

Development of Hardware-in-the-Loop System for Autonomous Small-Scale Aerial Vehicles.

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Abstract

This paper describes a hardware-in-the-loop system (HILs) development for a small-scale aerial vehicle with on-board automatic control system. The HILs is developed by integrating embedded real-time autonomous hardware to software for simulator of the flight vehicle dynamic, flight control, communication, navigation and visualization. The mathematic models of the aircraft were developed and its dynamic were simulated and visualized using X-Plane Flight Simulation. The interaction between automatic control hardware and computer simulation were done a communication module through UDP and Serial port. The using HILs is shown to be useful in evaluating functionality and performance prior to the flight test of our recently developed automatic control hardware and algorithm for an autonomous aerial vehicle.

Keywords: Hardware in the loop, Flight simulator, Automatic aerial vehicle

1. Introduction

In development new model aircraft or new algorithm for aircraft control for both military and civil aviation, if test with real aerial vehicle will has risk, expensive cost, long time testing required, and uncontrollable environment [1].

Currently, these exist computer programs have high capability for simulate flight dynamic. Those are realistic and high capability generate scenario (such as extremely weather). Flight Simulation Programs can show the behavior of flight condition by using graphic and numerical. Efficiency of aircraft and control system can get from this.

Hardware in the Loop system (HILs) is communication between external hardware (Controller Boards, Autopilot module, etc that contain with algorithm, sensor devices and control surface part) and computer (Similar real airplane). The computer will generate flight dynamics (as data from sensors, AHRS, GPS, Airspeed, and etc.) from flight simulation program. The aircraft's behavior can show real time and show by numerical, easy to plot for analysis performance.

In this paper, we present the design HILs for using in experiment algorithm of UAV by the commercial X-Plane 10 flight simulator. X-Plane 10 is used in simulate flight dynamic that receive command of control surface from external autopilot module. Then, X-Plane 10 will generate necessary flight dynamic parameters for autopilot module and analysis. Flight Dynamic parameters

and control commands transfer with C# programming interface via Ethernet, using UDP. Flight Dynamic will be monitored with GUI for the analysis [1] [2] [3].

Objective of this research develop to test, verify and study behavior of new model aircraft or new algorithm that is developed for aircraft.

2. X-Plane Flight Simulator

X-Plane 10 is realistic flight simulator; it has high capable of simulation aircraft and weather (Effect from other aircrafts or effect from thermals); Also, it has almost all database of geographic and world airport.

X-Plane 10 has realistic model of airplanes, helicopters and other aerial vehicle, that are already approved by Federal Aviation Administration (FAA) for full motion simulator to train commercial airline pilot[5].

For experiment in new aircraft model case, we can draw a new aircraft; new aircraft is designed; and configure other parameters by Plane-Maker (Fig. 1), that is included in the X-Plane 10's package. Parameters (CG., Weight, thrust and etc.) that can be able configure become from design and calculation form designer.

Computing and Simulating of X-Plane 10 use "Blade Element Theory" method; which involves breaking the aircraft down into many small elements and then finding the forces acting on each little element many times per second; to able calculate behavior of aircraft (Stall, turbulence,

complicate aerodynamic and etc.) more accuracy than “Stability Derivative”[6].

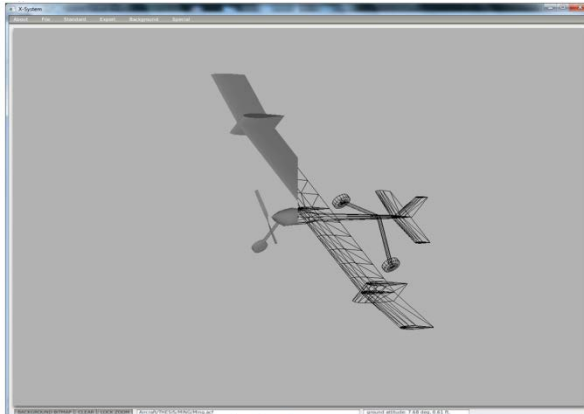


Fig. 1 Bachelor’s airplane model in Plane-Maker

Presenting of X-Plane 10 can present other parameters (Parameters are selected Fig. 2) 4 ways; 1. X-Plane 10 display value real time while simulate on screen. 2. X-Plane 10 display graph real time while simulate 3. X-Plane 10 save flight log to be text file that can open with Microsoft Excel or etc. Last, X-Plane 10 sends and receives parameters via UDP port. Data rate can be 0.1 to 99.9 Hz.

