Handheld Camera Stabilizer

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***Abstract* — This document discusses the motivation, hardware, programming, control scheme, and performance of a handheld camera stabilizer intended for handheld aerial videography in lightweight personal aircraft.**

***Index Terms* — Inertial measurement unit (IMU), frame design, aerial videography, microcontroller, servomotor, stability.**

I. Introduction

The main motivation behind the handheld camera stabilizer originated from Professor Michael Young, George Mason University. Professor Young approached the Spring 2014 University of Central Florida Electrical and Computer Engineering (UCF ECE) Senior Design I students about a personal need for a handheld, lightweight, and electromechanical camera stabilizer for personal use while in a passenger plane for greater filming quality. Professor Young chose Senior Design Group Three to design and build the camera stabilizer.

The following is a list of the general objectives and character of the handheld camera stabilizer system:

1) Provide enhanced videography.
2) Stabilizing against user motion.
3) Primary rotational compensation via electronic system.
4) Secondary linear vertical compensation via mechanical system.

The goal is to provide a simple-to-use, battery-powered, handheld camera stabilizer for amateur aerial videography using higher quality digital single-lens reflex (DSLR) cameras such as the Nikon 1, Canon Rebel, or Pentax K series. The primary objective of the project is to design a handheld camera stabilizer that will compensate for video disturbances that are introduced by human fatigue. The handheld camera stabilizer system must provide stable video quality for 1080HD filming, eliminating mechanical blur and refocus error.

II. Overview & Operation

The design philosophy for the handheld camera stabilizer was to create a compact, lightweight, easy-to-use camera stabilizer for vertical compensation. The following list are the general specifications and design requirements [1]:

- Single hand-held device.
- Must hold vertical position (z-axis) to within 1/8” with vertical transient jumps as much as 6”.
- Response time must be quick enough to eliminate all vertical movement as seen by the camera.
- Must have standard camera mount.
- Supports the weight of a Nikon 1 camera as well as smaller cameras.
- Runs on a single rechargable battery.
- Must weigh less than 9 oz.
- Operates for at least 30 minutes on a single charge with light to moderate turbulence.
- Power on/off switch.
- Green power ON LED flashes once every three seconds for about 100 milliseconds.
- LED flashes red when battery is low.
- Circuit must be delivered on a double-sided PC board with surface mount components and fits in the handle.

The handheld camera stabilizer is an easy-to-use design with minimal user knowledge to operate and a simple user interface. The user mounts the camera using a standard camera mount screw, initiates recording of the camera, push the rocker switch to the ON position (located on the handle), allow the handheld camera stabilizer to perform its start-up and calibration routine (indicated by a solid green LED on the handle), then the handheld camera stabilizer is in filming mode (indicated by a green blinking LED).

Once filming is done, the user simply pushes the rocker switch to the OFF position. At any time during filming if the battery voltage becomes low, the handheld camera stabilizer will indicate low power with a red blinking LED, to communicate to the user that the system should be powered off. If the user ignores the low battery warning, the LED will change to a solid red and the servomotors and accelerometers will power down. Following the solid red LED, the user should shut off the handheld camera stabilizer with the rocker switch.

To charge the battery, the user will ensure that the rocker switch is in the OFF position, connect the provided external battery charger into the port located on the bottom of the handle and be allowed more than 2 hours to fully charge. The battery charger should be set to 7.2 VDC.

III. Mechanical System Design

This particular mechanical design involves stability through the use of a parallel twin-axis servo motor system and support frame. This system design focuses on eliminating optical jitter that is introduced by human instability and fatigue. The emphasis of the motion stabilization was in the vertical z-axis to prevent the bumps and peaks experienced when flying above the clouds in a passenger aircraft.

While vertical turbulence can be mitigated through mechanical isolation, this design technique can only compensated for vibration frequencies that are introduced through human motion. To compensate for these vibrations, the mechanical design is comprised of two main component sections: two U-channels and a vertical handle grip.

