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Research Article

Designing autopilot system for fixed-wing flight mode of a tilt-rotor UAV in a virtual environment: X-Plane

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ABSTRACT

This paper describes an autopilot system design to regulate the altitude, heading and forward speed in the fixed-wing flight mode of the Osprey V22 VTOL (vertical takeoff and land) tilt rotor UAV accordingly to a reference, which is generated the trajectory sub-block. X- Plane flight simulator developed by Laminar Research, is used to test and optimize the parameter values of the autopilot system, which is designed using feedback, feedforward and PID controllers in MATLAB / Simulink environment (Software in the Loop- SIL). The receiver and sender blocks to perform the data interactions between MATLAB / Simulink and X-Plane flight simulator are created in MATLAB / Simulink environment. The receiver block is used to transfer data from the X-Plane flight simulator to the controller, while the sender block is used to transfer control signals from the controller to the X-Plane flight simulator program. The data communication between the two is UDP. The autopilot system under test is embedded in the Raspberry-Pi minicomputer and a hardware-in loop (HIL) test system created. The reaction of the control algorithm running on the Raspberry-Pi minicomputer to the virtual sensor data generated by the X-Plane flight simulator investigated. It is observed that, the Osprey-V22 aircraft can perform tasks autonomously in the horizontal flight mode, from the experiments and the results obtained. This study also describes the first stage of an undergoing project which aims to develop a robust autopilot for Osprey V22 VTOL UAV.

1. Introduction

In the last few years, researchers have shown great interest in the field of VTOL (Vertical Take-Off and Landing) aerial vehicles [1]. However, most of them are related with quadrotors. Besides these well-known platforms, many researchers recently concentrate on the tilt rotor aerial vehicles combining the advantages of horizontal and vertical flights. Because these new vehicles have no conventional design basis, many research groups build their own tilt-rotor vehicles according to the desired technical specifications and objectives [9]. One of them is fixed-wing VTOL UAV.

The fixed-wing VTOL UAV has a large flight envelope than traditional VTOL UAV since it can hover, and maneuver in 3D space like a multi-rotor as well as fly level forward flight efficiently at high cruise speed [3]. Notable VTOL aircrafts include the Bell XV-15, Bell-Boeing V22 and so on [4]. The development of V-22 aircraft spurred a great research and development effort in tilt rotor aerodynamics, flight control etc [2, 11]. Conventional tiltrotor vehicles are mechanically complex systems since it employs a swashplate and differential rotor tilting to control pitch and yaw, respectively [5].

The model of tilt rotor UAV that is called Osprey V22, is given in Figure 1. Osprey V22 is composed of fuselage, two wings with two trailing edge flaps at each of the wing, nacelles mounted at the wings tips, rotors mounted in front of nacelles and horizontal stabilizer with three flaps and two vertical fins with one rudder mounted on each fin. All components of the aircraft are rigid. The rotors have three blades fixed to the shaft by pitch bearing. The pitch angles of rotor blades are controlled by swash-plates for constant

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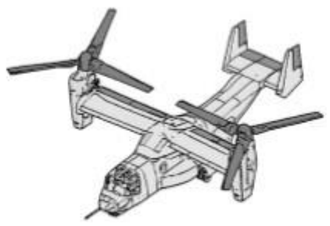
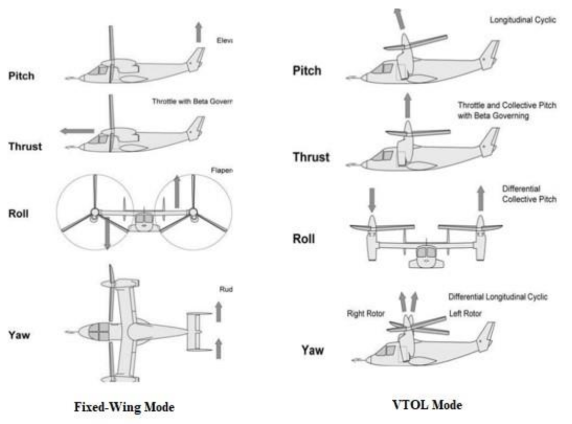


Figure 1. Osprey V22 tilt rotor UAV [23]

(collective) and harmonic (cyclic) components. The engine nacelles are placed at the tip of each wing. They may rotate about axis perpendicular to the fuselage plane of symmetry. [2]. The angle of nacelle rotation is between 0° and 97,5°.

The process of rotating the nacelles to transition between helicopter (vertical flight mode) and airplane (fixed-wing flight mode) modes is called conversion. Many scholars study on how to design the flight control system [12] for helicopter, airplane and conversion flight modes. The vertical and fixed-wing control mode of tiltrotor can be seen in Figure 2. There are some publications describing the mathematical modelling, simulation and control of the tilt wing and tilt rotor UAV [2,4,5,7,14-18]. For this reason, mathematical modeling will not be included in this study. Also, some researches are related with autonomous system performance maximization and minimum energy controller on tilt rotor UAV [25-26].

This paper describes an autopilot control design to change or maintain the altitude, heading and forward speed [20] in the fixed-wing flight mode of the Osprey V22 VTOL tilt rotor UAV accordingly to a reference, which comes from the trajectory generator block. Software-In-the-Loop (SIL) simulation is used to measure the performance of control algorithms. Thus, the controller parameters are set in a short time and with minimum cost. Raspberry Pi minicomputer, which is the hardware to be used in the system, was selected as the first step of creating the system necessary for Hardware-In-the-Loop (HIL) simulation and the necessary infrastructure for communication was established.


