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HILS-based Waypoint Simulation for Fixed Wing Unmanned Aerial Vehicle (UAV)

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ABSTRACT

Hardware in loop simulation HILS-based waypoint simulation for fixed wing unmanned aerial vehicles is proposed in this paper. It uses an open-source arducopter as a flight controller, mission planner, and X-plane simulator. Waypoint simulation is carried out in the flight controller and executed in an X-plane simulator through a mission planner. A fixed wing unmanned aerial vehicle with an inverted T tail configuration has been chosen to study and validate waypoint flight control algorithms. The data transmission between mission planner and flight controller is done by serial protocol, whereas data exchange between X-plane and mission planner is done by User Datagram Protocol (UDP). APM mission planner is used as a machine interface to exchange data between the flight controller and the user. User inputs and flight gain parameters, both inner loop and outer loop, can be modified with the help of a mission planner. In addition to that, the mission planner provides a visual output representation of flight data and navigation algorithm.

Keyword: Hardware in loop simulation; UAV; X-plane; Arducopter; Mission planner; Waypoint navigation; User datagram protocol

1. INTRODUCTION

Nowadays, Unmanned Aerial Vehicles (UAVs) play a potential role in reconnaissance, exploration, surveillance, rescue, traffic monitoring, land surveying, and disaster management[1]. Research activity has also been boosted by relatively small inexpensive unmanned aerial vehicle platforms' ready availability. Different types of unmanned aerial vehicle platforms such as fixed, rotary, and multirotor platforms are readily available in the market. Fixed wing unmanned aerial vehicles can fly longer endurances, whereas rotary wing UAVs do not need any runway to takeoff and landing[2-3]. In addition to that, it can hover over any desired position. Hovering is a flying phase in an unmanned aerial vehicle where all the forces and moments get balanced. Under this condition, UAVs can do critical operations like surveillance, traffic monitoring, and rescues operation.

The significant process of any autopilot design is tuning of its loop gain. There are three control loops in an autopilot: inner, outer, and autonomy loop[4]. The inner loop is mainly used to stabilize the attitude of an unmanned aerial vehicle, namely, roll, pitch, and yaw. The outer loop is used to control the position of an unmanned aerial vehicle, such as latitude, longitude, and altitude hold. The Autonomy loop is mainly used for indoor navigation, collision avoidance, landing site detection and navigation in GPS denied environment[5]. In general, the inner loop gain value has been fixed first, which helps achieve the desired flying qualities. Outer loop gain tuning is complex as it takes time and flight trails. Improper tuning of gain value may lead to a crash or loss of the unmanned aerial vehicle during its flight.

Eric R. Mueller[6] proposed a method to test linear and nonlinear control algorithms using hardware in the loop simulation. The author also discusses integrating sensors, avionics computers, and actuators into flight algorithms. Kamali,[7] *et al.*, proposed a design framework for flight control application. The main advantages of the proposed method are to auto-generate code from Matlab/Simulink and seamless integration of onboard autopilot integration. Guanghe,[8] *et al.* proposed hardware in the loop simulation for a tilt rotor unmanned aerial vehicle. They use identification methods to identify various system parameters for the mathematical simulation. The tricopter using X-plane and Matlab/Simulink was proposed by Guang,[9] *et al*. They designed a tricopter model in the plane maker and simulated it in flight simulator X-plane through Matlab/Simulink. Vision aided hardware in loop simulation proposed (HILS) by Gans,[10] *et al*. They simulated the realistic scene with the help of virtual reality software processed by the onboard camera. Jung,[11] *et al.* proposed a high-fidelity HILS model to incorporate sensor actuator dynamics. Gazebo-based Hardware in the loop simulation proposed by khoa,[12] *et al*. They developed middleware software to establish secure communication between hardware and quadrotor platform. Nagaty[13] proposed nonlinear quadrotor simulation framework along with nonlinear controller, *et al.* They propose nested loop control architecture for solving both inner and outer loop navigation problems.