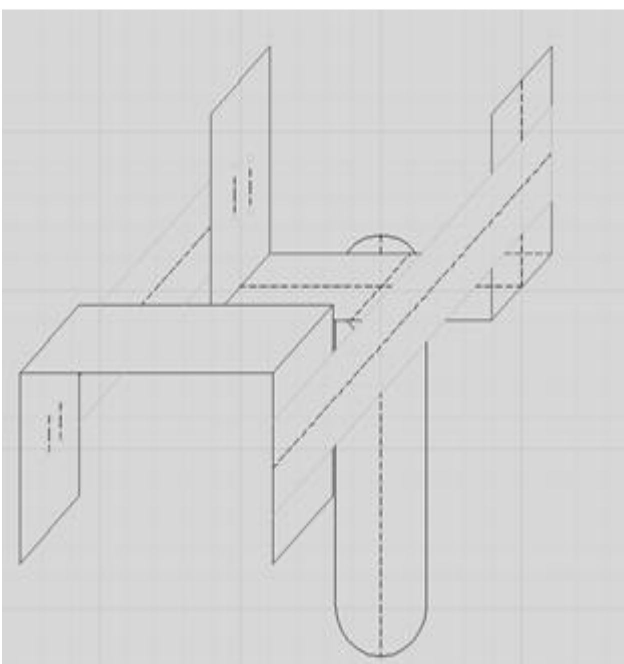


Figure 1: Rough AutoCAD mechanical draft of the handheld camera stabilizer frame, showcasing the camera and rear U-channels and handle.

A. Hardware Component Sections

The first major component sections are the two U-channels. Each channel will have a mounted servomotor for motion control. The camera will be mounted on to the base of the smaller U-channel. The smaller of the two servomotors will be mounted to the side of the same U channel. The larger U-channel will be connected directly to the grip. It also houses the larger of the two servomotors. There are two parallel arms that connect the two U-channels for motion control and frame support.

The two U -channels act as a pivot arm system for axis control. Each servomotor will be controlled through the main microprocessor and powered by the enclosed battery. Two inertial measurement units (IMU) sensors will be attached to the camera-mounting U-channel and on a PCB within the handle for acceleration and radial velocity data acquisition. The control will be determined by input data received from the inertial measurement unit. Acceleration and gyroscopic data will be used with the servomotors to maintain stability of the camera.

The material that was selected for the construction of the frame was 7075 aluminum. Aluminum is a very lightweight material yet it can provide the strength required of the frame design. To accommodate testing of various arm lengths, the aluminum material was purchased as a single channel with a length of 18” and a width of 1.5”. The channel was prefabricated with holes of diameter 0.5” encircled by smaller holes that allow for 6-32 hardware fastener mounting. By simply cutting the channel in the required lengths, the design team mounted the servos directly onto the channels since the holes perfectly supported standard servo size hardware.

The frame’s channel width was determined by the width of the Nikon 1 J1 camera model. As a result the camera U-channel is designed to support cameras of widths up to 4.2”. The rear U-channel is 4.5” in width to support hardware spacing requirements.

The other major component is the vertical handle grip. The handle/grip will house the necessary battery power supply as well as the printed circuit board. Embedded within the grip will be all necessary user interfaces including the power switch and the power indicator light. The handle is designed to provide an ergonomic and sure-fitted feel for the videographer, to provide a solid grasp and control of the handheld camera stabilizer. The handle is essentially a hollow cylinder that is made from a polymer material similar to polyvinyl chloride (PVC).

The handle's diameter is 1.5" to support the width of the internal PCB and battery systems. The length of the handle is 7" to house the electronic components and provide an ergonomic design for user satisfaction. To mount the handle, the cylinder contains two flat mounting caps on each end. When held vertically, the top cap is directly mounted using several hardware fasteners. This provides a flush plane for the rear U-channel frame to rest on. The bottom cap will be fitted to allow the user to directly connect the stabilizer to an external battery charger. The bottom cap will be attached using a polymer adhesive. Lastly, common cycling bar tape will be wrapped on the exterior of the handle to provide user comfort.

B. Theory of Operation

To operate the handheld camera stabilizer, the user will attach their camera on top of the smaller U-channel mount. Provided with the device is a universal ¼-20 mounting hub to attach the camera onto. Because different cameras have different mounting locations, the mounting hub is removable to accommodate different camera designs up to 4.2" in length and approximately 400g in weight.

