4-27-2022

Inertially Stabilized Gimbal

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Inertially Stabilized Gimbal

by

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An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

04/27/22

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Abstract

The goal of this project is to explore inertial stabilization in relation to a two-axis gimbal. The system is described, and a derivation of the mathematical model is given. Reference frames are defined, followed by a description of how to convert between reference frames. Sensors used for stabilization are described, specifically the inertial measurement unit, followed by a description of inertially stabilized platforms. The implementation of inertial stabilization is described as applied in the gimbal system, and suggestions are made on how to improve the robustness of the stabilization.

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List of Acronyms

LOS	Line-of-sight
HAVOC	High Altitude Visual Orientation Control
IMU	Inertial Measurement Unit
PID	Proportional, Integral, Derivative
KVL	Kirchhoff's Voltage Law
EMF	Electromagnetic Field
ECEF	Earth-Centered, Earth-Fixed
NED	North-East-Down
ECI	Earth-Centered, Inertial
ISP	Inertially Stabilized Platform

List of Symbols

v_a, V_a, v_f, or V_f	Voltage
R_a	Resistance
i_a or I_a	Current
L_a	Impedance
K_b	Back EMF coefficient
Ω or ω	Angular velocity
T	Torque
I	Motor moment of inertia

α	Angular acceleration
c	Damping coefficient
F	Force
r	Radius of motor coils
n	Number of turns of armature wire
L	Length of one turn of armature wire
K_T	Torque Constant
J	Moment of inertia
k	Spring constant
x_i, y_i, and z_i	Axes in inertial frame
x_E, y_E, and z_E	Axes in ECEF frame
x_e, y_e, and z_e	Axes in navigation frame
x_b, y_b, and z_b	Axes in body frame
ψ, θ, and ϕ	Euler Angles
w, xi, yj, zk	Terms of a quaternion
g	Acceleration due to gravity

1. Dedication

This project is dedicated to my family, my partner, Kelcie, and our wonderful dogs Clover and Basil.

2. Introduction

This project is an extension of a Senior Design Project developed for MAE 490 and MAE 491 Control Applications. In that project, the goal was to develop a two-axis gimbal that controls the line-of-sight (LOS) vector of a camera. This project will explore inertial stabilization, and how it is demonstrated in the stabilized gimballed camera system designed.

3. Background

3.1 Project Design

The gimbal system design was inspired by the University of Alabama in Huntsville Space Hardware Club High Altitude Visual Orientation Control (HAVOC) project's need for a stabilized gimbal to attach to the payload of a weather balloon in order to acquire stabilized footage in flight. The design was then simplified such that it would be mounted to a table to demonstrate its ability to control the line-of-sight of the camera. Many of the design requirements, especially regarding the system's size, weight, and ability to hold a GoPro Hero 8 camera, were derived from the requirements set by HAVOC.

The gimbal frame is assembled from 3D printed parts and houses two DC motors, an inertial measuring unit (IMU), a dual H-Bridge driver to drive the motors, and a Teensy 4.1 as the onboard microcontroller. There are also three sets of bearings which align using aluminum indexing rods. Each motor controls one axis, the azimuth (parallel to the table) and the elevation (perpendicular to the table).

The controller used in this project is a proportional integral derivative (PID) controller, a type of controller that consist of a proportional gain, an integrator and associated gain, and a differentiator and associated gain. This was implemented using the Teensy microcontroller. Each axis is controlled separately, using different gain values for each. The proportional gain, integral gain, and derivative gain were each found using a combination of simulations with MATLAB and Simulink and trial and error.

Figure 1: Rendering of Gimbal System

Note that figure 1 shows the gimbal system using two three phase brushless DC motors which were replaced by two DC motors in the final construction of the system. Additionally, the rendering does not include wiring, which consisted of wires coiled around the shaft of each motor.

3.2 System Model

When deriving the system model for the gimbal, the system was split into three major sections: the actuator (in this case DC motor), the system dynamics, and the sensor (an IMU). Each of these subsystems was then modeled as a transfer function. Finally, the three transfer functions were combined to form the total system transfer function.

3.2.1 Transfer Function of the Motor

To model the DC motor, the voltage input is converted into a torque as follows.

