Design and Development of VTOL

Mehul Damani
School of Mechanical and Aerospace Engineering

Ast Prof Ng Bing Feng
School of Mechanical and Aerospace Engineering

***Abstract* –** Electric vertical take-off and landing aircrafts (eVTOL), which are powered electrically and have the capability to hover, take-off and land vertically, have been receiving increasing attention in the quest for fully autonomous passenger air vehicles (PAV) and aviation giants such as Boeing and Airbus have already developed demonstrator aircrafts. The primary objective of our research was to design and develop a scaled down novel eVTOL prototype. Multiple test flights on the prototype were used to validate our design and choice of parameters and also to validate electrical propulsion as a viable means for passenger air vehicles. Structural design of the prototype was first completed on SolidWorks and carbon fibre rods were used to construct the frame. Care was taken to prevent the localisation of stresses and custom 3D-printed joints were designed to minimise take-off weight. Due to its versatility, Pixhawk was chosen as the default controller. Altitude inputs were provided by a barometer and LIDAR, orientation inputs by an IMU and localisation was done through GPS. A 6S Lithium Polymer (LIPO) battery was selected as the power source and was projected to provide a 10-minute hover endurance. Initial test flights were highly unstable and this was attributed to a badly tuned flight controller. Subsequent flights involved progressive tuning of Pixhawk parameters and minor adjustments in design until level flight was achieved in Altitude-Hold mode. The prototype was finally put through endurance tests and was successfully able to achieve the 10-minute projected milestone.

Keywords – eVTOL, control systems, structural design

1 INTRODUCTION

1.1 BACKGROUND

Recent decades have witnessed rapid urbanization and increase in traffic congestion in major metropolitan cities of the world. Consequently, both private and public ground transportation systems around the world have come under heavy pressure [1]. There has been a lot of recent work on smart ground traffic optimization systems. However, the gains from optimization alone will not be enough to tackle the fast-rising congestion and as a result, there has been growing interest in unconventional means of transportation such as underground and in the air [2]. This has resulted in the development of aerial vehicle concepts for intra-city passenger transportation, also known as “Urban Air Mobility” (UAM). Among the different UAM vehicle concepts, electric Vertical Take-off and Landing Aircrafts (eVTOL) have received widespread attention, primarily due to their ability to take-off and land vertically in congested areas and due to the recent advancements in battery technology and electric propulsion systems [3].

Recent work has involved the development of a wide variety of VTOL demonstrator aircrafts. CityAirbus, a demonstrator aircraft by Airbus, began ground testing in 2018. Bell Nexus, a hybrid eVTOL, was unveiled by Bell Labs in 2019. Lilium Jet, a 5-seater eVTOL with 36 engines completed its maiden flight in 2019 [4].

1.2 OBJECTIVE

The objective of this paper is to describe the development, validation and ground testing of a scaled eVTOL prototype. First, this paper describes the structural design of the prototype and justifies the choice of design parameters. Then, this paper elaborates on the architecture of the control system and describes both the software and hardware used. Last, this paper describes the ground tests conducted on the prototype, the progressive modification of control parameters until level flight was achieved and the endurance milestones achieved.

2 STRUCTURAL DESIGN

A 1:17.5 scaled prototype was developed to validate the feasibility of eVTOL in UAM. Initial numerical analysis was used to obtain target parameters for the scaled prototype. For a wingspan of 1.2m, a Maximum Take-off Weight (MTOW) of approximately 4.7kg was arrived at. The VTOL consists of 8 upward facing propellers for lift and 2 forward facing propellers for thrust. A full list of the scaled prototype specifications is shown in Table 1.

Scaled Prototype Specifications		
Parameters	**Estimated**	**Actual**
MTOW (kg)	4.8	4.75
Payload(kg)	2.6	2.7
Cruise Altitude (ft)	150	-

Cruise Speed (km/h)	75	-
Range (m)	40	-
Wingspan (m)	1.19	1.2
Empty Weight (kg)	2.1	3.4

Table 1. Scaled Prototype Specifications

The initial structural design of the prototype was conducted on SolidWorks with the aim of minimizing weight. Endurance has a highly negative correlation with weight and minimizing weight was key to achieving the targeted endurance milestone. Custom connectors were designed with multiple joints to combine the functionality of different connectors. The main materials used in construction of the prototype were PLA, CFRP and ABS. CFRP was chosen as the primary load-bearing material due to its high strength-to-weight ratio which gave it an advantage of conventional aerospace materials like Balsa wood. The selection of CFRP was in line with the objective to minimize the prototype’s weight.