Pitch
Elev
Thrust
Throttle with Beta Goverr
Roll
Flaper
Yaw
Rud
Fixed-Wing Mode
Pitch
Longitudinal Cyclic
Thrust
Throttle and Collective Pitch with Beta Governing
Roll
Differential Collective Pitch
Yaw
Differential Longitudinal Cyclic
Right Rotor
Left Rotor
VTOL Mode
Figure 2. Fixed-wing and VTOL control modes [23]

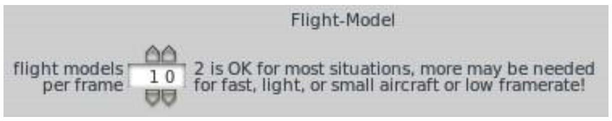
2. X-Plane Flight Simulator and its Settings

X-Plane is the flight simulator with the world's most realistic flight model. X-Plane is used by industry-leading stakeholders such as air force, aircraft manufacturers to predict flight characteristics of fixed and rotary wing aircraft with high accuracy. The existing aircraft models can be changed by the user, but the user can create custom plane or helicopter designs with Plane Maker software. In addition, the X-Plane simulation environment supports programming languages such as C / C++, MATLAB / Simulink, and Python [6]. There are settings on the X-Plane that need to be set for proper operation of the aircraft, and the configuration of the flight-model per frame is one of these settings. This can be done with the Operations & Warnings tab under the Settings menu in the X-Plane flight simulator program.

Value of this parameter is taken as 10 which is indicated in Figure 3 to guarantee that the model performs better during simulations.

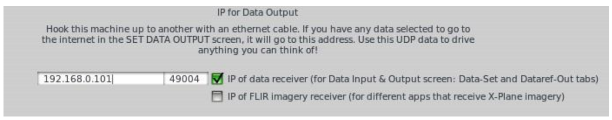
Another excellent property of the X-Plane is its skill to transmit and receive information with the outside world via UDP (User Datagram Protocol) [7]. MATLAB / Simulink provides blocks ready for UDP communication. Communication between X-Plane and MATLAB / Simulink can be achieved on the same computer using the internal address "127.0.0.1" of the network card, and two different computers can be used in case of setting the IP addresses of the sender and receiver blocks. Due to the fact that the communication will be done with UDP, MATLAB / Simulink and X-Plane flight simulator program can run on different computers.

In the "VTOL_Control_Example" model created in MATLAB / Simulink, the IP addresses of the sender and receiver blocks are "192.168.0.100" which is the IP address of the computer running the X-Plane flight simulator program. The network configuration on the X-Plane is shown in Figure 4 and Figure 5.


Flight-Model

flight models per frame 10 2 is OK for most situations, more may be needed for fast, light, or small aircraft or low framerate!

Figure 3. Flight model per frame


IP for Data Output

Hook this machine up to another with an ethernet cable. If you have any data selected to go to the internet in the SET DATA OUTPUT screen, it will go to this address. Use this UDP data to drive anything you can think of!

192.168.0.101 49004 [✓ IP of data receiver (for Data Input & Output screen: Data-Set and Dataref-Out tabs)]
IP of FLIR imagery receiver (for different apps that receive X-Plane imagery)

Figure 4. IP configuration

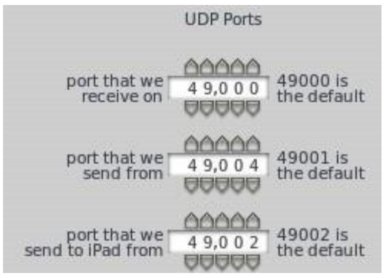


Figure 5. Port configuration

The data package of the X-Plane follows a standard format, which requires a header and a data set sequence. The header shown in Table 1 shows the following bytes [7]:

1. 0-3 bytes contain "DATA" characters indicating that it is a data packet [7].

2. The 4th byte is a internal (I) code and is not used for data transmission. It is normally defined as zero [7].

3. The bytes after the 4th byte in Table-1 are of interest to the state of the aircraft and the input and output data to be intervened can be defined by selecting appropriate places on the table in Figure 6.

The parameter selection in Figure 6 can also be done with automatically. The necessary specifications like IP number, Port number, Waypoint data and Input/Output data, which uses by UDP, can be written in PostLoadFcn under the model properties of Simulink.

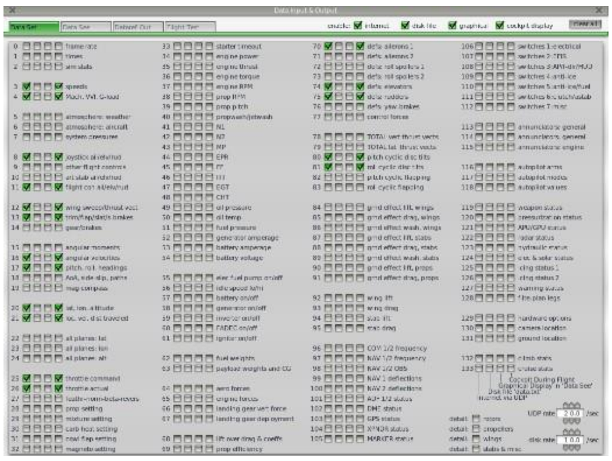


Figure 6. Selected parameters (input and ouput data)