3. The Test Platform

The test platform is compounded of Computer and Autopilot module presented in Fig. 3 In the block of computer, X-Plane 10 is used be flight simulator. X-Plane 10 transfers all data via

Ethernet UDP port 49000 (X-Plane 10 received) and port 49003 (X-Plane 10 Sent) then C# program will monitor aircraft’s status and transfer some data (Autopilot Module needed) to autopilot module via Serial. X-Plane 10 can be tracking path flight by third party program.

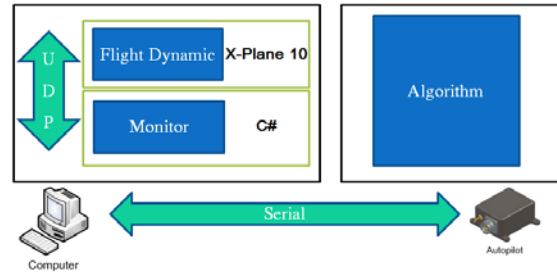


Fig. 3 Test Platform Block Diagram

In the block of autopilot, it is contained with algorithm, sensors, control surface controllers and other devices. The algorithm of autopilot is used to process data from computer. Data those are necessary for autopilot module be data from AHRs, GPS, Airspeed and Tachometer. After processed, autopilot module will generate command of aircraft’s control surfaces. Many autopilot modules can connect directly to Serial port of computer. But some autopilot module cannot connect with serial for testing, we must use microcontroller for translate data out from PWM to serial, and translate data in from serial to similar sensor protocol.

C# program is data translator from X-Plane

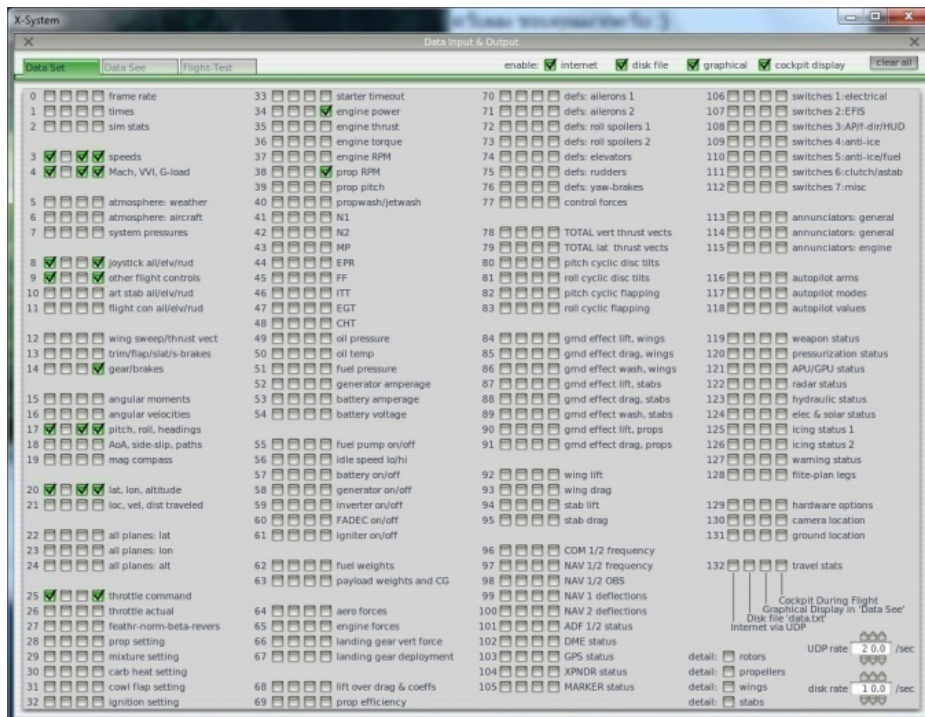


Fig. 2 Data input/output are selectable

10's UDP package to Serial protocol. Data package size from X-Plane 10 depend number of data out are selected. Package start with 4 byte of string "DATA". The fifth byte is type of data. The next 4 bytes is zero byte. Following 32 bytes represent 8 floating point data. X-Plane 10 data package pattern is shown in Fig. 4[1][4]. C# program can show data in GUI for the analysis. An example of user interface is shown in Fig. 5