Initially, hollow circular CFRP rods were chosen to construct the wing and body frames of the aircraft. However, ground testing with circular rods led to unstable flight performance, owing to the freedom in rotation of these rods about the longitudinal axis. This freedom in rotation caused misalignment in propellers’ lines of thrust which introduced biases in pitch, roll and yaw manoeuvres. Thus, a switch was made from circular to square rods which resulted in much more stability and limited, correctable biases.

The conceptual design of the full-sized eVTOL vehicle is shown in Figure 1 and the frame structure of the scaled prototype is shown in Figure 2. As shown in Figure 2, the wing group consists of 2 longitudinal spars and 4 transverse booms to support the motors.

Figure 1. eVTOL conceptual design

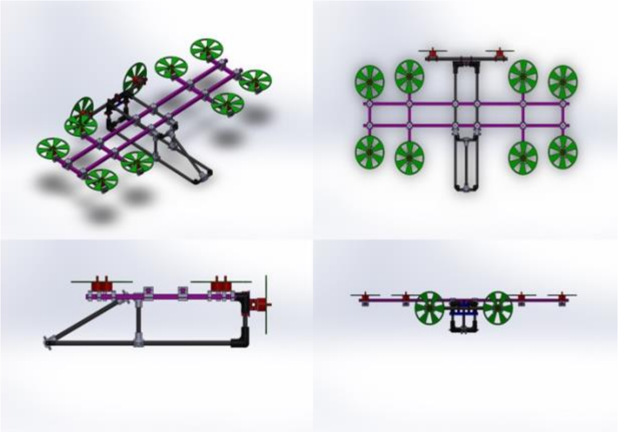

Figure 2. CAD drawings of frame structure

Although CFRP was used in construction of the frame, 3D printed parts are used for custom made designs such as mounting plates, connectors and the prototype body. The flexibility in design for 3D printed parts more than compensates for the lower strength-to-weight ratio. ABS is used as the printing material for critical components which are expected to be exposed to high stressed, such as the connectors connecting the wing and body groups. PLA is vulnerable to UV degradation, which makes it an unsuitable choice for these critical connections, particularly in outdoor flight conditions. However, PLA was used as the printing material for non-critical components housed in the interior of the prototype, such as the battery bay and the avionics components. The design of unconventional 3D-printed multifunctional connectors helped in significantly reducing the weight of the prototype. The entire outer body of the prototype was also 3D-printed, primarily due to its unconventional design and the requirement to minimize weight. Figure 3 shows the CAD drawings of the prototype with the outer body superimposed on it. Figure 4 shows the custom designed 3-D printed parts.

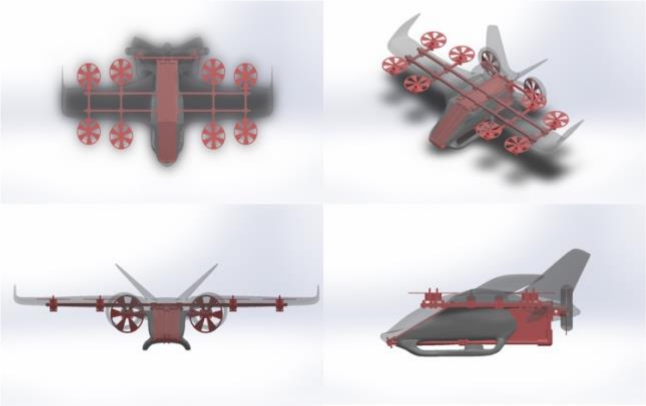

Figure 3. CAD drawings with outer body

Figure 4. 3D printed prototype parts

3 CONTROL SYSTEMS

3.1 SYSTEM ARCHITECTURE

The prototype's control system was built around Pixhawk, which is a general purpose open source flight controller [5]. The reasons for selecting Pixhawk are multifold. Pixhawk is highly versatile, and offers control architectures for a wide variety of airframes. It also offers support for numerous VTOL configurations, which are difficult to build from scratch owing to the high complexity of the VTOL transition phase. Additionally, the open-source nature of Pixhawk makes it highly customizable and the user has control of more than 200 parameters. The airframe of our prototype was a distorted version of the default OctoX architecture provided by Pixhawk as shown in Figure 5 [6]. As a result, significant control tuning was required to manually alter the default PID values until pitch, roll and yaw were stabilized.