3. MATLAB/Simulink Program and its Settings

Simulink is a block diagram based environment for model-based design that simulates multi-disciplinary systems. In Simulink environment; system level design, simulation, automatic code generation, continuous testing, and verification of embedded systems can be done. Simulink offers a graphical editor, customizable block library and solvers for modeling and simulating dynamic systems. Simulink integrated with MATLAB, you can use MATLAB algorithms in the model and move your simulation results to the MATLAB environment for further analysis [8]. The communication interface blocks are given in Figure 7. These two blocks consist of three sub-block. These are respectively UDP send/receive block, byte pack/unpack block and last one is embedded MATLAB functions. There are some settings on the Simulink that need to be set for proper communication with X-Plane flight simulator. One of them is IP and port configuration of UDP receive-send blocks. The communication block configurations of Simulink are given in Figure 8.

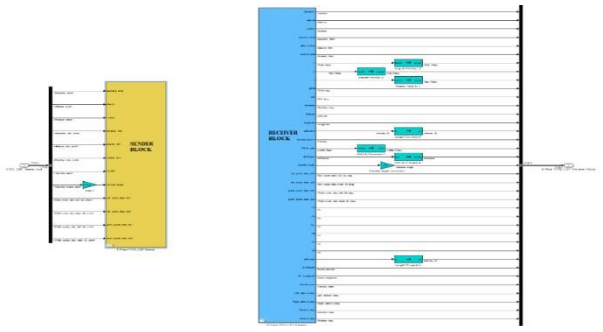
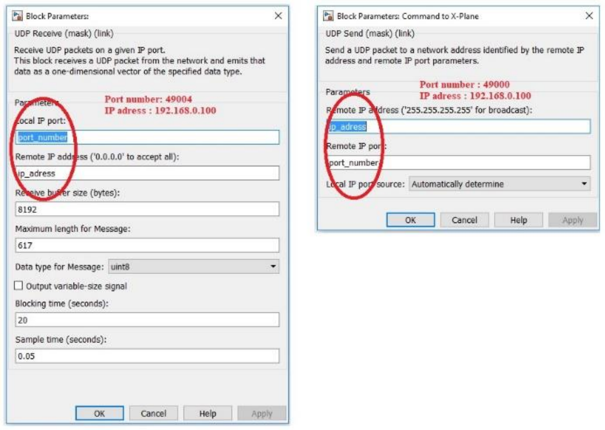


Figure 7. The communication blocks of sender and receiver



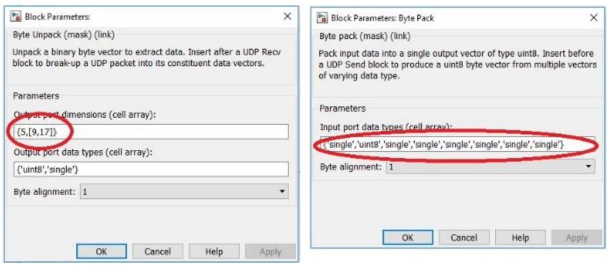
Block Parameters:
UDP Receive (mask) (link)
Receive UDP packets on a given IP port.
This block receives a UDP packet from the network and emits that data as a one-dimensional vector of the specified data type.
Parameters
Port number: 49004
IP adress : 192.168.0.100
Local IP port: port_number
Remote IP address ('0.0.0.0' to accept all): ip_adress
Receive buffer size (bytes): 8192
Maximum length for Message: 617
Data type for Message: uint8
☐ Output variable-size signal
Blocking time (seconds): 20
Sample time (seconds): 0.05

Block Parameters: Command to X-Plane
UDP Send (mask) (link)
Send a UDP packet to a network address identified by the remote IP address and remote IP port parameters.
Parameters
Port number : 49000
IP adress : 192.168.0.100
Remote IP address ('255.255.255.255' for broadcast): ip_adress
Remote IP port: port_number
Local IP port source: Automatically determine

Figure 8. UDP communication blocks (receive and send) ports configuration

Table 1 X-Plane data package pattern

Bytes	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	.	.	.	.	.	.	.	.	.	38	39	40	41
Value	D	A	T	A	I	L_1	L_2	L_3	L_4	B_{11}	B_{12}	B_{13}	B_{14}	B_{21}	B_{22}	B_{23}	B_{24}	.	.	.	.	.	.	.	.	.	B_{81}	B_{82}	B_{83}	B_{84}


Block Parameters:

Byte Unpack (mask) (link)

Unpack a binary byte vector to extract data. Insert after a UDP Recv block to break-up a UDP packet into its constituent data vectors.

Parameters

Output port dimensions (cell array): {5,[9,17]}

Output port data types (cell array): {'uint8','single'}

Byte alignment: 1

Block Parameters: Byte Pack

Byte pack (mask) (link)

Pack input data into a single output vector of type uint8. Insert before a UDP Send block to produce a uint8 byte vector from multiple vectors of varying data type.

Parameters

Input port data types (cell array): {'single','uint8','single','single','single','single','single','single'}

Byte alignment: 1

Figure 9. Byte unpack and pack settings

Also some settings are needed for byte pack and unpack blocks. Byte pack block is used just to pack the data in an array of bytes [7]. The configuration of the byte pack block is given right side of the Figure 9. Byte unpack block is used to unpack the data coming from X-Plane flight simulator through the UDP Receive block. Byte unpack block configuration is shown left side of the Figure 9. The unpack block is configured to output 5 bytes (the header), plus a matrix of 17 set of data [7] with 9 fields. With this configuration, the maximum length of the message will be 617 (5 bytes header + 17 set of data * 9 fields * 4 bytes each). This data can be seen left side in Figure 8. The input of the byte pack block is respectively header; internal code (generally zero) and the others are commands, which will be send to X-Plane flight simulator with UDP send block.