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A guidance algorithm and validation in software in loop simulation is proposed by Bittar,[14] *et al*. An outdoor navigation using an AR. Parrot quadcopter is proposed by Santana,[15] *et al*. They proposed the Kalman filter technique to estimate reliable data from onboard drones with the help of external GPS. A virtual flight test framework with design optimization technique helps payload optimization proposed by park[16], *et al*. Waypoint navigation and control for a parachute system was proposed by Gursoy,[17] *et al*. A waypoint tracking and heading control is presented in this paper and validated in different environmental conditions. Ariff,[18] *et al*. proposed Dubin's cure based slope soaring maneuvering technique which helps to estimate the designed trajectory with the minimal computational load. Gageik,[19] *et al*. compares the effect of different sensors and their influences on the indoor navigation of unmanned aerial vehicles. ROS-based waypoint tracking controller for autonomous vehicles proposed by Gutiérrez,[20] *et al*. They proposed a smooth waypoint interpolation technique and optimal control technique to track the robot at high speed in an urban environment.

A promising testbed platform is needed to check control law, gain, and its performances before being deployed into a real-time environment to deal with this issue. Here presented hardware in a loop simulation platform to test the outer loop waypoint navigation for fixed wing unmanned aerial vehicles. This platform helps the designer, researcher, and students to understand and visualize the working and execution of the waypoint navigation algorithm.

2. ARCHITECTURE OF THE PROPOSED PLATFORM

Hardware in loop simulation enhances the quality of testing the embedded system before being implemented into a real-time environment. In general, autopilot is an essential device that helps guide an unmanned aerial vehicle to complete a mission without intervention from a human pilot. The development of an autopilot needs several flight simulations and flight tests. It consumes more time, energy, and manpower. Any improper tuning of the algorithm and its gain value leads to losing the UAV or crashing it. So, there is a need for a platform to simulate flight control algorithms before the real flight. Any prototype flight controller may connect the proposed test platform to test and verify the algorithm.

The proposed architecture is depicted in Fig. 1, representing testing and simulating waypoint navigation through hardware in a loop environment. It consists of APM mission planner, X-plane simulator, arducopter flight controller, and RC transmitter/receiver. Based on the broad literature study, APM mission planner is selected for this research work for its open-source and compatibility with X-plane flight simulator through User Datagram Protocol (UDP). The X-plane simulator's data is fed through the mission planner environment to the autopilot. Similarly, the control output from autopilot is also fed back to the X-plane through the mission planner environment. Here the mission planner acts as an interfacing medium between the simulator and flight controller. In addition to that, it provides a visual interfacing element between user and control algorithm to tune control gain parameters. The proposed setup uses an eight-channel RC transmitter to command the unmanned aerial vehicle, which operates at about 2.4 GHz. The RC receiver receives the data transmitted from the RC transmitter and fed to the mission planner through its serial protocol at a baud rate of about 112500. Depending on the user command, the flight controller executes various maneuvers such as takeoff, cruise, waypoint navigation, loitering, and landing. This has been easily visualized in both mission planner and X-plane. Similarly, flight data from simulators are exchanged through the autopilot via serial port. The data exchange between the X-plane and flight controller makes the system operate in a closed-loop system.

