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A Gimbaled Platform for Micro Aerial Vehicle Autopilot Simulation and Calibration

by Justin L. Shumaker, Kamal S. Ali, and Lamarious Carter

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14. ABSTRACT This report describes a 3-degrees-of-freedom gimbaled platform designed to be used as a hardware in the loop simulator. This platform is designed to aid in the calibration and synchronization of micro aerial vehicles' autopilot components. This platform can also be used as a simulator allowing the autopilot to fly a computer model of the airframe. This allows for the quick and efficient verification of autopilot behavior with different airframes under various weather conditions within the lab.						
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Contents

List of Figures

List of Tables

1. Introduction

This report describes a gimbaled platform that can be used to calibrate small autopilots or inertial measurement units (IMUs) (*1*). This platform can also double as a flight simulator on which an autopilot can be evaluated and developed. The platform is controlled by five stepper motors (*2*), two for pitch, two for roll, and one for yaw. The stepper motors have a resolution of 0.18° per step using microstepping technology. To complement the stepper motors, optical shaft encoders are affixed to all three axes. The shaft encoders supply accurate readings of the platforms attitude. By placing the autopilot on the platform while actuating the platform to simulate flight, IMU data and the corresponding shaft encoder data may be collected. This data can be used to fine-tune the contribution from each of the IMUs sensors to minimize overall error. Furthermore, the data can also be utilized in the training of neural networks (*3*) or any other type of filter to further minimize IMU error.

The platform can also be configured as a synchronization tool, e.g., synchronizing IMU and video images for target geolocation. This is accomplished by placing both the video camera and autopilot on the platform where they are synchronized with the optical shaft encoders. The exact IMU data corresponding to each video frame can then be obtained, thus rendering the target geolocation system more accurate.

This platform has been integrated with X-Plane,[*] a Federal Aviation Administration-approved flight simulator. This software was chosen to handle the flight dynamics calculations and provide data to both the platform and autopilot. New flight surface positions can be generated by the autopilot or interface module, which are then passed back to X-Plane, where the resulting change in airframe attitude is rendered. This new attitude data is also passed to the platform's motor control system, updating the platforms attitude. In this configuration, global positioning system (GPS), as well as barometric and wind speed data generated by X-Plane, is supplied to the autopilot. For these sensors to operate correctly, additional hardware not yet integrated into the platform is required. Therefore, using the platform as a flight simulator will require modifying the autopilot code to accept the aforementioned data directly from X-Plane. Nevertheless, using the platform as a flight simulator will allow the evaluation of an autopilot's control algorithms using different airframes, as well as performance testing under different weather conditions at the click of a mouse button.

[*] X-Plane is a registered trademark of Laminar Research, Columbia, SC.

2. The Platform

Before creating the 3-degrees-of-freedom gimbaled platform, a 2-degrees-of-freedom platform was designed and constructed as a proof-of-concept. This platform was used to calibrate the pitch and roll for an IMU on an open source autopilot. After carefully analyzing the recorded data and making adjustments to the IMU algorithm, a 30% improvement in accuracy was realized, as shown in figures 1 and 2 (*4, 5*).

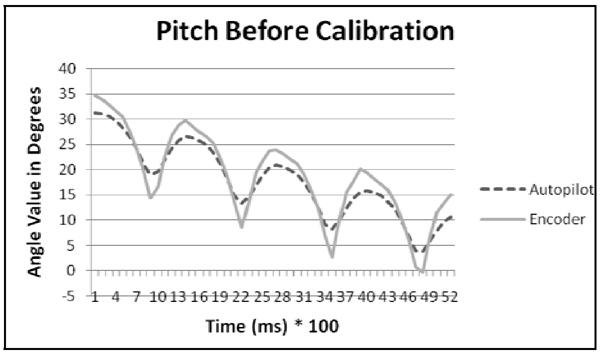

Figure 1. Before calibration.