Once the camera is securely attached to the device, the user will hold the stabilizer's handle grip vertically and turn on the device. An initial calibration will occur and the camera mounting will center itself perpendicularly to the handle grip. As the user experiences vertical changes as a result of fatigue and small turbulent variations, the handle grip will also experience these changes.

To compensate for these changes, data will be sent to servomotor attached to the large, back U-channel. By pivoting frame arms attached to the camera mount, the vertical differences will be mitigated and the camera will maintain its vertical center position. However, because the device uses rotational motion to adjust for vertical translations, the angle of the camera's focus point with respect to the handle grip will be changed. This is undesirable because the camera will no longer be pointed in the direction the user desires.

To mitigate the problem the second servomotor is used. By directly attaching the motor in axis to the camera mounting U-channel, the angle of the camera's line of sight can be adjusted. Whenever the camera is moved in the vertical direction, the back servomotor will rotate. In turn, the front servomotor will rotate in the opposite direction to adjust the camera's angle. At any given time, the two servomotors will maintain the same complementary angle pair to keep the camera mount parallel to the large, back U-channel and perpendicular to the vertical handle grip.

IV. Electrical System Design

A. Motors

For the electrical system, the first major consideration of the design team was determining which motors will be used. The design team reviewed several types of motor outputs including brushed DC motors, stepper motors, brushless DC motors, servomotors, and linear actuators.

The design team decided that for the output system, two servomotors would be used. The Hitec HS-5645MG servomotor will be used to support the stabilization required in the camera U-channel. The Hitec HS-5645MG servomotor has been found to be cost efficient while still being able to generate the torque needed to support the weight of about 16 oz. The fact that the Hitec servomotor can support a weight of up to 16 oz will prove to be useful in the sense that the Nikon 1 camera is about 12 ounces. The 4 oz buffer means that there is flexibility in choosing from a range of batteries that can weigh up to 4 oz.

The Hitec HS-7980TH servomotor will be used for the rear U-channel that is mounted directly onto the grip. It is more-than-capable of providing the necessary torque needed to lift the arm that supports the U-channel and camera. The chosen servomotors are also relatively energy efficient for the particular needs of this project compared to previously researched motor systems such as brushless DC motors. The servomotors will be directly powered by 7.4 V lithium ion battery.

Servomotor Configuration Table		
Hitec Servo	HS-5645MG	HS-7980TH
Torque	168 oz-in	611 oz-in
Weight	2.21 oz	2.7 oz
Max Current	1.3A	1.5A
Max Speed	0.18 sec/60°	0.21 sec/60°
Max Voltage	6V	7.4V
Gear type	Metal	Titanium
Motor Type	3-pole	Coreless
Support	Dual Bearings	Dual Bearings
Length	1.59 in	1.72 in
Width	0.77 in	0.88 in
Height	1.48 in	1.57 in

Table 1: Hitec HS-5645MG & Hitec HS-7980TH servomotor specifications [2] [3].

B. Sensors

The stability of the camera depends on understanding and reacting to the external jitter experienced by the turbulence of the aircraft and movement created by the user. In order to respond to the external forces to be compensated against, an IMU with acceleration and radial velocity data is needed. The MPU-6050 by InvenSense will be employed for such use.

The MPU-6050 is a 16-bit 6-axis internal measurement unit capable of three acceleration readings (x, y, and z-axis), three gyroscopic readings (same axes), and temperature reading. The MPU-6050 uses the I2C communication protocol. Below is a table of specifications:

MPU-6050 Specifications				
Device:	Accelerometer		Gyroscope	
Measurement:	Range	Sensitivity	Range	Sensitivity
Units:	g	LSB/g	°/sec	LSB/°/sec
Setting 0	±2	16384	±250	131
Setting 1	±4	8192	±500	65.5
Setting 2	±8	4096	±1000	32.8
Setting 3	±16	2048	±2000	16.4

Table 2: MPU-6050 6-Axis IMU Specifications [4]

Upon performing preliminary acceleration force simulations by driving a car on a rough road at slow speeds and recording the acceleration, it was found that the maximum acceleration magnitude was ±2g. The rear servo (HS-7980TH) can move at a maximum of 285.7 °/sec (no load). Thus, Setting 1 for the IMU clock seems appropriate with a ±4g and 500°/sec data threshold.

