of table hardware, table location, or long length of time between table uses. As seen in Figure 13, a removable platform lock is used in the table design. The most obvious reason for its use is to lock the platform in place while the air bearing is not in use or components are being added or removed from the platform. This lock is also used to calibrate the magnetometer. As can barely be seen in Figure 13, there are 12 small holes in the platform that are equally spaced around the table centre where the three spikes of the platform lock mate with the platform. Therefore, the platform can be held in 12 known horizontal orientations. These set orientations will be used when obtaining magnetometer calibration data. The ability to calibrate the magnetometer in the surroundings that it is being used is essential for obtaining precise calibration constants. See Section 6.3 for a detailed explanation of the magnetometer calibration.

3.10 Electronic Board Design

Both the OBC and the Magnetometer required custom in-house IC circuit design. The following section gives a short description of each design. See Appendix 7 for circuit diagrams.
3.10.1 OBC Board

In order to minimize size and power requirements, the OBC board was a custom design based around an ATMEG AT89C55 microcontroller. The board contains one RS-485 port to connect to the three stepper motor boards, Three RS-232 ports to connect to the tilt sensor, the off-board computer, and a future wireless link (see Section 8), and one RS-232 port (with an eight wire RJ-45 connector) that connects to the magnetometer. The OBC has four, 128k blocks of SDRAM and 64k of SRAM. The SDRAM is used to store the platform balance run data, of which it can hold just over 5000 data points. The SRAM is used as expansion memory for the microprocessor. The microprocessor chip has on-board memory that holds the OBC software.

3.10.2 Magnetometer Board

In order to save money (limited hardware budget), a magnetometer chip (Honeywell HMC-2003) was purchased and a small IC board was designed in-house to support it. Honeywell does offer a package with sensor and support electronics (HMR-2300) but it costs about $2000. In hindsight this package should have been purchased since the in-house board development was more complicated than expected.
The board contains amplifiers to amplify the analog signals coming from the three magnetometer chip outputs (one for each magnetic vector component). These amplified signals are fed into 12-bit A/D converters, which the OBC can then read. There is also an “integrated field strap” on the magnetometer chip which de-gausses the sensor. In other words, the sensing chip can be biased slightly if it comes in contact with a strong magnetic field. The field strap will statically clean the sensor and get rid of the bias. The magnetometer board has circuitry to drive these straps.

Calibration of Magnetometer Amplification

The amplification magnitude for the magnetometer signal had to be calibrated so that the A/D converters would see the greatest range of analog signal without saturation. This was accomplished by measuring the magnitude and direction of the earth’s magnetic field in the area where the motion table will be used. Then, by knowing the sensitivity of the sensor chip (100,000 nT/Volt) and the maximum input voltage of the A/D converters (5 volts), a calculation was performed to find the amplification magnitude (4.69). The amplifiers are hardwired with resistors to achieve the amplification factor. In the future, if the table is used at a different site the magnetometer output must be checked to see that it is not saturating the A/D converter. If the A/D converter is being saturated an appropriate amplification magnitude must be set by replacing the current amplification resistors with appropriate ones.

3.11 Autonomous Operation

Due to financial constraints the initial design has a hardwired serial connection between the on-board platform computer and the off-board desktop computer. This design does not impact on the balance quality obtainable by the system. It does, however, make the balancing process a bit more cumbersome since the serial cable will have to be attached and detached multiple times during a balancing process. In the future, the table should be fitted with a wireless communication device (see Section 8).
3.12 Table Cost Summary

Table 8 shows an abbreviated cost summary for the complete motion table. A more detailed price breakdown is contained in Appendix 8.

<table>
<thead>
<tr>
<th>Part #</th>
<th>Part Name</th>
<th>notes</th>
<th>Quantity</th>
<th>Source</th>
<th>Price (Can)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All Machined Parts</td>
<td>Parts shown in CAD drawing Appendix N/A</td>
<td></td>
<td>Machine Shop</td>
<td>$5,500.00</td>
</tr>
<tr>
<td>2</td>
<td>Spherical Air Bearing</td>
<td></td>
<td>1</td>
<td>Nelson Air</td>
<td>$5,270.00</td>
</tr>
<tr>
<td>3</td>
<td>MMU parts</td>
<td>Couplings, Ball Bearings, Linear Slides N/A</td>
<td></td>
<td>BERG inc</td>
<td>$1,540.00</td>
</tr>
<tr>
<td>4</td>
<td>MMU stepper motors</td>
<td></td>
<td>3</td>
<td>EAD inc.</td>
<td>$360.00</td>
</tr>
<tr>
<td>5</td>
<td>MMU stepper drivers</td>
<td></td>
<td>3</td>
<td>Pontech</td>
<td>$1,000.00</td>
</tr>
<tr>
<td>6</td>
<td>MMU lead screw and nuts</td>
<td>1 screw, 3 nuts</td>
<td>1</td>
<td>Techno-set</td>
<td>$200.00</td>
</tr>
<tr>
<td>7</td>
<td>Magnetometer sensor chip</td>
<td></td>
<td>1</td>
<td>Honeywell</td>
<td>$430.00</td>
</tr>
<tr>
<td>8</td>
<td>Magnetometer &amp; OBC boards</td>
<td>photoplotting of 10 boards of each</td>
<td>20</td>
<td>IC board shop</td>
<td>$690.00</td>
</tr>
<tr>
<td>9</td>
<td>Microcontroller chip</td>
<td>for OBC board N/A</td>
<td></td>
<td>Digkey</td>
<td>$907</td>
</tr>
<tr>
<td>10</td>
<td>Misc. electronics</td>
<td>chips for magnetometer and OBC N/A</td>
<td></td>
<td>electronics</td>
<td>$500.00</td>
</tr>
<tr>
<td>11</td>
<td>tilt sensor</td>
<td></td>
<td>1</td>
<td>Crossbow Technology</td>
<td>$1,400.00</td>
</tr>
<tr>
<td>12</td>
<td>air provider parts</td>
<td>fittings, tubing, regulator/filter N/A</td>
<td></td>
<td>Pneumatics store</td>
<td>$240.00</td>
</tr>
<tr>
<td>13</td>
<td>air bottle regulator</td>
<td></td>
<td>1</td>
<td>Air bottle supplier</td>
<td>$350.00</td>
</tr>
<tr>
<td>14</td>
<td>Concrete Base</td>
<td>supplies to make</td>
<td>1</td>
<td>Hardware store</td>
<td>$60.00</td>
</tr>
<tr>
<td>15</td>
<td>Manual Weights</td>
<td>Material to make</td>
<td>N/A</td>
<td>Metals store</td>
<td>$300.00</td>
</tr>
</tbody>
</table>

|                      |                               |                                             |          |                       |             |
|                      |                               |                                             |          | Total                 | $17,740.00  |

Table 8: Motion Table Cost Summary

3.13 CAD/Assembly Drawings

All the mechanical drawings were drawn in Mechanical Desktop 3.0. All component and assembly drawings are supplied in Appendix 5.
4.0 Balancing Algorithm

The Algorithm used to calculate the position of the MC with respect to the RC is derived using a rigid body motion equation with additional terms to account for the gravity-induced torque, torque from aerodynamic drag, and platform bending.

The rigid body motion equation was derived using two frames of reference: the Inertial Frame and the Body Frame. The inertial frame is fixed in space with its z-axis pointing down (see Figure 2) and the body frame is fixed to the motion table platform. Both frames share the same origin, which is also the rotational center of the platform. The rotation from the inertial frame to the body frame is defined using Euler angles in yaw-pitch-roll sequence. The mass center of the platform is fixed in the body frame and its position is represented by the vector “r” (see Figure 17).

4.1 Motion Equation

The motion equation for the table platform is [Hughes 1986]:

\[ J\ddot{\omega} + \omega^x J\omega = g_{aero} + g_{gravity} \]  

See Appendix 9 for a derivation of the external torque terms. Eq. 8 written out in component form is:

\[
\begin{bmatrix}
J_{xx} & J_{xy} & J_{xz} \\
J_{yx} & J_{yy} & J_{yz} \\
J_{zx} & J_{zy} & J_{zz}
\end{bmatrix}
\begin{bmatrix}
\dot{\omega}_x \\
\dot{\omega}_y \\
\dot{\omega}_z
\end{bmatrix}
+
\begin{bmatrix}
0 & -\omega_z & \omega_y \\
\omega_z & 0 & -\omega_x \\
-\omega_y & \omega_x & 0
\end{bmatrix}
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
=
\begin{bmatrix}
-D\omega_y (\sin\omega_x) \\
-D\omega_z (\sin\omega_x) \\
+M_{gy} -\cos\omega_x \cos\theta & -\sin\omega_x \cos\theta & 0 \\
\cos\omega_x \sin\theta & \sin\omega_x \sin\theta & 0 \\
\sin\omega_x \cos\theta & \cos\omega_x \sin\theta & 0
\end{bmatrix}
\begin{bmatrix}
g_{aero} \\
g_{gravity}
\end{bmatrix}
\]  

(9)
Symbols Definitions

- **ϕ** - Roll: angular rotation about the x axis, expressed in the body frame
- **θ** - Pitch: angular rotation about the y axis, expressed in the body frame
- **ψ** - Yaw: angular rotation about the z axis, expressed in the body frame
- **λ** - X axis Tilt: the angle, perpendicular to the inertial horizontal, between the body x axis and the horizontal (x-axis tilt sensor reading)
- **η** - Horizontal Tilt: absolute off-horizontal tilt of the table (see section 3.8)

- **ω_x, ω_y, ω_z** - Angular Rotation Rates about the x, y, and z axis respectively, expressed in the inertial frame

- **ω̇_x, ω̇_y, ω̇_z** - Angular Accelerations about the x, y, and z axis respectively, expressed in the inertial frame

- **r'_x, r'_y, r'_z** - Vector components of the mass center offset w.r.t. the rotational center when there is no gravity force bending the platform, expressed in the body frame.

- **A, B, C** - Components of the absolute change of the “r” vector (Δr) from no platform bending to full platform bending.

- **J** - 3x3 inertia matrix, defined in the body frame at the mass center.

- **D_x, D_y, D_z** - Coefficients of Aerodynamic Drag

- **M** - Total mass of the rigid body

- **g_{aero}** - Aerodynamic torque term

- **g_{gravity}** - Gravity induced torque term with platform bending included

- **g_a** - Acceleration due to gravity

Procedure for solving the equation

The terms in the equation are obtained in various ways. The inertia matrix of the body is calculated using a mass distribution estimate (see Section 6.2). From this information the total mass of the body is also calculated. The aerodynamic drag coefficients are estimated through experimental tests (see Section 6.3).

The Euler angles are derived from discrete-time sensor data that is recorded during platform balancing. Through numerical differentiation angular rates and angular accelerations are derived from the Euler angles. A least-squares method is then used to fit the data to the mathematical model and the MC offset vector r' and the Δr components (A, B, and C) are determined. This is achieved by inputting all the data to get an equation of the form:
\[
\begin{bmatrix}
a_1 \\
a_2 \\
\vdots \\
a_n 
\end{bmatrix}
_{3 \times 1} =
\begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_n 
\end{bmatrix}
_{3 \times 6}
\begin{bmatrix}
r'_x \\
r'_y \\
r'_z \\
A \\
B \\
C
\end{bmatrix}
\] (10)

where:  \( n \) is the number of sensor data points recorded

\[a_k = J\dot{\omega}_k + \omega_k^x J\omega_k - g_{aero},\] (11)

\[
B_k =
\begin{bmatrix}
0 & \cos \phi \cos \theta & -\sin \phi \cos \theta \\
-\cos \phi \cos \theta & 0 & -\sin \theta \\
\sin \phi \cos \theta & \sin \theta & 0
\end{bmatrix}
_{3 \times 6}
\begin{bmatrix}
1 & 0 & 0 & \sin \lambda & 0 & 0 \\
0 & 1 & 0 & 0 & -\sin \theta & 0 \\
0 & 0 & 1 & 0 & 0 & \cos \eta
\end{bmatrix}
_{3 \times 6}
\] (12)

A pseudo matrix inversion of the \( B \) matrix (the \( 3 \times 6 \) matrix above) is performed and the MC offset vector \( \Delta r \) and the \( \Delta r \) components (\( A, B, \) and \( C \)) are obtained:

\[
\begin{bmatrix}
r'_x \\
r'_y \\
r'_z \\
A \\
B \\
C
\end{bmatrix}
= \left[ \sum_{k=1}^n B_k^T B_k \right]^{-1} \sum_{k=1}^n B_k^T a_k
\] (13)
5.0 Software Design

5.1 Motion Table Software Overview

The balancing process of the Motion Table uses three software components. First, there is “on-board microprocessor software” that runs on the motion table’s OBC. This is the low-level code that controls the platform devices. Second, there is an “Off-Board Windows Terminal Program”, which runs on a desktop computer. The terminal program is used to control the OBC software through ASCII text commands via a serial connection. The third software component is Matlab code that also runs on the desktop computer. This code is used to do all the significant calculations. These three software components are designed to run seamlessly together to provide the motion table operator with an easy-to-use motion table software system.