First, the armature circuit is mathematically modeled using Kirchhoff's Voltage Law (KVL) to find current and demonstrate all of the voltages present within the dc motor.

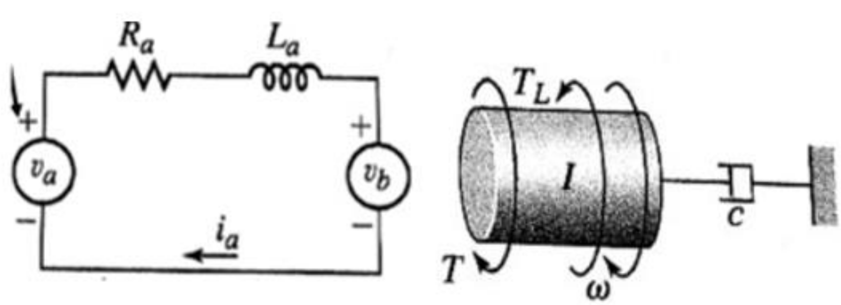

Figure 2: Diagrams of a DC motor

The KVL equation is applied in order to solve for current

$$v_a - R_a i_a - L_a \frac{di_a}{dt} - K_b \omega = 0$$

Where v_a is the voltage in, Ra is the resistance, i_a is the current, L_a is the impedance, K_b is the back EMF constant, and ω is the angular velocity.

Next the Laplace transform is taken

$$V_a(s) - R_a I_a(s) - L_a s I_a(s) - K_b \Omega(s) = 0$$

Then the transformed function is solved for current

$$I_a(s) = \frac{1}{L_a s + R_a}[V_a(s) - K_b \Omega(s)]$$

To find torque from current, the equation below is applied.

$$\sum T = I\alpha$$

T is torque, I is the motor moment of inertia, and α is angular acceleration.

This can also be written as

$$I\frac{d\omega}{dt} = T - c\omega$$

Where c is the damping coefficient.

The Laplace transform is taken as follows

$$Is\Omega(s) = T(s) - c\Omega(s)$$

Next, the equation is solved for angular velocity

$$\Omega(s) = \frac{1}{Is + c}[T(s)]$$

To derive the torque term, use the formula

$$T = 2Fr$$

Where F is the force acting on the armature, and r is the distance from the point the force acts on to the center line of the armature.

The force is the Lorentz force, which can be written as

$$F = i_a \frac{1}{2} nLB$$

Where n is the number of turns of wire and L is the length of one turn.

That can be substituted into the torque formula

$$T = i_a nLBr$$

The motor's torque constant is

$$K_T = nLBr$$

Which can be substituted into the torque equation, giving

$$T = K_T i_a$$

That can then be substituted into the angular velocity equation

$$\Omega(s) = \frac{1}{Is + c}\left(K_T I_a(s)\right)$$

When drawn as a block diagram, you see that the equations can be combined to form a transfer function with input voltage and output angular velocity, as shown in figure 2.

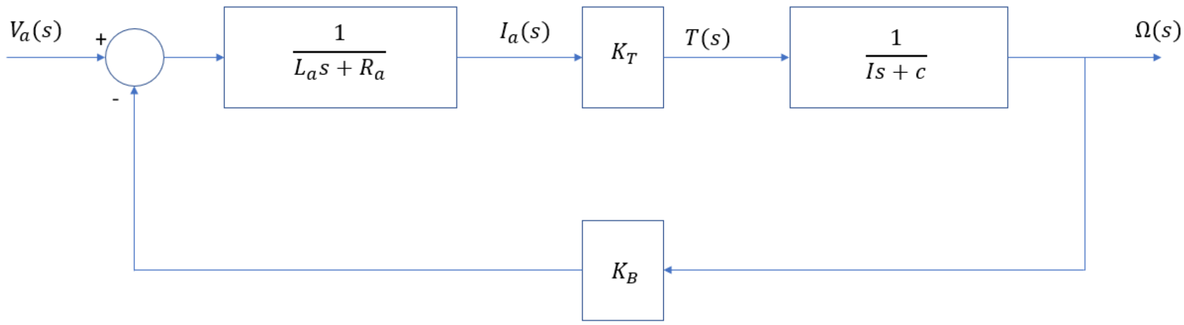

Figure 3: Block Diagram of a Motor

The block diagram can be visually rearranged so that the output is torque, and the angular velocity is in the feedback loop, as shown in figure 3. Note that this is mathematically correct, though it does not exactly represent the physical properties of the motor.

