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Development of Autonomous Navigation System for Fixed-Wing UAV

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ABSTRACT: This paper describes the implementation of a simple autonomous navigation system for a fixed-wing Unmanned Aerial Vehicle (UAV) capable of running on low-cost hardware. This is achieved by developing an optimized path determination algorithm and optimally scheduling various events like sensor reading. Further improvements to be done are also discussed in the paper.

KEYWORDS: Unmanned Aerial Vehicle (UAV), flight control system, autonomous navigation, autopilot

I. INTRODUCTION

Unmanned Aerial Vehicle (UAV) is a type of aircraft, including fixed-wing and rotary-wing, which do not require a human pilot to be on board. Unmanned Aerial Vehicles can be Remotely Piloted (RPV) or Autonomous. Unmanned Aerial Vehicles assist in tasks which are considered Dull like aerial survey, Dirty like monitoring of chemical agents and their intensity and Dangerous like surveillance and reconnaissance missions in enemy territories, where using manned vehicles is not a viable option.The recent developments in the VLSI and embedded system fields have further aided the development of the UAVs, making them more accessible by the civilian, industrial as well as academic entities.

UAVs are being used as efficient alternatives for different tasks, both in civil and military applications, as precision agriculture, disaster management, terrain mapping etc. Due to their usefulness, the use of UAVs is witnessing a rapid increase. UAVs are being used in fields apart from above mentioned, like recreation, aerial delivery and resupply, aerial photography etc. Most of these applications require UAVs with autonomous navigational capabilities.

Among the available types of UAVs, fixed-wing UAV is more suitable for high endurance flight like aerial mapping. The objective of this paper is to discuss a simple navigation and control algorithm for autonomous operations of a fixed-wing Unmanned Aerial Vehicle, which helps in expanding the use of UAVs by reducing the cost of the resulting hardware.

II. GENERAL STRUCTURE AND FLIGHT CONTROL

A. UAV Model Considered

UAV model considered is a traditional fixed-wing aircraft with a single motor, 2 ailerons, 1 elevator and 1 rudder.

Ailerons, elevator and rudder control roll, pitch and yaw of the aircraft respectively.

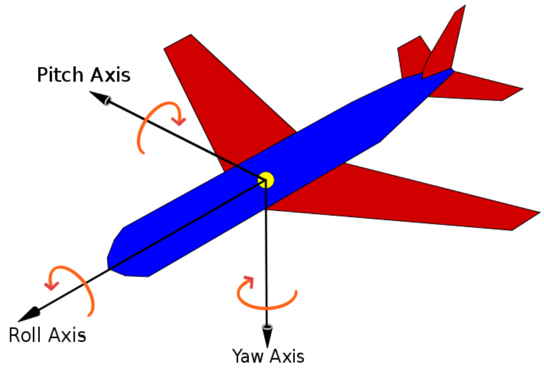

Fig 1. Axes of the selected UAV model (Source: Wikipedia)

B. Hardware

The system is designed around an ARM Cortex M3 processor running custom code that was developed in-house. Attitude determination is done using an intelligent 9 degree of freedom Inertial Measurement Unit (IMU) running sensor fusion algorithm at 100 Hz. The system also consists of a differential pressure sensor for airspeed measurement, GPS module for location and altitude data and a telemetry module for communication. The system is designed to have a refresh rate of 50 Hz.

C. Software

The software is divided into several modules, including auto take-off, auto-land, navigate, actuator control, attitude control. These modules have different refresh rates and are called using a timer.

III. DEVELOPMENT OF THE SYSTEM

A. Autonomous Take-off

Take-off mode is activated when the UAV is armed and Take-off command is issued and initial heading, altitude and position is stored. Auto-throttle is disabled, heading lock is activated and the throttle is set to maximum. Once the specified velocity is reached, the pitch angle is increased to a specified value. The take-off is marked as done once the assigned altitude is reached.

B. Navigation

In the navigation phase, auto-throttle and altitude hold are enabled to maintain specified airspeed and altitude. Position data is stored as a structure comprising Latitude, Longitude and Altitude. Waypoint positions are stored initially. After take-off is complete, the UAV enters navigation mode. Distance and bearing to the next waypoint are calculated each time navigate module is called. If the UAV enters the circle of specified radius around the waypoint, the waypoint is marked as reached and next waypoint is loaded. The distance and bearing are calculated using the Haversine formula (equations (3) and (4)).

$$\Delta\varphi = \varphi_2 - \varphi_1 \quad \ldots (1)$$

$$\Delta\lambda = \lambda_2 - \lambda_1 \quad \ldots (2)$$

$$d = 2R_{\oplus} \sin\left(\sqrt{hav(\Delta\varphi) + \cos(\varphi_1)\cos(\varphi_2)\, hav(\Delta\varphi)}\right) \quad \ldots (3)$$

$$\phi = \tan^{-1}\left(\frac{\sin(\Delta\lambda) - \cos(\varphi_2)}{\cos(\varphi_1)\sin(\varphi_2) - \sin(\varphi_1)\cos(\varphi_2)\cos(\Delta\lambda)}\right) \quad \ldots (4)$$