5.2 On-board microprocessor software

The “On-Board Microprocessor Software” is written in C and compiled for the OBC’s microprocessor. It is controlled through ASCII text through a serial line connection. The following figure is an overview of the five main on-board programs used in balancing the motion table. Note that the “Trim Mass Movement” and the “Active Balance Mode” programs have been written but due to lack of time were not able to be debugged.
The following is a description of the functionality of the five OBC programs:

- **Scan** - autonomously records sensor data/platform movement that is used to solve for the position of the platform's MC.

- **Mmu** - moves the MMUs to known positions to in turn move the platform's MC for balancing.

- **Balance** - autonomously senses the platform tilt and adjusts the MMUs to counteract the movement of the MC due to platform bending.

- **Tilt** - configures the built in tilt sensor filter and downloads tilt data for use in tilt sensor calibration.

- **Mag** - downloads magnetometer data for use in calibration of the magnetometer.
5.3 Off-board Windows Terminal

In order to communicate with the OBC software, the user must use a terminal program. The terminal program runs on the Desktop computer and sends and receives ASCII text from the OBC.

"Hyperterminal", a program that comes as part of the Microsoft Windows software package, is sufficient for this purpose. With this Windows software the user can both run all the programs on the OBC but can also capture sensor data that is being downloaded from the OBC to a file on the desktop computer. This is done by turning on the "Capture Text" mode found under the "Transfer" Menu. In order for the terminal program to communicate with the OBC, a serial cable must be connected between the desktop's serial port and the OBC's RS-232 port.

5.4 Off-board Matlab Software

There are three separate Matlab programs. One is used to calculate the magnetometer calibration coefficients. The second is used to calculate the tilt sensor calibration coefficients. And the third is used to calculate the MC offset values and flexible body coefficients used to balance the motion table. The following sections discuss each of these programs.

5.4.1 Magnetometer Calibration Algorithm

The Magnetometer calibration algorithm was taken directly from a paper written on the calibration of a similar three-axis, strapdown, solid-state, magnetometer [Liu 1990]. The calibration equation is derived from a conventional magnetic compass deviation equation [Malony 1978]. The conventional deviation equation is:

\[ \delta = M_1 + M_2 \sin \gamma + M_3 \cos \gamma + M_4 \sin 2\gamma + M_5 \cos 2\gamma \]  \hspace{1cm} (14)

where, \( \delta \) is the compass deviation angle, \( \gamma \) is the measured heading from the magnetometer, and \( M_1 \) through \( M_5 \) are calibration constants.
The measured heading $\gamma$ is calculated using

$$\gamma = \arctan\left(\frac{H_y}{H_x}\right)$$  \hspace{1cm} (15)

where, $H_x$ and $H_y$ are the x and y readings from the magnetometer, rotated to the level frame using the platform pitch and roll.

The final magnetometer heading (platform Yaw) is determined using

$$\psi = \gamma - \delta$$  \hspace{1cm} (16)

The tilt of the magnetometer is taken into account and extra calibration coefficients are added to Eq. 14 to account for the compass deviation due to tilt. The final compass deviation equation is:

$$\delta = M_1 + M_2 (\cos\phi - \beta, \sin\phi) \sin\gamma + M_3 (\cos\theta + \beta_1 \sin\theta \sin\phi + \beta_2 \sin\theta \cos\phi) \cos\gamma + M_4 \sin 2\gamma + M_5 \cos 2\gamma$$  \hspace{1cm} (17)

The calibration constants $M_1$ through $M_5$ and $\beta_1, \beta_2, \beta_3$ are found using the magnetometer calibration procedure found in Appendix 10. The Matlab program used in the calibration procedure is outlined in Figure 20. Also see Appendix 6 for descriptions of the Matlab code. See Section 4.1 for definitions of the remaining variables.
5.4.2 Balance Algorithm

The Matlab balancing algorithm inputs the platform properties and a set of balance run sensor data and outputs the MC offset and flexible body coefficients (see Section 4.0). A flow chart of the balancing algorithm is shown below. See Appendix 6 for Matlab code.
Raw Tilt Data
(16-bit integer)

\[ \theta = x_{\text{tilt}}, \phi = \arcsin \left( \frac{\sin(y_{\text{tilt}})}{\cos \theta} \right) \]

Calculate Absolute Tilt \( \eta \)

\psi, \theta, \phi, \eta

Numerically Differentiate Euler Angles \( \omega_x, \omega_y, \omega_z \)

Numerically Integrated Motion Equations

\[ r_x', r_y', r_z', A, B, C \]

Figure 21: Balance Algorithm Flow Chart
6.0 Using the Motion Table (Procedures)

All of the procedures described in this section are contained in Appendix 10.

6.1 Order of Procedures for Balancing of the table

A full calibration and balance of the table should be performed whenever a new ACS is mounted for testing or if the facility is moved to a new location. The magnetometer calibration should be performed alone if the surrounding change enough to affect the local magnetic field (e.g., a new environmental chamber is moved next to the motion table) or if more than one month has passed since the last calibration. The computer balance procedure should be performed at the beginning of every ACS testing day (if a fine balance is required) or at the discretion of the operator. The procedures described in this section should be executed in a certain order if a full calibration and balance of the table platform is performed. The following is the order in which the procedures should occur.

1. All the Mass and Inertia Determination for the test hardware should be determined and entered into the Inertia Determination Spreadsheet. The spreadsheet should also be used to determine a layout/placement plan for the test hardware. This should be done prior to the actual balance procedures so this procedure is not rushed and will give the operator more time with the other balance procedures.

2. The Tilt Sensor Calibration Procedure should be performed. This calibration does not depend on its surroundings and therefore can be performed even when the final test hardware is not mounted on the platform.

3. The test hardware should be mounted and the Manual Balance Procedure should be performed.
4. The Magnetometer Calibration Procedure should be performed. At this point all of the test hardware and weights should be added to the table.

5. The Computer Balance Procedure is the last procedure to be executed. All the specification data for the Matlab “table_solver.m” program should have been determined and input into the data file.

6.2 Mass and Inertia Matrix Determination

The total mass and the inertia matrix for the table platform have to be determined for use in the Computer Balancing Algorithm. These values have to be as accurate as possible with the facilities available to the operator. There are a wide variety of procedures that can be used to obtain these values (any can be used). The procedure used at UTIAS involved weighing each of the components making up a platform subsystem. Each component is then modeled in “I-DEAS” (engineering design software). The component masses are input and the components are assembled into subsystems within the I-DEAS software (e.g. MMU). The software then outputs a total mass and inertia matrix for each subsystem. A spreadsheet is then used to combine all the individual subsystems to provide an overall mass and inertia matrix for the platform.

6.2.1 I-DEAS

“I-DEAS” was used because it was accessible and the author is familiar with its use. Most 3D CAD software has the ability to determine mass properties; therefore the most familiar software should be used. It would also be possible to do this type of calculation by hand (or in the Inertia Determination Spreadsheet) by breaking a subsystem up into basic shapes. Inertia matrices can then be calculated for each basic shape [Boynton] and the matrices can be combined into the subsystem matrix.

6.2.2 Inertia Determination Spread Sheet

A preformatted spreadsheet was created which automatically calculates the platform’s total mass, inertia matrix, and MC offset. The inertia matrix, mass, and placement are input into the spreadsheet for each platform subsystem. All of the permanent platform subsystems are included on the spreadsheet including
the manual weight system. See Appendix 2 for a printout of the spreadsheet with permanent subsystem data. See Appendix 10 for details on how to use the Inertia Determination Spreadsheet.

6.3 Aero-Drag Determination

A simple trial and error method was used to determine the pitch and roll aerodynamic drag coefficients for the platform. This procedure should only be repeated if a different platform plate is used on the motion table. Both the pitch and roll drag coefficients should be approximately the same since the platform is a circular disk that is axisymmetric. Since the yaw movement of the platform, has a much smaller projected area of movement, it is assumed to be $1/5^{th}$ the value of the pitch and roll coefficients. The calculated values are: $Ba_{x,y}=0.03$ and $Ba_{z}=0.006$ (these values are dimensionless). See Appendix 10 for the detailed Procedure.

6.4 Tilt Sensor Calibration

The calibration of the tilt sensor involves recording sensor data in five known tilt positions, then running the matlab "tilt_biascal.m" program (see Appendix 6 for code) which takes the tilt data and outputs six calibration constants. The exact procedure is included in Appendix 10.

6.5 Magnetometer Calibration

The method for calibration of the magnetometer is taken directly from [Liu 1990]. The algorithm behind the magnetometer calibration is discussed in Section 5.4.1. The magnetometer calibration should be performed every time hardware is changed on the table, the surroundings are changed, or a long period of time (> 1 month) has passed since it was last performed. The calibration procedure is similar to the tilt calibration procedure except that the whole platform has to be oriented in 20 different positions (12 Horizontal, 8 tilted). The detailed procedure is found in Appendix 10.
6.6 Platform Balancing

There are two major balancing procedures that must be completed before the motion table is fully balanced. The first process is to manually balance the platform. This process involves intelligent placement of the hardware being tested, so that the hardware balances itself as much as possible. Then the manual balance weight system is used to balance the platform to within 0.5mm. Some of the placement of the hardware and manual weights can be determined beforehand using the Inertia Determination Spreadsheet (see section 6.1). The manual balancing procedure should take 1-2 hours. The second process is the computer balancing procedure. This procedure involves letting the platform freely rotate while the platform OBC is recording the platform movement. The sensor data is then input into the Matlab balancing program, “table_solver.m”, and the MC to RC offset distance and the flexible body coefficients are determined. The user then corrects for this offset by moving the MMU’s accordingly. The computer balancing is somewhat of an iterative process taking 2 to 3 data recording/MMU adjustments, each time getting a more accurate MC offset measurements. Each iteration should take 10 to 20 minutes. The detailed balancing procedures are found in Appendix 10.

After the balancing procedures are complete there are two types of balance that the platform can attain: Static Balance and Dynamic Balance. These concepts are covered in Section 3.8 and the procedures for implementing these balance modes are detailed in Appendix 10.
7.0 Quality of Motion Table Workings (Testing Results)

7.1 Quality of Sensor Output

The output of both the magnetometer and the tilt sensor were scrutinized. The following sections summarize this scrutiny.

7.1.1 Magnetometer

Table 9 shows ten samples of magnetometer data taken at a sampling rate of ten hertz. The magnetometer was mounted on the motion table and the platform was stationary at the time of the data sampling. As the table shows, the horizontal (X & Y) axes are relatively noisy, with the count values varying ±70 counts. This converts to a measurement variation of ±2 μTeslas, which would translate to angle measurement noise of ±6°. The vertical (Z) axis, on the other hand, is much less noisy, ±9 counts or ±0.25 μTesla.

| Magnetometer Data in A/D Counts (stationary platform, 0° ≈ 2070 counts) |
|-----------------|-----------------|-----------------|
| X               | Y               | Z               |
| 2434            | 2062            | 3538            |
| 2362            | 2114            | 3548            |
| 2372            | 2168            | 3544            |
| 2312            | 2070            | 3544            |
| 2262            | 2120            | 3542            |
| 2364            | 2030            | 3550            |
| 2356            | 2102            | 3532            |
| 2320            | 2126            | 3546            |
| 2320            | 2126            | 3546            |
| 2376            | 2090            | 3534            |

Table 9: Sample of Magnetometer

The axis noise difference was found not to be inherent in the sensor but is part of the electro-magnetic environment. This will in turn produce noisy Yaw angle data but until a less noisy environment is found to house the motion table there is nothing that can be done to fix the problem.