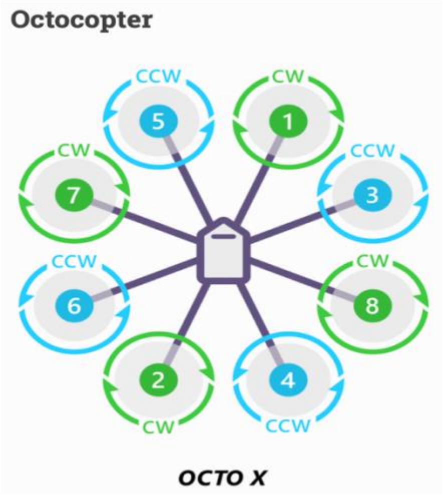

Figure 5. Pixhawk OCTOX Airframe

The pixhawk controller consists of many inbuilt sensors and multiple input ports to provide sensor data. Two inbuilt Inertial Measurement Units (IMU) provided orientation data to the flight controller. An externally connected GPS and compass were used for localization of the VTOL. A downward facing LiDAR was used to provide altitude data when close to the ground. This was necessary since the inbuilt barometer was unreliable and noisy when flying close to the ground. An Extended Kalman Filter (EKF) was enabled on the flight controller to fuse IMU and LiDAR data. A telemetry unit was connected externally to the Pixhawk to provide essential flight and battery status information in real time to the workstation. Finally, externally connected transmitters and receivers were used to enable manual line-of-sight control of the VTOL.

The input data to the Pixhawk controller was processed by the control algorithm which output 8 Pulse Width Modulation (PWM) signals to control the 8 brushless motors. The 8 PWM signals were first passed to 8 Electronic Speed Control (ESC) units. All ESC units were connected to a common 8-output power distribution board which was powered through a 6S Lithium Polymer (LiPo) Battery. A separate 3S LiPo battery was used to provide power to the Pixhawk board. The primary motive of doing so was to protect the Pixhawk board in case of battery failure or a power surge in the 6S LiPo battery which was being drained vigorously by the 8 motor system.

Table 2 provides a summary of the components used in the avionics system and Figure 6 provides the prototype circuit diagram.

Item	Specifications
Flight Controller	Pixhawk 1 Autopilot
GPS Module	Ublox 8N High Precision GPS Built-in Compass
LiDAR	Benewake TF-mini S
Telemetry Set	100mV 433 MHz FPV set
Receiver	Futaba R7008SB 2.4GHz
Transmitter	Futaba 14SGA 14 Channel 2.4 GHz
PDB	200A Power Distribution Board
ESC	FlyColor 45A BLHeli_32
Motor	T-motor F80 Pro KV1900
Battery	Turnigy 6S 10000mAh 12C LiPo Pack
	Turnigy 3S 2200mAh 30C LiPo Pack

Table 2. Avionics Components List

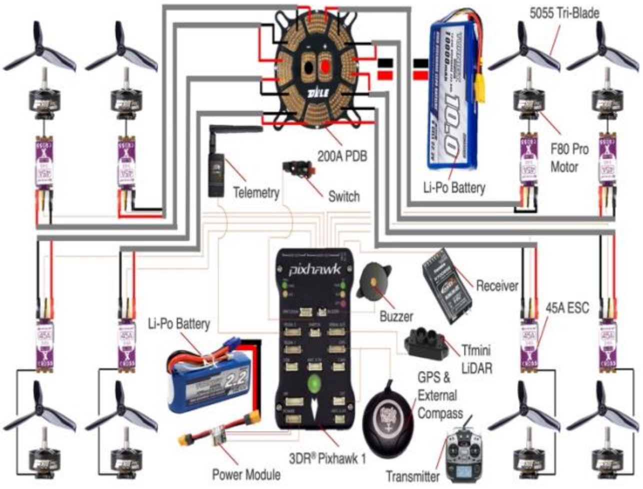

Figure 6. Prototype Circuit Diagram

3.2 CONTROLLER DESIGN

Our prototype had functionalities of both a multi-copter and a fixed wing aircraft. Thus, the control algorithm for the eVTOL was not constant but dependent on its flight mode – Hover, Transition or Forward Flight. PID controllers were used to drive the parameters to the desired set-points [7].

