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# Flight Test Data Analysis of Hybrid Vertical Take-off and Landing Unmanned Aerial Vehicle

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***Abstract***—A Hybrid Unmanned Aerial Vehicle (UAV) has both advantages of multirotor and fixed-wing UAV. This unique design leads to a more complicated airframe and control design compared to those of a conventional drone. Integrating two platform of UAV (multirotor and fixed-wing) also requires carefully consideration to safely operate this hybrid UAV. This paper discussed the flight scenario that includes flight modes and parameters to be determined before flight. This leads to the development of the flight procedure as an important prerequisite for a successful flight.

***Keywords***—Hybrid, UAV, VTOL, fixed-wing, multirotor



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## I. Introduction

NOWADAYS, Unmanned Aerial Vehicle (UAV) has been researched and applied for diverse practical used [1]. Hybrid Vertical Takeoff and Landing (VTOL) UAV is a novel concept of UAV which integrates fixed-wing and multirotor configuration so that it has the capability of vertical takeoff and landing with high range and long endurance mission. This VTOL UAV configuration can be developed for a wide range of applications for which there is no need of runway during takeoff and landing while maintaining the efficiency, speed, and range of a normal fixed-wing UAV. The versatility of a hybrid VTOL UAV comes not only from its capability to perform VTOL flight and fixed-wing flight, but also the capability to transition between the two modes (hover to flight forward and vice versa) safely. A simulation that demonstrates such capability is reported in [2] for a hybrid three-rotor flying wing UAV.

However, the transition between the two modes is not as well-understood as the other two modes. This is proved by difficulty for a human operator in flying the UAV in transition mode. The difficulty can be contributed to the high nonlinearity of the flight condition, as well as to the presence of many unidentified uncertainties.

In this paper, we study the performance of our hybrid UAV design in transition flight. We start our study by performing flight tests in order to assess the feasibility of transition flight with the given UAV configuration. A working control system for each VTOL flight and cruise flight were prepared before performing transition flight. We take this approach as our design was built readily with its control equipment available for either fixed-wing flight or VTOL flight. This approach will be followed by analytic approach at latter stage of our research.

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## II. Hybrid UAV Specification

The specification of the proposed hybrid UAV was formulated based on the enhancement of a conventional fixed-wing UAV [3] with VTOL capability. This exercise lead to the selection of configuration complied with the DRO (Design Requirements and Objectives). The comparison study of a number of hybrid UAVs provided valuable information at the start of the design process.

Compared to normal multirotor or fixed-wing UAV, this hybrid UAV is significantly heavier, less aerodynamic and produces more vibration and heat [4]. Beside airframe constrain, there also systems and control constraints. The battery should provide energy for 5 rotors and the flight controller for hybrid UAV is not available in the market therefore we developed it in-house.

The general specifications of our hybrid UAV design are summarized in **Table 1**.

**Table 1 Specifications of the hybrid UAV**

| Specifications | |
|---|---|
| MTOW (kg) | 6 |
| Payload (kg) | 1 |
| Wing span (m) | 1.9 |
| Cruise speed (m/s) | 18 – 30 |
| Operating altitude (AGL) | 70 – 200 |
| | |
| Capability | Vertical take-off and landing |
| Material | Composite |
| Hybrid type | Separate lift and thrust hybrid |
| Propulsion | Electrical power |

**Figure 1** shows the 3D model of designed hybrid UAV which includes the information of its material used. Most of the airframe is using Glass Fiber Reinforced Plastic (GFRP) with foam core. Specific area such as control surfaces and tail boom are using Carbon Fiber Reinforced Plastic (CFRP) with foam

core to give high strength capability and maintain stiffness of the movable area (control surfaces).

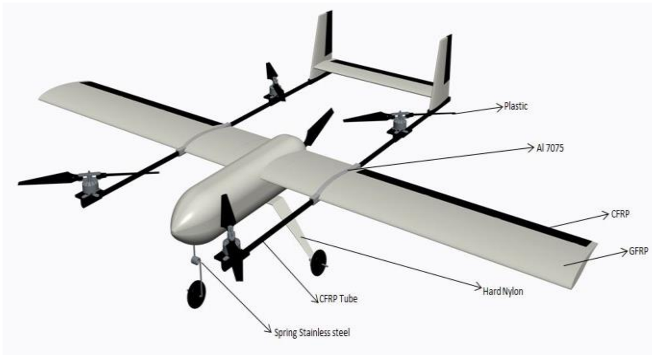


**Figure 1 Three dimensional model of the UAV**

**Figure 2 Actual product**

**Figure 2** above is the result of manufacturing process, complete with its avionics and propulsion systems. Manufacturing process is doing in-house of our research center building in Jatinangor, Indonesia.

