Abstract—In this paper, we present the design and verification of a hybrid vertical takeoff and landing (VTOL) unmanned aerial vehicles (UAV) of the type named dual-system or extra propulsion VTOL UAV. This paper features the comprehensive system development of such VTOL UAVs from all aspects, including the aircraft design and implementation, onboard devices integration, ground station support, and long distance communication. We proceed with aerodynamic analysis, mechanical design, and controller development. Finally, we verify by experiment that this hybrid VTOL UAV has the desired aerodynamic performance, flight stability, endurance and range. In addition, with the designed flight controller, the VTOL UAV can achieve full autonomous flight in a real outdoor environment. It serves a good platform for future research, such as vision-based precise landing, motion planning and quick 3-D mapping, as well as service applications, such as medicine delivery.

I. INTRODUCTION

During the last decades, unmanned aerial vehicles (UAV) have been widely used in both military and consumer areas such as surveillance, tracking, monitoring and aerial photography. These UAVs are mainly classified into two types: fixed-wing UAVs and rotary-wing UAVs and each type has their own advantages and drawbacks. As for fixed-wing UAVs, they have several features, such as high cruising speed and altitude, high flight efficiency and large cabin, which means they can fulfill many tasks that require the vehicle to carry a heavy payload or achieve long endurance and range. However, fixed-wing UAVs have their limits. A fixed-wing airplane needs a runway or catapult to take off and land, which imposes restrictions on its applications. Rotary-wing UAVs, on the other hand, can take off and land vertically, which makes these vehicles suitable for a wide variety of environments. But rotary-wing vehicles do not have long endurance or range. It is still a challenge to develop a small-scale UAV, which is able to achieve long flight endurance and range and at the same time takes off and lands vertically. Hybrid vertical takeoff and landing (VTOL) UAVs are a suitable solution for this problem; they combine the concepts of fixed-wing and rotary-wing UAVs in a single platform, thus inheriting the advantages of both.

There are several types of hybrid VTOL UAVs, including tail-sitter, tilt-rotors and dual-system UAVs.

*Research supported by Hong Kong ITF Foundation (ITS/334/15FP).
All authors are with the Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong, China. hguad@connect.ust.hk, xlva@connect.ust.hk, eezxli@ust.hk, eeshaojie@ust.hk, eefzhang@ust.hk
as a propeller. In [4], [5] and [6], the structure design, aerodynamic analysis and flight control were addressed. [7] shows another configuration of tilt-rotor, which also called tilt-wing VTOL UAV. The main drawback of a tilt-rotor VTOL UAV is its complicated structure, which increases the aircraft weight and cost.

C. Dual-system VTOL UAVs

A dual-system VTOL UAV has two independent propulsion systems for hover and level flight. As seen in Fig. 2, the aircraft takes off vertically using the lift force generated by the four lifting rotors. During this phase, the push motor will be turned off and the whole aircraft behaves like a quadrotor [8], its position as well as attitude are controlled by the differential thrust of the four rotors. After reaching the desired altitude, the aircraft starts transiting to level flight by turning on the push motor to gain forward speed. Once the cruise speed is reached, the four lifting rotors will be turned off and the whole aircraft behaves like a conventional fixed-wing airplane. The control of the position and attitude is achieved by the push motor and control surfaces such as the ailerons, elevators and rudders. Since the propulsion systems for hover and level flight are independent, they can be optimized for both flight modes separately. Other than motors and propellers, all parts of a dual-system VTOL UAV are assembled rigidly and no moving parts are involved. As a result, they are easy to design, manufacture and maintain.

In this paper, we present the development of a dual-system hybrid VTOL UAV from a holistic system design perspective. The primary goal of the designed aircraft is to deliver a lightweight parcel, such as first aid medicine, at a distance of over 30 km, while maintaining a relative small size for better portability. The designed unmanned aerial system has all the key components for safe and reliable operation, including autonomous navigation, robust flight controller, first-person-view (FPV) camera, long distance communication, ground station, etc. The detailed aerodynamic design, analysis, mechanical consideration and flight controller development are presented. The designed aircraft is shown in Fig. 1. As validated by real flight tests, the developed UAV can achieve the required flight range and fully autonomous operation.