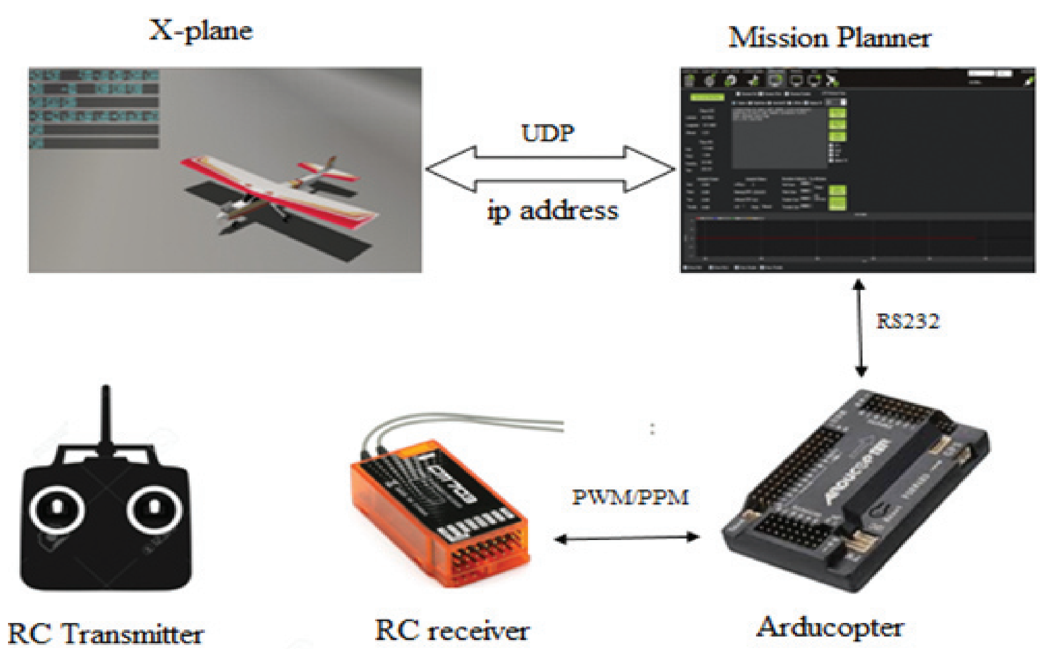

Figure 1. The architecture of hardware in the loop simulation.

2.1 Flight Control Hardware

Figure 2 shows the hardware platform used for the proposed platform. Arducopter autopilot is chosen for the proposed research work because of its open-source and compatibility with X-plane simulators. Arducopter, previously called APM copter, is a multicopter version of the open-source ardupilot platform. It is an open-source project developed in 2010 by a diverse team of professionals, engineers, hobbits, computer scientists, and community contributors. It supports almost all vehicle systems such as quadcopters, tricopters, hexacopters, rovers, bots, and balance robots. It uses ATmega 2560 as the central processing unit to execute the inner and outer loop control algorithm. It consists of a 3 axis gyroscope, accelerometer, and magnetometer for attitude estimation, and it uses GPS for outer loop waypoint navigation. In addition to that, it supports various sensors like collision sensor, sonar, voltage/current sensor, optical sensor depending upon user choice and sensor availability. The user may easily enable or disable the sensor and its gain parameters by selecting the sensor in the application tab of the mission planner. The autopilot can easily communicate with external software either by serial protocol or user datagram protocol. UDP is mostly chosen for exchanging high data rates between mission planner and X-plane simulator. Low data rate serial protocol is preferred for exchanging data between autopilot and mission planner.

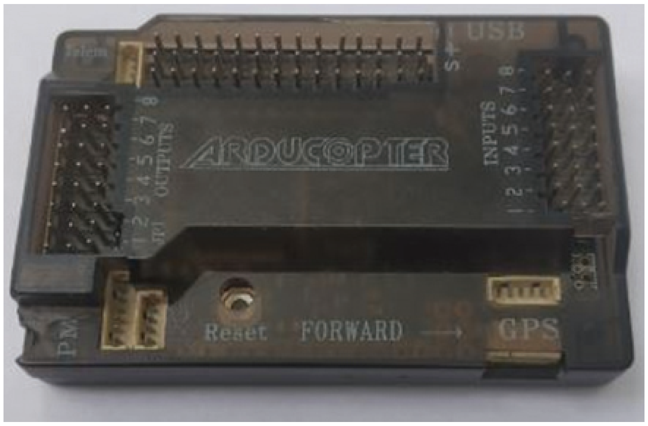

Figure 2. Arducopter hardware.

2.2 X-Plane Simulator

X-plane is a simulator for professionals, pilots, and academicians with high render graphics and its supporting packages. X-plane comes with packages, namely plane maker and airfoil maker. Both help creates subsystems, models, and airfoil needed to create a working model airplane in the X-plane environment. These packages help create more realistic graphics and create more realistic dynamics of an aircraft. It uses blade elementary theory to calculate its force and moments, which are needed for calculating the static and dynamic response of an aircraft model. Here, X-plane utilizes the User Datagram Protocol for data transportation.