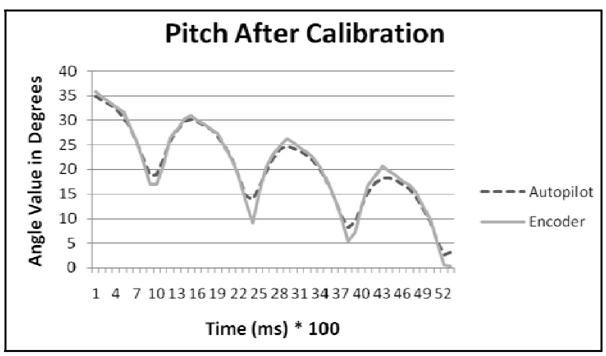

Figure 2. After calibration.

While the calibration changes made a vast improvement to the IMU's software, the platform was not without its limitations. First, the platform's linkages used an inferior friction fit, resulting in the potential accumulation of error during sudden jerks. Second, the platform was restricted to very small autopilots measuring a maximum of 3- × 5-in area. Third, there were time synchronization errors between the platform and autopilot. Fourth, and most significant, the platform was limited to pitch and roll measurements only.

Fortunately, the time synchronization was an issue that could be corrected in software. With the platform and autopilot operating in a 25-Hz open loop configuration, it was determined that the data could be shifted by 1.6 T (64 ms) to synchronize the autopilot data with the shaft encoders. This result can be seen in figures 3 and 4.

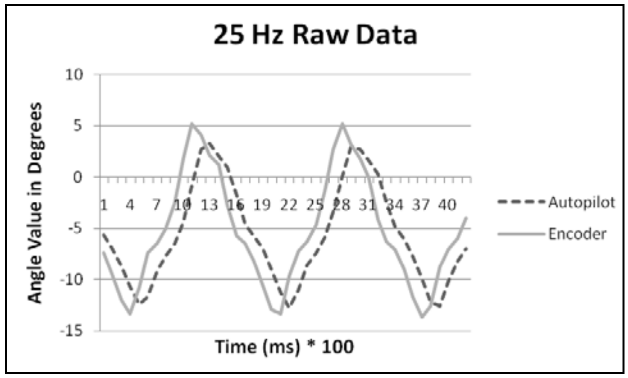

Figure 3. Before shifting.

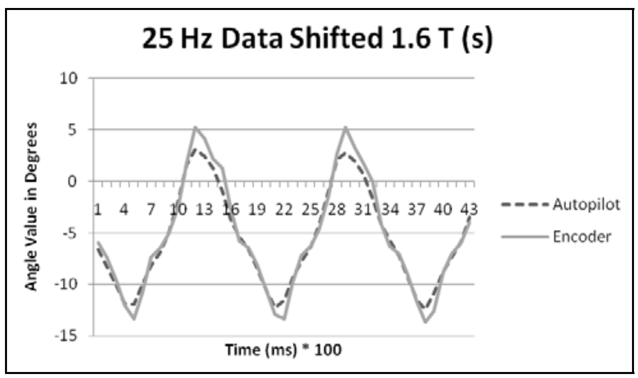

Figure 4. After shifting.

A new gimbaled platform was conceived to overcome the limitations of the previous one, as shown in figure 5. The new platform was designed to host an autopilot with dimensions up to 5 × 7 in. Like its predecessor, the central mounting plane rotated freely to any desired azimuth and elevation. Stepper motors were used to control the platform's rotation, while optical shaft encoders were used to report the platform's exact angular position. A pair of stepper motors was used to rotate the platform about the pitch axis, while two larger stepper motors rotated the platform about the roll axis. A fifth stepper motor with planetary gearbox, having a ratio of 10:1, was mounted to the base of the platform to control the yaw axis.