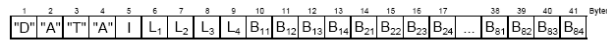


Fig. 4 X-Plane 10 data package [1]

Operating of the HILs is developed describe by flowchart in Fig. 6 it separates to 2 parts.

First part, Graphic User Interface (GUI) is path create graph, get input from user and show all parameter. Also, GUI part is create COM PORT communication, that use for communicate between computer and Autopilot module.

Second part, Main Program is part communicate between X-Plane 10 and outside via UDP port, then it split data to collect each parameter types. Also, it packs data to be string for send to autopilot module.

Furthermore, in receive data from serial case, we use interrupt method that do not lost time while autopilot module process and send data back. When received data back will collect data

to each type, and then wait time for send to X-Plane in the main program part.

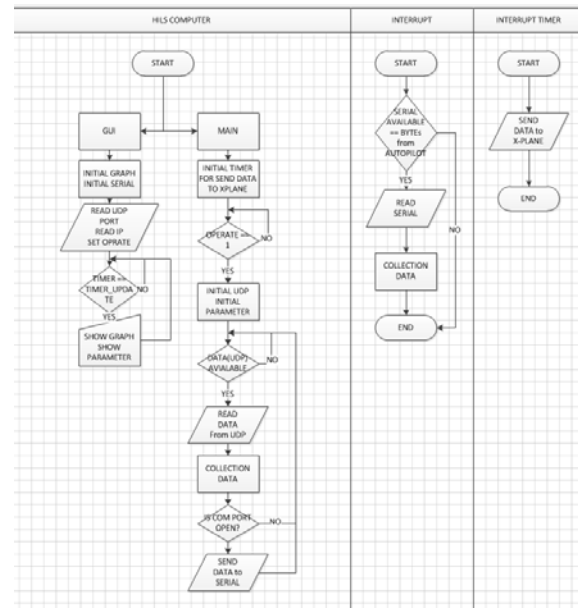


Fig. 6 Flow chart of Program HILs

4. Application Example

Testing HILs with microcontroller Arduino Mega 1280 that is autopilot module by receive aircraft's parameter from program interface that was developed. Parameter from X-PLANE 10 is similar to IMU such as latitude, longitude,