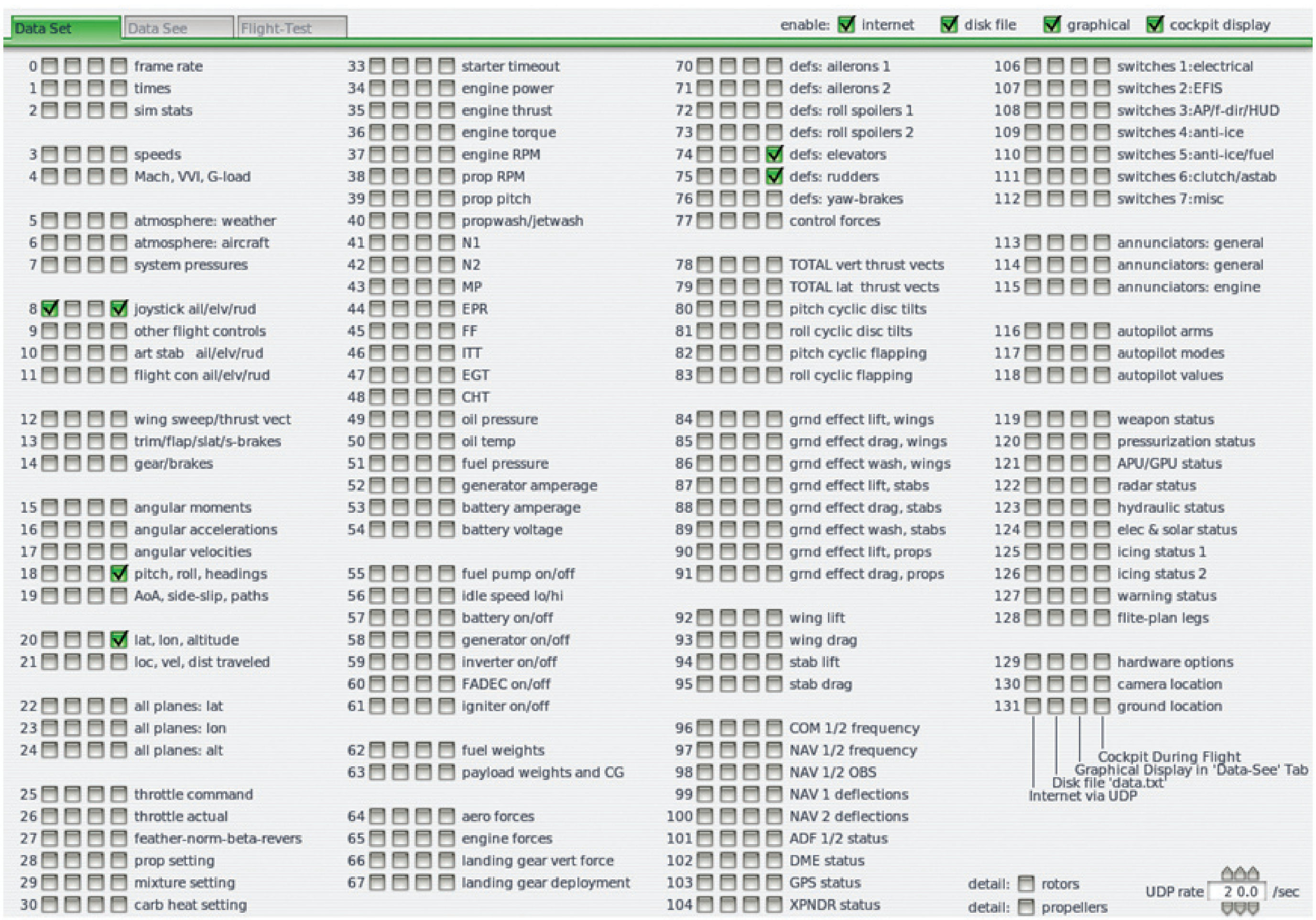

Figure 3. Data setting tab in X-plane.

2.3 Mission Planner

Mission planner is windows-based ground control software developed by Michael Oborne to support ardupilot and another open-source autopilot. It provides an application interface between user and flight control algorithm. It allows users to easily configure and access various flight parameters and gain values. It also helps to continuously monitor and display various flight data throughout the entire flight mission. It easily interacts with the user through its graphical formats. It supports easy setup, flying, and flight logging capabilities of unmanned aerial vehicles which helps to configure the autopilot within a short span of time. Mission planner extends its support for different UAV platforms such as fixed wing, rotary wing, multicopter, rovers, self-balance robot, and underwater vehicles.

Figure 4 represents the interfacing tab in the mission planner environment. It helps to connect the onboard flight control algorithm into an X-plane simulator. It runs on the user application layer, which helps to interact with both the X-plane simulator and autopilot. It receives output data from the simulator through the UDP protocol and is fed to the flight controller through the serial port. Similarly, the received input commands from the user are also fed to the X-plane simulator through UDP via its serial port. Mission planner would act as a middleware application, helping to exchange information between flight controller and simulator. The COM tab in the mission planner helps connect the flight controller to the assigned port at a baud rate of about 115200. Similarly, the connection between X-plane and mission planner is made by assigning a local IP address and port number of the system which runs the X-plane. The IP address 127.0.0.1 is the default address if both mission planner and X-plane run on the same computer.