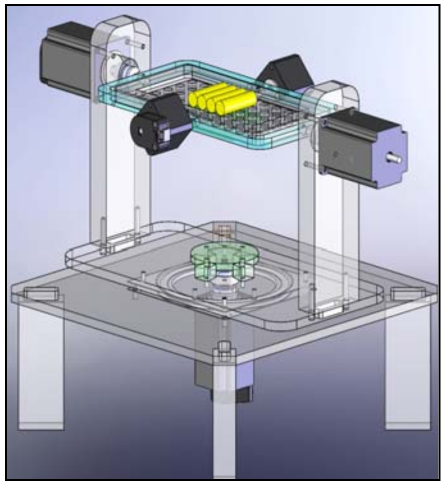

Figure 5. Three-axis gimbaled platform.

Due to the large angular inertia in the upper portion of the platform, a stepper motor with sufficient torque was necessary to prevent the motor from skipping steps while undergoing high accelerations. Each skipped step resulted in 7.2° of error. Initially, when the yaw motor was connected directly to the platform base, excessive skipping was observed, especially when rapid yaw changes were attempted. To ensure that yaw motor did not skip, a quick calculation of the necessary torque was made and compared the motor's capabilities. The holding torque of the motor was obtained from its torque frequency curve, as shown in figure 6 (*2*).

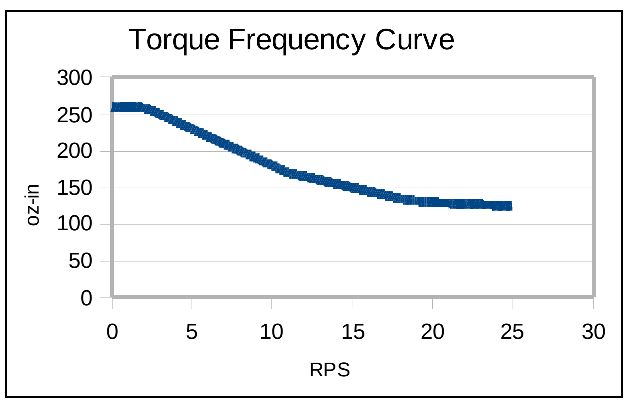

Figure 6. Stepper torque vs. frequency.

The torque generated by the platform, τ, is a product of the angular acceleration, α, and the inertial tensor, *I*, as follows:

$$\tau = I\ \alpha\,. \tag{1}$$

The inertial tensor can be approximated using the following, where *m* is the mass and *r* is the radius:

$$I = mr^2\,. \tag{2}$$

The upper platform's 4-kg mass and 0.18-m radius made it necessary to use a gearbox to overcome the inertial load. A planetary gearbox with a gear ratio of 10:1 was used to scale the stepper motor's torque an order of magnitude higher, eliminating all skipping.

Each axis on the platform used a dedicated Geckodrive 201 stepper motor driver. For the pitch and roll axes where two motors were used, the wirings of each motor were mirrored. This prevented these motors from opposing each other in rotation. The inputs to each Geckodrive consisted of a direction, step signal, and 30-V source. A current-limiting resistor was used to protect the motors from overcurrent. For each motor to perform a microstep, the Geckodrive requires a falling edge transistor-to-transistor logic (TTL) signal on the step signal input. Both direction and step signals were driven by an Atmel AT91SAM7S64 ARM7, a 32-bit microcontroller with four pulse width modulation hardware generators, three of which are used.

The linkages in the new platform utilized an improved locking pin system that minimized slipping between the motors and interconnects. All five stepper motors used shaft couplers to interface the platform. Upper and lower portions of the platform are interfaced through a 6-in ball bearing swivel that allows the upper segment to rotate freely with minimal friction. A custom-designed shaft coupler, denoted by its green color in figure 7, is used to interface the yaw stepper motor and gearbox to the upper portion of the platform.