The embedded function is responsible to convert quadruple bytes into a single format floating point, which are then converted into double format to be used by the following blocks [7].

4. Design of the Trajectory Generator and Control System

The Simulink model consist of four part, these are trajectory generator block, controller block, communication interface block, and finally visualizer block. This Simulink model can be seen from Figure 10. The trajectory generator block, given in detail at Figure 11, is responsible to generate references for the aircraft in order to perform the desired mission. For this reason, a MATLAB function is written in Simulink. This function consists of two basic algorithms. These are waypoint switching and heading reference generation. The trajectory generator block creates heading reference for the attitude controllers in order to drive the aircraft to the next waypoint.

Waypoints are made up from three parts, i.e., latitude, longitude and altitude. The reference value of altitude directly comes from the waypoint list, but the heading reference angle must be computed. The heading angle can be computed by using line of sight (LoS) formula, given in Equation (1).

$$LoS = atan2\left[\frac{Lon_{wp} - Lon_{vtol}}{Lat_{wp} - Lat_{vtol}}\right] * 180/\pi \qquad (1)$$

By using Equation (1), the reference-heading angle is found between -180° and 180°. Bu the actual heading angle of aircraft, which is read from X-Plane via UDP, is between 0° and 360°. So it must be shifted to the interval, -180° and +180°, in order to follow the shortest path. For this reason, a short code is written in MATLAB.

Way point switching scheme is explained as follows. A variable, called as waypoint index, holds the current active target waypoint, and its initial value is one. When the aircraft reach the waypoint, the waypoint index is increased. But how the system decide a waypoint is reached. First of all a distance variable (D) between plane and active target waypoint is defined and computed by using Equation (2), and the unit of D is degree. The distance (D) is then converted from degree to meter by using "Haversine" formula (given Appendix A). When the distance is less than or equal to a threshold R (D ≤ R in Figure 12), it is understood that the waypoint is reached. R is computed by Equation (3). Here β is the bank angle and V is the airspeed of the aircraft.

$$D = \sqrt{\left(Lon_{wp} - Lon_{vtol}\right)^2 + \left(Lat_{wp} - Lat_{vtol}\right)^2} \qquad (2)$$

$$R = 0.3048 * \left[\frac{V^2}{11.26 * tan\,(\beta)}\right] \qquad (3)$$

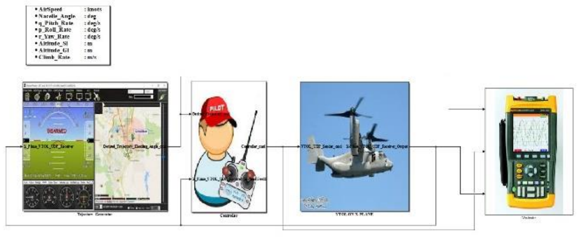


Figure 10. Simulink model of VTOL fixed-wing UAV control system for airplane mode

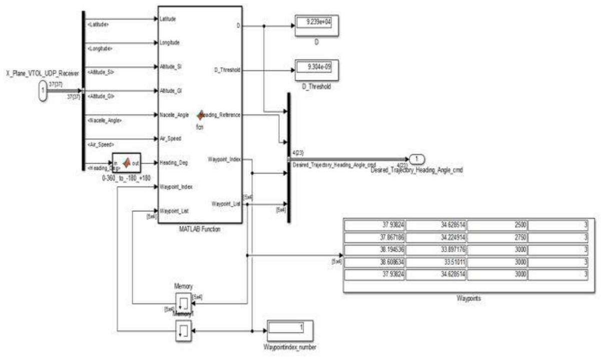


Figure 11. Trajectory generator block

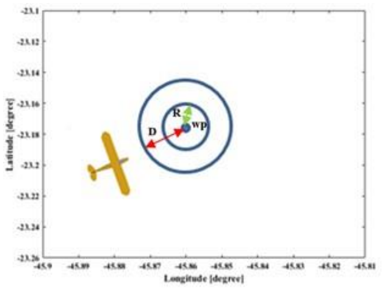


Figure 12. Distance between VTOL and waypoint [7]

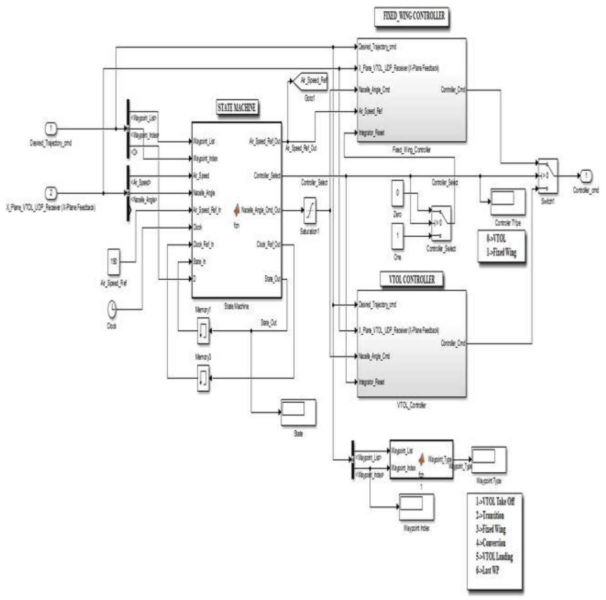


Figure 13. Controller model at MATLAB/Simulink

The control block is designed to alter and stabilize the VTOL aircraft altitude, heading, and forward speed in order to track their references [20], which comes from the waypoint list in trajectory generator block. The controller model at the MATLAB / Simulink is given in Figure 13. The controller block includes both feedback and feedforward control scheme. The feedback control loop is responsible for longitudinal, lateral direction of the aircraft.