## III. FLIGHT SCENARIO

In general, the nominal flight of the Hybrid UAV can be distinguished into 5 different stages:

1. Vertical take-off
2. Transition from hover to forward flight
3. Forward flight
4. Transition from forward flight to hover
5. Vertical Landing

The transition stage is the most critical stage of all the flight phases. To come up with the safe and stable switch between hover and forward flight, we have been focusing on the transition stage algorithm and control in our early research phase. **Figure 3** shows our final algorithm for transition from hover to forward flight based on a separate lift and thrust mechanism.

**Figure 3** shows the brief of transition scenario which is designed to establish smooth transition [5]. Based on the results of many flight tests, we determined that $V_{th1}$ = 12 m/s and $V_{th2}$ = 18 m/s taking into account of the basic performance of the UAV.

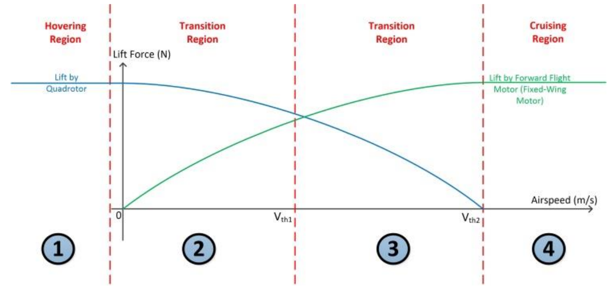


**Figure 3 Transition scenario - hover to forward flight**

### *A. State 1*

Lift force is gained by Quadrotor thrust. The thrust is used to gain sufficient and safe altitude for applying transition stage/mode. Besides, the UAV is stabilizing its attitude whilst gaining certain altitude.

- Gain of Quadrotor Attitude Control from Ground Control Station is fully applied to the UAV
- Control surfaces (Aileron, Rudder, Elevator) are in*activated*
- Flight mode: altitude hold

### *B. State 2*

- Lift force is gained by combination of Quadrotor thrust and Fixed-Wing (wing and tail) lift. These combination force are applied to maintain altitude and attitude of the UAV
- The value of Quadrotor thrust is automatically adjusted by the autopilot using altitude hold mode
- Gain of Quadrotor Attitude Control from Ground Control Station is fully applied to the UAV
- Control surfaces (Aileron, Rudder, Elevator) are still *inactivated*
- Percentage throttle of Forward Flight motor is initially *activated automatically* to last state of throttle stick on remote control, while throttle of quadrotor is fully automatic to maintain altitude and attitude
- Flight Mode: altitude holds for quadrotor and stabilizes for fixed-wing

### *C. State 3*

- Lift force is gained by combination of Quadrotor thrust and Fixed-Wing (wing and tail) lift
- The value of Quadrotor thrust is automatically adjusted by the autopilot using altitude hold mode
- Gain of Quadrotor Attitude Control from Ground Control Station applied to UAV is attenuated. The attenuation value is proportional with the increment of UAV airspeed
- Control surfaces (Aileron, Rudder, Elevator) are activated
- Percentage throttle of Forward Flight motor is automatically switch to manual
- Flight Mode: altitude hold for quadrotor and stabilize for fixed-wing

### *D. State 4*

- Lift force is gained by UAV fixed-wing thrust
- Quadrotor are inactivated
- Gain of Quadrotor Attitude Control is inactivated
- Control surface (Aileron, Rudder, Elevator) are still activated. Attitude of the UAV is fully controlled by control surfaces of the UAV only
- Percentage throttle of Forward Flight motor (for Fixed-Wing mode) can be adjusted manually
- Flight mode: stabilize

## IV. TEST SET-UP

The purpose of these tests are to validate the result of theoretical and computational analysis of UAV; and to provide data where no quantitative prediction can be made; and the most important is to prove the transition (hover to forward flight and back) capability of the UAV both the design and the controller. The flight controller is developed by modifying existing flight controller of normal fixed-wing and multirotor UAV.