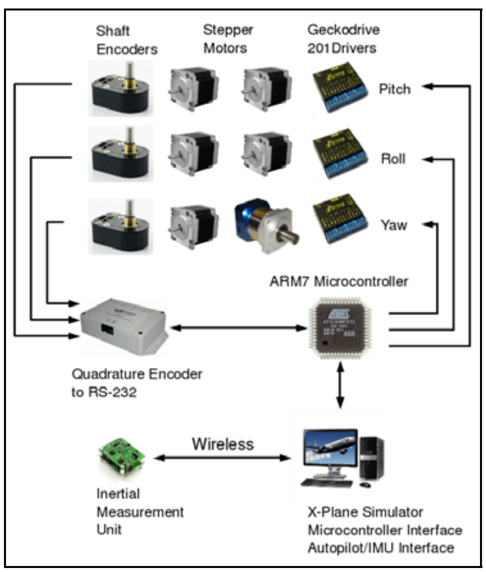

Figure 7. System diagram.

Three U.S. Digital optical shaft encoders having a resolution of 2000 steps per revolution are affixed to the stepper motors to measure angular position (*6*)—one each for pitch, roll, and yaw, respectively. The optical shaft encoders interface to a U.S. Digital AD5-S Quadrature Encoder to SEI adapter. This adapter interfaces with the ARM7 microcontroller, reading the three encoder values using an RS-232 interface at 115,200 baud.

3. Actuation

NEMA 17 and 23 stepper motors were used to control the platform. These motors were powered by Geckodrive 201 drivers that support microstepping, a technology to increase overall angular accuracy through the fractional energizing of adjacent coils. These drivers, which can deliver up to 7 amps, have high input impedance allowing TTL level signals to control the motors.

The microcontroller was used to control the motors, process angular data from the encoders, and receive angular update commands from the computer. The stepper motors were updated at 20 Hz, the X-Plane's default rate. A custom software module was created to interface X-Plane to the ARM7 microcontroller via the computer's RS-232 port. During each update, the microcontroller received a sequence of bytes from the computer containing three angles for pitch, roll, and yaw, respectively. The microcontroller then polled each of the three encoders for their angular values. Based on the stepper motors current and desired position, a pulse width modulation (PWM) frequency was calculated and set for each motor; this instructed the motors to rotate the platform to the desired attitude.

4. Angular Measurement

Should the motors happen to slip due to an unexpected mechanical or software error, using optical shaft encoders ensures that motor slippage will not affect the resulting attitude. The optical shaft encoders with a resolution of 2000 steps per revolution were chosen to match the stepper motor's 2000 steps per revolution under the influence of microstepping. However, in the case of the yaw stepper motor, there are 20,000 steps per revolution due to the planetary gearbox having a gear ratio of 10:1. Therefore, the optical encoders are capable of detecting a single microstep from the stepper motors. For the pitch and roll axes, this equates to 0.18° per step and 0.018° for yaw resolution.

5. The Hardware in the Loop Simulator (HILS) System

The platform was designed to operate in two different modes—open loop and closed loop. These modes provide a means of testing the autopilot's performance under different conditions in a controlled environment. This type of testing allows for fine-tuning of the control algorithm on the autopilot, as well as the reduction of IMU errors. Once testing is complete, the autopilot should be mission ready when it leaves the lab. Such a methodology provides minimal risk testing and calibration of the autopilot and control algorithms (*7*, *8*).

6. Open Loop System

When the system is configured for open loop, the autopilot is placed on the gimbaled platform, and the computer is programmed to actuate the platform such that it subjects the autopilot to designated attitudes. The autopilot sensors report these attitudes back to the computer, and the shaft encoders provide a precise measure of the exact attitude. This setting allows the calibration of the autopilot's IMU using the difference between the reported and actual attitudes.

This setting can also be used to correct errors in the IMU attitude algorithms. By compiling IMU data together with the corresponding shaft encoder data, filtering techniques such as neural networks or Kalman filters can be employed to minimize errors in the IMU's algorithms (*3, 9–12*).

In addition to calibrating IMU hardware, the platform could be used as a synchronization apparatus. An example of a system that can greatly benefit from such an apparatus is the target geolocation acquisition (TGA) system. A TGA setup consists of a camera, GPS, and IMU. Sensor fusion would then occur between the camera frame, IMU attitude, and GPS position to determine an approximate ground position based for a designated pixel in the camera frame. Synchronization of data from these sensors has a direct impact on the geolocation accuracy (*13*).