The feed-forward terms are used to correct errors caused by coupling movements [20-22]. The control algorithms for the altitude and attitude, i.e., roll, pitch and yaw, of the VTOL tiltrotor aircraft are designed based on PID controller. All controllers contain inner and outer loops. Heading angle is indirectly controlled by aileron through roll angle (Figure 14). The reference roll signal is generated accordingly the error between reference heading angle and current heading angle. The reference-heading angle comes from trajectory generator block. The output of the outer loop is the reference signal for inner roll controller and is saturated in the interval, $[-45^{\circ}, 45^{\circ}]$. The roll controller is responsible for stabilizing the aircraft's roll angle. It utilizes ailerons to alter the roll angle of the aircraft [20]. Aileron commands are sent to X-Plane and are limited to -1 to +1 by software. All parameters of heading controller is given in Table 2.

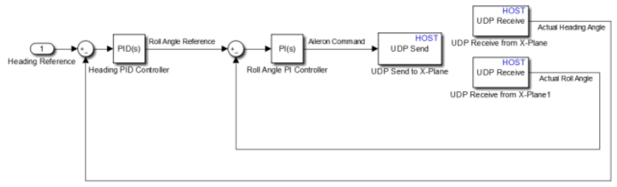


Figure 14. Inner and outer feedback loops for heading controller.

Table 2. Parameters for heading controller.

Heading PID	K_p	3.5
	K_i	1.0
	K_d	0.5
Roll PI	K_p	0.01
	K_i	0.0002

The longitudinal control system emphasizes the altitude and the forward speed. The altitude controller is implemented in a cascade form (Figure 15). The output of this controller is the reference for pitch controller inner loop. Then the output of pitch controller is the angle of the elevator control surface. Thus, both pitch angle and altitude of the aircraft are ensured to be under control [20]. The maximum pitch angle is limited to -10° to +15° by software. These values should be transformed to X-Plane elevator control surface commands in some limits that is -1 and +1. All parameters for altitude controller is given in Table 3. For forward speed control PI control is implemented and the parameter values of the controller are Kp=0.02 and Ki=0.1, respectively. In addition, a feed forward control gain (Kpff=0.015) is multiplied by altitude error and then added to the output of the forward speed controller to compensate the loss of the altitude.

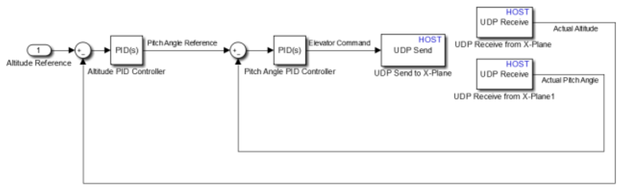


Figure 15. Inner and outer feedback loops for altitude controller.

Table 3. Parameters for altitude controller.

Altitude PID	K_p	0.2
	K_i	0.02
	K_d	0.01
Pitch PID	K_p	0.1
	K_i	0.1
	K_d	0.01

5. Implementation and Application Results

In this study, a laptop, a PC and Raspberry Pi are used as to develop control architecture, to run flight dynamics and to implement controller respectively, as shown in Figure 16. The Raspberry Pi is a low cost, credit-card sized computer that plugs into a computer monitor or TV, and uses a standard keyboard and mouse. It is a capable little device that enables people of all ages to explore computing, and to learn how to program in languages like C, Scratch and Python [24]. The Raspberry Pi can be seen on Figure 17.

Simulink Support Package for Raspberry Pi Hardware enables to create and run Simulink models on Raspberry Pi hardware. The support package includes a library of Simulink blocks for configuring and accessing I/O peripherals and communication interfaces. After creating Simulink model, it can be simulate, tune algorithm parameters until get it just right, and download the completed algorithm for standalone execution on the device. With the MATLAB Function block, MATLAB code is incorporated into the Simulink model. With Simulink support package for Raspberry Pi, the algorithm developed in Simulink can be deployed to the Raspberry Pi using automatic code generation [19].
At the end of this process, an embedded control system was made and autopilot control system is then run on the Raspberry Pi in a standalone fashion.