$\varphi_1, \lambda_1 = latitude\ and\ longitude\ of\ present\ location,$

$\varphi_2, \lambda_2 = latitude\ and\ longitude\ of\ next\ location,$

$$R_\oplus = Radius\ of\ the\ Earth$$

$$hav(\theta) = (\sin\frac{\theta}{2})^2, d = distance, \phi = bearing$$

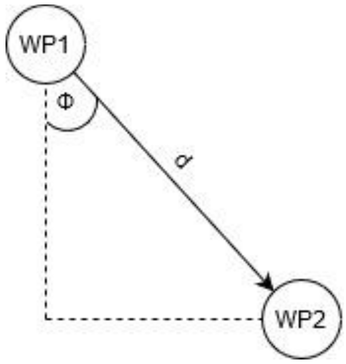

Fig 2. Waypoint Navigation

C. Autonomous Landing

Landing mode is entered if the altitude set for the next waypoint is zero. In landing mode, the descent angle is calculated using the equation (5). The pitch setpoint is set to the calculated descent angle, and speed is set to the specified approach speed. After the UAV reaches a set minimum altitude, the navigate module is disabled and heading lock is activated till the UAV reaches the ground. After landing, the throttle is set to minimum and the UAV enters idle mode.

$$\emptyset = \tan^{-1}(\frac{altitude}{distance\ to\ land}) \quad \ldots (5)$$

D. Control Layer

This layer provides low-level control of the UAV for stabilization of the UAV attitude. The errors between the desired pitch, heading, airspeed and altitude set by the guidance layer and the current attitude read from the IMU, Airspeed sensor and GPS module are sent as inputs to 4 PID controllers to produce actuation command for the ailerons, elevator, rudder and throttle. The control layer runs at a frequency of 50 Hz which is the refresh rate for the servos used in UAVs.

E. Flight Envelope

A flight envelope is defined to prevent the UAV from noticing extreme attitudes. The flight envelope constants are given in the below table.

Table I. Flight Envelope Parameters

Parameters	Lower Limit	Upper Limit
Pitch angle	-15º	20º
Roll angle	-30º	30º
Heading	0º	359º
Throttle	0	100%
Airspeed	0	56 m/s

F. Sensor Refresh Rates

A 9 degree of freedom Smart Inertial Measurement Unit (IMU) running proprietary sensor fusion algorithm is used for attitude determination. The IMU outputs data at 100 Hz, the average of 2 readings are taken to get a stable value. The GPS module runs at a refresh rate of 5 Hz and the Airspeed sensor is read at 50 Hz. The below table enlists the sensors and sensor refresh rates.

Sensor Refresh Rates

Sensor	Measurements	Refresh Rates
IMU	Pitch, Roll and Heading angles	100 Hz
GPS	Latitude, Longitude and altitude	5 Hz
Airspeed sensor	Airspeed	50 Hz

G. Proposed Design of the System

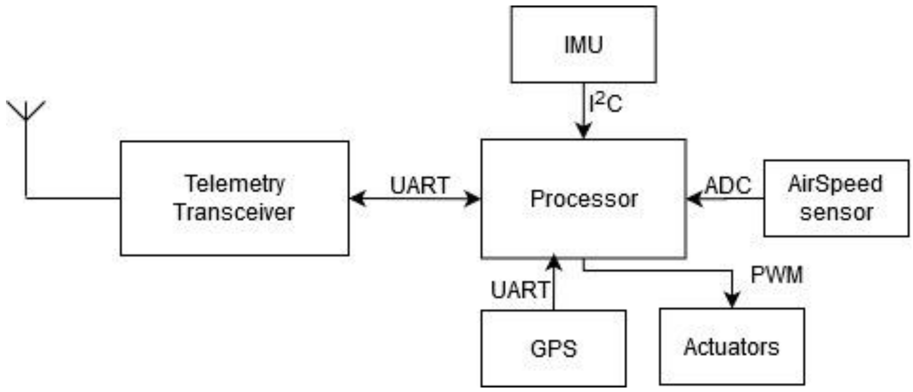

Fig 3. Proposed Design of the Navigation System

Figure 3 shows the proposed solution for the autonomous navigation system. The system embeds all the required sensors essential to perform the autonomous flight.

IV. RESULTS AND DISCUSSION

X-Plane 11 was used to validate the proposed system using Hardware in the Loop Simulation. The simulation used a Cessna 172 model, with associated parameters including stall velocity. The parameters for the simulation are given in Table III.