As previously mentioned, the handheld camera stabilizer will use two IMUs; one in the handle as a base-reference of acceleration and rotation movements, and a second on the camera U-channel for secondary comparison and error of the compensation. The challenge is to have the camera U-channel to experience normal acceleration conditions (1g) for stability while the handle moves up and down.

C. Microcontroller

In order to control all of the various components of the handheld camera stabilizer a microcontroller unit (MCU) will be employed. The MCU needed to have a small footprint, I2C communication compatibility, adjustable pulse-width modulation (PWM) outputs, and normal clock speed. Originally the Texas Instruments MSP430 line of MCUs was used, but due to the large footprint, poor quality of documentation, and internal clock configuration issues a different MCU had to be used. Due to time constraints and deadlines, the ATMega328p by Atmel is being used. The ATMega328p is a 32-pin TQFP MCU with six PWM outputs, 8-bit RISC architecture, 32 KB of programmable flash memory, 7 mm by 7 mm footprint, two-wire interface (TWI) compatible with I2C, with many various and reconfigurable analog-to-digital converters (ADC) and interrupt capabilities [5]. The ATMega328p is clocked with a 16 MHz ceramic resonator and powered by a 5 V linear regulator.

The MCU will serve as the controller for the servomotors, provide I2C communication with the IMUs, provide battery monitoring via an ADC pin, initiate an n-channel MOSFET kill switch for the servomotors if battery voltage drops below a safe level, provide the user interface via a bi-color LED (red and green), and perform all necessary calculations, conversions, and decisions for camera stability.

The I2C clock is set to 400 kHz, meaning that all necessary data from one IMU can be received in under 860 µs. The PWM signal length to control the servomotors will be 4.11 ms, with sweep length varying between 0.78 ms and 1.92 ms. To measure the battery voltage, the ATMega328p housed within the handheld camera stabilizer has a measured internal pin impedance of 11.3 MΩ, the ADC pin will be in parallel with a 1 MΩ ceramic resistor tied to ground, with another 1 MΩ pull-up resistor tied to the positive battery terminal.

All programming for the ATMega328p will be done with the Arduino IDE, due to time-constraints, excellent documentation, simple user interface, wide device compatibility and usage (available for Mac, PC, Linux, and Android), and open source and educational ethics.

D. PCB

The mechanical assembly of the various electrical components has to fit within the 1.25 internal diameter of the PVC piping used for the handle, thus width is the largest constraint of the printed circuit board (PCB). For simplicity of the design and lower cost of large-scale manufacturing, a double-sided PCB will be used. For simplicity of selecting various passive parts easy, all capacitors and resistors are 0603 (the smallest a team member can solder with the naked eye). The PCB was designed so that the MCU can be programmed on-board, and all connections easily probed and tested. All off-board connection will be soldered onto the through-hole wire pads. Below is a near-scale illustration of the PCB:

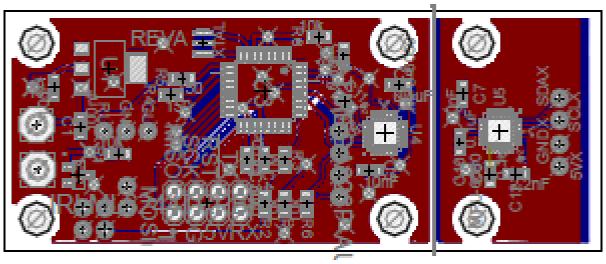


Figure 2: Near-scale illustration of handheld camera stabilizer PCB

The final dimensions of the PCB are 1.10” by 2.71”, with a removable secondary IMU (as seen on the right). Various components had to be changed and tested from the original schematic, swapping 3.3 V and 5 V linear regulators and attached components for a single 5 V linear regulator with only two 0603 capacitors. Another component swap as 16 MHz crystal oscillator with two 15 pF companion 0603 companion capacitors with a smaller 16 MHz ceramic resonator with built-in 15 pF capacitors.

To make manufacturing and part-ordering easy, the PCB only uses three different values of resistors and five different values of capacitors. All parts are available in large quantities exceeding 90k (as of 7/10/2014) and have an expected sales life till 2024, except for the ATMega328p MCU (Atmel would not disclose expected product lifetime).

