International Journal on Advanced Science Engineering Information Technology

Vol.11 (2021) No. 5
ISSN: 2088-5334

HILS of FPV-2600 UAV using MyRIO-1950 as Optimal Flight Control System

Herma Yudhi Irwanto [a,*], Idris Eko Putro [a], Saeri [a]

[a] *Indonesian National Institute of Aeronautics and Space, Jl. Pemuda, No. 1 Jakarta, 13320, Indonesia*
Corresponding author: [*]herma.yudhi@lapan.go.id

***Abstract*— Hardware in the Loop Simulation (HILS) system was successfully implemented to the embedded MyRIO-1950 on board as the flight control system (FCS) in FPV-2600 UAV modeling in X-Plane flight simulator. The modeling is carried out step by step using the Loop Simulation (SILS) and HILS software. In the SILS step, Labview and X-Plane succeeded in combining data communication via User Datagram Protocol (UDP) and controlling the vehicle to autopilot by waypoints mode. The subsequent development is to move the whole SILS results program into HILS, which involves software and hardware directly by combining the Predictive Control Model (MPC) as a linear simulation control model and PID as classical control, successfully controlling the FPV-2600 in a flight mode simulation in manual, stability and autopilot by waypoints. The simulation is done by doing a flight test manually and stability directly using remote control manually and stability using the remote control to analyze flight performance and vehicle stability. Furthermore, the simulation of autopilot by waypoints by tuning the MPC's predictive and control horizon is related to the inner loop control on the roll and pitch, and the PID gain tuning is related to the altitude and the waypoints target. In this simulation, MyRIO-1950 as hardware can be used as a real-time simulation control for MPC and PID integrated into HILS, and this will be very useful for initial procedural reference before flying the FPV-2600 in the actual flight test.**

***Keywords*— Hardware in the Loop Simulation (HILS); Model Predictive Control (MPC); Field Programmable Gate Array (FPGA).**

Manuscript received 11 May. 2020; revised 6 Jun. 2020; accepted 19 Feb. 2021. Date of publication 31 Oct. 2021.

I. INTRODUCTION

FPV-2600 is a low-speed glider aircraft used for aerial photography, as its name stands for First Person View / FPV (Fig. 1). An FPV aircraft is equipped with cameras for taking both static images and video. Thus, it needs to maneuver and fly stably to reduce vibration that may decrease the quality of photos and videos taken by the camera.

Fig. 1 FPV-2600 aeromodelling

Like general UAV, FPV-2600 is also based on 6-DOF (degree of freedom) that can fly and maneuver with three fields of motion: aileron, elevator, and rudder, plus thrust from the engine. It also has an autopilot system with not only manual flight mode, enabling it to fly automatically both in stability and autopilot by waypoints. The autopilot system available in the market is equipped with general and easy-to-use strategy control, namely PID [1]-[3].

The development of improved control technology, followed by developing a more compact and sophisticated onboard controller, has enabled many heavy and complicated control strategies, such as LQR, Sliding Mode, Neural Network, and MPC [4]–[8]. Those newest control strategies can be implemented using relatively small controllers nowadays.

Direct implementation of HILS from X-Plane Flight simulator to one of National Instrument products is MyRIO-1950, which is equipped with reconfigurable input and output. FPGA-based, the platform is suitable for making high-level processes, which is needed in complex and challenging application and fast control processes.

Design and development of Flight Control System (FCS) that was based on MPC and PID using MyRIO-1950 was the right solution in prototyping using the HILS, in which the data from X-Plane in the form of attitude and position were replaced with IMU and GPS to be used in real-time as FCS in the real flight test [9], [10].

The second chapter of this paper will elaborate on a mathematic model, which is the base of optimal control of MPC used in the flight simulation, followed by a vehicle model created in X-Plane flight simulator as its program visualization. Moreover, the third chapter of this paper explains the hardware in the loop simulation, which was used in both inner loop and outer loop simulation, by engaging MyRIO-1950, followed by remote control to describe the real condition in manual mode, stability mode, and autopilot mode. The chapter will also explain the result of the integrated simulation between MPC and PID in-vehicle maneuver.