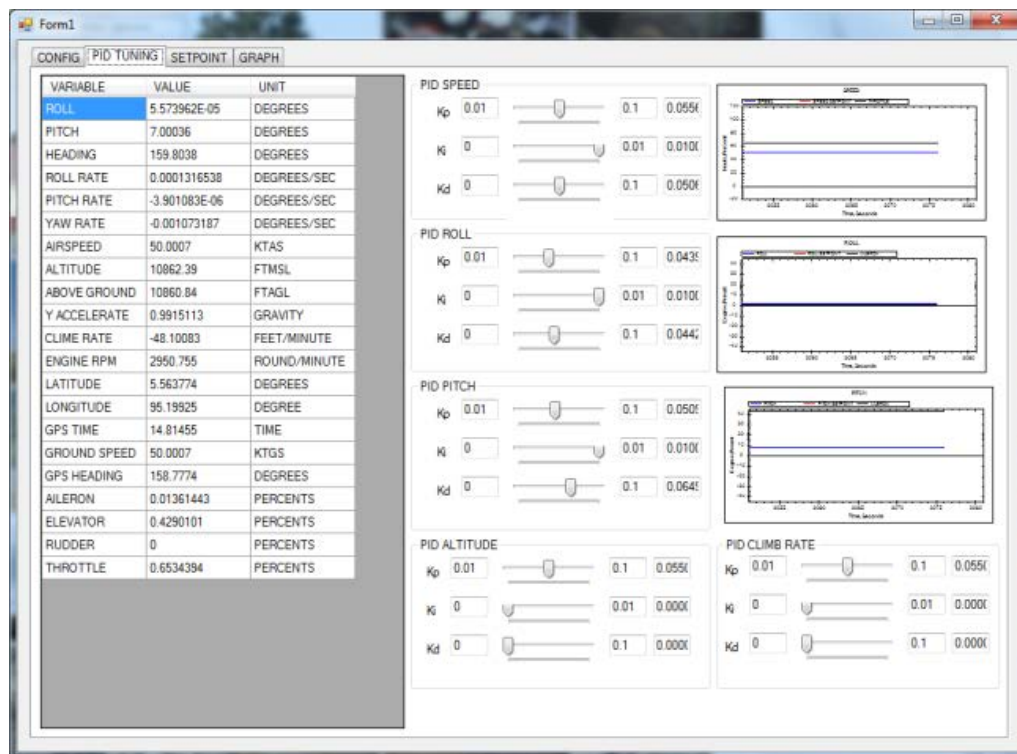


Fig. 5 User Interface

airspeed, altitude, climb rate, roll, pitch and heading. After calculated, it will send control surface command to computer via Com port. The autopilot module has function to follow waypoints that working as Fig. 7. It separates into 2 levels; the first - High level that is a navigator part and the second - Low level that is attitude stabilizer of aircraft. In this experimental, researcher identify position 3 waypoints (Fig. 8) are the first waypoint at Suvarnabhumi airport as 13.691067N, 100.760867E. the second waypoint at Chulachomklao Fort as 13.537850N, 100.583550E. And the last waypoint at Chaophraya River between Yannawa district and Klongtoey district as 13.704583N, 100.556183E. This system will begin at the high level which has 3 stages. Stage 1, check the current position from X-plane 10 to determine distant, with Haversine equation (Eq.1), less than 500 meters or not. If so, it will be changed to next waypoint.

$$D = 2r \sin^{-1} \sqrt{\sin^2 \left(\frac{\phi_2 - \phi_1}{2} \right) + \cos \phi_1 \cos \phi_2 \sin^2 \left(\frac{\lambda_2 - \lambda_1}{2} \right)}$$

(1)

When D is a distant in kilometers unit, r is an Earth's radius that used 6371 kilometers, ϕ_n is latitude of n position, λ_n is longitude of n position.

Then move to stage 2, calculate bearing angle (θ) from Eq.2. Calculate by used the current position with waypoint's position to be a roll set point angle.

$$\theta = \tan^{-1} \left(\frac{\sin(\phi_2 - \phi_1) \cos \phi_2}{\cos \phi_1 \sin \phi_1 - \sin \phi_1 \cos \phi_2 \cos(\phi_2 - \phi_1)} \right)$$

(2)

The last stage of high level is evaluating set point of altitude due to differentiate between each waypoint.

In the next step, we will focus on low level. In this level it keeps status of 5 parts of aircraft with PID that compound with; first part, airspeed stabilizer that control throttle directly. Second part, rolling stabilizer of air craft that control from different between "heading" and "bearing" which can effect to aileron control. The third part is altitude stabilizer that comes from the different

between current altitude and altitude of waypoint which may change climb rate set point. The fourth part is climb rate stabilizer which come up with current climb rate set point, from the third part, that effect to pitch angle. Finally, pitch angle stabilizer which come from current pitch angle and pitch angle set point and cause of changing elevator angle. PID gain of 5 parts come from experimental.