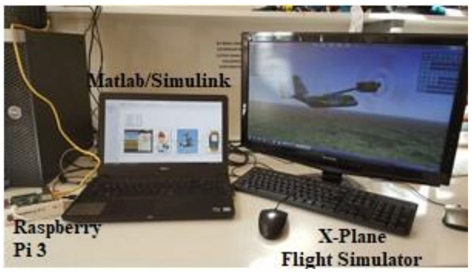


Figure 16. Implementation of autopilot test platform

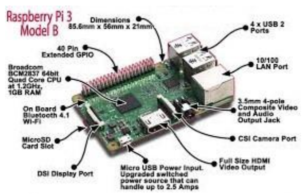

Raspberry Pi 3 Model B
Dimensions 85.6mm x 56mm x 21mm
4 x USB 2 Ports
40 Pin Extended GPIO
10/100 LAN Port
Broadcom BCM2837 64bit Quad Core CPU at 1.2GHz, 1GB RAM
3.5mm 4-pole Composite Video and Audio Output Jack
On Board Bluetooth 4.1 Wi-Fi
CSI Camera Port
MicroSD Card Slot
Full Size HDMI Video Output
DSI Display Port
Micro USB Power Input. Upgraded switched power source that can handle up to 2.5 Amps

Figure 17. Raspberry Pi 3

Communication between Raspberry Pi and X-Plane occurs through ethernet port using via UDP.

The parameter of the Waypoint List is given in Table 4 for testing the autopilot performance. The list consist of five waypoints. First and last is the same point but the altitude is different each other. We requested to move around the waypoint by coming to the fifth waypoint through the transition points from the autopilot. For this reason, the simulation is started by using "Get Me Lost" function of the X-Plane flight simulator. In Figure 18, the simulated flight path according to the "Waypoint List" data is given on the Google Maps. The straight lines show the references and dashed line shows the real path of the aircraft. In addition, the 3D flight path on X-Plane is also given in Figure 19. The result, which is taken in Figure 18-19, represents one tour on the route. The responses of the controller for the flight path are given in Figure 20-29. In the Figure 20, the altitude behavior of the controller is given.

Table 4. Waypoint List

Waypoints List	Latitude (°)	Longitude (°)	Altitude (m)
Waypoint_1	37.938240	34.628514	2500
Waypoint_2	37.867186	34.224914	2750
Waypoint_3	38.194536	33.897176	3000
Waypoint_4	38.608634	33.510110	3000
Waypoint_5	37.938240	34.628514	3000

The blue line represents the altitude reference and dashed red line is altitude response of the controller with respect to sea level in meters. Some overshoot occurs instant the switching of waypoint, because the lift of the wing is decreasing. For this reason, pitch of the aircraft increases to maintain the altitude and airspeed increases for a short time. Figure 21 shows the airspeed response of the all flight path.

The maximum overshoot of the airspeed is less than 6 percent, and then airspeed is decreased by the controller and tracks the reference value.