II. Material and Method

This research was conducted in 2 steps, modeling and HILS, which directly involved MyRIO as the hardware. Modeling includes mathematical models and flight, simulation models. This section also explained MPC as a primary control strategy in maneuvering, especially in the inner loop stability block control.

A. Modeling FPV-2600

FPV-2600 has a wingspan of 2600 mm, a length of 1500 mm, and an empty weight of 2100 grams. With a wing area of 66 dm^2 and a wing loading of 31.9 g/dm^2, it is a very stable glider aircraft, suitable as a vehicle to test the flight control system being developed. This simulation needs FPV-2600 modeling for the development of the real-time flight control system. The previous development of the flight control system successfully used only a PID control, so the next step was to try to integrate one optimal control strategy model, which was MPC, to reduce more error and get a smoother attitude. The use of MPC required a mathematic model as a reference in control. Here is the linear model of directional longitudinal and lateral dimensions of FPV-2600.

$$\begin{bmatrix}\dot{u}\\ \dot{\alpha}\\ \dot{q}\\ \dot{\theta}\end{bmatrix}=\begin{bmatrix}-3.03e-06 & 4.74e-04 & 0 & -9.8\\ -2.34e-06 & -4.56e-06 & 1 & 0\\ 4.44e-16 & -7.81e-11 & -2.01e-10 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ \alpha\\ q\\ \theta\end{bmatrix}+\begin{bmatrix}-2.46e-05\\ -1.61e-05\\ -1.91e-09\\ 0\end{bmatrix}\delta_E \quad (1)$$

$$\begin{bmatrix}\dot{\beta}\\ \dot{p}\\ \dot{r}\\ \dot{\psi}\end{bmatrix}=\begin{bmatrix}-9.88e-08 & 0.0032 & -1 & 0.49 & 0\\ -7.66e-11 & -8.60e-11 & 3.87e-11 & 0 & 0\\ 1.66e-16 & -1.85e-12 & -1.39e-12 & 0 & 0\\ 0 & 1 & 0.0032 & 0 & 0\end{bmatrix}\begin{bmatrix}\beta\\ p\\ r\\ \psi\end{bmatrix}$$

$$+\begin{bmatrix}-3.23e-08 & -4.22e-06\\ 4.01e-11 & -3.34e-12\\ 4.99e-11 & -1.62e-11\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta_A\\ \delta_R\end{bmatrix} \quad (2)$$