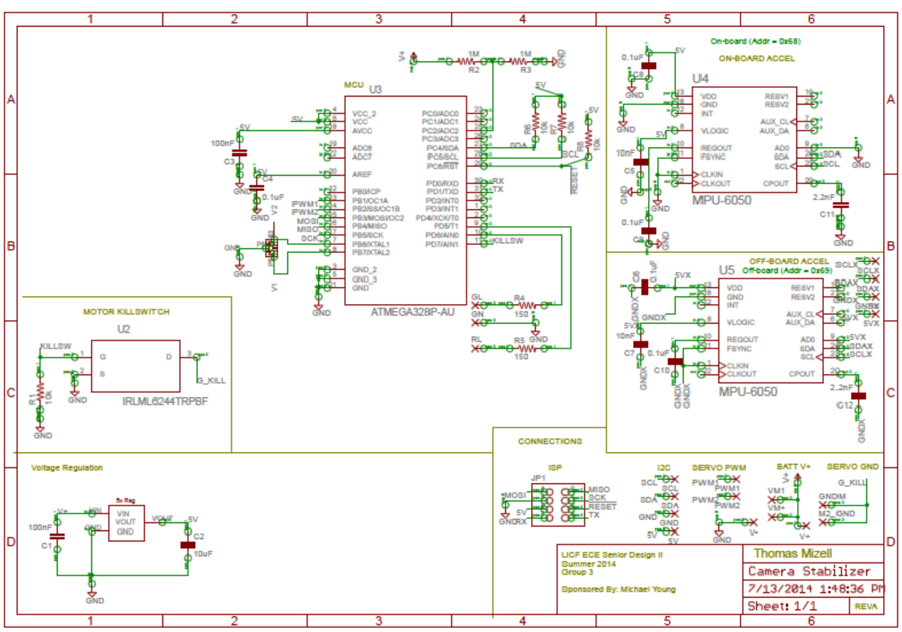


Figure 3: Final Schematic

The board has two power density regions, one where voltage is 7.2 V and currents are expected to peak at 3 A (for the servomotors), and another region at 5 V and less than 50 mA. To ensure that there is no current leakage from one power plane to the other, the higher powered region was isolated using 0603 sized power diodes and isolated copper region. All routing widths are designed to handle three times the expected current draw.

The PCB will be mounted with #6 width machine bolts with appropriate nylon washers and steel spring washers. Any battery connections with the board (for MOSFET kill switch) will use 16 AWG 24-strand copper wire for flexibility, and I2C communication lines will use 24 AWG solid core wire. There is an off-board rocker switch that connects the batteries to the servomotors and PCB. The PCB needs to have one direct connection with the positive terminal of the battery to monitor the battery voltage, and the ground connecting to the negative terminal of the battery for the MOSFET kill switch.

E. Power

For the final design that will be going towards the electrical system, the power component will be supported by a lithium ion battery as well as battery charger. The particular lithium ion battery that has been chosen for the handheld camera stabilizer project is the Tenergy Lithium Ion 18650 battery. As for the battery charge, the Tenergy TLP-2000 Smart Charger has been selected.

One of the biggest advantages of choosing the Tenergy Lithium Ion 18650 battery is the fact that it is a small light weight battery and yet can still provide 7.4V and 5200mAh. Both of the Hitech servomotors require at least an operating voltage of 7.4V and draw up to a max current of 2 amps. The accelerometer requires an operating voltage of 3.46V and draws up to a max current of 3.8mA. The Tenergy Lithium Ion 18650 battery high energy density can very comfortably meet the requirements of all the electrical components that will be going into the final design of the camera stabilizer.

Not only can the Tenergy Lithium Ion 18650 battery meet the requirements but it can run all the devices while the components are drawing max current at the same time for at least an hour. This insures that the thirty minute minimum requirement for the battery to run on a single charge can very easily be provided by the Tenergy Lithium Ion 18650 battery.

Another reason that the Tenergy Lithium Ion battery was chosen as the power supply option for the final design of the camera stabilizer project is due to the fact that it is a high quality rechargeable battery pack. The battery does not suffer from any type of memory effect and has a built in chip integrated circuit chip that protects the battery from overcharge and over discharge which ultimately. This particular feature allows the Tenergy Lithium Ion 18650 battery to have a very prolonged life.