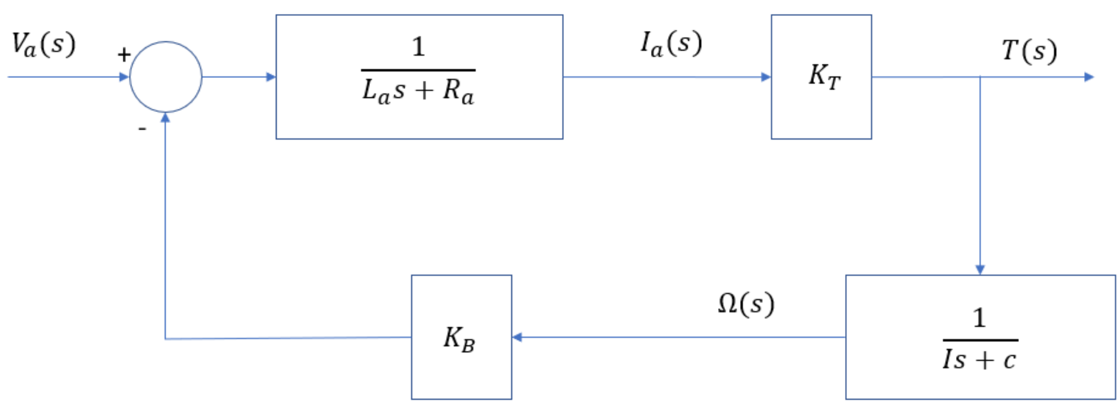

Figure 4: Rearranged Block Diagram of a Motor

Now the transfer functions can be combined into a single transfer function.

$$\frac{T_m(s)}{V_a(s)} = \left[\frac{\frac{K_T}{L_a s + R_a}}{1 + \frac{K_b}{Is + c}\left(\frac{K_T}{L_a s + R_a}\right)}\right] \cdot \frac{L_a s + R_a}{L_a s + R_a}$$

This can be simplified.

$$\frac{T_m(s)}{V_a(s)} = \frac{K_T}{L_a s + R_a + \frac{K_b K_T}{Is + c}} \cdot \frac{Is + c}{Is + c}$$

And finally, the combined equation.

$$V_a(s) \rightarrow \frac{K_T(Is + c)}{(L_a s + R_a)(Is + c) + K_b K_T} \rightarrow T_m(s)$$

For the purposes of this project, the motor's moment of inertia, because it is much smaller than the moment of inertia for the gimbal in both directions, can be considered negligible, which means the final equation can be simplified once more, giving this equation.

$$V_a(s) \rightarrow \frac{K_T c}{(L_a s + R_a)c + K_b K_T} \rightarrow T_m(s)$$

3.2.2 Transfer Function of the Gimbal Dynamics

When modeling the system dynamics of the gimbal, the torque input from the actuator is converted to an angular position output as follows:

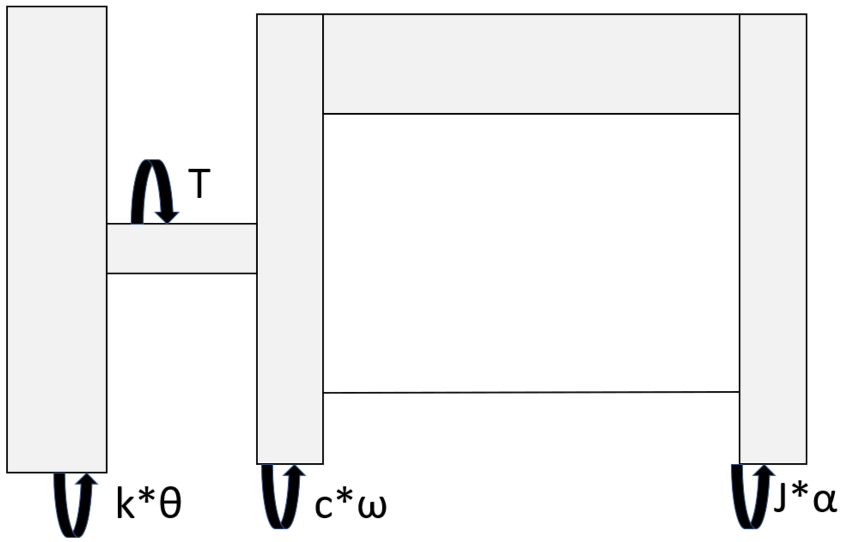

Figure 5: Free Body Diagram of a Motor

The system acts similarly to a mass-spring-damper system, but instead of force, distance and the derivatives of distance, torque, angular position, and the derivatives of angular position are used. This gives the equation:

$$J\ddot{\theta} + c\dot{\theta} + k\theta = T$$

Where J is the moment of inertia, $\ddot{\theta}$ is the angular acceleration, c is the damping coefficient, $\dot{\theta}$ is the angular velocity, k is the spring constant, θ is the angular position, and T is the torque.

Next, the Laplace Transform is taken,

$$Js^2\Theta(s) + cs\Theta(s) + k\Theta(x) = T(s)$$

The equation is solved for angular position.

$$\Theta(s)(Js^2 + cs + k) = T(s)$$

Finally, it is simplified into a transfer function.

$$\mathrm{T}(s) \rightarrow \frac{1}{Js^2 + cs + k} \rightarrow \Theta(s)$$

3.2.3 Transfer Function of the Plant

The sensor converts the angular position output of the gimbal dynamics into a voltage via a constant, selected as a sensor gain. The entire system can be shown as a block diagram.

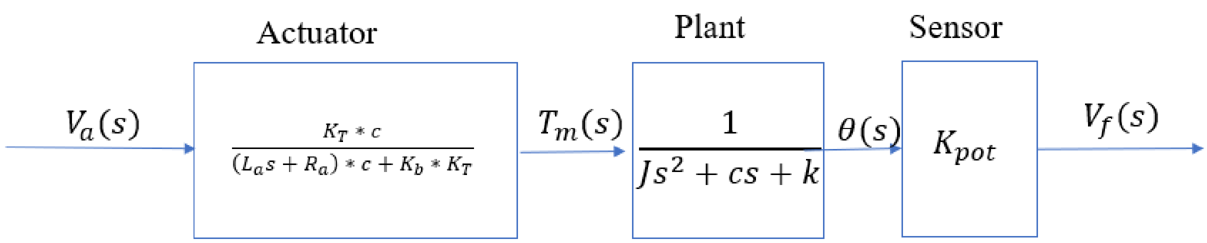

Figure 6: Block Diagram of the Entire System

Because these transfer functions are blocks in series, they can be multiplied together to form one combined transfer function,

$$V_a \rightarrow \frac{K_T * c * K_{pot}}{((L_a s + R_a) * c + K_b K_T) * (Js^2 + cs + k)} \rightarrow V_f(s)$$

Since the gimbal rotates in two axes, two variations of this transfer function are necessary. However, the derivation for both is the same, only the constants (particularly J, but also likely c and k) will differ between the two.

4. Inertial Stabilization

Inertial stabilization is a method of stabilization that mitigates disturbances, meaning in this case that the base of the gimbal could be lifted off the surface of the table and the camera would continue to hold its commanded LOS. This is done by stabilizing the camera in relation to the earth rather than in relation to the gimbal's base or the surface on which it sits. This can be done in many ways, but first a set of reference frames must be established.

4.1 Reference Frames

In inertial stabilization, it is necessary to first establish multiple sets of axes or coordinate systems. In this case, the most important frames are an inertial frame and a body frame. However, there are also important frames such as an Earth Centered, Earth Fixed (ECEF) frame, a frame that has its origin fixed at the center of the Earth and rotates as the Earth does, a navigational system, which has its origin fixed on the surface of the earth where the z axis is

pointed towards the center of the Earth and the x and y axes are pointed towards local north and local east respectively. This is also commonly known as a North-East-Down (NED) frame. Some sensors also use their own sensor frame, which is typically defined by the manufacturer.