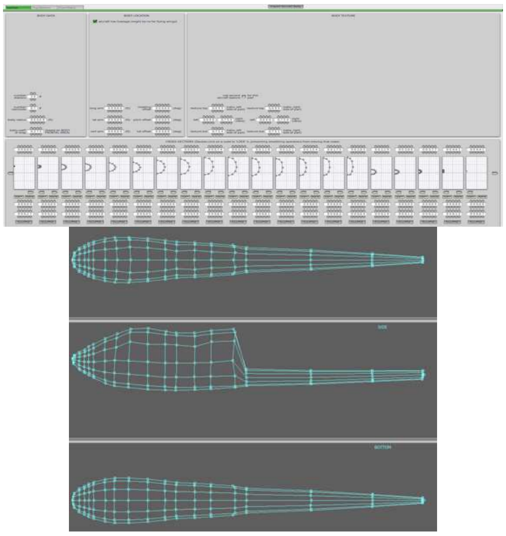

Fig. 2 Fuselage setting

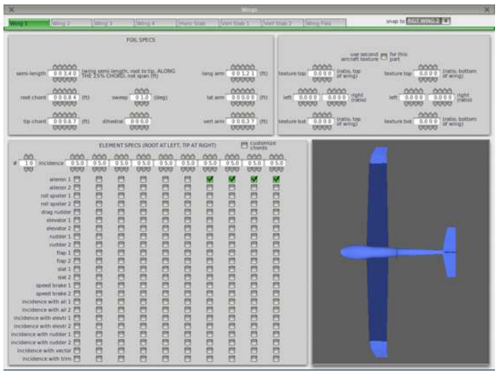

Fig. 3 Wing design

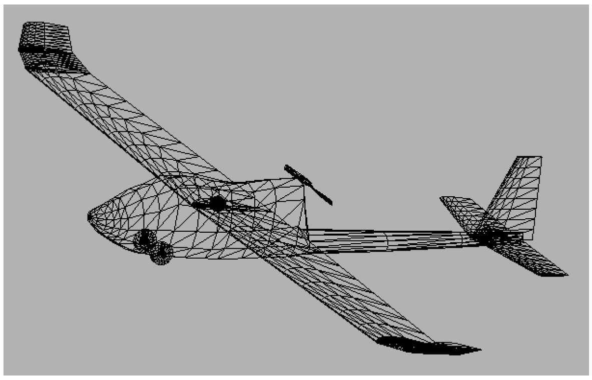

Fig. 4 Airframe model FPV-2600

Adding to the mathematic model, the position and attitude of FPV-2600 are visualized in the simulation model motion in X-Plane (Fig. 4). The creation of the model included design fuselage (Fig. 2), wing (Fig. 3), engine position and setting, control geometry, landing gear set, weight, and balance, etc. [11]-[12].

B. Hardware in the Loop Simulation (HILS) and Prototyping

The simulation was done using HILS method, involving two units of computer and one unit of flight control system (Fig. 5) [13]-[16]. The first computer, which was called the dynamic computer, functions as the X-Plane handling. It was a high-end computer with good capacity for rendering, having a minimal VRAM of 2 GB. Meanwhile, the second computer served as the monitoring and controller computer, which functioned to receive X-Plane's attitude and position and send data of field motions (aileron, elevator, rudder, and engine) to X-Plane. The controller computer's second function was handling the flight control system for the processes of close loop stability and navigation control.

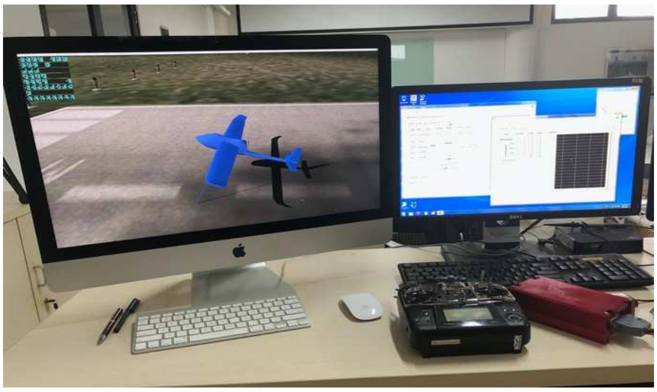

Fig. 5 Hardware in the loop simulation

In this simulation, MyRIO-1950 (Fig. 6) was used as the flight control system, and Labview 2015 was the programming language. MyRIO-1950 was a controller based on Xilink Zynq-7010 667 MHz FPGA (Field Programmable Gate Array) and Arm Cortex A9 that had 2 ch UART, 32 ch DIO (Digital Input Output), 4 ch AO (Analog Output) and 8 ch AI (Analog Input). The feature was sufficient to control a flying vehicle. MyRIO-1950 was also completed with connection with real (Inertial Measurement Unit) IMU, GPS, radio telemetry, and battery Lithium Polymer (LiPo) as the power system required in the actual flight test in the next step.

Fig. 6 MyRIO-1950

The programming involved block Control Design and Simulation Labview to handle the use of MPC (Model Predictive Control), which precisely handled some parts of inner loop stability, namely roll and pitch. Meanwhile, PID controlled more on outer loop navigation, such as altitude keeping and heading control.

Communication between the dynamic computer and controller computer used UDP (User Datagram Protocol), while communication between the controller computer and flight control system used a shared memory since both computers had Labview as the basic programming. The simulation was completed with HEX based protocol to communicate using its GCS (Ground Control System).

Labview programming involves a lot of module control design and simulation for operating the control strategy MPC. With a memory size as big as 512 MB, MyRIO-1950 was able to compile all contents related to the MPC to use programming so that it would be used as a stand-alone controller. For the use of simulation between computers, MyRIO-1950 offered a shared memory to store variables simultaneously so that the simulation process could work in real-time.