7. Closed Loop System

In the closed loop configuration, the autopilot drives the simulator as the simulator drives the platform. Between each time step of the simulator, the autopilot reads its IMU to obtain new attitude data. This attitude is then processed by a control algorithm on board the autopilot, e.g., a proportional integral derivative (PID) controller or a model predictive controller, etc. This control algorithm determines the adjustments necessary to the vehicles control surfaces to meet the desired attitude. These control surface adjustments, such as throttle, elevator, rudder, and aileron, are then transmitted to the simulator.

Once the simulator receives these updates, its internal flight dynamics engine calculates a new attitude based on the user-selected airframe. These new Euler angles are transmitted to the ARM7 microcontroller, instructing the stepper motors to match the new attitude. Once the new attitude is reached, the feedback loop is closed and the process repeats.

This feedback loop typically runs at a frequency of 20 Hz but is capable of running at higher or lower frequencies as well. The frequency may be set in the Data Input and Output menu of X-Plane. The frequency is a function of the aircraft's stability and speed profile. As a general rule of thumb, the smaller or faster the aircraft, the higher the frequency. The airframe used during testing was the N163MV Cirrus Jet. Because of this aircraft's high stability, an update frequency as low as 5 Hz is acceptable.

8. X-Plane Interface Module

Communications with X-Plane occur through a custom-designed interface module, behaving as a stand-alone program. It has the choice of executing an internal control algorithm on the X-Plane data or propagating it to the autopilot. The interface module connects to X-Plane over a network port using the user datagram protocol (*14*). Once the module establishes a connection with the X-Plane server, it immediately begins transmitting data. The frequency and content of this information is defined by the user in the Data Input and Output menu of X-Plane.

The items selected under the Data Set menu can be seen in table 1. These items are specific to version 9.0 of X-Plane and may vary with other versions. The data is received in a little endian binary format. Regardless of whether an application uses the X-Plane data, it must receive it in order to send data of that type back to X-Plane. After all data is received, the module stores it in a local data structure.

Table 1. Items selected under X-Plane's Data Set menu, version 9.0.

X-Plane v9.0 Line Item	Description
3	Speed, vertical speed
11	Flight con ail/elv/rud
17	Angular velocities
18	Pitch, roll, headings
20	Lat, lon, altitude
21	Loc, vel, dist traveled
35	Engine thrust
39	Prop pitch

Before any control algorithm processes the data from X-Plane, the attitude data must be converted and sent to the microcontroller. The microcontroller would then perform one of two different actions. Either the X-Plane data can be propagated to the autopilot or it can be passed to a local control algorithm. If the data is propagated to the autopilot, it will typically use its IMU data in lieu of the X-Plane attitude data. However, passing the data does not prohibit the autopilot from using all of the X-Plane data as a type of virtual IMU. In either situation, the module must wait for the autopilot to return new control surface data. When the data is passed to the local control algorithm, the calculation of new control surface data is performed with minimum latency.

9. The Microcontroller

The same microcontroller was used to process data from the encoders, receive data from the computer, and drive the stepper motors to a specific position. Virtually any microcontroller with two or more RS-232 ports and three or more PWM generators can be used. An RS-232 interface at 115,200 baud is connected to the U.S. Digital AD5 Quadrature Encoder device, and another RS-232 interface at 115,200 baud is connected to the computer. Three PWM outputs are connected to the Geckodrive 201 drivers to control pitch, roll, and yaw stepper motors, respectively. Three general-purpose IO lines, which control motor direction, are connected to the Geckodrive 201 drivers as well.