The magnetometer calibration procedure was performed and the following calibration values were found (see Eq. 17 for calibration equation):

\[ M_1 = -0.1769, M_2 = 0.01943, M_3 = 0.008323, M_4 = 0.01208, M_5 = 0.01720, \beta_1 = 0.01469, \beta_2 = -11.66 \text{ and } \beta_3 = -7.935 \]
The calibration values along with the magnetometer calibration data was then put back through a conversion algorithm and the following headings were calculated (see Table 10):

<table>
<thead>
<tr>
<th>Yaw Angle</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
<th>210</th>
<th>240</th>
<th>270</th>
<th>300</th>
<th>330</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw Error</td>
<td>-0.898</td>
<td>0.682</td>
<td>-0.907</td>
<td>1.118</td>
<td>-0.394</td>
<td>-0.511</td>
<td>0.310</td>
<td>0.345</td>
<td>-0.157</td>
<td>-0.490</td>
<td>0.260</td>
<td>0.641</td>
</tr>
</tbody>
</table>

Note: all measurements are in degrees

**Table 10: Horizontal Magnetometer Heading Errors**

The first row of table 10 shows the actual platform yaw angle (all the platform positions are horizontal). The second row shows the error of the yaw angle that was calculated using the magnetometer data after calibration. 40 samples were taken at each of these positions so there is averaging taking place. When a balancing run is performed only one sample will be recorded at each position but because the balancing algorithm averages to get the MC offset, the magnetometer noise shouldn’t have a great effect on the MC offset error.

<table>
<thead>
<tr>
<th>Tilt Angle (degrees)</th>
<th>Roll Tilts (Pitch = 0)</th>
<th>Pitch Tilts (Roll = 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-20</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Yaw Angle Error (degrees)</td>
<td>-5.840</td>
<td>-1.283</td>
</tr>
</tbody>
</table>

**Table 11: Tilted Magnetometer Heading Errors**

All the tilt readings were taken at a yaw angle of 30 degrees. The second row in table 11 shows the tilt angle of the platform. The third row is the error of the yaw angle that was calculated using the magnetometer data after calibration. The pitch values are comparable to the errors found in Table 10 but the roll errors are significant. This was found to be due to the magnetic vector direction changing with horizontal position. The only way to solve this problem is to find a more favorable area for housing the magnetometer.
7.1.2 Tilt Sensor

Table 12 shows ten samples of tilt sensor data taken at a sampling rate of ten hertz. The tilt sensor was mounted on the motion table and the platform was stationary at the time of the data sampling. As the table shows (the LSB counts show the noise), the tilt sensor data is relatively clean. This is expected since there should be no large environmental gravity vector distortion. See Section 3.9.3 for discussion of the count to tilt angle conversion equation.

![Table 12: Sample of Tilt Sensor Data](image)

<table>
<thead>
<tr>
<th>MSB Pitch</th>
<th>LSB Pitch</th>
<th>MSB Roll</th>
<th>LSB Roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>55</td>
<td>64</td>
<td>79</td>
</tr>
<tr>
<td>0</td>
<td>54</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>0</td>
<td>52</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>0</td>
<td>50</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>0</td>
<td>49</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>0</td>
<td>47</td>
<td>64</td>
<td>78</td>
</tr>
<tr>
<td>0</td>
<td>47</td>
<td>64</td>
<td>78</td>
</tr>
<tr>
<td>0</td>
<td>49</td>
<td>64</td>
<td>78</td>
</tr>
<tr>
<td>0</td>
<td>48</td>
<td>64</td>
<td>77</td>
</tr>
</tbody>
</table>

7.2 Computer Balance Trials

The motion table platform was set up with 10 kg of dummy weight to simulate the ACS test hardware (see Figure 22). It was then manually balanced and all the sensor calibrations were done. The first computer balance run output MC offset and bending values of (all values are in millimeters):

$$r'_x = -0.0208, r'_y = 0.0146, r'_z = 0.1677, A = -0.00756, B = 0.0146, C = -0.0238$$

Using the MMU's the platform's MC was moved to counteract the above calculated MC offsets. The x and y components of the MC were set to zero (MC$_x$ was moved $0.0208$ mm and MC$_y$ was moved $-0.0146$ mm) and the MC$_z$ component (while maximum plate bending is present; platform is horizontal) was set to zero.
0.1 mm (MCz was moved -0.677 mm). A second computer balance run was then performed to get more accurate offset and bending values. The values were:

\[ r'_x = -0.0105, r'_y = 0.00992, r'_z = -0.2116, A = -0.00429, B = 0.00910, C = 0.3190 \]

Again using the MMU's the platform's MC was moved to counteract the above-calculated MC offsets. The x and y components of the MC were set to zero (MC, was moved 0.0105 mm and MCy was moved -0.00992 mm) and the MCz component was set to 0.1 mm (MCz was moved -0.0074 mm, this was calculated using 0.1 mm - (r'_z + C)). Five more computer balance runs were performed to confirm the predicted MC position and the accuracy of the balance algorithm outputs. No MMU adjustment was made between the balance runs. The values were:

Run #1) \[ r'_x = -0.00115, r'_y = 0.000923, r'_z = -0.257, A = -0.00425, B = -0.00715, C = 0.346 \]

Run #2) \[ r'_x = -0.00220, r'_y = 0.00189, r'_z = -0.262, A = 0.00300, B = -0.0109, C = 0.362 \]

Run #3) \[ r'_x = -0.00166, r'_y = 0.000439, r'_z = -0.224, A = -0.0132, B = 0.0139, C = 0.298 \]

Run #4) \[ r'_x = -0.000391, r'_y = 0.00299, r'_z = -0.244, A = 0.00253, B = -0.0147, C = 0.335 \]

Run #5) \[ r'_x = -0.00267, r'_y = 0.000200, r'_z = -0.225, A = -0.00298, B = 0.0139, C = 0.315 \]

The platform becomes noticeably more balanced with each of the first three balance runs and the outputs of the balance algorithm follow accordingly. To confirm the final MC position, the z component of the MC was set to 0.02 mm (while full plate bending is present). From the "bending" spreadsheet the platform stable/unstable point should be at 20° tilt (see Figure 23). This point was confirmed by tilting the platform 19° and releasing it. The platform rocked back to the horizontal position. The platform was then tilted to 21° and released and it became unstable and tilted to the 45° bearing limit and stopped.
During the balance runs the MC was not able to brought closer than 0.1 mm because the air currents in the testing area would overwhelm the stabilizing gravity torque and cause the table to rotate past the stable/unstable tilt angle, causing the platform to go unstable. At 0.1 mm offset the unstable tilt angle is at 45° and therefore the platform cannot become unstable. It was also noticed that when the MC is brought closer than 0.1 mm the air current torques become relatively large (compared to the gravity torque) and cause erratic pendulous motion which creates large errors in the calculated MC offset values. The table therefore must be protected from extraneous air currents if a higher degree of balance is needed.

When the MC is further away from the RC (the first couple of balance runs), the solver algorithm is less accurate calculating the bending coefficients ($A$, $B$, and $C$). This is due to the platform bending having a relatively small effect on the platform movement. When the MC is brought closer to the RC the bending has a pronounced effect and the solver algorithm is able to more accurately calculate the bending values. The horizontal bending values ($A$ and $B$) are relatively small and the algorithm is not able to calculate these on a consistent basis. For example, these values should always be positive but they seem to switch sign regularly. It is possible, that when the platform is able to be balanced using a smaller initial MC offset (i.e. 0.01 mm) that the algorithm might be able to better calculate these horizontal bending coefficients.
8.0 Conclusions / Future Work

A motion table was designed, built, and is currently in working order. The hardware cost a total of approximately $18,000 (Canadian Dollars).

The Matlab simulation work determined that the use of rate sensors on the platform was not needed and in fact decreased the balancing performance once very fine balances are attained. It was shown that an off-the-shelf tilt sensor (outputting roll and pitch) and an off-the-shelf magnetometer (used to calculate yaw) would be sufficient to determine the MC position to approximately 2% of what the MC offset is during the recording of the platform motion data. In this manner, the platform can be incrementally balanced to the limit of the MMUs and flexible body movement of the platform. It was shown, however, that the flexible body movement was much greater than expected, on the order of 0.1 mm of MC movement over the platform's range of tilt. Therefore, there are three balancing options. First, to design and build a stiffer platform. This would cost more money and time (something we didn't have for this thesis). Second, to place the MC in a known position, that guarantees stability at all tilt angles, and accordingly accept the large gravity torques. In this case, the torques would get as large as 0.008 N-m which is 80 times the requirement of a maximum gravity torque of 0.0001 N-m. Third, to write OBC software that would sense the tilt of the table and actively move the MMUs to counteract the movement of the MC. The last option is obviously the best option since it would require no extra hardware. For this thesis only the second option was available since there wasn't enough time to implement the last option.

There were significant air currents present in the motion table testing area (due to air conditioning in the room). It was noticed that the currents interfered with the finer of the static balances (see Section 7.2). This problem has to be addressed if more accurate platform balances want to be achieved, and especially if dynamic balancing is used. For example, a small plastic barrier could be erected around the motion table to shield it from air currents.
The magnetometer turned out to be a noisy sensor, with noise levels of 4% of the magnitude of Earth’s magnetic vector. After some detective work it was concluded that the noise was due to a magnetically noisy environment and not the sensor itself. It is suggested that a less magnetically noisy location is found to house the motion table.

As was mentioned, not all of the motion table features that were envisioned at the start of the thesis could be implemented. This was mostly due to time constraints but as well, the envisioned features were in retrospect slightly ambitious. The following sections discuss the parts and features of the motion table that were unable to be completed.

**OBC Software Completion**

As discussed in Section 5.2, two of the OBC software components, the “Trim Mass Movement” and the “Active Balance Mode” programs, have been written but due to lack of time were not able to be debugged. The Platform can be balanced without the use of these components but with little work these components could be working, making the table balancing procedure both easier and more effective.

**Rigid Platform**

A very stiff platform could be designed and built in the future. This would decrease the movement of the MC negating the need to use the “Active Balance Mode”. It would also enable the balancing algorithm to get more accurate calculations of the MC offset.

**Autonomous Operation**

The balancing algorithm for the platform dictates that the on-board computer cannot be physically connected with the desktop computer while recording the uninhibited motion of the platform. However, between the recording of platform movement the OBC and the desktop computer have to be able to talk to each other. The current way of connecting the two computers is through a physical RS-232 cable which has to be connected and disconnected between balancing operations. It would be more efficient to have a wireless connection (IR or RF) between the OBC and the desktop. This could be done with an off-the-shelf
wireless serial connection. There is also a built in RS-232 port on the OBC to enable the addition of this feature.

**GUI User Interface**

Windows based, GUI (Graphical User Interface) software was partially designed, using Visual Basic, to take the place of the Windows Hyperterminal program (see Appendix 11). This software provides the motion table user with easy to use interface to the low-level, ASCII text driven, OBC software. The software consists of one main window where the user can choose one of the five functions that the OBC software performs. The sixth window allows the user to set the properties of the serial port connection between the OBC and the desktop computer. The five software functions are as follows:

1. **Logging Platform Motion:** Start a balance run which autonomously records platform sensor data that is used to calculate the MC of the table. This window also allows you to download this sensor data onto the desktop computer for processing.

2. **Trim Mass Movement:** Allows the user to move the platform MMU’s to the specific position required to balance the table platform.

3. **Active Balance Mode:** Accepts the MC offset and Flexible Body Coefficients and puts the platform into an autonomous, open-loop, balance mode. This mode is used to correct for dynamic flexible body motion of the platform (see Section 3.8).

4. **Tilt Sensor Calibration:** Allows the user to input linear calibration coefficients for the tilt sensor. It also allows the user to change the cut-off value of the tilt sensor’s built-in low-pass filter.

5. **Magnetometer Calibration:** This software mode allows the user to record and download sensor data from the OBC that is used in the calibration of the magnetometer. This process differs from the "Logging Platform Motion" process
because the sensor data is recorded while the OBC and the desktop computer are connected by a hardwire serial connection. See Section 6.3 on details of the magnetometer calibration process.