Figure 5 represents the waypoint entry tab in the mission planner, which helps upload waypoints into the Arducopter flight controller. Desired latitude and longitude waypoints are selected by clicking or dragging on the map in the tab. The selected waypoints are easily uploaded into the flight controller by selecting the upload button on the tab. Users can add or delete waypoints while the waypoint algorithm is in execution mode. The mission planner also supports uploading any third-party or pre-planned flight path (waypoints) into an onboard algorithm that helps carry out a mission as quickly as possible. In addition to that, it also allows users to feed their Geo-cache location map, which helps to fly the unmanned aerial vehicle in a GPS denied environment.

2.4 Hils Test Platform Setup

Figure 6 shows the experimental HILS test platform set up to carry out the proposed research work. Two computational systems, one runs a mission planner, and the other runs an X-plane simulator, are used in the proposed research work. Data exchanges between these two computational systems are established through User Datagram Protocol (UDP). In addition to that, the mission planner also interacts with the flight controller through its serial protocol. The output data from the simulator, such as the current latitude, longitude, and heading of an unmanned aerial vehicle, are received by the flight controller via mission planner.

Similarly, the data from the flight controller is fed as input to the simulator through the mission planner. The output data from the simulator are compared with the desired latitude-longitude position, and the error signals have been generated with the help of the great circle and haversine formula. Two ways exchange of data between the flight simulator and flight controller via mission planner makes the system operate in closed-loop hardware in the loop environment. A joystick connected in the mission planner environment executes various input commands such as takeoff, cruise, and waypoint navigation. The RC receiver connected to the APM autopilot

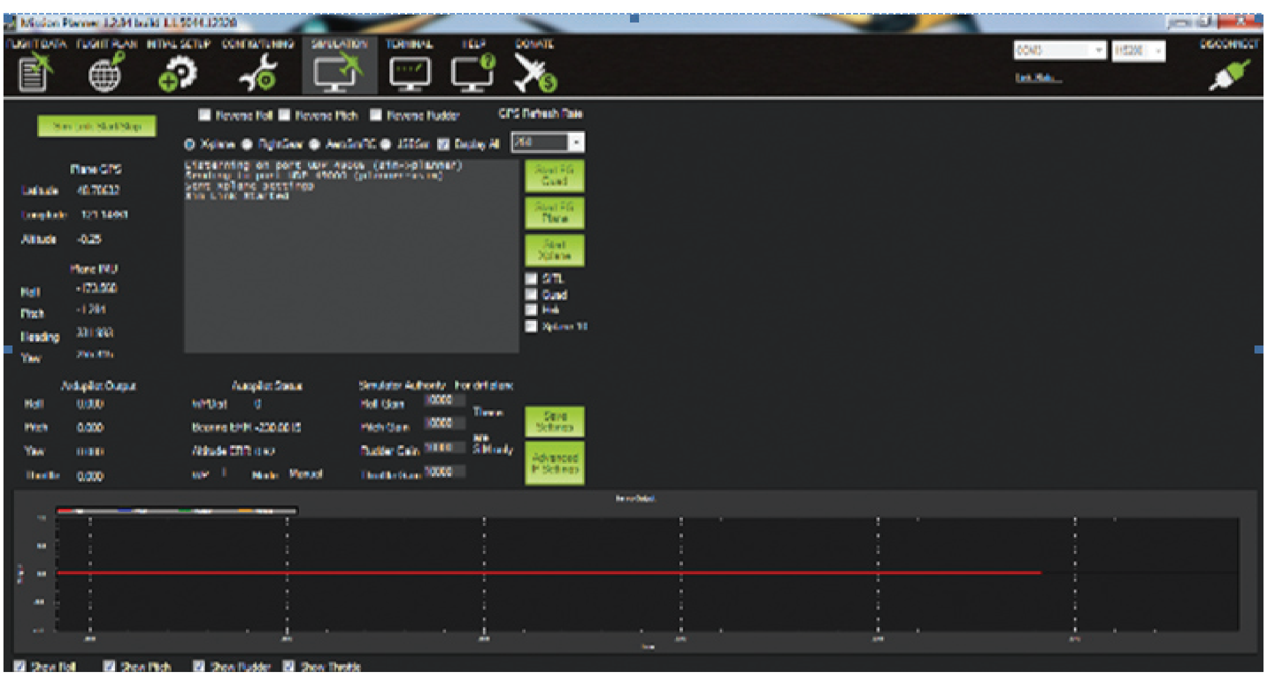

Figure 4. Interfacing tab in mission planner environment.

also receives these user-desired input commands, which are fed as input to the flight control algorithm. The mission planner executes various flight maneuvers depending on the user input and command. This can be easily visualized in the mission planner environment and X-plane simulator.

the figures, it is noted that, as soon as the waypoint execution command is issued from the RC transmitter/Mission planner, the UAV will initiate and takeoff from the runway and reach its targeted altitude and start stirring towards its consecutive waypoints, which have already fused into the autopilot.