The frequency of the microcontroller's master clock and PWM generators determine the frequency range of the stepper motors as well as the resolution of stepper motor control. The microcontroller was configured to operate at 48,054,857 Hz. This is a function of the 18.432-MHz crystal oscillator and the phase locked loop multiplier and divider hardware within the microcontroller. The divider register was set to 14, and the multiplier was set to 73. Finally, a postscale division of 2 was applied, i.e.,

$$MClk_{Freq} = \frac{Freq_{\mathrm{OSC}} \times PLL}{Postscale \times Divider} . \tag{3}$$

The master clock frequency of the microcontroller dictates the range of frequencies that can be chosen for PWM generators. Each PWM generator has separate registers for the 16-bit period and duty values. Furthermore, there exists a register to divide the master clock for the PWM generator's frequency. Presently, the master clock is divided by 256, slowing the PWM frequency by that factor. The period register is set to a hexadecimal value of 0xFFFF, resulting in a period of 349.13 ms. Hence, the PWM outputs can generate a square signal between 2.86 Hz and 93.86 kHz. Since a full revolution of the pitch and roll stepper motors requires 2000 steps, while the yaw requires 20,000 steps, this equates to rotational rates spanning from 8.58×10^{-2} to 2.82×10^{3} revolutions per minute. This is clearly an acceptable range for providing slow to fast control over the stepper motors. Note that most stepper motors do not function beyond 3 kHz.

It is also worth mentioning that as the PWM period decreases, the frequency error increases. This error is the result of having fewer bits available to represent smaller values. For example, if the desired period is 1,000.25, the closest integer value the hardware can represent is 1000, resulting in an error of 0.025%. If the desired period is 1.25, the closest integer value the hardware can represent is 1, resulting in an error of 20%. A graph of the maximum error curve can be seen in figure 8.

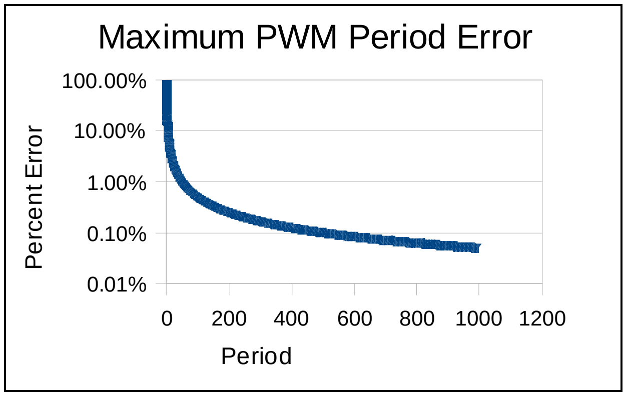

Figure 8. Maximum error curve for the PWM period values.

Once powered up, the microcontroller sends several initialization commands to the U.S. Digital AD5 Quadrature Encoder. The first of these commands is a baud rate change. The AD5 default communications rate is 9600 baud. To keep latency at a minimum, the microcontroller instructs the AD5 to change its communication rate to 115,200 baud. The second set of commands instructs the AD5 to reset the internal counter for each encoder to 0. Therefore, the current position of the platform is set as 0 for each axis. The last initialization command is a poll on all three encoder channels to ensure that communications are working.

Once the initialization sequence on the microcontroller has completed, it functions as an event-driven process. X-Plane is set to output data at 20 Hz. The data sent to the microcontroller consists of three signed 16-bit values for pitch, roll, and yaw, respectively. The sign of the value denotes the direction in which the motors will spin. Therefore, the values for each axis can range from –32,768 to 32,767. These values signify the position that each motor should now assume. For pitch, which has a range of –90° to 90°, the range of values are –500 to 500. For roll, which has a range of –180° to 180°, the range of values are –1000 to 1000. For yaw, which has a range of 0 to 360°, the range of values is 0 to 20000. Each time the X-Plane module sends data to the microcontroller, it has to convert the pitch, roll, and yaw angles from X-Plane to the 16-bit values mentioned previously. Once the microcontroller has received the data, it polls the encoders for their current positions. For each axis, a difference between current and new positions is calculated, i.e.,

$$\sigma = \left(\frac{\text{Position}_{new} - \text{Position}_{cur}}{\text{Period}} \right). \tag{4}$$

The product of this equation is a PWM period, as shown in the following:

$$PWM_{period} = \frac{\tau}{\sigma}. \tag{5}$$

The PWM period, in turn, defines the PWM frequency that corresponds to the angular velocity necessary to rotate the stepper motor from its current position to its new position as in the following:

$$\tau = \left(\frac{MClk_{Freq}}{256} \right). \tag{6}$$

If X-Plane is configured to update at 20 Hz, then the period between updates is 50 ms. The PWM duty is always half the PWM period. This can be accomplished by shifting the PWM period value to the right by 1 bit and storing that value in the PWM duty.