These tests are divided into two main test, ground test and flight test. The purpose of ground test is to ensure airframe and avionics systems are comply with requirements thus the UAV will perform the flight as we expected. Ground test consist of:

- Inspection of vehicle structural integrity.
  The UAV is a modular design to make it simple to carry. Every joint must be well integrated to maintain airframe rigidity.
- Verification of weight and balance.
  Weight and balance check will give us the location of actual center of gravity (CoG) in all axis, X, Y, and Z. Location of CoG will affect the performance and stability of UAV.
- Operation of avionics systems (controller, navigation, power source and wiring).
  All data of avionics system operation range must be collected as the limit of flight operation. Beside the ability of UAV, range and endurance determine by how far the navigation system could cover the communication and how long the battery could power the motors.
  Flight controller has all the flight scenario, flight parameters and failsafe when emergency situation is occurred.
- Motors run up to ensure nominal static motor performance.
  We held simple test which obtain static thrust of the motors. By adding drag of propeller by its movement in air, we could obtain dynamics thrust. It provides whether the motor and propeller configuration will have enough thrust to move forward the UAV or not.
- Controlled taxi-testing.
  Taxiing test is essential for conventional takeoff (using runway).
- Weather & test area safety.
  Because the UAV is in development stage (experimental UAV) testing area must be clear from inhabitant. Weather data of the test such as wind speed, etc. is known before flight.
- Ground support system readiness.
  The most important of ground support is ground control system (GCS). With GCS we can plan the flight and observe it while the UAV flies. Moreover, GCS is the place we can execute failsafe for emergency situation if remote controller is error.
- Pre-flight check.
  This pre-flight check is the second layer of safety procedure before flight. It does the entire ground test concisely. This is a part to ensure the readiness of the UAV to fly. It commits just before the flight.

After ground test is completely done, the series of flight test is planned. Chronologically, flight test consist of indoor hover test, outdoor hover test, forward flight test using conventional takeoff and landing, and full flight test with transition. It is important to ensure hovering and forward-flight are going well before transition being tested.

**Figure 4 Outdoor hover test**

## V. FLIGHT TEST DATA ANALYSIS

In this paper, the discussion is objected to one flight test only. This flight duration is 4 minutes long, consist of 5 stages that are:

- Stage 1 → 68.75 seconds vertical take-off.
- Stage 2 → 10.75 seconds transition from hover to forward flight.
- Stage 3 → 106.375 seconds forward flight.
- Stage 4 → 2.125 seconds transition from forward flight to hover.
- Stage 5 → 52 seconds vertical landing.

**TABLE 2 FLIGHT MODE DURING FLIGHT**

| Flight Stage | Time (s) | Flight Mode |
|---|---|---|
| (1) Vertical Takeoff | 0 – 68.75 | Manual and Altitude Hold |
| (2) Transition (2) | 68.75 – 79.5 | Altitude Hold and Stabilize |
| (3) Forward Flight | 79.5 –185.875 | Stabilize |
| (4) Transition (4) | 185.875 - 188 | Stabilize |
| (5) Vertical Landing | 188 – 240 | Manual |

**Figures** 5, 6, 7 and 8 are flight data that are extracted from autopilot, respectively show flight mode, throttle percentage (of all 5 motors), airspeed, and attitude (roll and pitch) graph of hybrid UAV from time to time. All graphs are segmented according to its stage from vertical stage 1 (vertical takeoff) to stage 5 (vertical landing).

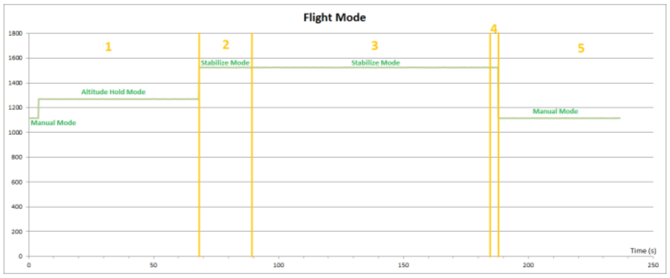


**Figure 5 Flight mode vs. time (s)**

**Table 2** and **Figure 5** tell the alteration of flight mode during actual flight based on flight scenario. Because there are 2 configuration (fixed-wing and multirotor) in 1 vehicle, it needs 2 flight modes during transition for each configuration.

Manual mode is used at the very first of the flight during stage 1 (vertical takeoff) untill the UAV reach the height of about 5m above the ground before switched to altitude hold mode. Manual mode is also used during the last stage (vertical landing) for safety reason.

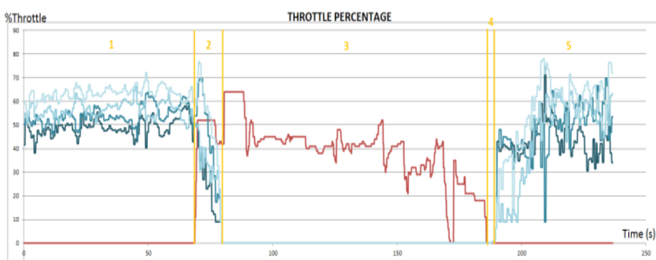


**Figure 6 Throttle (%) vs. time (s)**

Graph above is throttle (in %) of all motors. The blue curves are quadrotor throttle, and the red one is forward-flight-motor's throttle. Forward-flight-motor's throttle is initially activated automatically when entering transition (hover to forward flight) (stage number 2), from 0% throttle to the last state of throttle stick on the remote control. Last state of throttle stick on the remote control is used to adjust quadrotor throttle to maintain its position. This increment of fixed-wing throttle is automatically going on, gradually within 1 second, only then automatically switched to manual adjustment. Meanwhile the throttle of quadrotor is gradually shutting down right after the UAV reach its required minimum speed. Those are according to designed flight scenario.