The complete pipeline for the controller is shown in Figure 7. An estimator uses multiple sensor inputs to compute the vehicle state. A controller takes the desired set-point and the current estimated state of the vehicle and outputs a corrective action to drive the current state towards the desired set-point. A mixer takes the controller outputs and maps them to individual motor commands. This mapping is specific for a vehicle type, and depends on various factors such as the vehicle's rotational inertia and the arrangement of motors with respect to the center of gravity.

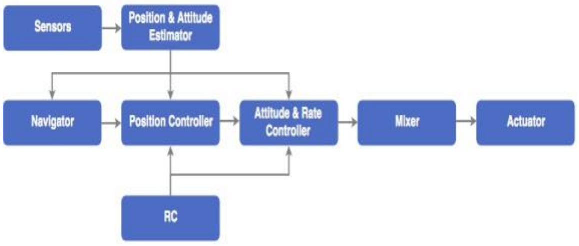

Figure 7. Control pipeline

During hover, the multi-copter controller will be in operation while during forward flight, the fixed wing controller will be in operation. During the highly complex transition manoeuvre, both controllers will work in conjunction to pass control gradually from one mode to the other.

4 TESTING

Initial testing on the prototype was conducted without the outer body attached, in an indoor environment with a take-off weight 500-700 grams below the MTOW. Since testing was conducted in an indoor environment, GPS was not accessible and the prototype didn't have the capability of very accurate localization. Initial flights showed heavy imbalance, with constant manual inputs needed to stabilize the VTOL. The heavy imbalance in initial flights was due to a variety of reasons. The Center of Gravity (CG) wasn't placed properly, primarily due to failure in accounting for the impact of the 6S LiPo battery on the CG position. More importantly, the initial flights were conducted with a badly tuned controller, and iterative improvement of PID parameters based on observations was necessary.

Subsequent test flights involved progressive tuning fixes to the controller [8]. Roll and pitch sensitivity parameters were decreased due to the aggressive nature of the VTOL. Initial flights had a tether attached to the prototype to constrain it and prevent major damage in case of a loss in control. As the VTOL became better tuned, the tether was removed to allow free climbing to a level altitude. The VTOL also faced significant imbalance close to the ground due to ground effects caused by the high speed propellers. PID tuning of the aircraft helped significantly and the VTOL gained stability and required fewer manual stick manoeuvres to stabilize. Figure 8 shows the prototype in stable flight.

Figure 8. Prototype in stable flight

The final phase of testing aimed to stabilize the prototype's altitude using 'Altitude Hold Mode' and to conduct endurance tests to verify the numerically calculated values. However, it was observed that the prototype dropped altitude rapidly whenever Altitude Hold Mode was activated [9]. This sharp drop in altitude is shown in Figure 9. This was initially attributed to a faulty altitude sensor, but the problem remained even after trying LiDAR, SONAR and Pressure Sensor as primary Altitude sensors.

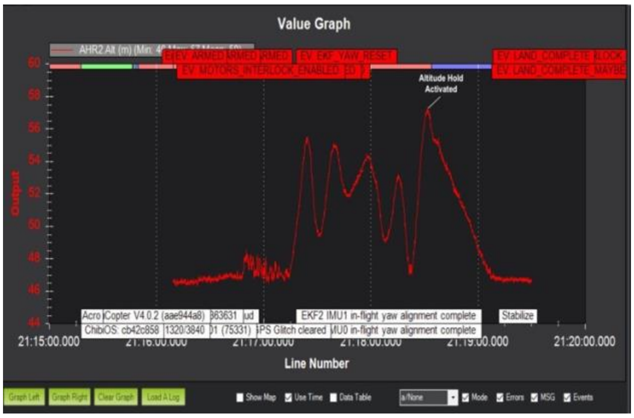

Figure 9. Initial Altitude vs Time graph

After analysis of various flight logs, it was found that the throttle required to hover was around 35%. The minimum throttle level required for the default Altitude Hold mode was 40%. Thus, when the throttle was at 35%, Altitude Hold mode executed a controlled descent which was the reason for the sharp drop in altitude. The minimum throttle level required was then lowered to 30% using the “THR_DZ” parameter, also known as the deadband parameter. Subsequent flights showed that our analysis had been correct, and our prototype was successfully able to maintain altitude as shown in Figure 10. The aircraft’s PID parameters were then further fine-tuned increase roll and pitch stability. Finally, endurance tests were conducted on the prototype with a fully charged 6S LiPo battery. It was observed that the aircraft was successfully able to hover beyond the projected 7 minutes.