C. Model Predictive Control (MPC)

The case of FCS development for an autonomous flight vehicle requires input attitude data from the Inertial Measurement Unit (IMU), the position data from GPS, and control using the remote control. Simultaneously, the output is an action for each field of motion (aileron, elevator, rudder, and engine) and sending data via telemetry.

The use of control strategies has been done in previous simulations using PID control that the use of MyRIO based on FPGA (Field Programmable Gate Array) in its function as main FCS has many advantages in programming. With FPGA, it is possible to do parallel programming to complete 2 or more processes simultaneously [15]–[16]. Therefore, to maintain stability in the inner loop control that requires a fast and accurate response, MPC only handles roll and pitch or controls the ailerons and elevators. Simultaneously, the maneuver toward the yaw's target or control is still carried out with the PID control. The combination of this MPC and PID and parallel programming for each of the roll, pitch, and yaw sections will produce an autopilot maneuver towards a predetermined target.

1) Inner Loop Stability MPC: This MPC replaces the PID in controlling the aileron and elevator related to roll and pitch input. With the FPGA parallel programming, when the stability mode requires that the roll and pitch have a value of 0 deg, MPC control process automatically will do it respectively and simultaneously for the value of aileron to roll and elevator to pitch, to hold at 0 deg (Fig. 7). If the FPV-2600 maneuvers in a bank to turn (BTT) mode by only relying on the ailerons and elevators without involving the rudder.

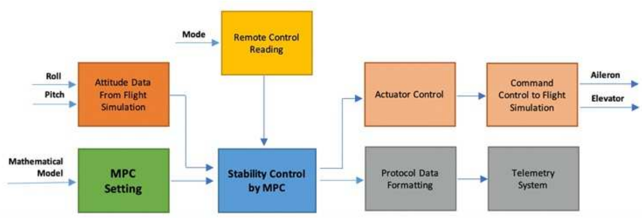

Fig. 7 Inner loop stability block diagram

2) Outer Loop AutoPilot by Way Points using PID and MPC: This is far more complex than the inner loop above for the outer loop section. FPV-2600 has a mission to maneuver to achieve its targets. This means the roll value is not 0 deg, and the pitch value is also adjusted to the specified altitude setting, plus the value of yaw/heading that must point to the target. The combination of MPC and PID with FPGA base FCS makes it easy to achieve targets from each specified waypoint [17]-[20].

Achievement of the altitude target still uses PID, which is fed to the elevator control with input pitch data using MPC. While the aileron control using roll data also uses MPC, based on the calculation of the target heading using PID by comparing the difference between the heading and yaw data against the heading that must be achieved at that time (Fig. 8).

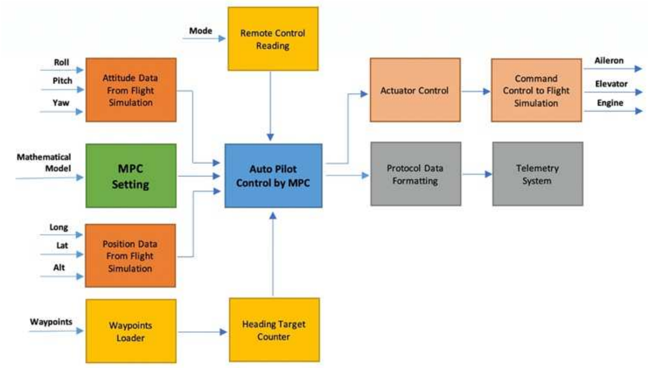

Fig. 8 Outer loop autopilot block diagram

III. Result and Discussion

With the HILS method, this simulation is done in a close loop by presenting attitude data and position data from the X-Plane flight simulator, forwarded by the computer controller to FCS MyRIO for processing into the FPV-2600 motion field command and sent back to the flight simulator. This HILS also allows MyRIO to receive mode data from the remote control and send process data to GCS on a separate computer.