Certain calculated values may produce singularities that prevent the hardware from functioning properly. If σ in equation 5 is 0, then its best to turn the PWM generator off or set it to its lowest frequency. If the PWM period is too low, then the stepper motors may be driven at a frequency higher than capable. Bounds checking should always be performed.

10. Platform Evaluation

The HILS system was put through a testing and evaluation cycle to verify its accuracy in an open-loop configuration. An autopilot was mounted to the platform and instructed to transmit its IMU data at the highest rate possible to a ground station running on a desktop computer. A take-off and loitering sequence using several PID controllers was programmed into the X-Plane interface module. This permitted the N163MV Cirrus Jet to autonomously take off and loiter once achieving an altitude of 4000 ft. The PID controller for level flight was intentionally designed to cause the aircraft to porpoise. This behavior provided more features to study within the data set. IMU data from the autopilot and X-Plane were logged for ~170 s. Both data sets were time shifted to account for latency in the autopilot's wireless communications link.

11. Results

The data presented in figures 9–11 is based on the very first data captured from the gimbaled platform. The porpoising in pitch can clearly be seen, while the roll data remains relatively constant until a counterclockwise loitering sequence occurs. Both the pitch and roll curves matched the expected curve very well (see figures 9 and 10). The subtle differences are believed to be caused by a small amount of backlash in the coupling between the stepper motors and platform. The yaw curve has almost no correlation with the expected curve (see figure 11). The error seen is twofold. The first source of error is the result of the autopilot being indoors and not having a read on magnetic north. The second, and more significant one, is a result of the electromagnetic interference (EMI) produced by the stepper motor's magnetic fields. The effect of pitch on yaw motors is visible in the yaw results.

Rather than rely on magnetometers, most autopilots acquire true heading from GPS, which is more reliable at higher speeds. For autopilots that use GPS (*15*) for heading, these yaw errors are irrelevant.

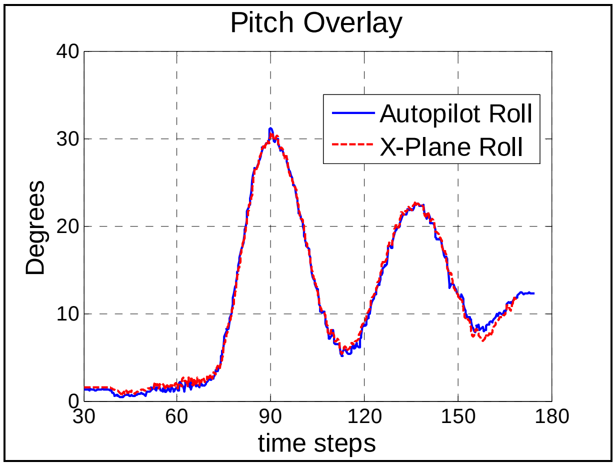

Figure 9. Pitch overlay.

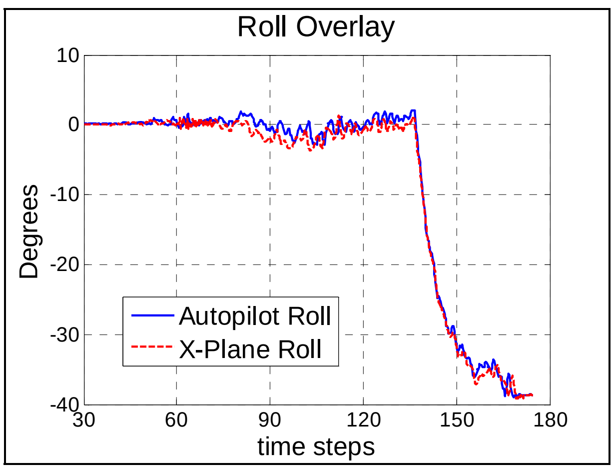

Figure 10. Roll overlay.