The remainder of this paper is organized as follows. The aerodynamic and mechanical design, as well as onboard devices integration, are detailed in section II. Position controllers, attitude controllers and VTOL mixer are presented in section III. Section IV presents the details of the experiment setup and results discussion. And finally section V draws the conclusion.

II. System Design

A. Airframe and Propulsion System Selection

As mentioned before, the designed aircraft is expected to achieve a flight range of 30 km. For this purpose, a variety of devices need to be used, including video transmitter for aircraft status monitoring, telemetry for long distance data communication, radio control (RC) extender for emergency piloting, etc. Their estimated weights are summarized in table I, where the units are in grams.

<table>
<thead>
<tr>
<th>Device</th>
<th>Quantity</th>
<th>Weight (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video transmitter</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Telemetry</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Battery</td>
<td>1</td>
<td>900</td>
</tr>
<tr>
<td>Flight control board</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Lifting motors</td>
<td>4</td>
<td>70</td>
</tr>
<tr>
<td>ESCs for lifting motor</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Pusher motor</td>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>ESC for push motor</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>Others</td>
<td>N.A.</td>
<td>200</td>
</tr>
<tr>
<td>Total weight</td>
<td>N.A.</td>
<td>1750</td>
</tr>
</tbody>
</table>

The item "Others" includes servo motors, wires, pitot-tube, GPS, etc. The total weight estimated for all of the devices is around 1.75 Kg. In our work, we intend to adopt a commercially available fixed-wing airplane as the starting point to develop a hybrid VTOL UAV due to their proved flight stability and performance. Table II shows the key configurations of a number of commercial-off-the-shell fixed-wing airplanes.

<table>
<thead>
<tr>
<th>UAV</th>
<th>Mini SkyHunter</th>
<th>SkyHunter</th>
<th>Talon</th>
<th>Ranger EX757-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span</td>
<td>1238</td>
<td>1800</td>
<td>1718</td>
<td>1380</td>
</tr>
<tr>
<td>Gross Weight</td>
<td>760</td>
<td>900</td>
<td>1050</td>
<td>750</td>
</tr>
<tr>
<td>MTOW (gram)</td>
<td>2500</td>
<td>3500</td>
<td>3000</td>
<td>1100</td>
</tr>
<tr>
<td>Payload</td>
<td>1740</td>
<td>2100</td>
<td>1950</td>
<td>350</td>
</tr>
</tbody>
</table>

It can be seen that Mini Skyhunter has the smallest size while achieving the required payload capacity. A smaller size

1 The unit of weight is in gram
is preferable so to increase its maneuverability and ease of the flight test. The detailed parameters of such an airplane are summarized in table III, where mean chord, wing area and aspect ratio (AR) are measured on a real airplane. The cruise speed is recommended by the manufacturer. \( e \) is the Oswald efficiency factor which is typically between 0.7 and 0.85 and can be computed from AR [9].

To compute the Reynolds number \( Re \), the commercial software Proli is used. Supplying the airspeed; characteristic linear dimension, which is defined as the mean aerodynamic chord (MAC); and cruise altitude, which is 100 m for our application to the software, yields the Reynolds number \( Re = 2.3 \times 10^6 \).

Lift coefficient \( C_L \) [9] is calculated for level flight where the maximal takeoff weight \( MTOW = 24.5 \text{ N} \) and cruise speed \( V = 15 \text{ m/s} \). As pointed out in [10], the total drag of a typical airplane consists of three parts: parasitic drag \( D_0 \), wave drag \( D_w \) and induced drag \( D_i \). The wave drag occurs when the airplane’s speed is near the speed of sound and can be safely ignored in our case where the flight speed is far from the speed of sound. As shown in [11], the total drag, when parameterized by drag coefficient, can be expressed as

\[
C_D = \frac{S_{wet}}{S} \cdot C_{fe} + \frac{C_L^2}{\pi \cdot AR \cdot e} \tag{1}
\]

where the typical value of \( S_{wet}/S \) for the Mini SkyHunter is around 4, as seen in [12], and the skin friction coefficient \( C_{fe} \) is drawn from [13].