A. Processing by MPC

Handling of roll and pitch condition by MPC looked pretty good. Based on the formula (1) and (2), the prediction and control horizon MPC settings are performed as in Table I, producing all conditions of points set earlier could be followed, which is seen from the concurring lines in Fig. 9. In the simulation, MyRIO has included a remote-control receiver, as shown in Fig. 5, which means the system was connected wirelessly to the remote control. So, the flight test simulation was controlled directly in manual, stability, and autopilot mode, similar to the future real flight test.

TABLE I
Setting Prediction and Control Horizon

Dimension	Pre Horz	Control Horz
Lateral Directional	10	2
Longitudinal	8	2

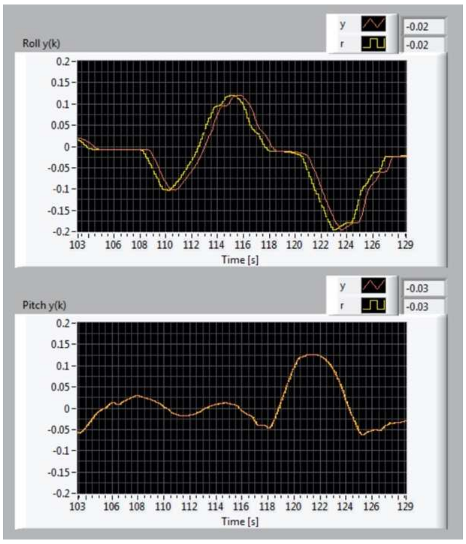

Fig. 9 Roll and pitch control by MPC

There are four important components used in Labview's MPC programming, that is Create MPC Controller, Update MPC Window, Implement MPC Controller, and Discrete State-Space (Fig. 10). These four components are used fully in the completion of formula (1). In this case, the linear model of longitudinal directional, which is only affected by elevator motion.

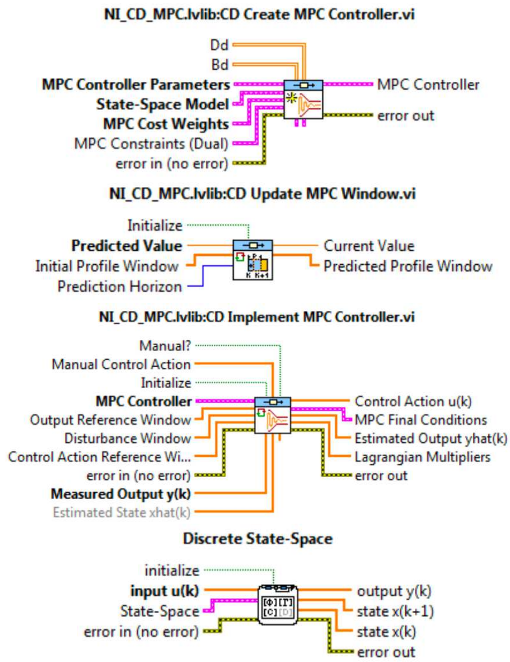

Fig. 10 MPC components in Labview

TABLE III
MPC Components and Function

MPC Components	Function
Create MPC Controller	Creates a model predictive control (MPC) controller for a state-space model
Update MPC Window	Calculates the appropriate portion, or window, of the setpoint or disturbance profile of a signal from time k to time k + prediction horizon
Implement MPC Controller	Calculates the control action u(k) to apply to the plant
Discrete State Space	Implements a system model in discrete state-space form

In Fig. 9, r shows the current value to be achieved, and y (k) is the output. As for the lateral directional block shown in formula (2), the MPC Window Update must be replaced by the MPC Window Update (Multiple) (Fig. 11), because 2 motion fields influence this formula, which is an aileron and rudder. Output this component is 1 dimension array.

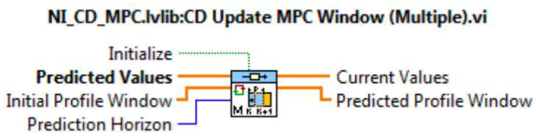

Fig. 11 Update MPC Window (Multiple)

B. *Stability Control*

Flight stabilization is referred here to be a vehicle that will remain in a flat condition for the roll and pitch, even if there is interference either by the surrounding environment or intentional disturbance using the remote control. This stability test is carried out at a constant speed.