Based on the graph above, average percentage of forward-flight motor's throttle during forward flight is 40%. Forward-flight motor's throttle will be decreasing gradually to 0% when entering transition (forward flight to hover) stage within 2 seconds only then the quadrotor throttle will turning on and increase manually.

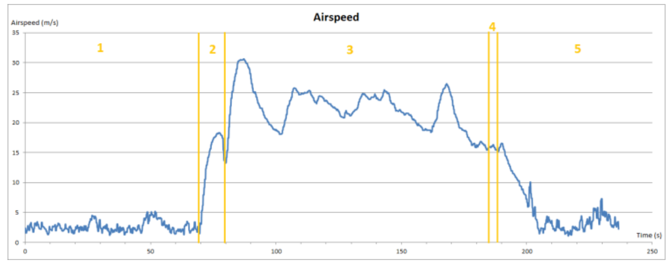


**Figure 7 Airspeed (m/s) vs. time (s)**

During vertical take-off and landing, wind speed is subjected as forward airspeed. At the moment, average wind speed is 2.6 m/s. **Figure 7** show airspeed measurement without noise filter.

During transition, while quadrotor are used to maintain altitude and attitude, the forward airspeed is generated by forward-flight motor. It takes 10.5 seconds to reach the required airspeed (18 m/s) for the quadrotor to automatically shut down and the UAV starts the forward flight like a normal fixed-wing UAV. Average airspeed during forward flight is 21.8 m/s.

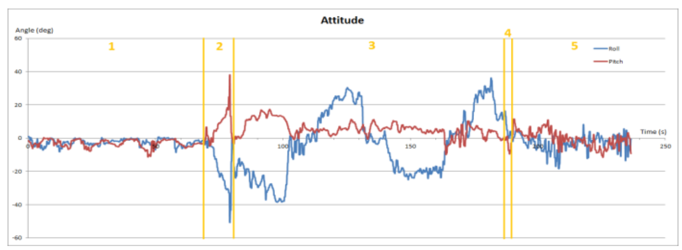


**Figure 8 Roll and pitch (deg.) vs. time (s)**

Before flight, PID parameters were tuned using HILS method and the result is used for quadrotor and fixed-wing mode. Since there is no appropriate software for simulating transition, thus the PID at this stage is combination of quadrotor PID and fixed-wing PID.

Visually, the UAV fly stable. At transition condition from hover to forward flight, once minimum airspeed required is achieved and quadrotor begin to inactivated, there is a jolt that caused UAV to pitch up (see figure VIII).

## VI. Conclusion

For safety reason and maturity of the design, it is important to simulate the flight on the desk before flight at the field. The automatic flight control system is designed using Hardware-In-the-Loop-Simulation (HILS) method by integrating flight controller hardware, X-Plane as visualizer, and Simulink as performance data receiver. The simulation is done for quadrotor and fixed-wing mode, but not for the transition stage. It needs a lot of effort to build simulation for transition stage.

Test result during successful transition flight is presented. This result proves that transition flight is a feasible flight, although some undesired response was exhibited during quadrotor deactivation (figure VII). This unsafe response must be dealt with by identifying which motion mode that contribute to such response. The first step to achieve it is by constructing a motion dynamic model of our design to gain more insight to our design's motion characteristics.

However, this result provides preliminary proof for the existence of control solution for transition flight that better control system may be constructed after making some improvements. Since the most critical stage of hybrid UAV flight phase is transition, it should be considered carefully when designing transition algorithm. It also important to prove quadrotor and fixed-wing mode are going well before taking transition test.

## VII. Future Work

The appropriate flight control will be developed and installed to make the UAV fully autonomous. The airframe and systems will be improved to achieve optimal performance [6,7,8,9].

For longer flight endurance, electric-powered propulsion system can be substituted by fuel-engine.

High current during the transition from hover to forward flight when the entire motor are activated causing overheat and may melt the tin-soldered component. This can be solved by add cooling system in UAV. It makes the freestream air to flow inside fuselage where all of the systems are located and finally that air will suck out by the rotation of pusher propulsion system.

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