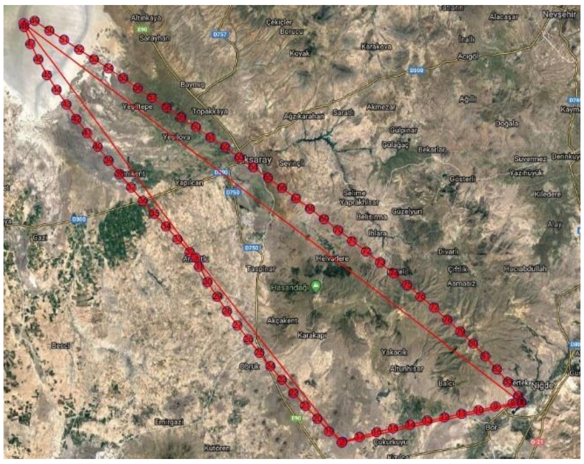


Figure 18. Flight path for waypoint list on X-Plane

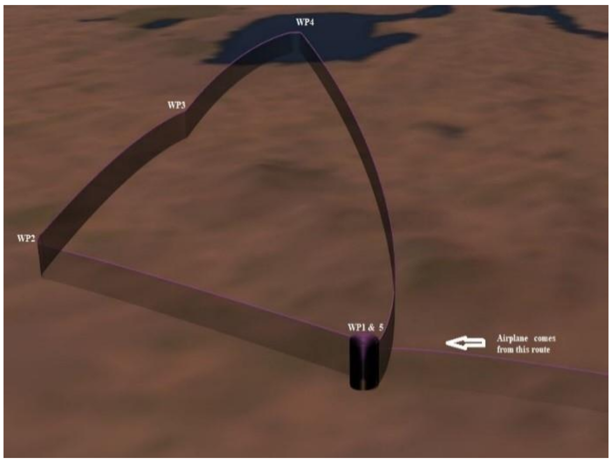


Figure 19. 3D Flight path for waypoint list on X-Plane

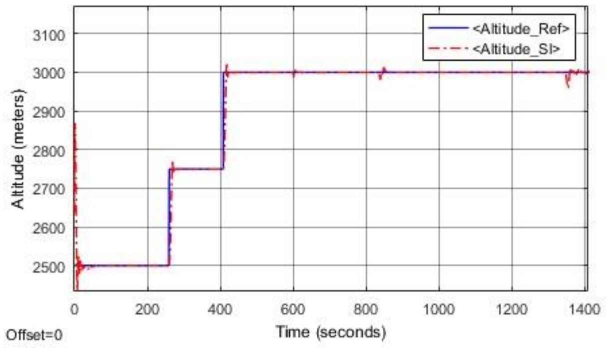


Figure 20. Altitude response

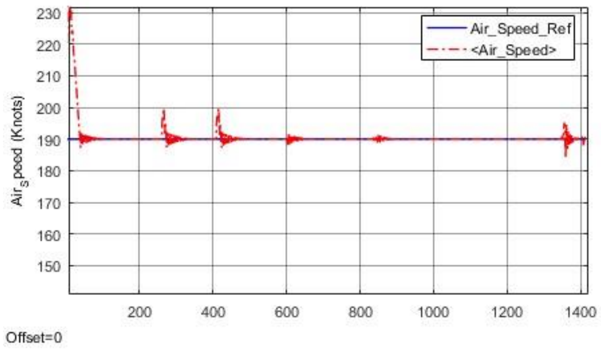


Figure 21. Forward speed response

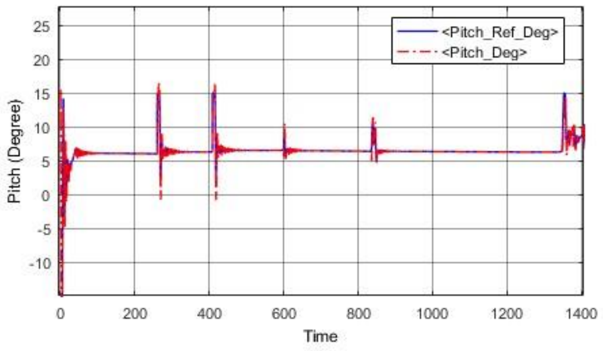


Figure 22. Pitch response

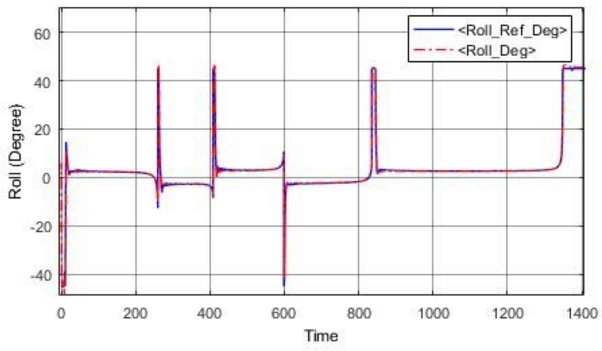


Figure 23. Roll response

The solid blue lines of the Figure 22, 23 and 28 represent the reference values of the pitch, roll and heading, respectively. Dashed red lines are the response of the aircraft. The pitch value is limited between -10° and +15° and the roll value is limited between -45° and +45°. The heading angle is changing between -180° and +180°.

In airplane mode due to a combination of having zero angle of incidence in the wing and the thrust line being above the centerline of the aircraft, the pitch reference of the Osprey V22 about 7 degrees. The aileron and elevator command and surface deflections are given through between 0 and 1400 sec in Figure 24-25. It is clear from the Figure 24, aircraft tracks the aileron reference command, which is generated by the inner loop of the roll controller block.

Elevator command and surface response looks like not tracking each other in Figure 25. The reason is related the elevator trim value, which is produced with altitude error by a cross coupling gain.

Figure 26-28 is related with heading response of the heading controller. The reference latitude and longitude values and the controller response for these values are given in Figure 26 and 27, respectively. In addition, the detailed reference values of latitude and longitude can also be found at Table 4.