After determining the aerodynamic configuration of the aircraft, we proceed to the propulsion system design. For a hybrid VTOL UAV, there are two sets of propulsion systems, namely the four lifting rotors for takeoff, landing and hover flight, and the push motor for level flight. Table IV summarizes the key parameters of a few motor-propeller pairs specifically designed for multirotors.

It is clear that the thrust produced by the four lifting rotors has to be greater than the force of gravity acting on the vehicle. To keep a sufficient margin for maneuvering, the thrust/gravity ratio is designed to be 1.3. The resulting maximal thrust of each motor is therefore 0.81 kg, making DJI E310 a good choice.

In a similar way, thrust produced by the push motor is designed to be 2 times greater than the drag force in order to gain sufficient maneuverability, such as during acceleration, banking turns, and level flight. That is:

\[
T = 2 \cdot D = 2 \times \frac{1}{2} \rho V^2 S C_D = 2 \times 0.5 \times 1.157 \times 15^2 \times 0.21 \times 0.064 = 3.498N. \tag{2}
\]

With this requirement, we investigate a few motors and propellers designed for fixed-wing airplanes, as summarized in table V. It can be seen that the Sunny Sky X2216 is the right fit for our needs.

### TABLE III
**Detailed Parameters of Mini SkyHunter**

<table>
<thead>
<tr>
<th>Mean Aerodynamic Chord (MAC)</th>
<th>Wing area</th>
<th>Cruise speed</th>
<th>AR</th>
<th>( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 cm</td>
<td>0.21 m²</td>
<td>15 m/s</td>
<td>7.28</td>
<td>0.83</td>
</tr>
<tr>
<td>( \rho ) MTOW</td>
<td>( Re )</td>
<td>( C_L )</td>
<td>( C_D )</td>
<td></td>
</tr>
<tr>
<td>1.157 kg/m³</td>
<td>2500 gram</td>
<td>2.3 \times 10^6</td>
<td>0.896</td>
<td>0.064</td>
</tr>
</tbody>
</table>

To keep a sufficient margin for maneuvering, the thrust/gravity ratio is designed to be 1.3. The resulting maximal thrust of each motor is therefore 0.81 kg, making DJI E310 a good choice.

In a similar way, thrust produced by the push motor is designed to be 2 times greater than the drag force in order to gain sufficient maneuverability, such as during acceleration, banking turns, and level flight. That is:

\[
T = 2 \cdot D = 2 \times \frac{1}{2} \rho V^2 S C_D = 2 \times 0.5 \times 1.157 \times 15^2 \times 0.21 \times 0.064 = 3.498N. \tag{2}
\]

With this requirement, we investigate a few motors and propellers designed for fixed-wing airplanes, as summarized in table V. It can be seen that the Sunny Sky X2216 is the right fit for our needs.

### TABLE V
**Parameters of Motors and Propellers for Fixed-Wing Airplane Models**

<table>
<thead>
<tr>
<th>Name</th>
<th>KV</th>
<th>Thrust (N)</th>
<th>Propeller</th>
<th>Efficiency (g/W)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SunnySky X2826</td>
<td>880</td>
<td>4.9</td>
<td>12 \times 6</td>
<td>0.068</td>
<td>14.8</td>
</tr>
<tr>
<td>SunnySky X2216</td>
<td>880</td>
<td>3.92</td>
<td>10 \times 4.7</td>
<td>0.072</td>
<td>14.8</td>
</tr>
<tr>
<td>SunnySky X2814</td>
<td>900</td>
<td>4.9</td>
<td>11 \times 7</td>
<td>0.070</td>
<td>14.8</td>
</tr>
</tbody>
</table>