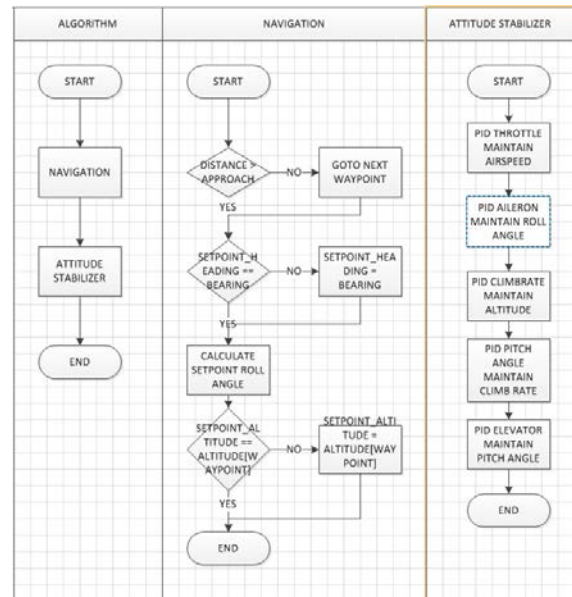


Fig. 7 Algorithm flow chart

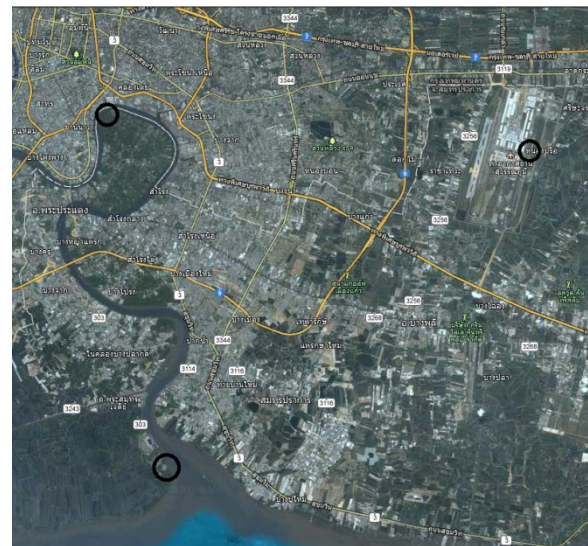


Fig. 8 Position of Waypoints

The pattern of transfer data between autopilot and the developed software use similar form with X-Plane 10, that send via UDP, by send decimal data in floating point 4 bytes per each data, because of its precision data and small size, in experimental was used baud rate 115200 bps is a maximum rate of Arduino can accept, in

order to keep the lowest of delay in data transmission and for precision reason.

5. Results

The random is beginning in the initial position and starting with Autopilot system to follow waypoints. The result represent in Fig. 9

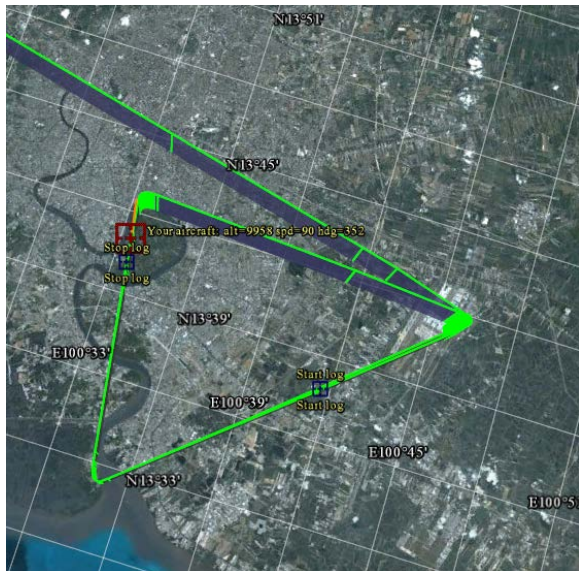


Fig. 9 Path Tracking

In Fig. 9, the initial position is shown as green line from the top left then aircraft changes attitude to go to the first waypoint. When the aircraft is approaching 500 meters, the target waypoint will be changed to second waypoint. The second waypoint has bearing angle in 228.31 degrees. Before changing the waypoint, aircraft has heading approximately 100 degrees. Bank clockwise is closer than bank counter clockwise thus aircraft will change set point of heading. Stabilizer of roll system keeps heading in that direction. If aircraft has bank angle, it will effect to airspeed and altitude as well.

The green line from Fig. 9 is flight path logger that use black box flight logger program to keep data while simulate. Then plot paths on map with Google Earth (by using latitude, longitude, speed and heading)

When airplane change waypoint, each waypoint has difference position, speed and altitude so adaptive of control surface will come automatically that stated in Fig. 10.