Inertia Tensor Test

This could be a student project using the motion table. There is a possibility that the table could be configured to calculate its own inertia tensor. This would provide a more accurate inertia tensor to use in the table balancing algorithm than a piecewise manual hand calculation of the tensor which is being used presently. It would require that the ACS actuators be in some way linked to the platform's OBC. See [Holemans 1997].
References


Crookston, J., “Small satellite attitude control simulator (SSACS) inertia testing methods”. Student project paper, Utah State University, 1992.


Hughes, P. C., Spacecraft Attitude Dynamics, John Wiley and Sons, Toronto, 1986.


Appendices

Appendix A: Computer simulation Code and Results

The electronic versions of the simulation code (m-files) can be found on the UTIAS/SFL server under
\Enterprise\User$\Public\Facilities\Motiontable\simulation_code\n
The simulation code results can be found in the “algorithm_errors.xls” file on the UTIAS/SFL server under
\Enterprise\User$\Public\Facilities\Motiontable\simulation_results\n
The following is a description of all the matlab motion table simulation programs:

A.1 Platform Movement Simulation Programs

motion_sim.m – simulates the movement of the table using the motion equations and an ODE solver and
creates discrete angle and rate data to input into the solvers. Table parameters are input through the
"table_it" file. outputs the angle and rate data into the "table_st" file.

State_dot.m – this is a function called by “motion_sim.m” that holds the ODE solver

p_state.m - is a function that is used by "motion_sim.m" to graph the angle and rate data. this is a visual
aid to help the user to see how the table is moving.

motion_sim2.m – this is the same as the “motion_sim.m” file except it takes into account the non-rigid
body bending of the platform.

State_dot2.m – this is a function called by “motion_sim2.m” that holds the ODE solver.
A.2 Platform C of M Position Solver Programs:

`ae_cgoff.m` - takes "table_it" and "table_st" data. only uses angle data. filters the data with a low pass filter. differentiates and transforms (rotation matrix) data to get the angular rate data. then uses the integration solver to solve for the CG offsets.

`d_cgoff.m` - takes "table_it" and "table_st" data. numerically differentiates the rate data to get the angular acceleration data. plugs the nine data types into the motion equations to get the CG offsets.

`i_cgoff.m` - takes "table_it" and "table_st" data. numerically integrates the motion equations. plugs in the angle and rate data to get the CG offsets. (used in the more complex solvers)

`is_cgoff.m` - takes "table_it" and "table_st" data. uses a simplified form of the motion equations and integrates them in closed form. takes the angle and rate data and solves for the CG offset. This is the solver algorithm that Utah State used.

`e_cgoff.m` - takes "table_it" and "table_st" data. solves for the acceleration data by inputting the angle and rate and cgoffset data back into the motion equations. then errors are added to the Inertia matrix and the Aerodynamic factors. the CG offsets are then solved for with no errors due to numerical solver error.

`ie_cgoff.m` - takes "table_it" and "table_st" data. uses the integration solver ("i_cgoff.m") but adds errors to the Inertia matrix and the Aerodynamic factors to the solver. it also adds normal and noise errors to the angle and rate data. i.e. this is a full blown error addition solver.

`ief_cgoff.m` - is exactly the same as "ie_cgoff.m" solver except that it filters the angle and rate data through either or both low-pass filters and Fast Fourier Transform filters. then puts the filtered data into the solver.
utah_comp.m - is a lot like the "ie_cgoff.m" solver, in that it adds errors to the data, except that it uses the simplified motion equations used in "is_cgoff.m" as its final solver. This algorithm was made to try and simulate the Utah state table to see if these types of simulations would predict the Utah state cg-offset calculation limit.

check.m - takes "table_it" and "table_st" data. Uses the angle, rate and offset data to put into the integrated solver. Then outputs the value of each side of the motion equations. This is done to show that the values calculated by the "motion_sim" program are valid.

angle_wtest.m - takes "table_it" and "table_st" data. Adds error to the angle and rate data. Filters the data through either or both low-pass filters and Fast Fourier Transform filters. Then displays the original data, the error data, and the filtered data. This is a visual aid to test the filters.

p_state2.m - is a function used by the "angle_wtest.m" program to graph just the rate data. This is a visual aid for the user to see the errored and filtered data.
Appendix B: Inertia Matrix/MC Calculation Spreadsheet

The inertia matrix/MC calculation spreadsheet can be found in the “motion_table.xls” file on the UTIAS/SFL server under \Enterprise\User$\Public\Facilities\Motiontable\.

The following pages are printouts of sections of the above-mentioned spreadsheet.
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<td>0.000525</td>
<td>175</td>
<td>0.0084875</td>
<td>175</td>
</tr>
<tr>
<td>L</td>
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<td>175</td>
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<td>175</td>
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<tr>
<td>L</td>
<td>0.000030</td>
<td>150</td>
<td>0.0056865</td>
<td>175</td>
</tr>
</tbody>
</table>

**Total Weight:** 0.1809499 kg

**Total Length:** 350 m
Appendix C: Motion Table Stand Vibrational Analysis

Derivation of Natural Frequency of Motion Table Stand

The Motion table stand can be modeled as a beam with a mass at one end (the platform) and fixed at the other (the base). A closed form solution to the natural vibration frequency of this model is [Inman 1994]:

\[
\omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{3EI}{ml^3}} \tag{A.1}
\]

where: \( E \) = Modulus of Elasticity of stand = 7e10 N/m³

\( l \) = Moment of Inertia (cross section of stand) = 4.34747e-6 m⁴

\( m \) = tip mass (mass of platform) = 20 to 40 kg

\( l \) = length of beam (stand length) = 0.6 m (since there are fins on the stand)

Solving the equation for the two different masses gives:

with \( m = 20 \) kg; \( \omega = 459.71 \) rad/sec = 73.17 Hz;

with \( m = 40 \) kg; \( \omega = 325.07 \) rad/sec = 51.74 Hz.
Appendix D: Data/instruction sheets for all Components

The following pages contain the data sheets or catalog information for all the off-the-shelf motion table components that were purchased.

Air Bottle Regulator

Manufacturer: Victor Equipment Company
Model: SR 450 E
Max inlet Pressure: 3000 psi
Outlet pressure Range: 0 – 400 psi

Table Filter/Regulator

Manufacturer: Wilkerson
Mounting Bracket Model: GPA-95-968
Filter Model: F16-04-000B G95
Regulator Model: R16-04-000A E95
Regulator Specifics:
Inlet Air Pressure: 300 psi Max
Operating Pressure Range: 0-125 psi
Operating Air Temperature: 79 deg C Max

Platform Battery

Manufacturer: Panasonic
Model: LC-R121R3PU
Battery type: Sealed Lead-Acid
Voltage: 12 Volts
Permanent Magnet Stepping Motors 1.8°

EAD Size 17 permanent magnet DC stepping motors are precision bidirectional devices with position accuracy of +/-5% non-cumulative. Motors are totally enclosed with permanently lubricated ball bearings. Standard motors have 4 or 6 leads. Motors with 5 or 8 leads can be furnished to meet existing applications.

ELECTRICAL RATINGS

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Voltage VDC</th>
<th>Current amp/phase</th>
<th>Resistance Ohm/phase</th>
<th>Inductance mH/phase</th>
<th>Holding Torque oz-in</th>
<th>Voltage VDC</th>
<th>Current amp/phase</th>
<th>Resistance Ohm/phase</th>
<th>Inductance mH/phase</th>
<th>Holding Torque oz-in</th>
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<tr>
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<td>0.95</td>
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<td>17.0</td>
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MECHANICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Model Series</th>
<th>Rotor Inertia oz-in-sec</th>
<th>Weight oz</th>
<th>Length &quot;L&quot; in</th>
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<tr>
<td>G8K</td>
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<td>EBK</td>
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<td>BBK</td>
<td>51x10^-3</td>
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APPLICATIONS
Compassing
Navigation Systems
Attitude Reference
Traffic Detection
Proximity Detection
Medical Devices

Three-Axis Magnetic Sensor Hybrid
HMC2003

A complete 3-axis magnetometer with analog output in a 20-pin hybrid DIP package. Uses Honeywell's sensitive HMC1001 and HMC1002 MR sensors and precision instrumentation amplifiers to measure x, y and z axes. Patented integral field straps are accessible for applying offset fields or closed loop operation.

FEATURES AND BENEFITS

Small Cost Effective Package
DIP-20 footprint (1 in. x .75 in.) allows easy insertion into system-level boards, reducing development costs.

Solid State
All components are solid state, improving reliability and ruggedness compared to mechanical fluxgates.

Wide Dynamic Range
Accurately measures fields from 40 micro-gauss to ±2 gauss at 1V/gauss. Low noise instrumentation amplifiers with 1kHz low pass filters, reject unwanted noise. There are no flux concentrators used in this design that can lead to hysteresis and non-repeatability.

Internal Reference
An externally accessible +2.5V reference improves measurement accuracy and stability. An on-board excitation current source reduces temperature errors and regulates the power supply input.

Offset and Set/Reset Straps
Magnetic field offsets or closed loop circuits can be applied using the built-in straps. Output signal accuracy may be enhanced by using the integral set/reset straps.

Non-Magnetic Material
All components are especially selected and packaged in nonmagnetic material to reduce magnetic distortion and offsets.
Honeywell's three-axis magnetic sensor hybrid uses three permalloy magnetoresistive transducers and custom interface electronics to measure the strength and direction of a magnetic field. These transducers are sensitive to magnetic fields along the length, width, and height (x, y, z axis) of the 20-pin dual-in-line hybrid. Fields can be detected less than 40 microgauss and up to ±2 gauss. Analog outputs are available for each x, y, z, axis from the hybrid. With the sensitivity and linearity of this hybrid, changes can be detected in the earth's magnetic field to provide compass headings or attitude sensing. The high bandwidth of this hybrid allows anomaly detection of vehicles, planes and other ferrous objects at high speeds.

The hybrid is packaged on a small board (1 in. x 0.75 in.) and has an on-chip voltage reference that operates from a single 6 to 15 V supply. The hybrid is ideal for applications that require two- or three-axis magnetic sensing and have a very tight size constraint and/or have their own electronics and only need a magnetic transducer front-end.

Integrated with the transducer bridge circuit is a magnetically coupled strap that replaces the need for external coils and provides various modes of operation. The Honeywell patented field offset straps (Xoff+ and Xoff-, etc.) can be used to electrically apply a magnetic field to the bridge to buck, or offset an applied field. This technique can be used to cancel unwanted ambient magnetic fields or in a closed loop field nulling measurement circuit. The offset straps nominally provide a 1 gauss field along the sensitive axis per 48 mA of offset current through it.

Magnetic transducers can be affected by high momentary magnetic fields that may lead to output signal degradation. In order to eliminate this effect, and maximize the signal output, a magnetic switching technique can be applied to the bridge using the SR+ and SR- pins that eliminates the effect of past magnetic history. Refer to AN-201 for applications information on Set/Reset operation.

---

**CIRCUIT DIAGRAM**

**PINOUT DIAGRAM**

**PACKAGE DRAWING**

<table>
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<tr>
<th>Symbol</th>
<th>Millimeters</th>
<th>Inches</th>
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<td>A1</td>
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<tr>
<td>D</td>
<td>25.91</td>
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<tr>
<td>e</td>
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<td>H</td>
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<th>Typ</th>
<th>Max</th>
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<td>15</td>
<td></td>
<td>VDC</td>
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<td>-2</td>
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<td>V</td>
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<td>V/gauss</td>
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<td>±1 gauss</td>
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<td>%FS</td>
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<tr>
<td></td>
<td>Applied Field Sweep</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linearity Error</td>
<td>±2 gauss</td>
<td>1</td>
<td>2</td>
<td></td>
<td>%FS</td>
</tr>
<tr>
<td></td>
<td>Applied Field Sweep</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hysteresis Error</td>
<td>3 sweeps across ±2 gauss</td>
<td>0.05</td>
<td>.1</td>
<td>%FS</td>
<td></td>
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<tr>
<td>Repeatability Error</td>
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<td>.1</td>
<td>%FS</td>
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<td>Ω</td>
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<td>Offset Strap Sensitivity</td>
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<td>47.5</td>
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<td>Set/Reset Strap Resistance</td>
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<td>Null Field Tempco</td>
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<td></td>
<td>ppm/°C</td>
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<td>Set/Reset used</td>
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<td></td>
<td>ppm/°C</td>
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<td>°C</td>
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<td>85</td>
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<td>°C</td>
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<td></td>
<td>g</td>
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<td>Vibration</td>
<td></td>
<td>2.2</td>
<td></td>
<td></td>
<td>g rms</td>
</tr>
<tr>
<td>Power Supply Effect (shifts in Null Field Offset or Sensitivity)</td>
<td>Power Supply varied from 6 to 15VDC with ±1 gauss Applied Field sweep</td>
<td>0.1</td>
<td></td>
<td>%FS</td>
<td></td>
</tr>
</tbody>
</table>

(1) Unless otherwise stated, test conditions are as follows: power supply = +12VDC, ambient temp = 25°C. Set/Reset switching is active.
(2) Units: 1 gauss (G) = 1 Oersted (in air). 1G = 79.58 A/m, 1G = 10E-4 Tesla, 1G = 10E5 gamma.
(3) Transient protection circuitry should be added across V+ and Gnd if an unregulated power supply is used.