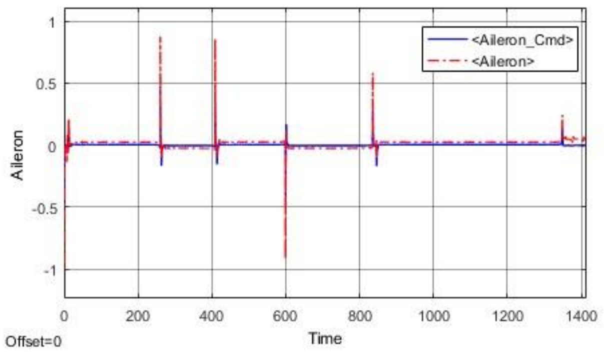


Figure 24. Aileron surface response

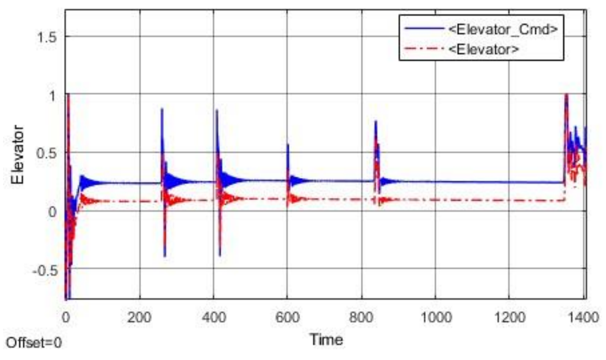


Figure 25. Elevator surface response

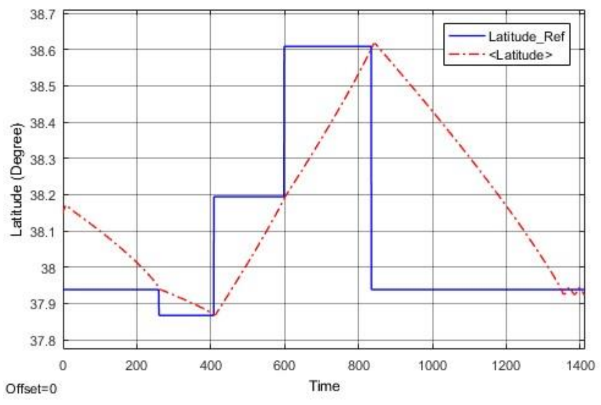


Figure 26. Latitude reference and response of the lateral controller

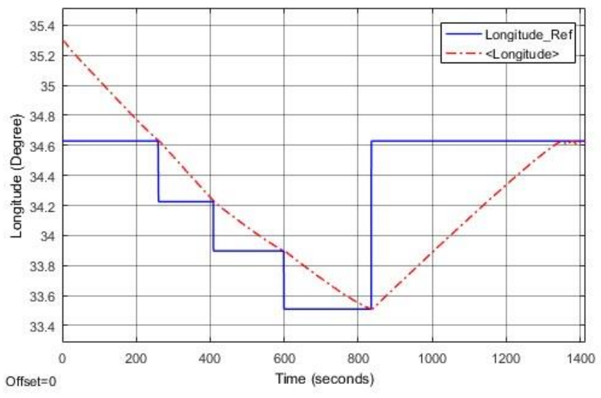


Figure 27. Longitude reference and response of longitudinal controller

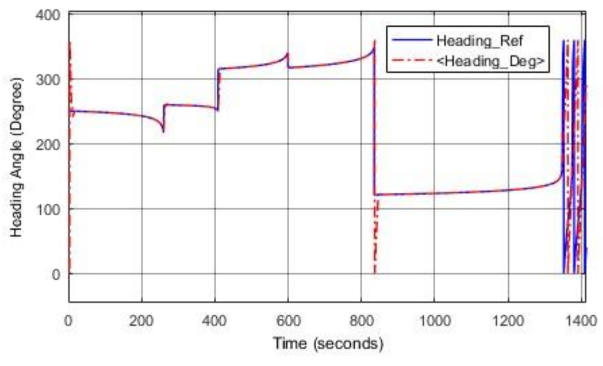


Figure 28. Heading response

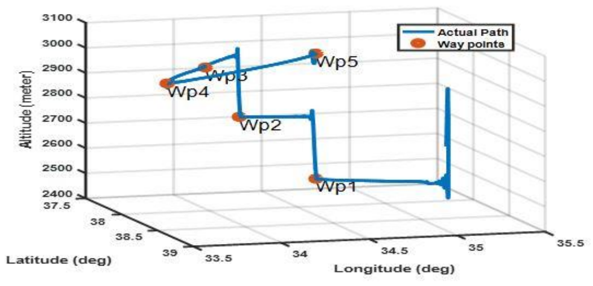


Figure 29. 3D Flight path of waypoint list

The heading response of the heading controller is given in Figure 28. It is clear from the Figure 28; aircraft tracks the reference-heading angle, which is generated by the trajectory generator block. Actually, heading reference is changing between -180 and +180 degree, but we convert this data to 0-360 degree because we get the data from X-Plane like this. In Figure 28, approximately at 825 seconds one spike is shown. However, this data is actually the same data (360 degree equals 0 degree) and it occurs from the discontinuity. Last part of the Figures 20-28 belong to loiter mode of the aircraft that is turn around the waypoint 5 at 3000 m sea level.

Figure 29 shows, the 3D vehicle position of the trajectory-tracking task. As it can be observed, the vehicle tracks the desired trajectory.

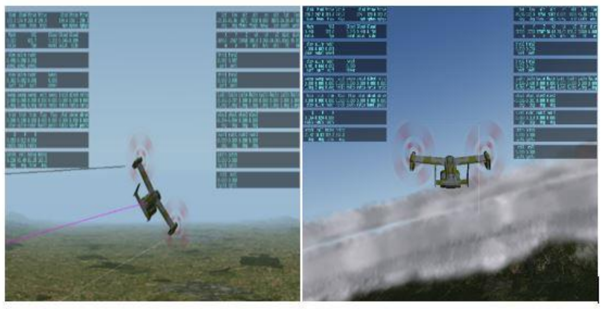


Figure 30. Roll and pitch response of the aircraft

In Figure 30, a snapshot of the aircraft is given during the flight.

6. Conclusions and Future Works

With this study, an autopilot control design is made to change or maintain the altitude, heading and forward speed in the fixed-wing flight mode of the Osprey V22 aircraft accordingly to a reference, which comes from the trajectory generator block. Software-In-the-Loop (SIL) simulation is used to evaluate the controls and algorithms, because it is easy and fast way to verify the controller, leading to minimize the cost and time. Raspberry Pi minicomputer, which is the hardware used in the system, was selected as the first step of creating the system necessary for Hardware-In-the-Loop (HIL) simulation. An embedded control system is made such that successful implementation of an autopilot system is then run on the Raspberry Pi as a standalone application. Communication between Raspberry Pi and X-Plane is provided through their Ethernet port using UDP.

The future work will be based on developing robust controller, instead of classical PID, for vertical take-off /landing and transition mode for Osprey V22 aircraft. Then, a platform will be built, which aid autopilot systems study and design. This platform will allow to us to monitor the aircraft responses for a designed autopilot system with high degree of realism.

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Nomenclature

VTOL	: Vertical Take-off and Landing
UAV	: Unmanned Air Vehicle

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Appendix

A. Haversine Formula Matlab M.File

```
function d = haversine (lat1,lon1,lat2,lon2)
 R = 6378.137;            % Radius of earth in km
 dlat  = radians(lat2- lat1);
 dlon = radians(lon2- lon1);
 lat1= radians(lat1);
 lat2= radians(lat2);
 a = (sin(dlat./2))^2+cos(lat1)*cos(lat2)*(sin(dlon/2))^2;
 c = 2 * asin(sqrt(a));
 d = R * c * 1000;        %meters
end
```