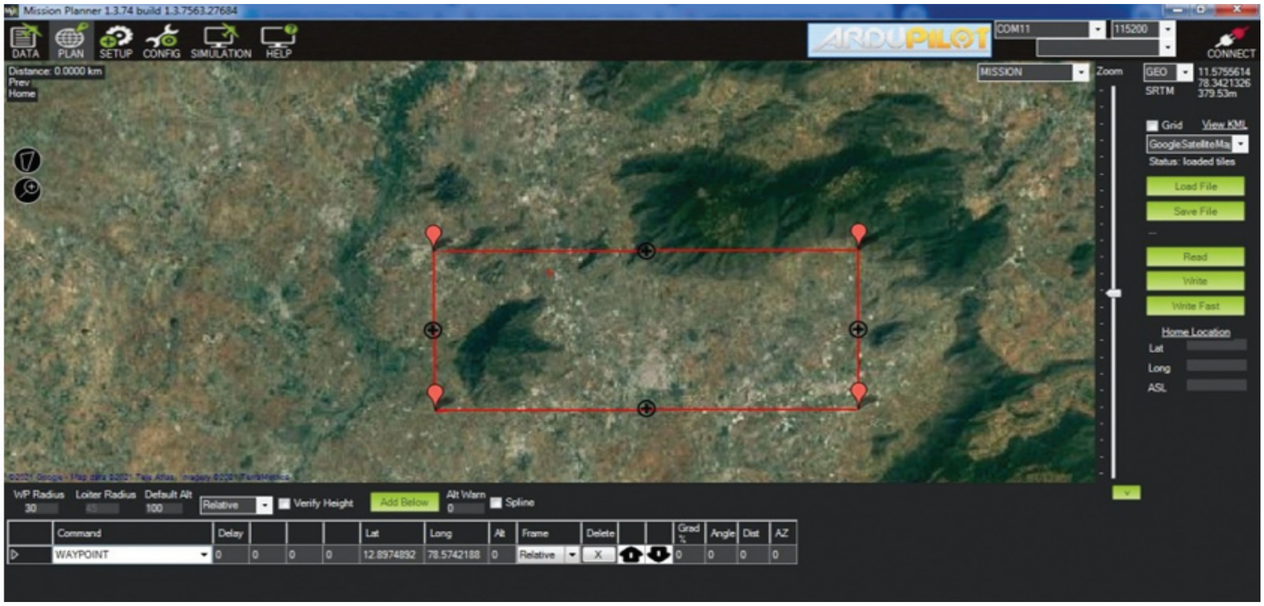

Figure 5. Waypoint entry tab in mission planner.

Figure 6. Experimental HILS test platform setup.

3. RESULT AND DISCUSSION

Figure 7 shows outputs of waypoint navigation for fixed wing unmanned aerial vehicles executed under HILS and mission planner environments. Once the input command is received from the RC transmitter, the autopilot executes the waypoint navigation algorithm and commands UAV control surfaces to move towards their targeted waypoint. Navigation towards targeted waypoints is achieved by measuring relative distance and direction of flight with the help of haversine and great circle formula. The direction of flight concerning the earth's true north and targeted waypoint heading provides a control angle that drives the rudder or aileron to make the unmanned aerial vehicle fly towards the next waypoint. Hardware in loop simulation under the X-plane environment is revealed in Fig. 8. From

Figure 9 shows the real-time execution of the waypoint algorithm in the real-time environment. The algorithm uses a waypoint that we already tested in the HILS environment. Initially, the waypoints are fused into the ardupilot flight controller through a wireless modem. During the flight trail, the UAV starts to take off from the runway and reaches an altitude of about 100 meters. Once it reaches the desired altitude, the UAV starts turning towards the left to reach its first waypoint. During the process, it is noted that the UAV uses the aileron control surface for heading turn. After reaching the second waypoint, the consecutive third, and fourth waypoints are executed. It is noted that the results produced by both simulator and real-time are nearly close to each other. This will gain confidence in the simulator to test various algorithms before implementing them in real-time.