Honeywell reserves the right to make changes to any products or technology herein to improve reliability, function or design. Honeywell does not assume any liability arising out of the application or use of any product or circuit described herein; neither does it convey any license under its patent rights nor the rights of others.
May 19, 1999

Mr. Noah Hansen  
Institute for Aerospace Studies  
University of Toronto  
4925 Dufferin Street  
Toronto, Ontario M3H 5T6

Dear Noah:

Enclosed is the 4 inch Spherical air bearing #1442 you ordered on 03-29-99. We at Nelson Air Corporation would like to thank you for the opportunity to provide this bearing to you. We certainly hope that it will meet your needs and wish you luck with your project. The bearing was tested here at our facility and performed extremely well. With no additional weight other than the sphere itself ‘liftoff’ occurred at <2 PSI and a flow of 2 SCFH. The pressure was then increased up to 80 PSI and a flow of 11 SCFH was recorded. 60 PSI is the recommended pressure to use.

PLEASE NOTE: Avoid any movement of the mated surfaces within the bearing when there is no air pressure being supplied. The bronze portion of the bearing will score very easily with the slightest bit of dirt, dust, or other contamination.

Sincerely,

John Michaud  
Production Assistant
**CXTILT02E**

The CXTILT02E inclinometer offers outstanding resolution, response speed, and accuracy. The CXTILT02E measures the tilt angle of an object with respect to the horizontal in a static environment. To measure tilt, also called roll and pitch, the sensor makes use of two micro-machined accelerometers, one oriented along the X-axis and one along the Y-axis.

The CXTILT02E is a "smart" sensor with an on-board micro-controller, A/D converter, and temperature sensor. The combination of sensing elements and digital electronics yields a system requiring no user calibration. The sensor's resolution and settling time are programmable, allowing the CXTILT02E to be customized for various applications.

**CXTILT02EC**

**Minimum Temperature Drift**

In more demanding measurement applications, where high accuracy must be maintained over a wide temperature range of -40 to 85°C, the CXTILT02EC provides superior performance. The CXTILT02EC employs Crossbow's Softsensor™ Calibration and an on-board temperature sensor to internally compensate for temperature induced drift.

**Linearized**

The CXTILT02EC is also characterized by extremely high linearity and designed specifically for use in construction environments. This extremely high linearity is achieved through Crossbow's proprietary Softsensor™ linearization calibration.

---

**ORDERING INFORMATION**

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<thead>
<tr>
<th>Part#</th>
<th>Description</th>
<th>Angular Range</th>
<th>Temperature Range</th>
<th>Accuracy (±20°C)</th>
<th>Accuracy (±45°C)</th>
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</thead>
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<tr>
<td>CXTILT02E</td>
<td>Enhanced</td>
<td>±75°</td>
<td>0 to 70°C</td>
<td>±0.4°</td>
<td>±1.5°</td>
</tr>
<tr>
<td>CXTILT02EC</td>
<td>Enhanced &amp; Compensated</td>
<td>±75°</td>
<td>-40 to 85°C</td>
<td>±0.1°</td>
<td>±0.1°</td>
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Specifications

<table>
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<th>CXTILTO2EC</th>
<th>Units/Remarks</th>
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<tr>
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<td>± 75°</td>
<td>± 75°</td>
<td>From Horizontal</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>See Table 1</td>
<td>See Table 1</td>
<td></td>
</tr>
<tr>
<td>Setting Time</td>
<td>See Table 1</td>
<td>See Table 1</td>
<td></td>
</tr>
<tr>
<td>Null Angular Offset</td>
<td>0.5°</td>
<td>0.5°</td>
<td>Provided w/sensor</td>
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<td>Angular Drift w/Temp</td>
<td>1.5°</td>
<td>0.7°</td>
<td>Over Temp Range</td>
</tr>
<tr>
<td>Nonlinearity (±45°)</td>
<td>&lt; 3%</td>
<td>0.3%</td>
<td>Measured at 25°C</td>
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<tr>
<td>Transverse Sensitivity</td>
<td>1%</td>
<td>1%</td>
<td>Typical</td>
</tr>
<tr>
<td>RS-232 Interface</td>
<td>9600</td>
<td>9600</td>
<td>Baud</td>
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<tr>
<td>Temperature Range</td>
<td>0 to 70°C</td>
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<tr>
<td>Supply Voltage</td>
<td>50 - 60V</td>
<td>8 - 30V</td>
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</tr>
<tr>
<td>Supply Current</td>
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<td>2.5 lbs</td>
<td>feet</td>
</tr>
<tr>
<td>Cable Length</td>
<td>2.5 feet</td>
<td>2.5 feet</td>
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</table>

Notes

All frequency break points are 3 dB single pole. ±6 dB per octave roll-off. Nonlinearity is the deviation from a best fit straight line at full scale. Transverse sensitivity is error measured in the primary axis output created by forces induced in the orthogonal axis. Zero g drift is specified as the typical change in 0 g level from its initial value at +25°C to its worst case value at +T max or -T min. Transverse sensitivity error is primarily due to the effects of measurement (i.e., much of it can be tuned out by adjusting the package orientation. Specifications subject to change without notice.

Table 1. Resolution vs. resolution-level configuration

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<thead>
<tr>
<th>Resolution-Level</th>
<th>Lowpass Frequency (kHz)</th>
<th>Resolution (deg/Hz)</th>
<th>Resolution (deg/s)</th>
<th>Time Constant (s)</th>
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<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>0.006</td>
<td>0.024</td>
<td>0.010</td>
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<tr>
<td>1</td>
<td>50</td>
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<td>0.17</td>
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</tbody>
</table>

Figure 2. Block Diagram of CXTILTO2E

Figure 3. CXTILTO2E Aluminum Package

Crossbow

408/965-3300 • FAX 408/324-4840 • www.xbow.com
Serial RS-232 Interface

The serial RS-232 interface consists of three lines RD (Receive Data), TD (Transmit Data), and GND (Ground). These three lines are used to asynchronously transmit serial data between the host (PC or other computer) and the CXTILT02E. The signal levels are ±9V so that the interface is directly compatible with the RS-232 standard. Communications should be configured to 9600 baud, 8 data bits, 1 stop bit, no start bits, no parity, and no flow control.

The CXTILT is configured and polled by sending commands via the serial link. Commands consist of single and multiple byte instructions sent from the host to the CXTILT02E. The CXTILT02E responds by sending single byte and multiple byte packets back to the host. When sending successive commands (e.g., polling the CXTILT02E for angular information), it is recommended that the controlling software wait for a complete response from the CXTILT02E before issuing new commands. Table 2 lists the contents of each packet, and Table 3 shows the commands and responses of the unit.

Angular Resolution

The angular noise limits the resolution or granularity with which small angular changes can be detected. The angular noise is dependent on the measurement bandwidth. The measurement bandwidth is the set of frequencies to which the tilt sensor responds. Decreasing the measurement bandwidth increases the resolution. At the same time, however, decreases in measurement bandwidth also increase the settling time of the sensor. If the measurement bandwidth is set too low, the tilt sensor may take an unacceptably long time to settle to its final value. The CXTILT02E is unique in its ability to provide high-resolution and short settling time. The CXTILT02E is factory configured to the default resolution and settling time listed in the Specifications section, as well as shown in Table 1. The CXTILT02E is also unique in its ability to be user configured for different measurement bandwidths (and hence resolution and settling time). The sensor is configured via the RS-232 interface.

<table>
<thead>
<tr>
<th>Byte</th>
<th>Description</th>
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<tr>
<td>0</td>
<td>Header (always 255)</td>
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<tr>
<td>1</td>
<td>Pitch MSB (0-255)</td>
</tr>
<tr>
<td>2</td>
<td>Pitch LSB (0-255)</td>
</tr>
<tr>
<td>3</td>
<td>Roll MSB (0-255)</td>
</tr>
<tr>
<td>4</td>
<td>Roll LSB (0-255)</td>
</tr>
<tr>
<td>5</td>
<td>Checksum (8 bit sum of bytes 1-4)</td>
</tr>
</tbody>
</table>

Table 2. Contents of angle packet

Setting the Resolution Level

The measurement bandwidth of the tilt sensor is configured via the RS-232 interface. The serial command "N" followed by a "resolution level" (0-9, binary) is sent to the CXTILT02E to configure the measurement bandwidth. The "resolution-level" is simply an unsigned number between 0 and 9 that sets the measurement bandwidth internal to the CXTILT02E. The CXTILT02E changes the digital filtering internal to the sensor in response to this command. Table 1 shows the resolution and settling time constant for various values of resolution level. Note that the CXTILT02E returns to the default resolution level (5) upon power-up and must be re-configured.
Customizations

Custom packages and serial output features of the CXTILT02E are available for OEM customers. Please contact the factory for more information.

<table>
<thead>
<tr>
<th>Command (ASCII)</th>
<th>Command (Integer)</th>
<th>Function Description / Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>82</td>
<td>Reset. Resets the CXTILT firmware. An ASCII 'H' (72) is sent in response.</td>
</tr>
<tr>
<td>G</td>
<td>71</td>
<td>Get Angle Packet. The CXTILT returns its current angular position. The data is in a 6 byte packet defined in the adjacent table.</td>
</tr>
<tr>
<td>N &lt;0-9&gt;</td>
<td>78 &lt;0-9&gt;</td>
<td>Set Resolution Level. A 2 byte command sequence that configures the CXTILT's internal digital filter. The second byte, an integer of value 0-9, sets the level of filtering.</td>
</tr>
<tr>
<td>C</td>
<td>67</td>
<td>Continuous Mode: Transfers packet continuously at maximum rate.</td>
</tr>
<tr>
<td>S</td>
<td>83</td>
<td>Stop Continuous Mode.</td>
</tr>
</tbody>
</table>

Table 3. CXTILT02E Serial Commands

Development Software

Crossbow development software X-VIEW is shipped with the CXTILT02E for use with PCs running MS Windows95. The software demonstrates the functionality of the CXTILT02E. It is a convenient way to get started with system development, evaluate the performance of the CXTILT02E sensor, or use the CXTILT02E in straightforward leveling applications. The software is a run-time application based on National Instrument's LabView software and requires a 486 and Windows95. The software is shipped on a 3.5" floppy disk. For software installation, simply copy the INSTALL file on the disk to your hard drive and double click. Figure 5 shows a screen shot of the display.

 Calibration

The CXTILT02E is factory calibrated and, in most circumstances, requires no on-site calibration by the user. The sensor’s scale factor and offset are calibrated at the factory, and this information is stored in the system EEPROM. The limitations in absolute accuracy are errors in alignment induced during mounting, accuracy limitations in the factory calibration jig, and long term drifts in the electronic components. When better than 0.6° of “absolute” accuracy is required, the sensor should be leveled on-site. Also if the part has been placed in storage for an extended time period or exposed to temperature extremes, calibration for absolute level is recommended. The on-site procedure is to simply place the CXTILT02E on a known level surface and read the angular value it is reporting. The sensor should in theory read 0.00, but the sensor might report a slight offset. Record this offset and subtract it from all of the readings reported by the CXTILT02E. This procedure delivers the best absolute accuracy performance.