In the case of changing waypoint from first one to second one, aircraft will calculate new heading and adjust aileron for bank to that angle which seen in this case the aircraft will bank clockwise, command to control aileron is a positive value and not exceed than 30 degrees.

Due to the limit of maximum bank angle is 30 degrees. When heading close to the bearing angle that calculated on previously, bank angle will getting to close to zero angle.

When taking the bank, the following things are changed such as airspeed and altitude. In Fig. 10 the black line from the middle graph will be lead phase which means the bank can cause the reducing of the airspeed and altitude. After that airspeed stabilizer will maintain airspeed suddenly in the same way with altitude, altitude stabilizer will adapt elevator to maintain altitude.

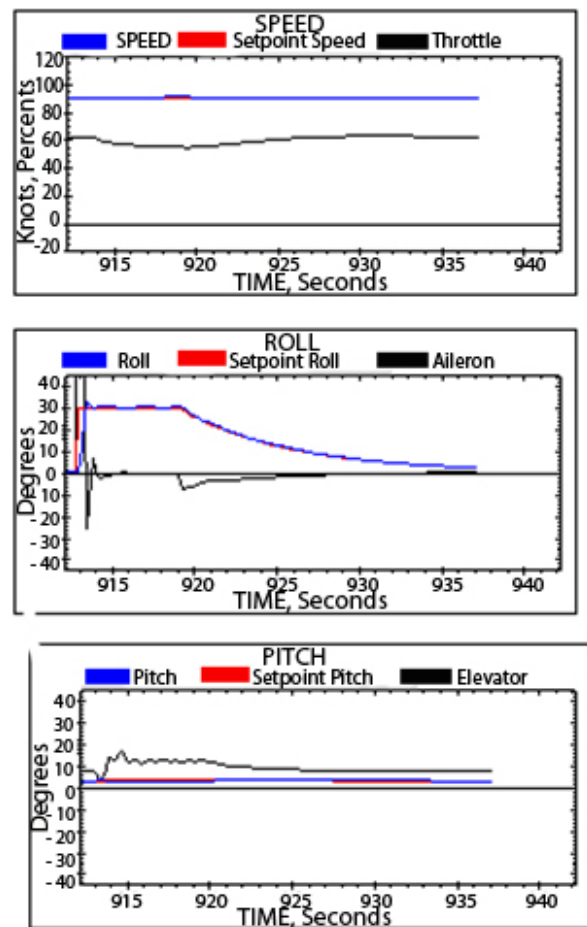


Fig. 10 Data While Translate Waypoint

Fig. 10 in each graph combines with 3 lines; blue line is a current airspeed or angle, red line is set point of angle or airspeed, and black line is value of control surface or throttle in percentage unit. The top graph represents airspeed. In the middle graph shows roll angle. The bottom graph explains the pitch angle.

Transfer data between computer and autopilot module, sending the data to autopilot module deliver the data 64 bytes of size use baud rate 115200 bps at 4.4 milliseconds. Followed by

data was calculated in stabilize system every 20 milliseconds (50 Hz).and send the data back to computer with 41 bytes package size at 2.85 milliseconds. From the experimental, if computer has too much load, the delay will occur. Therefore, autopilot module will not receive the real time data plus the data could not accuracy enough. Hence, computer used to be HILs should get performance by X-Plane 10 required.

6. Conclusion

This paper is development of HILs which is a platform in order to test autopilot module. It can simulate behavior of aircraft and save flight logger data. To contact with autopilot module was used through com port but it has the limitation of the maximum transfer rate at 115200 bps and 50Hz of update data rate. This limitation cannot do the control loop in a high rate but the initial experiment used control loop at 50Hz and spend data package not too high.

Sometimes has an error in data package and turn that data into unreliable data and autopilot module will reject the error package.

Although, the transfer data take time approximately 4-5 milliseconds that enough to resend data in case of error data in the other hand, it need to build error package checker and acknowledgment. If user requires a high rate of control loop or large package, it may use the other communication that has a faster com port.

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