4. CONCLUSION

The proposed research work presents the HILS-based waypoint testing bed platform and its importance in navigation. Fixed wing unmanned aerial vehicle is elected for this investigation to realize the algorithm in software and hardware environments. The proposed platform helps to simulate waypoint navigation with the help of both X-plane and mission planner environments. The platform helps autopilot engineers, students, and students validate their navigation algorithm before taking it into a real-time environment. The proposed setup allows users to monitor and alter tuning parameters to achieve desired responses at various flight conditions. Finally, the gain values are validated by implementing the algorithm in a real-time environment, and the results are verified. The current work proposed in this research focuses only on fixed wing unmanned aerial vehicles. This work may extend to multirotor platforms to benefit researchers and students working on multirotor UAV platforms.

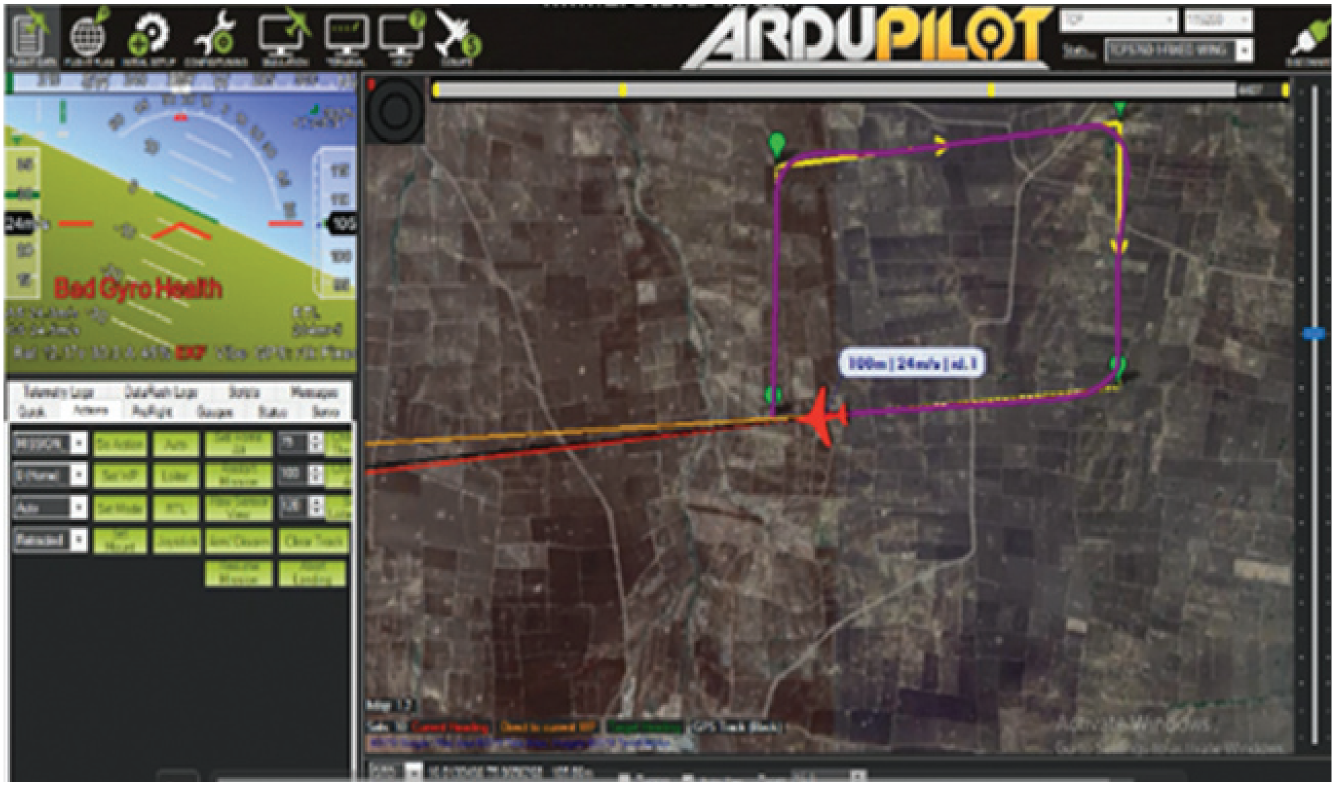

Figure 7. Waypoint navigation executed in HILS environment.