Crossbow

408/965-3300 • FAX 408/324-4840 • www.xbow.com
Product Information Sheet

Part Number: CXTILT02-EC
Serial Number: 9914531
Calibration Date: Mon. Aug 02, 1999

Position | Pitch Error (deg) | Roll Error (deg) |
---------|------------------|-----------------|
Flat     | -0.08            | -0.02           |
+45° Tilt| 0.02             | 0.13            |
-45° Tilt| -0.22            | -0.14           

version: CXTILT mfg 1.062

Technical Support
For further technical assistance, contact Crossbow Technology.

Crossbow Technology
41 East Oaggatt Drive
San Jose, CA 95134

Phone: 408.965.3300
Fax: 408.324.4843
URL: http://www.xbow.com
Email: info@xbow.com
Oldham Coupling
3/32" to 5/8" Bore
Brass or Aluminum Hubs  Acetal Polymer Center Block

Max. Shaft Penetration
- Simple Construction
- No Backlash
- Corrosion Resistant
- Reduces Vibration
- Electrical Isolation
- No Lubrication Required

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<th>SET SCREW STYLE</th>
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<th>OD</th>
<th>L</th>
<th>Rated Working Torque Oz.In.</th>
<th>Angular Parallel</th>
<th>Hub Material</th>
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Blank hubs, set screw hubs, and clamp hubs are interchangeable within the same series, special combinations will be assembled to order.

1-800-232-BERG
## Ball Bearings

**Precision ABEC-3 and ABEC-7** 3/64” to 1/2” Bore

**440C Stainless Steel** Single Row

---

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<th>ABEC-7 STOCK NUMBER</th>
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<td>-</td>
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---

For Ultra Precision Bearings With Bore Tolerance -.0001/-0002 Add -U To Part Number e.g. B1-36-S-U

Metric sizes available from stock.

**Ultra Precision Bearings With Bore Tolerance**

**Ultra Precision Bearings With Bore Tolerance**

**1-800-232-BERG**
A wide range of loads can be isolated by choosing the correct thickness, durometer and varying the number of pads. The pads are designed to offer isolation for all types of static and dynamic systems. Higher disturbing frequencies and lower temperatures are parameters that indicate the need for a lower durometer pad. Ideal for applications with heavier loads.

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<td>SIP-5</td>
<td>2 1/4 DIA. X 1/4</td>
<td>160-240</td>
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W. M. Berg, Inc. manufactures a complete line of off-the-shelf linear ball slides and linear crossed roller slide bearings. Made to the highest quality standards, components must pass strict inspection requirements at each stage of manufacturing. These Quality Control steps ensure precise, uniform, linear movement with low friction and minimum side-play.

Available in inch or metric sizes, and in travel lengths ranging from 1/2 inch to 24 inches, slides have flat, parallel, and smooth mounting surfaces. Equipped with mounting holes, they are shipped ready to install, with no need for modifications or adjustments.

### Linear Ball Slides

W. M. Berg Inc. Linear Ball Slides are designed to provide precise linear movement for light to medium loads. Their construction, as shown in Figure 1, consists of precision Grade 5 balls rolling along ground wire ways. Since the rolling contact surface is a point, the bearing ways are self-cleaning, expelling matter which may deposit on their surfaces.

![Figure 1](image1.png)

### Linear Crossed Roller Slides

W. M. Berg Inc. Linear Crossed Roller Slides are designed to provide precise linear movement for medium to heavy loads. Their improved stiffness and rigidity mean long term reliability under the punishment of vibration and shock conditions. Their construction as shown in Figure 2 consists of precision rollers rolling along ground flat ways. Since the rolling contact surface is a line, they can support greater loads than the ball slides.

![Figure 2](image2.png)

- **Straightness of Travel** = Precision Series - .0005 in./in.
- **Closability of Travel** = Precision Series - .0001 in.
- **Life** = 10 x 10^6 in. of Travel at Safe Load Capacity
- **Coefficient of Friction** = .003
- **Safe Load Capacity** = Rated Load Capacity

*Inspection Report Available for This Accuracy*

Berg Manufacturing "The Mark of Quality"

1-800-232-BERG
**TOP MOUNTING HOLE CONFIGURATION FOR SLIDE LRSF-60**

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<th>STOCK NUMBER</th>
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<th>C</th>
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See page E9 for additional specifications.
Additional Literature Available:

- Machines and Slides, Electronics & Software

- Compact Table with Self-Contained Electronics for CAD/CAM, engraving and prototyping

- CAD/CAM systems featuring software for full 3D machining, signmaking and engraving, and six sizes of XYZ tables

- DIN Cabinets, Card Cages and Components

- Robotic End Effectors, Tool Changers, Linear Cylinders
**Acme Lead Screws**

### FEATURES
- All Techno lead screws are centerless ground and standard rolled
- Lead accuracy of ± 0.15" per foot or better
- All screws have straightness tolerance of 0.10" per foot
- Screws have burnished finish of 32 RMS or better due to the rolling process
- Special grade of project 70 #303 stainless steel used for uniform grain structure to improve lead accuracy and finish

### ACME LEAD SCREW SELECTION

<table>
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<tr>
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#### SCREW SIZES

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<th>Lead Dia.</th>
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* Single start screws may be ordered in left hand on special order.

** Techno is a registered trademark of Shapin

### ANTI-BACKLASH SUPERNUTS

**FEATURES**
- Self-Lubricating
- Low Friction
- Lighter Weight: 1/5 the weight of bronze.
- Longer Life: To 75 million inches travel.

#### MATERIAL:
- Turcon® X (Acetal - Teflon & Silicon filled)

#### TEMPERATURE RANGE:
- Min: 32°F, Max: 180°F

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<tr>
<th>Catalog Number</th>
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<th>O.D. - # Thds. - Starts</th>
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<th>Max. Load in lbs. for Zero Backlash</th>
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**SUPERNUTS**

#### MATERIAL:
- Turcon® X (Acetal - Teflon & Silicon filled)

#### TEMPERATURE RANGE:
- Min: 32°F, Max: 150°F

**FEATURES**
- Low Cost
- Self-Lubricating
- Easy Installation
- Low Friction
- Lighter Weight: 1/5 the weight of bronze.
- Longer Life: To 75 million inches travel.

#### SUPERNUTS

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* Nut has ribbed body shape within the .710 dimension above

** It is recommended that dynamic load ratings be reduced by 50% for continuous duty applications.

**Hunt面试**
The STP100 is the perfect choice for small to medium stepper motor applications where step precision to 32 bits is required. The STP100 is divided into four functional blocks (Embedded Microprocessor, Stepper Logic, Motor Driver Circuit, and Serial Line Drivers). The embedded microprocessor gives the STP100 the ability to keep track of an absolute motor position. Among other things, the position is a signed 32-bit number. Other features of the STP100 that are microprocessor controlled include:

Motor acceleration and deceleration  
Human readable command set  
Multiple board command processing  
Cued commands  
STP100 board status queries:  
(Motor Position, Pin Conditions, etc.)

The stepping logic for the STP100 is supplied by a SGS Thompson Stepper Chip with built-in current limiting and step logic. The driver chip supplies up to two Amps per stepper motor winding. The STP100 has the ability to drive both RS-232A and RS-485 serial lines.

The STP100 accepts commands in the form of serial data from a host computer and outputs amplified control signals for a bipolar stepper motor. There are four general purpose I/O lines that can be used for detecting home positions or motor limits. In addition, two of the I/O lines can be configured as 8-bit analog to digital converters.
With the addition of a PONTECH PP232-485F you can take advantage of the STP100 onboard RS-485 multiple drop network connection for addressing up to 255 boards. Cued commands can then be used for controlling two or more axis systems.

Possible uses for the STP100 include automated manufacturing systems, x-y tables, and robotics.

Features:

- RS232 or RS485 interface
- Addressable up to 255 boards
- Controls Bi-polar Stepper Motors up to 2 Amps/phase
- Chopping current limiting
- Full, half or wave step modes
- Acceleration/deceleration ramping
- Speed, direction, position changing while motor is in motion
- 32-bit absolute position tracking
- 4-bit digital I/O for home limits
- Over temperature protection
- Power Supply (Motor) : 5VDC to 46VDC
- Power Supply (Logic) : 7VDC to 15VDC
- May use one supply if motor supply is in range of logic supply
- Dimensions: 4.3" x 2.4" x 1.1"
The sample interface code below uses QBASIC to communicate with the STP100.

```
OPEN "COM1:9600,N,8,1" FOR RANDOM AS #1
DO
  PRINT: PRINT "**STP100 Controller**"
  INPUT "Board ID Number :"; IDS
  INPUT "Position of Stepper :"; Position$  
  PRINT #1,"BD";IDS  
  PRINT #1,"MI";Position$
LOOP
```

Below is a sample screen of above program when run.

```
**STP100 Controller**
Board ID Number : 1
Position of Stepper : -200
Enable Board with ID # = 1 move Stepper to position -200

**STP100 Controller**
Board ID Number : 0
Position of Stepper : 0
Returns all steppers to home position if ID # = 0, all STP100 boards will be enable

**STP100 Controller**
Board ID Number : 2
Position of Stepper : 1000
Enable Board with ID # = 2 move Stepper to position 1000

GO TO PRICE LIST and ORDER FORM
```
Appendix E: CAD Mechanical / Assembly Drawings

The CAD mechanical / assembly drawings can be found on the UTIAS/SFL server under
\\Enterprise\User$\Public\Facilities\Motiontable\drawings\

The following pages are printouts of all the drawings found in the above-mentioned directory.
Material: 1/4" Aluminium
Quantity: 1 of 1
Notes: strike lines for welding placement
Material: 1/4" Aluminium
Quantity: 3 off
Notes: - to be welded between 'Base' and 'Post'
Material: 3/8" Aluminum sheet
Quantity: 1 off

Notes:
- All machining done after welded to "Stand Post"
- "Air Bearing" attaches to 10-24 threads
Material: 4.5" schedule 40 Aluminum Pipe

Quantity: 1 off

Notes:
- scribe 3 lines 120 deg apart for welding placement
- actual dia of pipe 5.25" ± 0.01"
- 3/8" holes should be drilled with "plateform lock"

Revision A

Description: Motion Table Stand Post

Date: 06/07/99

Scale: 1:5

Checked by: Huge Chessler
Material: Stainless Steel
Quantity: 3 off

Notes: 1/4-20 thread screws into "Platform Lock Post". This connection should be as tight a fit as possible.
Material: Aluminum Base & Stainless Steel Posts
Quantity: 1 off

Notes:
- Post connections; wherever makes them straightest
- 2 3/8" thru holes to be drilled with "Stand Post"
- "Lock Pins" fit into 3/8" thru holes
- "Platform Lock Spikes" screw into 1/4-28 threads.
Material: 1/4" thick Aluminum Plate
Quantity: 1 off
Material: 6061-16 Aluminum

Quantity 6 ..off

Notes: Centre line of 6 1/2 thread should pass thru the hole centre line in the plane of the bottom side.
Material: 2" L-bar Weldable Aluminum
Quantity: 3 off
Notes:

Motion Table
Magnetometer Post Base

UNITS: inches
TOLERANCES: ±0.01 inches unless otherwise specified
DRAWN BY: Noah Hunsen
CHECKED BY: Huge Chessier
DATE: 06/21/99
SCALE: 1.5:1
DATE REVISED: 0
REVISION #: 0
Material: 1/4" 6061 T6 Aluminium Plate

Quantity 2 off

Notes - Drill three holes, connect to motor and screw mounting plates.