Table II. Simulation Parameters

Parameters	Value
WP1	Lat = 47.5113, Lon = -122.3128
WP2	Lat = 47.5628, Lon = -122.3096
WP3	Lat = 47.6493, Lon = -122.3046
WP4	Lat = 47.7053, Lon = -122.3233
WP5	Lat = 47.8218, Lon = -122.2806
WP6	Lat = 47.8632, Lon = -122.2853
WP7	Lat = 47.8976, Lon = -122.2853
Airspeed	50 m/s
WP Radius	50 m
Altitude	610 m above ground level

The result of the navigation is shown in Figure 5. The simulation started with an initial heading of 180º. Autonomous navigation stated after finishing the take-off phase, which resulted in a 180º turn which can be observed in Figure 5.Figure 6 shows the planned path for the simulation. Roll, Pitch and Yaw PID response, and Airspeed and Altitude plot mode are shown in Figure 7 and Figure 8 respectively.

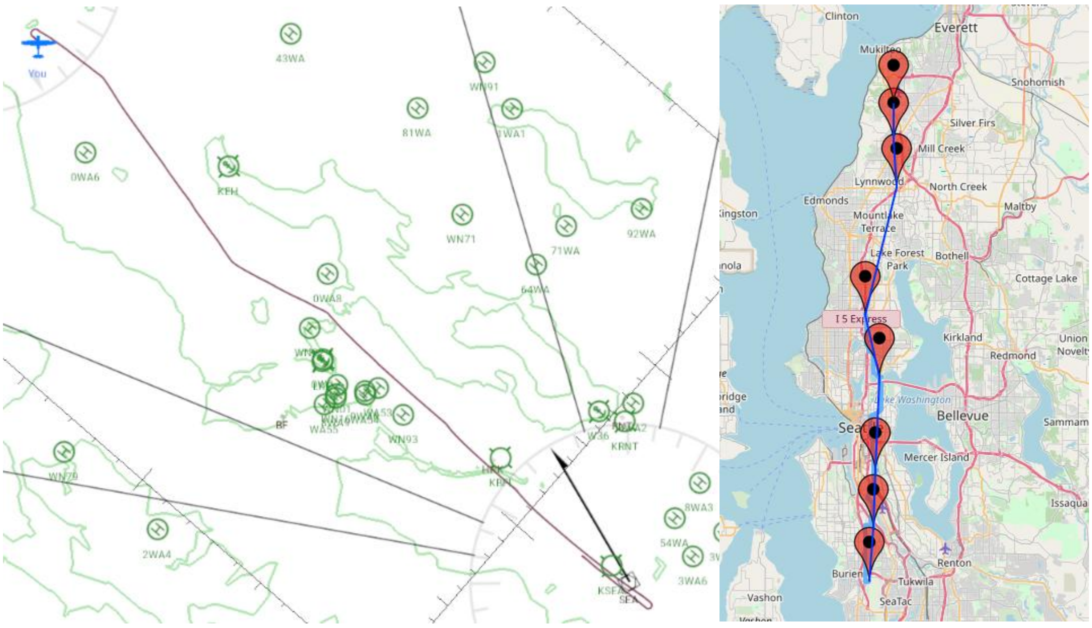

Fig 4. Path Followed by the Plane in the Simulation and specified Path for the Simulation