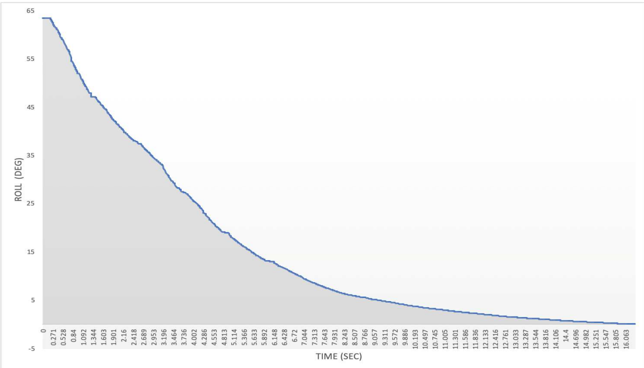

Fig. 12 Roll stabilization

In the simulation, the vehicle is flown in the manual mode and after the vehicle's condition is stable in the air. The flight stabilization performance test is then carried out by giving disturbance to the roll and pitch conditions. The result is that with a 63 deg roll disturbance to the right, the FPV-2600 manages to flatten its position in just 16 seconds (Fig. 12). Thus, when the pitch-up disturbance is done by 45 deg, the vehicle becomes flat, stable within 10 seconds (Fig. 13). The chart in Fig. 9 also proves that vehicle stabilization is faster for pitching disturbance than roll.

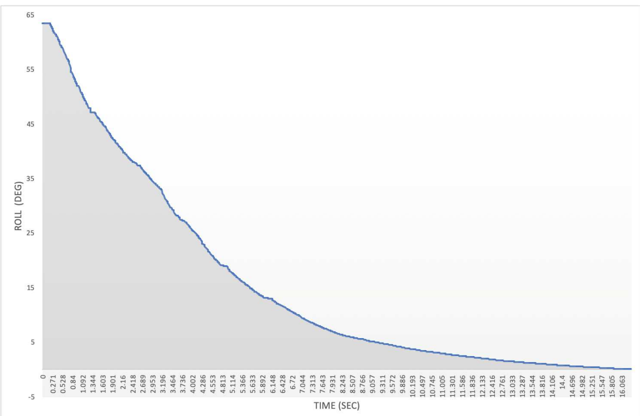

Fig. 13 Pitch stabilization

C. *AutoPilot by Way Points*

As illustrated in Fig. 8, more calculations must be done for the control in autopilot mode because it includes the vehicle's position, the coordinates of the target, the altitude that must be reached, and the speed setting that must be used. Each block performs its calculation in parallel, and the results are fed to the blocks that need these parameters. In this autopilot mode, the PID and MPC control strategies are combined.

The autopilot simulation via HILS showed that the FCS worked properly by flying through 4 waypoints set earlier. For example, the following charts are displayed relating to flight performance from WP1 to WP3, with speeds ranging from 130 to 144 km/h. In Fig. 14, the heading (vehicle to the target) shows the vehicle always approaches 0 deg when it goes to its target WP, while the yaw is the vehicle's direction towards the earth's magnetic field like a compass. Details of the setting and achieving the target data can be seen in Table III.

TABLE III
SETTING TARGET AND ACHIEVEMENT DATA

	WP1
Coordinat Target	106.6169, -6.3779
Altitude Target	250 m
Range between WP	-
Time Achievement	-
	WP2
Coordinat Target	106.6013, -6.3855
Altitude Target	200 m
Range between WP	2.0 km
Time Achievement	61.2 seconds
	WP3
Coordinat Target	106.5859, -6.3777
Altitude Target	150 m
Range between WP	2.07 km
Time Achievement	50 seconds