Green through to mount linear slide.
Material: 1/4" 6061-T6 aluminum plate
Quantity: 1 off

Notes:
- Blue thru holes connect to motor and screw mounting plate.
- Green threads to mount linear slide
- White threads to mount to Vertical MMU Stand
Material: 1/4" 6061-T6 Aluminum Plate
Quantity: 3 off
Notes: #32 holes and 0.250" hole are to mount motor
Material: 1/16" Aluminum Plate

Quantity: 2 off (2 plates)

Notes: Two #6-32 holes should be counter sunk on different sides of the two plates.
Material: 0.062" 6061-T6 Aluminum Plate
Quantity: 3 off
Notes: 0.5" hole for bearing, sliding fit
Material: 1/4" 6061-T6 Aluminum Plate
Quantity: 1 off
Notes: 9/64" holes to connect to MMU base
Appendix F: Matlab Calibration & Solver Code

The Matlab calibration and solver code (m-files) can be found on the UTIAS/SFL server under
\Enterprise\User$\Public\Facilities\Motionable\solver\
Appendix G: Electrical Board Drawings and Schematics

The electrical board drawings and schematics can be found on the UTIAS/SFL server under \\
Enterprise\User$\Public\Facilities\Motiontable\boards\n
The following pages are printouts of the electrical board schematic files.
Appendix H: Cost Quotations

The cost quotations can be found on the UTIAS/SFL server under
\Enterprise\User\Public\Facilities\Motionable\cost\
Appendix I: Derivation of equations

1.1 Derivation from Tilt Sensor Roll to Euler Angle Roll

The tilt sensor or inclinometer uses micro-machined cantilevered bars with strain gages. Gravity puts strain on the bars in proportion to the angle between the bar axis and the gravity vector. When calibrated the sensor outputs the angle, perpendicular to the horizontal plane, from the horizontal to the sensor axis. Since the Euler angles are defined in order of Yaw – Pitch – Roll (z – y – x), Pitch is read directly from the tilt sensor but roll is affected by the pitch of the platform and has to be corrected using a derived formula.

The derivation of the roll correction equation is as follows:

Define (as seen in Figure A.1):

\[ r_a = \sin \phi \]  \hspace{1cm} (A.2)
\[ r_b = \sin \lambda \]  \hspace{1cm} (A.3)

where, \( \lambda \) is the angle, perpendicular to the horizontal plane, from the horizontal plane to the y-axis of the body frame (this angle is the x axis tilt reading from the tilt sensor), \( \phi \) is the roll Euler angle (expressed in the body frame), and \( \theta \) is the pitch Euler angle (expressed in the body frame).
From Figure A.1 we see that:

\[ \cos \theta = \frac{r_b}{r_a} \]  \hspace{1cm} (A.4)

Substituting Eq. A.2 and Eq. A.3 into Eq. A.4 gives:

\[ \sin \phi = \frac{\sin \lambda}{\cos \theta} \]  \hspace{1cm} (A.5)

Therefore, pitch is equal to:

\[ \phi = \arcsin \left( \frac{\sin \lambda}{\cos \theta} \right) \]  \hspace{1cm} (A.6)
1.2 Derivation of the Plate Bending formula

The formula for bend of a circular plate is [Cook 1985]:

\[ w = \frac{0.0505Pa^2}{D} \]  
(A.7)

where:

\[ D = \frac{Et^3}{12(1-\nu^2)} \]  
(A.8)

where:  
- \( w \) = distance of downward bend of the outer edge of the plate
- \( P \) = normal force placed around the edge of the plate
- \( a \) = radius of the plate
- \( E \) = modulus of elasticity of the plate material
- \( t \) = thickness of the plate
- \( \nu \) = poisson's ratio for the plate material

From Eq. A.7 we know that the outer edge of the plate bends linearly with the force applied because \( a \) and \( D \) are constants. Therefore, the MC of the plate will also move linearly with the force applied. In this case the force is gravity and the component of gravity that is normal to the plate's surface varies with the cosine of the absolute off-horizontal tilt of the platform. Therefore:

\[ r_z = r_z' + C \cos \eta \]  
(A.9)
where: \( r_z \) = z component of the RC to MC distance, expressed in the body frame

\( r_z' \) = z component of the RC to MC when there is no gravity force bending the platform, expressed in the body frame

\( C \) = the absolute position change of the MC z component from no gravity to full gravity.

\( \eta \) = the absolute off-horizontal tilt of the table, expressed in the inertial frame

We can derive a formula for \( \eta \) as a function of Euler angles by noting that \( \eta \) is the angle of Euler Parameters (or Quaternion) when only the tilt angles (pitch and roll) are taken into account (yaw is zero).

The following equation is taken from a text [Hughes, 1986]:

\[
\eta = \arccos \left( \frac{1}{2} (trace C_{th} - 1) \right) \quad (A.10)
\]

where: \( C_{th} \) = rotation matrix from horizontal to tilted position

\[
C_{th} = [C_{roll}][C_{pitch}] = \begin{bmatrix}
\cos \theta & 0 & -\sin \theta \\
\sin \phi \sin \theta & \cos \phi & \sin \phi \cos \theta \\
\cos \phi \cos \theta & -\sin \phi & \cos \phi \cos \theta
\end{bmatrix} \quad (A.11)
\]

therefore:

\[
\eta = \arccos \left( \frac{1}{2} (\cos \theta + \cos \phi + \cos \theta \cdot \cos \phi - 1) \right) \quad (A.12)
\]
1.3 Derivation of Gravity Induced Torque

Torque is the applied force multiplied by the distance to center of rotation (perpendicular to applied force).

In vector form:

\[ \mathbf{g}_{\text{gravity}} = \mathbf{r}_b \times m \mathbf{a}_g \]  \hspace{1cm} (A.13)

where:  
\( \mathbf{g}_{\text{gravity}} \) = external gravity torque  
\( \mathbf{r}_b \) = position of MC relative to RC, expressed in the body frame  
\( m \) = mass of the body  
\( \mathbf{a}_g \) = acceleration due to gravity

Only \( \mathbf{a}_g \) needs to be converted to the body frame since \( \mathbf{r}_b \) is already defined in the body frame. Therefore:

\[ \mathbf{a}_{gb} = C_{\text{roll}} C_{\text{pitch}} C_{\text{yaw}} \mathbf{a}_g \]  \hspace{1cm} (A.14)

where, \( \mathbf{a}_g \) is the gravity vector in inertial frame.

Since our inertial frame is defined with the z-axis pointing down. Eq. A.14 is written as:

\[ \mathbf{a}_{gb} = \mathbf{a}_g \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ \sin \phi \sin \theta & \cos \phi & \sin \phi \cos \theta \\ \cos \phi \cos \theta & -\sin \phi & \cos \phi \cos \theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]  \hspace{1cm} (A.15)

Therefore, after taking the cross product, Eq. A.13 becomes:

\[ \mathbf{g}_{\text{gravity}} = m \mathbf{a}_g \begin{bmatrix} r_y (\cos \phi \cos \theta) - r_z (\sin \phi \cos \theta) \\ -r_z (\cos \phi \cos \theta) - r_x (\sin \theta) \\ r_z (\sin \phi \cos \theta) + r_x (\sin \theta) \end{bmatrix} \]  \hspace{1cm} (A.16)
Due to the platform bending \( r_z \) is not constant and varies with table tilt as follows

\[
\begin{align*}
  r_x &= r_x' + A \sin \lambda \\
  r_y &= r_y' - B \sin \theta \\
  r_z &= r_z' + C \cos \eta
\end{align*}
\] (A.17, A.18, A.19)

Eq. A.19 is derived in the previous derivation. Eqs. A.17 and A.18 are equivalent to Eq. A.19 except that the gravity components are in the horizontal axis and therefore the cosine of the tilt angle is replaced with sine of the tilt angle.

Therefore, Eq. A.16 becomes:

\[
  g_{\text{gravity}} = ma_g \begin{bmatrix}
  (r_x' + B \sin \theta)(\cos \phi \cos \theta) - (r_z' + C \cos \eta)(\sin \phi \cos \theta) \\
  -(r_x' + A \sin \lambda)(\cos \phi \cos \theta) - (r_z' + C \cos \eta)(\sin \theta) \\
  (r_x' + A \sin \lambda)(\sin \phi \cos \theta) + (r_z' + B \sin \theta)(\sin \theta)
  \end{bmatrix}
\] (A.20)

Factoring the \( r \)'s and \( A, B, C \)'s out of the matrix gives:

\[
  g_{\text{gravity}} = ma_g \begin{bmatrix}
  0 & \cos \phi \cos \theta & -\sin \phi \cos \theta \\
  -\cos \phi \cos \theta & 0 & -\sin \theta \\
  \sin \phi \cos \theta & \sin \theta & 0
  \end{bmatrix}
  \begin{bmatrix}
  1 & 0 & 0 & \sin \lambda & 0 & 0 \\
  0 & 1 & 0 & 0 & -\sin \theta & 0 \\
  0 & 0 & 1 & 0 & 0 & \cos \eta
  \end{bmatrix}
\begin{bmatrix}
  r_x' \\
  r_y' \\
  r_z'
  \end{bmatrix}
\] (A.21)
Appendix J: Balancing Procedures

J.1 Order of the Table Balance/Calibration Procedures

The motion table balance/calibration procedures should be carried out in a certain order when a full calibration and balance is performed. The following is the order in which the procedures should occur.

1. All the Mass and Inertia Determination for the test hardware should be determined and entered into the Inertia Determination Spreadsheet. The spreadsheet should also be used to determine a layout/placement plan for the test hardware. This should be done days/weeks in advance of the actual balance procedures.

2. The Tilt Sensor Calibration Procedure should be performed. This calibration does not depend on its surroundings and therefore can be performed even when the final test hardware is not mounted on the platform.

3. The test hardware should be mounted and the Manual Balance Procedure should be performed.

4. The Magnetometer Calibration Procedure should be performed. At this point all of the test hardware and weights should be added to the table.

5. The Computer Balance Procedure should be performed. All the platform parameter data for the "table Solver.m" program should have been determined and input into the "table_it.m" data file.
J.2 Use of the Inertia Determination spreadsheet

The Inertia Determination Spreadsheet is contained in the Inertia section of the "Motion_Table.xls" spreadsheet file.

- The gray areas of the spreadsheet are locked cells that should not have to be altered.

- The MC position calculation can be used for pre-test component/weight placement determination. If the mass properties of the test hardware are known before the hardware is mounted on the platform, both the placement of the hardware and manual balance weights can be predetermined by making the MC position in the spreadsheet, as close to zero as possible.

- The "MMU weight offset" cells can be used to quickly update the platform inertia matrix used in the balance algorithm if the MMU mass positions change significantly during the balance procedure.

- A separate spreadsheet area is provided to determine the inertia matrix of the manual balance weights at each attachment point. This spreadsheet includes the precise weights of the components of the manual balance weight system. One attachment point is done at a time. The output of this spreadsheet is input into the platform inertia sheet.

- A separate spreadsheet area is also provided for determination of the wiring harness inertia matrix. Each row in the sheet represents one straight section of wire. The first section of rows pertain to wires running in the global x-axis, the second section is for wires running in the y-axis, and the third section for wires running in the z-axis.
J.3 Method for Aero-Drag Coefficient Determination

The following method was used to determine the pitch and roll aerodynamic drag coefficients. Both these values should be approximately the same since the platform is a circular disk that is axisymmetric. Since the yaw movement of the platform has a much smaller projected area of movement, this value is assumed to be $1/5^{th}$ the value of the pitch and roll coefficients. This procedure should not have to be repeated since the values should not change for this platform (values are: $Ba_{\alpha}=0.03, Ba_{\beta}=0.006$, dimensionless).

1. Use the basic platform (only air bearing sphere and circular platform with nothing attached). The less weight the platform has, the greater the effect of drag on platform movement, making the effect easier to measure. As well, the inertia matrix of the platform is much simpler to calculate and more accurate. The aerodynamic drag of the rotating platform with no hardware should be similar to the drag with hardware, since the projected area of the platform and not the shape of the surface affect roll and pitch drag.

2. Get MC offset and Inertia matrix from I-DEAS (should be very accurate since only made from two basic shapes).

3. Do an FEM model to get bending coefficients (easy due to basic shape) or use a closed-form bending solution (may not even have an effect since there is no weight).

4. Start the platform rocking in one axis at a specified initial tilt. Then record the time for the platform to reach half the initial tilt amplitude using the “manual tilt gauge” as a guide (see picture).
5. Alter the aerodynamic coefficient in the simulation code (motion_sim.m) until it outputs a
pendulous waveform with the same half-life.
J.4 Tilt Sensor Calibration Procedure

The calibration of the tilt sensor involves recording sensor data in five known tilt positions, then running the matlab "tilt_biascal.m" program which takes the tilt data and outputs six calibration constants. The exact procedure is written below.