The Tenergy Lithium Ion 18650 battery is very lightweight which comes in handy in keeping the overall device as lightweight as possible. Also, due to its small size, the battery will be able to fit into the handle and reduce the dimensions of the handheld camera stabilizer.

Rather than having to remove the battery from the handle when its charge has depleted, the senior design team has elected acquire a suitable battery charge to go along with the Handheld Camera Stabilizer. The Tenergy TLP-2000 Smart charger is compatible with the Tenergy Lithium Ion 18650 battery and several other lithium ion batteries. It has a led display indicator to inform the user when the battery if fully charged. The Tenergy TLP-2000 Smart charger is capable of detecting when that battery is fully charged and stop the charging process. This feature will insure to optimize the life time of the battery.

V. Control

In order to prevent any jitter or unstable imaging there are many methods employed to keep the image stable and clear. These methods include IMU data filtering, jerk detection, calculating needed motor speeds with a mathematical model of the physical handheld camera stabilizer system, and servomotor overshoot prevention.

Previous to using the mentioned control methods, using a combined PID controller of the motor positioning and IMU data averaging proved to be too complex or not sufficient enough. Since the system has very well-known characteristics such as loaded motor speeds and set physical dimensions, a physical model was employed along with data filtering and predictive programming to ease and gently move the camera into the desired position and acceleration range.

A. IMU Data Filtering

The MPU-6050 is an extremely sensitive and accurate device when it comes to measuring acceleration data. Unfortunately, any small changes in acceleration produce noise in the overall signal. Originally the ±2g setting was used (with 1 g represented as binary value 16384) and there was much noise in the line. After adjusting the settings on the IMU to the ±g settings (with +1 g represented as binary value 8192), much of the noise was mostly unnoticeable. Thus, this value was has been kept and will remain as the range for acceleration and gyroscopic data.

Upon further inspection, the IMU still shows show small amounts of noise in the data, thus a rolling average filter has been used. The rolling average we were most satisfied with involved a delay of 15 ms between readings with two previous readings and the current reading. Below is an example of such a filter.

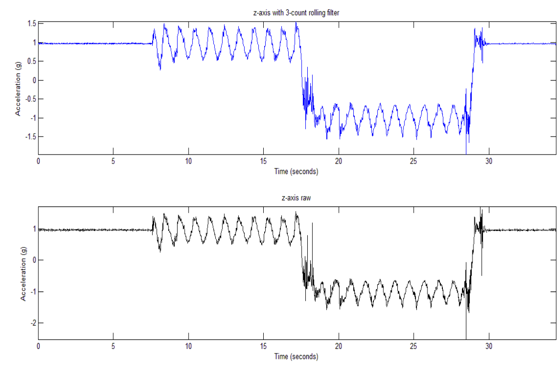


Figure 4: Rolling Average Filter vs. Raw Data

$$a_{AVG} = [a_0 + a_1 + a_2] \div 3$$

Equation 1: Implemented Rolling Average Filter

There is still further development that has to be done with the filtering of the IMU data.

B. Physical Model

The handheld camera stabilizer has known qualities. Under a normal load the rear servo (performs the heavy lifting) can move, on average, at 128.4 °/sec with the heaviest camera (Nikon 1) attached to the camera mount. The distance between the servo axes is 3.81". The servo has a response time of 120 ms. With this information, a simple model has been developed to determine what angle the back servomotor needs to move to in order to compensate for the linear acceleration sensed in the handle IMU. Below is the physical model.

$$\theta = (a/r) * \Delta t^2 - \theta_{prev}$$

Equation 2:Arm position versus linear acceleration

The known variables in equation two are Δt (120 ms) and r (3.81" = 0.09677 m), while a is are variable, represents as 8192 IMU data = 9.81 m/s^2. Thus, if the last known value of the angle is recorded, the model for arm motion becomes the following.

$$\theta = 0.00139\text{a} - \theta_{prev}$$

Equation 3: Final arm position equation

Likewise, the camera-mounting servomotor will move in an opposite angle to keep the camera pointed perpendicularly to the stabilizer handle. This feature enables the user to be able to point the camera at the desired angle while maintaining stability. So far this method has worked well for image stabilization. Once in a while the arm will swing over the 180° mark, where the equation does not hold. Further development of this system will be implemented as the deadline draws near.