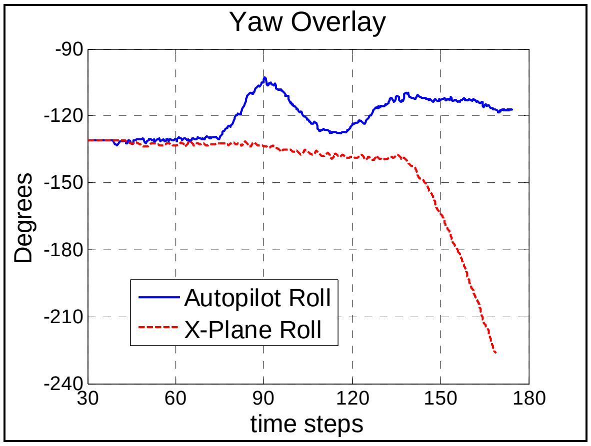

Figure 11. Yaw overlay.

12. Future Work

The next generation gimbaled platform incorporates a more comprehensive hardware suite for testing both open source and closed source autopilots. The additional hardware will provide the autopilot sensors with artificially generated signals for GPS, barometric pressure, wind speed, temperature, humidity, and magnetic heading. The software will also be enhanced to make the configuration process a more user-friendly one.

The GPS signals will be artificially generated using a pair of devices that receive coordinate data and generate the corresponding GPS signals. The GPS simulator chosen for this project is the CAST SIMCOMIII developed by CAST Navigation, allowing for the simulation of up to 12 satellites. This will be coupled with CAST Navigations CAST130, which is a real-time trajectory input system. The GPS data from X-Plane will be sent to the CAST SIMCOMIII, thus allowing any GPS equipped autopilot to obtain a GPS location using its receiver.

To control altitude, a pressure-controlled chamber will be constructed around the gimbaled platform. Inside, the chamber pressure can be set to the appropriate altitude. In doing so, the autopilot can detect altitude changes directly from its sensor. A duct and fan will be used to drive air out of the chamber to control the internal pressure.

To simulate wind speed, a fan will be placed in a close-ended cylindrical tube. Two outlets with the same diameter as the pitot tube will be placed at the back of this cylinder. One of these outlets will be connected to the autopilot’s pressure sensor, normally connected to the pitot on the outside of the airframe, while the other will be connected to another pressure sensor. The autopilot will then use its ported pressure sensor and pitot tube to measure wind speed.

Temperature and humidity need only be controlled within the chamber. Therefore, by replacing part of the enclosure with a thermoelectric plate along with fans to circulate the air, the temperature of the air surrounding the autopilot can be controlled.

To allow for the evaluation of autopilots that rely on magnetic heading, the motors in this platform will have to be completely shielded or moved to minimize interference with the magnetometer. A possible solution is to use linear actuators and move the motors away for the autopilot and magnetometer. Although a valid solution, the range of motion in pitch and roll may be limited. One other possible solution is to use piezoelectric motors. This would effectively eliminate the undesirable electromagnetic field produced by the stepper motors.

13. Conclusions

A 3-degrees-of-freedom gimbaled platform was designed and built as a development tool for autopilots. The platform proved very effective in minimizing IMU errors. The platform was also used in an open loop setting, which allowed X-Plane to fly the platform. The results showed high accuracy in pitch and roll, with the yaw severely affected by the EMI of the stepper motors.

The results obtained show that this system can be developed to serve as a universal flight simulator for small autopilots. After being completely developed, this system will allow small autopilots to be placed on the platform and fly any airframe under any weather condition in the laboratory. This will greatly speed up the autopilot development cycle as well as establish guidelines for autopilot evaluation.

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