1. Look up the factory provided tilt sensor zero offset values (in degrees). Plug the tilt sensor directly into the desktop computer using the serial cable provided with the tilt sensor (make sure the 9 volt battery on the cable is still good). Start the "X-view" software that was provided with the tilt sensor and input the two zero offset values in the software.

2. With the platform locked in place, adjust the three adjustment screws on the "platform lock" to level the platform, using the "X-view" tilt sensor output as the guide.

3. Plug the tilt sensor back into the OBC and plug the OBC into the desktop serial port. Start the Window's "Hyperterm" program on the desktop computer. Start the "tst_tilt" program on the OBC.

4. Start the "Record to file" feature in Hyperterm. Using the "tst_tilt" program on the OBC, record 40 lines of tilt data while the platform is in the level position. Then pause the "Record to file" feature in the Hyperterm program.

5. If the tilt sensor is bolted to the platform, unbolt it now. Using a machinist's steel 45 degree angle (see picture) put the tilt sensor in a positive 45 degree roll (0 degree pitch) position. Unpause the record feature in...
Hyperterm and record 40 more lines of tilt data while the tilt sensor is in the 45 degree position.

6. Repeat step #5 for -45 degree roll, 45 degree pitch, and -45 degree pitch. This should make a total of five tilt sensor orientations with 40 lines of tilt data recorded for each tilt position in one data file.

7. Open the tilt data file and edit out any non-tilt data lines so there are only 200 lines of tilt data in the file (no blank lines).

8. Start matlab and run the “tilt_biascal.m” program which will output the calibration coefficients. Before running this program open it and make sure the parameters in the beginning of the program are correct (especially the name of the tilt data file).
J.5 Magnetometer Calibration Procedure

The magnetometer calibration should be performed every time hardware is changed on the table, the surroundings are changed, or a long period of time (> 1 month) has passed since it was last performed. The calibration procedure is similar to the tilt calibration procedure except that the whole platform has to be oriented in 20 different positions (12 Horizontal, 8 tilted). The detailed procedure is as follows:

1. Lock the table platform in the orientation that you would like to be defined as zero degrees yaw using the platform lock. Make sure the table and the surroundings are as they will be when the ACS testing will occur. This ensures that the magnetic environment will be the same during the calibration and the balancing procedures.

2. The platform must first be leveled (doesn't matter if the tilt sensor calibration has been completed). Look up the factory provided tilt sensor zero offset values (in degrees). Plug the tilt sensor directly into the desktop computer using the serial cable provided with the tilt sensor (make sure the 9 volt battery on the cable is still good). Start the "X-view" software that was provided with the tilt sensor and input the two zero offset values in the software.

3. The bearing air supply should be turned on and the air bearing pressure should be checked to ensure the bearing can support the weight of the platform. The platform/bearing sphere is then lowered into the air bearing cup using the adjustment threads on the Platform Lock.

4. Adjust the three adjustment screws on the "platform lock" to level the platform, using the "X-view" tilt sensor output as the guide. Make sure that the air bearing is still taking most of the weight of the platform, i.e. don't raise the bearing sphere out of the bearing cup when adjusting the Platform Lock threads.
5. Plug the tilt sensor back into the OBC and plug the OBC into the desktop serial port. Start the Window’s “Hyperterm” program on the desktop computer. Start the “tst_mag” program on the OBC.

6. Start the “Record to file” feature in Hyperterm. Using the “tst_mag” program on the OBC, record 40 lines of magnetometer data while the platform is in the level position. Then pause the “Record to file”.

7. Lower the Platform Lock (by taking the pins out, don’t adjust the threaded points) and rotate the platform to the next yaw position. Then reengage the platform lock (put the pins back in) to hold the platform in the new yaw position.

8. Repeating steps #6 and 7, record 40 lines of magnetometer data at each of the successive 12 horizontal yaw positions (following a positive yaw rotation) that are possible with the table lock in place.

9. Disengage the Platform Lock and using a camera tripod and the tilt locking components (see picture), lock the “pitch” of the platform (should now only rotate in the roll axis). Use a second tripod to hold the roll of the platform in a certain orientation.

10. Use the “tilt_deg2raw.m” matlab function to determine what the raw output of the tilt sensor should be at the eight tilt positions [-20 0], [-10 0], [10 0], [20 0], [0 -20], [0 -10], [0 10], [0 20].
11. Start the OBC program “tst_tilt”. While the tst_tilt program is outputting raw tilt data in real time (ask for the max number samples) adjust the height of the locking tripod so that the raw tilt data shows the pitch to be at zero degrees. Adjust the height of the second tripod to hold the roll of the platform in –20 degree position. Once both tilt axis are fine-tuned to the wanted tilt, switch to the “tst_mag” OBC program, start the “Record to file” function in Hyperterm, and output 40 samples from the magnetometer.

12. Repeat step # 9 for the seven other tilt positions. Stop the Record function in Hyperterm.

13. Open the magnetometer data file and edit out any non magnetometer data lines so there are now 800 lines of magnetometer data in the file (no blank lines).

14. Start Matlab and run the “magcal.m” program which will output the 8 calibration coefficients.

Before running this program open it and make sure the parameters in the beginning of the program are set correctly (especially the name of the magnetometer data file).
J.6          Platform Manual Balancing Procedure

This process involves intelligent placement of the hardware being tested, so that the hardware balances itself as much as possible. Then the manual weight system is used to balance the platform to within 0.5mm. Some of the placement of the hardware and manual weights can be determined beforehand using the Inertia Matrix Spreadsheet (see Use of the Inertia Determination Spreadsheet). The procedure for the manual balance process is as follows:

1. The specifications of all the test hardware should be input into the Inertia Determination Spreadsheet. The hardware placements should be arranged so that the x and y MC offsets are as close to zero as possible. Addition of Manual Balance Weights into the spreadsheet should also be done to get a course approximation of how much weight and how far off the platform it needs to be placed in order to coarsely balance the table.

2. All the hardware to be tested has to be mounted to the platform, wired up, and ready for testing. All the MMU’s should be “homed”, meaning all the MMU weights have to be moved to their middle position. This is done by directly connecting the desktop computer to each MMU stepper driver board using an RS-232 serial cable. Using the Windows “Hyperterminal” program type in the appropriate commands to center the MMU’s (a list of commands is provided in Appendix 12).

3. The ¼” threaded balancing rod is placed into the platform ¼” thread sites wherever possible and locked into place with a brass nut. Some of the 12, ¼” thread sites may be covered by hardware and therefore cannot be used to secure balancing weights. Generally, only four axisymmetric sites are needed and the ¼” threaded rod only needs to be extended on the underside of the platform (the addition of the test hardware causes the MC to be above the RC and therefore the weights have to be added below the RC).
4. The amount of manual balance weight needed, as determined in step #1, should be secured in place on the ¼” threaded rod using a brass nut on each side of the weight to secure it at the proper position along the rod. The aluminum tube/spacer should not be used until the final weight position is known.

5. The bearing air supply should be turned on and the air bearing pressure should be adjusted so that it will support the new weight of the platform with hardware and weights mounted. The platform/bearing sphere is then lowered into the air bearing cup using the adjustment threads on the Platform Lock. Once the bearing is taking all the weight of the platform the platform lock should be lowered.

6. The weights should be adjusted vertically (using the nuts) on the rod so that the platform has a rocking period of 5-10 seconds. This provides a course balance in the z-axis.

7. Weight is then added and taken away on each of the symmetric pair of rods till the platform rests in a horizontal position (or as close as possible to the horizontal).

8. The weights are then raised vertically (all the same distance) until the balance of the platform is within its flexible body space, i.e. it is stable with small oscillations but becomes unstable if the platform is tilted too far.

9. Procedures 6, 7 and 8 have to be done in parallel for this process to be relatively quick and painless.

10. The MMU linear screws can be adjusted by hand for finer manual balancing but in general they should be kept close to their middle position.
11. A perfect manual balance will have the platform sitting in a near horizontal resting position (< 5 degs). And the platform will not become unstable until it tilts past 40 degrees.
J.7 Computer Balancing Procedure

This procedure involves letting the platform freely rotate while the platform OBC is recording the platforms movement. The sensor data is then input into the matlab balancing program, “table_solver.m”, and the MC to RC offset distance and the non-rigid body coefficients are determined. The user then corrects for this offset by moving the MMU’s accordingly. The computer balancing is somewhat of an iterative process taking 2 to 3 data recording/MMU adjustments, each time getting a more accurate measure of the MC offset values. Each iteration should take 10 to 20 minutes. The procedure for the computer balancing process is as follows:

1. Once the manual balancing procedure is completed the platform should move freely in a continuous pendulous fashion without becoming unstable. This type of free movement is required to get proper sensor data for the computer balance algorithm.

2. Connect the OBC serial connection to the desktop computer and start “Hyperterm” in Windows. Start the “scan” program on the OBC. Input the initial parameters for the data run. The total number of samples taken should always be the same no matter what balance iteration you are on (2000 to 4000 samples/run). The sampling rate is determined by noting the time it takes the table to oscillate once. The data should cover at least two full table oscillations. Therefore, the total number of samples should be divided by the time it take the table to do 2 oscillations giving the time between samples. To accommodate the speed of the OBC this number should not be below 50 milliseconds.

3. The bearing air supply should be turned on and the air bearing pressure should be checked to ensure the bearing can support the weight of the platform. Lower the platform/bearing sphere into the air bearing cup using the adjustment threads on the platform lock. Disengage the platform lock so that the platform is free to rotate in the bearing.
4. Put the OBC "scan" program in data collection mode and disconnect the serial line to the OBC. Start the platform rocking in a pendulous manner (try to make the platform oscillation amplitude no more than 20 degrees). Make sure the data collection program has enough delay so that the data doesn’t start to get recorded until the platform is moving freely. Let the platform move freely until the OBC program has stopped data collection.

5. Reconnect the serial line to the OBC and start the "Capture Text" mode in Hyperterm, then download the collected OBC data.

6. Open the "Table_it.txt" file and make sure all the correct parameters are set for the data run (see the "table_solver.m" file for the "Table_it.txt" formatting). Open the Data file that was just downloaded and erase any lines in the file that are not data lines (there should be no blank lines).

7. Start Matlab and run "table_solver.m". This will return the position of the MC relative to the RC and the three bending constants.

8. The MMU’s now need to be positioned to compensate for the MC offset values. This is done by directly connecting the desktop computer to each MMU stepper driver board using an RS-232 serial cable. Using the Windows “Hyperterminal” program type in the appropriate commands to move the MMU weights the calculated distances (a list of commands is provided in Appendix 12). The platform MC should be adjusted so that the x and y axis offsets are zero and the z axis offset is 1/5th of the table bending constant, C. This means that the platform should go unstable at approx. 14 degrees. The MMU movement distance can be calculated using the MMU section of the “Motion_Table.xls” spreadsheet file. As well, the z axis MC movement can be approximated using the “bending” section of the “Motion_Table.xls” spreadsheet file.

9. Steps 2 through 7 should be repeated, making sure that the movement of the table, while the sensor data is being recorded, does not exceed the 14 degree unstable tilt. This final step should
be repeated until it is felt that a more accurate measurement is no longer being attained with successive balance iterations.
J.8 Balance Modes

There are two balance modes that the platform can be configured for:

**Static Balance**

Connect the desktop computer to the OBC via the serial cable and adjust the MMU’s using the OBC “motor” program so that the MC x-axis and y-axis offsets are zero and the z-axis offset is equal to the table bending constant (using the Balance Constants that were determined in the Computer Balancing Procedure). In this way there is a known pendulous torque on the platform that varies with the platform tilt which the ACS hardware will have to compensate.

**Dynamic Balance**

Connect the desktop computer to the OBC via the serial cable and adjust the MMU’s using the OBC “motor” program so that the MC x-axis and y-axis offsets are zero and the z axis offset is equal to the table bending constant, \(C\).

Open the OBC “balance” program and input the balance constants \((A, B, C)\) that were determined in the computer balancing procedure.

Run the Real-Time Balance Compensation Mode. The MMU’s should now be compensating for the MC movement as the table tilts in different orientations.

Disconnect the desktop computer serial cable and keep the Balance compensation mode running while you are running the ACS tests.
Appendix K: Off-board windows code

The off-board windows code (Visual Basic files) can be found on the UTIAS/SFL server under \Enterprise\User$\Public\Facilities\MotionTable\windows\.