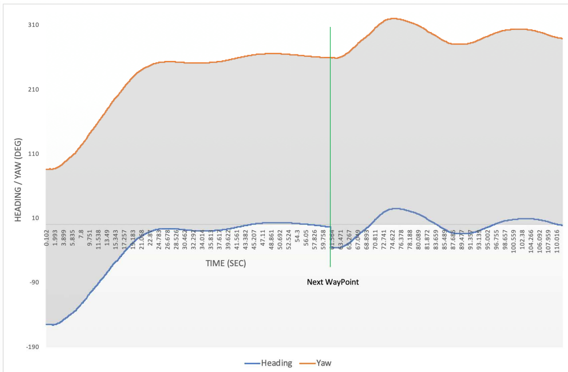

Fig. 14 Heading performance

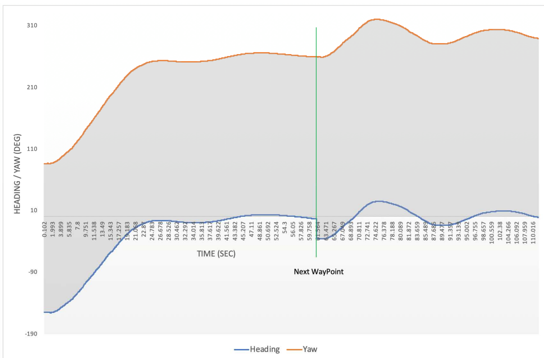

Fig. 15 Target range achievement

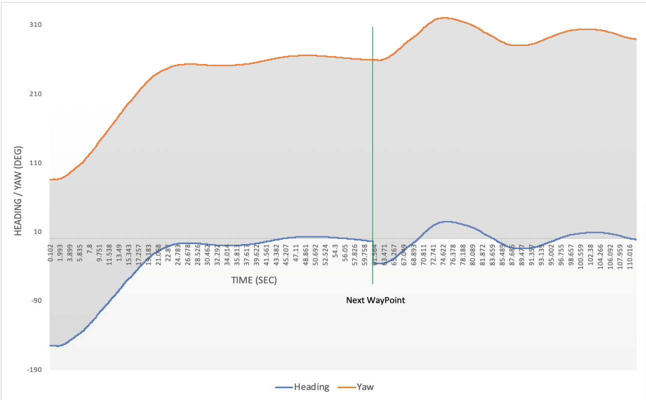

Fig. 16 Altitude performance

Fig. 15 above shows the vehicle's distance to the target, which is getting shorter when it leads to WP. In the beginning, from WP1 to WP2, the distance is getting farther away. It is caused by the change in heading in the direction of WP2 is quite sharp (-155 degree, see Fig. 14), so the vehicle is flying with the soaring maneuver. Moreover, when the vehicle has reached at least 20 m from the target, the FCS will direct it towards the next target. At present, it is within the calculation of the distance to the target in the closest set distance is 20 m. Fig. 16 shows the FCS control of the altitude that must be achieved by the vehicle following the altitude setting in Table III. PID calculates the desired altitude target, and the results are fed to the input pitch controlled by MPC.

D. Ground Control System (GCS)

Monitoring and controller computer receives and sends data to X-Plane and displays the entire data process in real-time. Moreover, the monitoring model in Fig. 19 is a display that can later be used as a true GCS with data sent via telemetry replacing UDP. Furthermore, this computer's second function in HILS is to control the entire programming process carried out by MyRIO through shared memory variables because they use Labview in their programming language.

In the HILS condition, all input and output variables can be monitored and changed in value, both offline and online, while the program is running. The HILS is quite easy and helps in the development of flight control systems in this research. As one example, Fig. 17 ensures that the MPC parameters used in formulas (1) and (2) have been correctly implemented in the process of vehicle stability and autopilot.

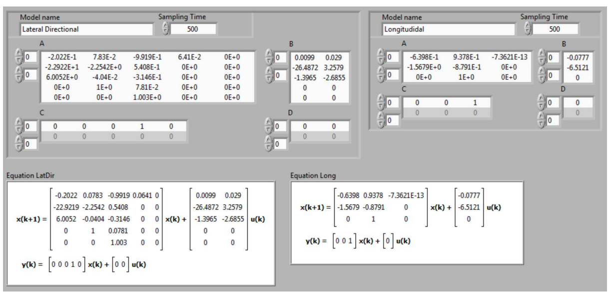

Fig. 17 MPC parameter

To facilitate the analysis, data storage facilities are also provided for the analysis variables, such as some charts produced in the results and analysis above.