Another note, the angle is actually "ticked though", meaning that the control signal to the servo motor works the servomotor up to that position, rather than relying on the actual speed of the motor itself. Again, further development of this system is underway.

C. Jerk Detection

The drastic change in acceleration when moving upward to downward or vice versa causes many little jitters and shakes to the camera system. In order to prevent such motion, within the average filter program is a variable that tracks the change in acceleration over the course of 60 ms. If the changes in acceleration start becoming above a programmed maximum, then the acceleration constant in the physical model will be slowed down to prevent any jerking of the camera. This jerk value is being tested and is under development at the moment.

D. Servomotor Overshoot Prevention

As mentioned in the physical model, the angle value for the back mounted servomotor is ticked through to allow a smooth yet quick response. As the servomotor gains momentum it can miss the desired angle and have to correct itself, thus causing jerk. In order to prevent servomotor overshoot, as the angle is ticking through and approaching the desired angle, the last 10-20% of the movement will be slowed down to allow the motor to gain it's torque once again to be able to stop at the desired angle with better accuracy. This is being developed in cogitation with the jerk detection.

VII. CONCLUSION

These past two semesters have been a very valuable and rewarding experience for the senior design team. Having to work in a group setting has allowed all the individual members to increase important skills that will be needed in pursuing our individual goals in the future. Of the many skills attained from this project are writing technical papers, performing presentations and most importantly, working coherently in a group setting.

One of the most rewarding experiences was understating and appreciating the amount of work and research that went into designing and building the handheld camera stabilizer. We found ourselves going through various types of design schemes before settling on one. Even after settling on one it seemed that every week or so we would need to change to microcontroller or the motor wasn't strong enough and so on and so forth. From these various challenges we believe is valuable lesson that things will not always go our way and we must learn to prepare according for any setbacks that may occur.

One thing to also note is how working on this senior design project has helped bring in most, if not all the information we attained from the past courses that we have taken up till now. One of the most important being the information gained from Electronics 2, Engineering Analysis and Computation, and Embedded systems.

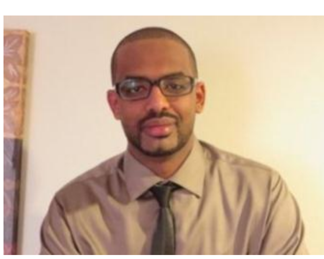
Acknowledgement

Throughout the process of designing the handheld camera stabilizer, the design team has sought out the help and consultation of professors and engineers. The senior design team is very grateful for all their contributions towards this project and would like to acknowledge the following people: Professor Michael Young, Dr. Samuel Richie, Dr. Jiann Yuan, and Dr. Aman Behal.

Biography

Thomas Mizell is currently a senior at the University of Central Florida. He plans to graduate and receive a Bachelor's of Science degree in Electrical Engineering in December of 2014. Thomas will also be graduating with a minor in Mathematics. Thomas has been an engineering intern for Siemens and Qualcomm and has worked as an electrical engineer for Circuitronics Corporation. Currently Thomas is a private tutor and is currently seeking a career with design start-ups or in the manufacturing sector. His interests are in digital communications, manufacturing quality assurance, and overall tinkering.

Alexander Pennock is currently a senior at the University of Central Florida. He plans to graduate and receive a Bachelor's of Science degree in Electrical Engineering in August of 2014. Alex has been an engineering intern for Disney and currently holds a position as Sr Engineering Assistant for the Quality Assurance department. Alex's goals are to obtain a role within their Design and Engineering department while working to earn his license as a Professional Engineer in Florida. His interests are in robotics and control.



Ahmed Salih is currently a senior at the University of Central Florida. He plans to graduate and receive a Bachelor's of Science degree in Electrical Engineering in August of 2014. Ahmed has been an electrical engineering intern for Piper Aircraft INC. Currently, Ahmed works for Valencia College as a Mathematics Tutor. Ahmed interest are in electronics design, power systems and mathematics. He is actively seeking employment and hopes to start his career in electrical engineering in the near future.

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