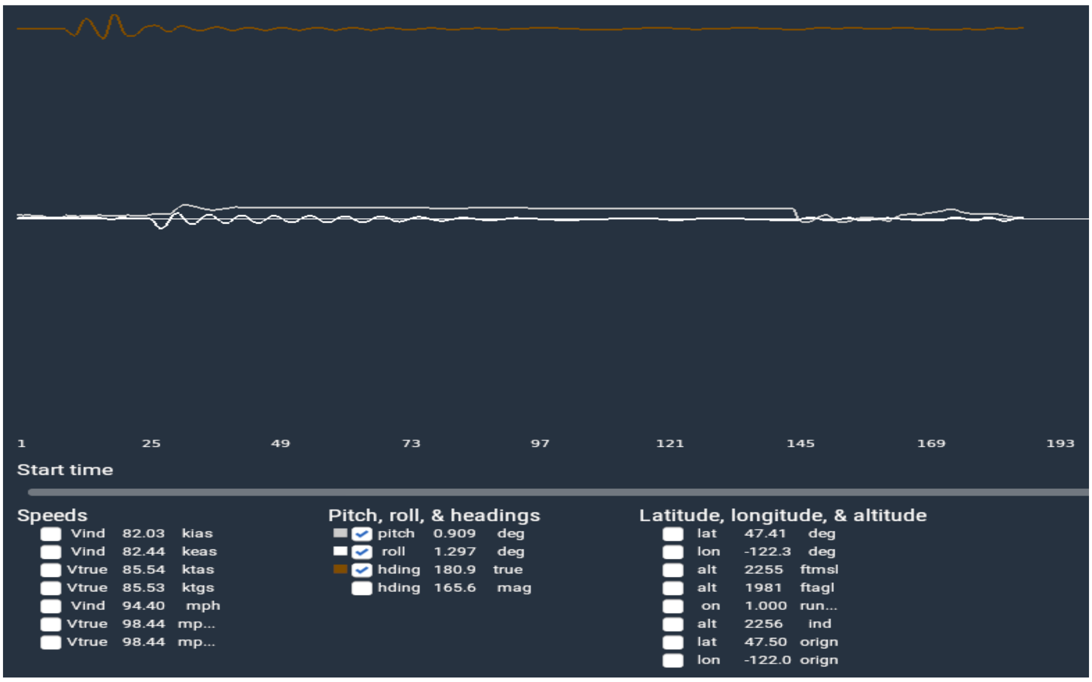

Fig 5. Roll, Pitch and Yaw axis PID response

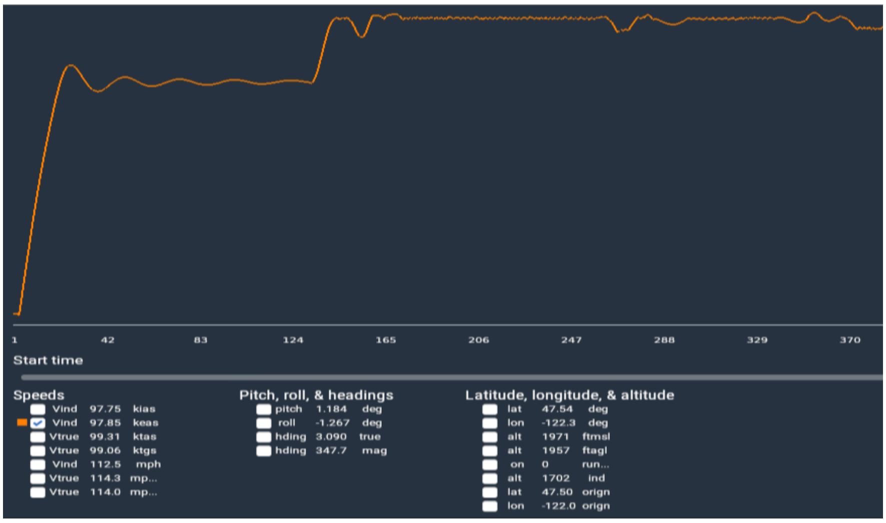

Fig 6. Airspeed vs time plot

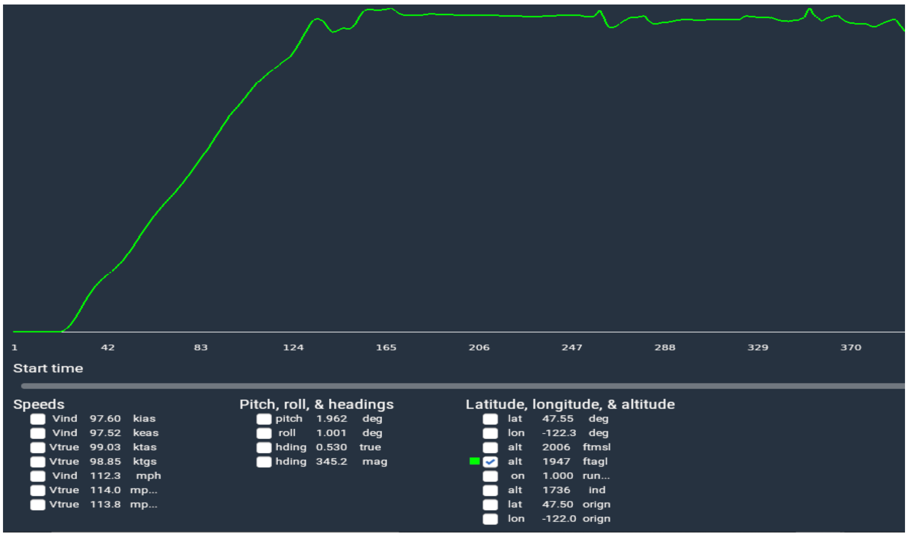

Fig 7. Altitude above sea-level vs time plot

V. CONCLUSION AND FUTURE WORK

This paper described the design and development of an autonomous navigation system for fixed-wing UAVs. The system allows custom waypoints which can be modified by the user and autonomous navigation and control by following a specified trajectory, airspeed and altitude. The system proposed is computationally less intensive, hence can be implemented in low-cost hardware as described.

As future works, we plan to add PID auto-tuning capability, emergency modes like Return to Launch, Manual override, a Ground Station software capable of running in a PC instead of separate ground station module. The final system will be tested the system on a real UAV.

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