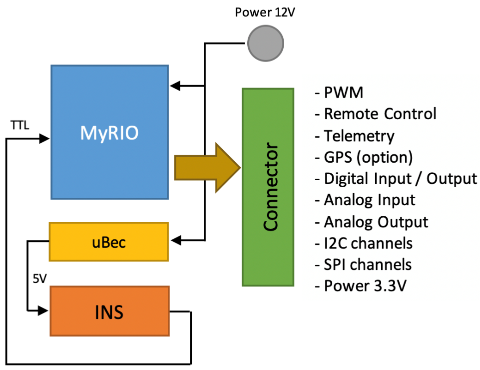

Fig. 18 MyRIO block diagram

Besides that, MyRIO (Fig. 18) itself has prepared several connectors for the real flight test needs, including 5 input I/O channels for remote control, 1 channel I/O for GPS, 6 channels PWM output for servo motor, 1 channel TTL UART for IMU / INS (Inertial Navigation Unit), 1 channel TTL UART for telemetry and connectors for I2C also SPI for other needs later. Here, Fig. 19 shows the simulation result of the flight test using autopilot mode, and Fig. 20 shows a moment when FPV-2600 was flying in autopilot by way points in the simulation.

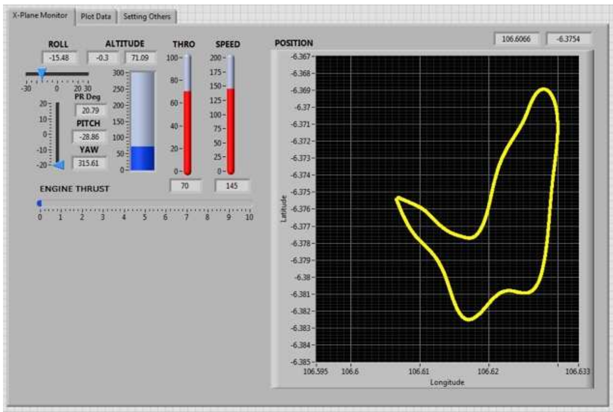

Fig. 19 Simulation result of FPV-2600

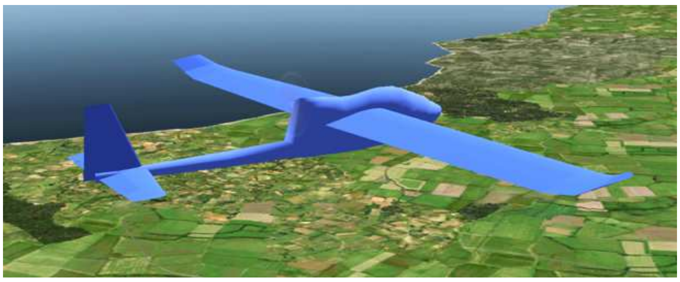

Fig. 20 FPV-2600 on simulation

IV. Conclusion

HILS has been implemented in developing the flight control system for aero modeling of a UAV, FPV-2600. Software and hardware in the development are based on Labview, so they can be easily embedded in the FPGA base MyRIO controller, MPC, and PID in close loop control can be implemented with X-Plane flight simulator. All hardware and 3D visualization in X-Plane shows that the efficacy of MyRIO based prototyping has worked well. In the future, the result of this simulation can be implemented directly in the actual flight test.

NOMENCLATURE

μ	speed	ft/sec
α	angle of attack	rad
q	pitch rate	rad/sec
θ	pitch angle	rad
	elevator	deg
β	side slip angle	rad
ρ	roll rate	rad/sec
γ	yaw rate	rad/sec
ψ	yaw	rad
δ_A	aileron	deg
δ_R	rudder	deg

ACKNOWLEDGMENT

The authors are grateful to the Deputy of Aerospace Technology and Head of Rocket Technology Center for the facilities and supports in completing this research activity. I would also like to thank my colleagues in Rocket OnBoard System Program for all help provided both directly and indirectly.

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