4.1.1 Inertial Frame

The inertial frame of reference is the frame for which all of Newton's laws are true. For example, F=m*a, Newton's second law, is only true when acceleration is measured in reference to the inertial frame. The inertial frame is at rest somewhere in the universe, but for the purpose of most navigation and stabilization purposes, especially in aircraft, the inertial frame can be estimated such that the origin is at the center of the earth. However, this approximation uses the assumption that the force due to the Earth's rotation about the sun is negligible, meaning that it is not applicable for some applications such as space travel. This frame is also sometimes known as the Earth Centered Inertial (ECI) frame, indicating that it, though centered at the center of Earth like the ECEF frame, it does not rotate with the Earth.

4.1.2 Body Frame

A body frame is any frame centered on the body, often at the center of mass or center of gravity. The x-z plane is typically coincidental with the body's plane of symmetry if it has one. If the sensor frame is not the same as the body frame, usually due to the placement of the sensor, there must be a transform to allow the two frames to match. In the case of this project, the body frame is oriented such that the LOS vector aligns with one of the axes of the body frame.

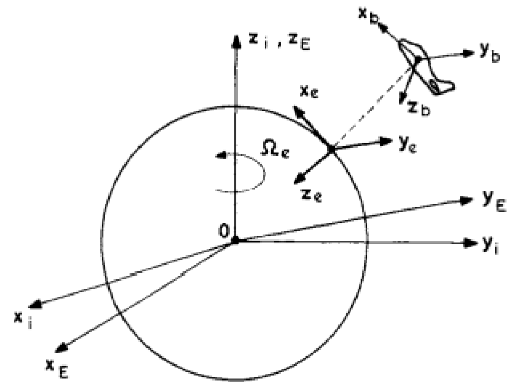

Figure 7: Illustration of Frames

Figure 7 shows several different frames, where x_i, y_i, and z_i are the axes in the inertial coordinate system, x_E, y_E, and z_E are the axes in the ECEF coordinate system, x_e, y_e, and z_e are the axes in the navigation system, and x_b, y_b, and z_b are the axes in the body frame. The large circle represents the Earth, and the airplane represents the body or vehicle.

4.2 Converting Between Frames

In order to use these frames for stabilization, there must be a method of converting between different coordinate systems. This can be accomplished by multiple different methods, including Euler angles, a group of three angles that describe the spatial relationship between two frames and can be expressed as a transformation matrix – a matrix that uses sines and cosines of the Euler angles to describe the values that must be multiplied by a vector in one frame in order to convert it to a vector in another. The three Euler angles are commonly shown as ψ, θ, and ϕ. The axes are rotated about these angles in a particular order in order to align the two coordinate

systems. These angles can be used to derive the rotation or transformation matrix. In fact, MATLAB contains a command (eul2rotm) that converts a set of Euler angles to a rotation matrix.

Another method of converting a vector from one coordinate frame to another is called a quaternion, which is similar to a vector but is in four-dimensional space rather than three. As such, a quaternion has four terms, a real number *w*, and three imaginary numbers, defined in the same way as a vector, *xi, yj,* and *zk*. In fact, a position vector could be expressed as a quaternion where *w* is equal to zero. Quaternions are most often used for rotation, where *w* represents the number of degrees or radians that another vector or angle must be rotated about the vector represented by the other three terms. Using quaternions means that only four values are needed for a given transformation, rather than the nine values necessary for a transformation matrix. However, the method for transformation using quaternions, something known as the 'sandwich product', is more complicated than using matrix multiplication to transform with a transformation matrix. Additionally, it is much simpler to find a transformation matrix library than to find one for quaternions.

4.3 Sensors

In order to perform any stabilization, or any control for that matter, a system must include sensors. For the case of the gimbal system there are a few sensors that may be applicable. Firstly, potentiometers. A potentiometer is a relatively simple sensor that shows the angular position of something like a motor shaft. In the case of this gimbal, one potentiometer would be placed on each axis, concentric with the motor shaft, giving angular position in the azimuth direction and in the elevation direction. These measurements would give orientation

within a body frame, centered at the point where a line coincident with each axis' motor shaft would meet. This method could be used for inertial stabilization, though it would be necessary to know the body's position and orientation in relation to an inertial frame, which would be possible only if the body was fixed in a position where the position and orientation in an inertial frame were known (useless in the case of lifting the gimbal and moving it to prove inertial stabilization), or if an inertial measurement unit was placed on the base of the system.