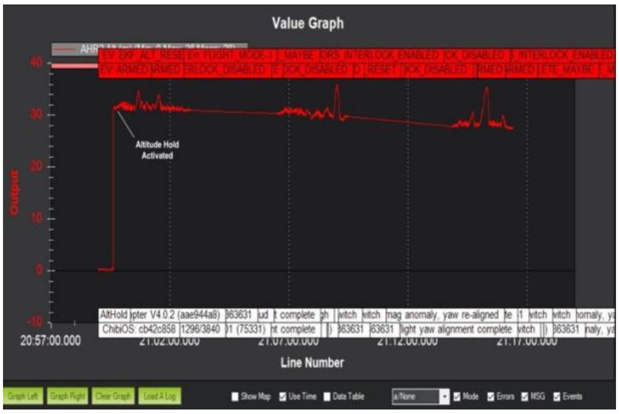

Figure 10. Altitude vs Time graph after Deadband correction

6 CONCLUSION

This paper described the design, assembly and control of a 1:17.5 scaled VTOL prototype. With rising populations and traffic congestion, the interest and demand in unconventional means of transport is only expected to grow and VTOL’s are leading the way in Urban Air Mobility (UAM). Our prototype was able to achieve and exceed the projected endurance using electric propulsion. The increasing advancements in electric propulsion is another promising sign for the future of VTOL’s. Extensive work was done on developing and tuning the control system and this was validated by the stability of the prototype in the final phases of testing. In the final phase of testing, the prototype is able to execute stable hover flight and corresponding manoeuvres. Future work will try to integrate the fixed wing controller with the multi-copter controller and successfully execute transition from one to the other.

ACKNOWLEDGMENT

I would like to express gratitude to Nanyang Technological University (NTU) for providing me with the resources and support to undertake research in VTOL development. I would also like to thank my supervisor Ast/P Ng Bing Feng from the school of Mechanical and Aerospace Engineering at NTU. His experience and insights gave direction and invaluable support to this project. Lastly, I would like to thank my team members, Mr Orion Dai Yuhui, Mr Jonas Erlmann and Mr Wong Zheng Xiong without whom this project would not have been possible.

“I would like to acknowledge the funding support from Nanyang Technological University – URECA Undergraduate Research Programme for this research project.”

REFERENCES

[1] Organisation for Economic Co-operation and Development and European Con-ference of Ministers of Transport (ECMT), *Defining and characterising congestion*. Managing Urban Trac Congestion, Paris: Organisation for Economic Co-operation and Development : European Conference of Ministers of Trans-port (ECMT), 2007. Available: https://www.itf-oecd.org/sites/default/files/docs/07congestion.pdf.

[2] W. Broere, “Urban underground space: Solving the problems of today’s cities,” *Tunnelling and Underground Space Technology*, vol. 55, pp. 245–248, 2016.

[3] Y. Liu, M. Kreimeier, E. Stumpf, Y. Zhou, and H. Liu, “Overview of recent endeavors on personal aerial vehicles: A focus on the us and europe led research activities,” *Progress in Aerospace Sciences*, vol. 91, pp. 53–66, 2017.

[4] EVTOL Aircraft Directory. (2020, June 22). Retrieved June 28, 2020, from https://evtol.news/aircraft/

[5] Dronecode. (2020, Mar. 30). Pixhawk 1 flight controller [Online]. Available: https://docs.px4.io/v1.9.0/en/flight_controller/pixhawk.html.

[6] Ardupilot. (2019) Motor order diagrams [Online]. Available: https:// ardupilot.org/copter/docs/connect-escs-and-motors.html.

[7] Controller Diagrams. (n.d.). Retrieved June 28, 2020, from https://dev.px4.io/master/en/flight_stack/controller_diagrams.html

[8] Ardupilot. (2019). Basic tuning [Online]. Available: https://ardupilot.org/ copter/docs/basic-tuning.html.

[9] Ardupilot. Altitude hold mode [Online]. Available: https://ardupilot.org/ copter/docs/altholdmode.html.