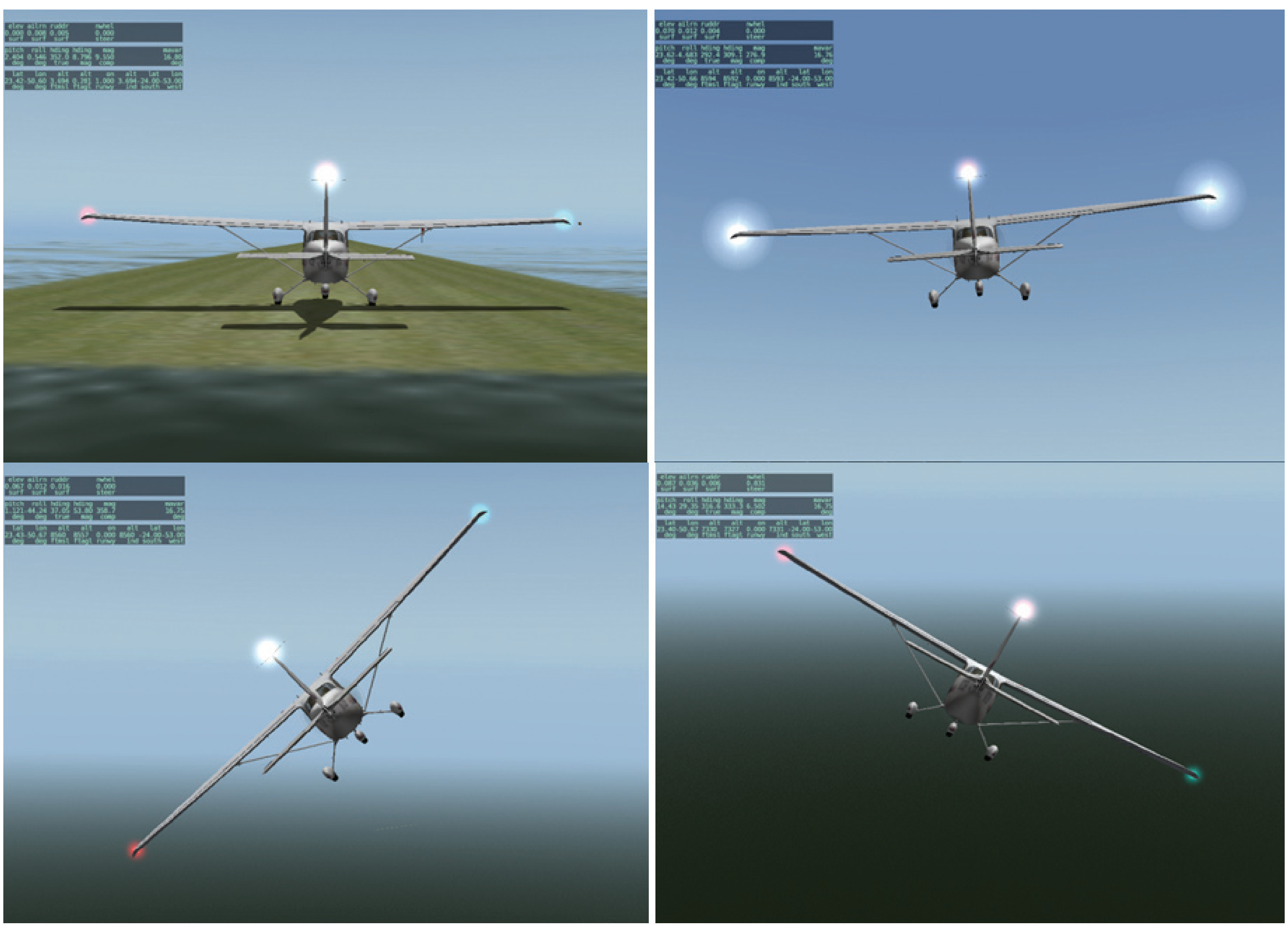

Figure 8. HILS executed under X-plane environment.

Figure 9. Real-time implementation of waypoint navigation.

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He contributed to the current study for conceptualization, methodology, and hardware implementation.

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He contributed to this manuscript's conceptualization, Matlab simulation, and preparation.