4.3.1 Inertial Measurement Unit

An inertial measurement unit (IMU) takes measurements in an inertial frame. The IMU used in this case takes measurements using an accelerometer, a gyroscope, and a magnetometer and uses an onboard processor to compute the three-dimensional orientation. When the sensor is horizontal in relation to the surface of the earth, the accelerometer should read 9.81 m/s^2, or g, the acceleration due to gravity. As the sensor's orientation changes, so does the acceleration, meaning that the angle in reference to the Earth can be calculated using the tangent of the value using gravity. The magnetometer measures magnetic fields, giving orientation in relation (when there is no major interference) to the Earth's north pole. Additionally, the gyroscope measures angular velocity within an inertial frame. When the IMU is calibrated, the coordinate frame is centered at its current location. This means that the gimbal system is an inertially stabilized platform (ISP). While it can be used as mentioned in section 4.3, to establish the entire system's location within an inertial frame, it would be much simpler to place it on the camera (or in other gimbal systems, the payload). This would mean that sensors measuring angles such as potentiometers would be redundant, as the IMU would measure the

angular position of the camera directly. The only transform necessary is a slight shift downwards so that one axis of the frame could be coincidental with the LOS vector.

4.4 Inertially Stabilized Platform

An ISP is generally regarded as any platform with the goal of holding the LOS vector, or more basically any system that prevents rotation within an inertial frame. Many ISPs include a tracking system, meaning that the LOS follows a moving target. In many cases, an ISP requires only a gyroscope or gyro sensor, which measures orientation in an inertial frame. However, using the IMU gives a more accurate reading. Because it uses the IMU, the gimbal project as it exists is an ISP. Figure 8 shows a simplified version of an ISP, where the gimbal acts in only one axis. It shows that as the base moves, the LOS remains stable due to the measurements taken by the gyro sensor.

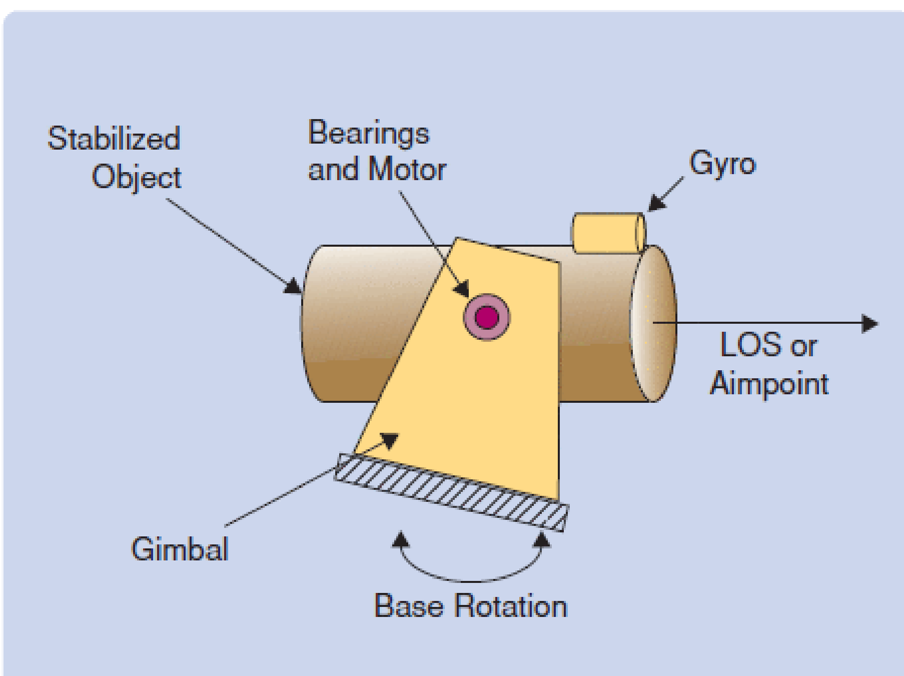

Figure 8: Example of a Simple ISP

5. Results

The gimbal as it exists is nearly inertially stabilized, though it works best only when small disturbances are applied. It is possible to move the base and the LOS stay in position, as long as the base is not moved far. This is because of the large amounts of friction in the system, meaning that the motors must reach a higher torque to overcome them than is ideal. This could be fixed by mitigating that friction in a number of ways. Some friction is added due to the motors, which are DC motors with a gearbox, and some friction is added by the wiring, which is coiled around each axis. The friction due to the motors would be best fixed by using brushless DC motors (as was planned for in the initial design but could not be implemented due to their complexity and the time constraints) and the friction due to the wiring could be minimized by using a slip ring. Also, there were malfunctions with the sensor that could not be accounted to sensor drift. The sensor seemed to read that there were abrupt direction changes when it was being turned continuously, meaning that the angle reading would increase, then begin to decrease, then increase again, even when the direction did not change. This error may have been due to magnetic fields from the building's steel construction or from the sensor's location near the motor.

6. Recommendations

Due to the sensor's size and relative lack of robustness in measurement, the stability of the gimbal is less accurate than it could be if using a more robust IMU, as the one used is better applied in a toy than an actual scientific instrument. Additionally, IMU's often accumulate error as they continue to take readings. Also, the math model could be more accurate if disturbances

were accounted for, such as creating a system of transfer functions where one has disturbance as an input or using a state space model. Also, it would be beneficial to spend more time calculating the transfer function or sensor gain of the IMU sensor, as the current math model only accounts for some scalar value, which is not given in the sensor's data sheet. Other, more complex, methods of control may be helpful, such as fuzzy control or H_∞ control. Finally, the controller currently in use controls only angular position, and controlling angular velocity may allow for more robust control.

7. Acknowledgments

I would like to thank Dr. Richard Tantaris, the faculty advisor for this project, as well as Nick Balch, Evan Golley, Quyen Nguyen, and Logan Turner, fellow members of the team that designed and created the gimbal project. Other acknowledgments include UAH MAE faculty members Dr. Daniel Armentrout, Dr. Nagavenkat Adurthi, and Jon Buckley.

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9. Appendix

BOSCH	BNO055 **Data sheet**	Page 13

1.2 Electrical and physical characteristics, measurement performance

Table 0-2: Electrical characteristics BNO055

Operating Conditions BNO055						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Start-Up time	T_{Sup}	From Off to configuration mode		400		ms
POR time	T_{POR}	From Reset to Normal mode		650		ms
Data Rate	DR	s. Par. Fusion Output data rates				
Data rate tolerance 9DOF @100Hz output data rate (if internal oscillator is used)	DR_{tol}			±1		%
Operating Conditions Accelerometer						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Units**
Acceleration Range	g_{FS2g}	Selectable via serial digital interface		±2		g
	g_{FS4g}			±4		g
	g_{FS8g}			±8		g
	g_{FS16g}			±16		g
Output Signal Accelerometer (Accelerometer Only Mode)						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Units**
Sensitivity	S	All g_{FSXg} Values, T_A=25°C		1		LSB/mg
Sensitivity tolerance	S_{tol}	Ta=25°C, g_{FS2g}		±1	±4	%
Sensitivity Temperature Drift	TCS	g_{FS2g}, Nominal V_{DD} supplies, Temp operating conditions		±0.03		%/K
Sensitivity Supply Volt. Drift	S_{VDD}	g_{FS2g}, T_A=25°C, $V_{DD\_min} \le V_{DD} \le V_{DD\_max}$		0.065	0.2	%/V
Zero-g Offset (x,y.z)	Off_{xyz}	g_{FS2g}, T_A=25°C, nominal V_{DD} supplies, over life-time	-150	±80	+150	mg
Zero-g Offset Temperature Drift	TCO	g_{FS2g}, Nominal V_{DD} supplies		±1	+/-3.5	mg/K
Zero-g Offset Supply Volt. Drift	Off_{VDD}	g_{FS2g}, T_A=25°C, $V_{DD\_min} \le V_{DD} \le V_{DD\_max}$		1.5	2.5	mg/V
Bandwidth	bw_8	2nd order filter, bandwidth programmable		8		Hz
	bw_{16}			16		Hz
	bw_{31}			31		Hz
	bw_{63}			63		Hz
	bw_{125}			125		Hz
	bw_{250}			250		Hz
	bw_{500}			500		Hz

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Figure 9: IMU Sensor Data Sheet