### B. Mechanical Design

Even though the main airframe is adopted from a commercial-off-the-shell airplane, the integration of four lifting rotors for vertical takeoff and landing introduce new problems that need to be carefully considered. A major challenge is the structural design and precise landing in
the presence of cross wind. The four lifting motors are located around the fuselage systematically along the X axis and Y axis, as shown in Fig. 3. The vertical tails of the main airframe, primarily designed for enhancing the directional stability of the aircraft during level flight, introduce a considerable aerodynamic moment in the yawing during hover flight in the presence of cross wind. This aerodynamic moment, together with other aerodynamic disturbances from the wing and fuselage, will affect the hover accuracy and landing reliability. In order to mitigate this situation, a large yawing moment that usually exceeds the reaction torque of a typical motor-propeller pair is required. As such, the four lifting motors of the vehicle are inclined along their diagonal lines by a small angle \( \delta \). As shown in Fig. 3, the green circle arrow indicates the direction of the motor reaction torque, and the red arrow represents the inclination direction. With this design, the total moment in yawing is the sum of the torque produced by the motor thrust projected to the body \( X - Y \) plane and the motor reaction torque. In addition, as the motor inclination is along the motor diagonal lines, the torque can be maximized with the same motor thrust and inclination angle.

C. Others

To constitute a comprehensive unmanned aerial system that is able to perform a mission fully autonomously and with the capability of communicating with a ground station in real time to report its flight status, such as air data, position and battery status, as well as for receiving commands from the ground station in case of an emergency or mission re-planning, several onboard devices need to be integrated. After investigating the current commercial-off-the-shelf devices, we have settled on the devices given in Table VI.

As the designed aircraft is expected to achieve a flight distance of 30 km, to support its long distance operation, an automatic antenna tracker (AAT) is used to extend the connection between the aircraft and the ground station. An AAT can track the aircraft using its GPS signal, by way of an antenna installed on the ground station that can always point to the aircraft. By doing so, the data link can be greatly enhanced. Telemetry is used to connect the vehicle and ground station to download flight status and upload commands sent from the ground station in real time. A lightweight first person view (FPV) camera and the associated video transmitter are used to monitor the aircraft’s surrounding environment in real time. A radio extender is used to extend the operation range of the radio controller. The flight controller used is a Pixhawk autopilot open hardware and software platform [14]. The Pixhawk autopilot has integrated the necessary sensors for autonomous navigation, such as a magnetometer for measuring the direction of south, an accelerometer for measuring the direction of gravity, gyros for measuring angular rate and a barometric altimeter for measuring the altitude of the aircraft. With this open source platform, we designed our own flight controller, as discussed in next section, in detail. Other key components such as a pitot-tube, GPS and data transmitter are also used although are not shown in Table VI.

Fig. 4 shows the entire unmanned aerial system that has been implemented. The whole system consists of a ground station, a pilot, and the unmanned aerial vehicle. The ground station is a PC running Q地面control (QGC) [15] software for logging and displaying the aircraft status, an AAT for aircraft tracking and connection enhancement, and an external monitor that displays the onboard FPV video as well as the flight status of the aircraft such as the airspeed, distance, altitude, speed and attitude. A pilot can maneuver the aircraft directly via a radio controller if in manual testing mode, or simply monitor the aircraft status and take over its control in case of emergency if in fully autonomous flight mode.

### III. Flight Control System Design

The block diagram of our flight control system is shown in Fig. 5. It can be seen that the whole flight system consists of three level controllers: position controller, attitude controller, and VTOL mixer.

Comprising the first level are three position controllers: a transition controller, rotary-wing position controller, and fixed-wing position controller, which are running simultaneously. A position controller receives the desired position from
either human pilots or navigation way points and computes the desired attitude and thrust, which are then fed to a signal distribution module. The signal distribution module maps the desired attitude from the transition controller as well as, rotary-wing position controller to the same attitude controller, called the VTOL attitude controller, and maps the attitude from fixed-wing position controller to the corresponding fixed-wing attitude controller. The thrust of the three position controllers are fed to a VTOL mixer for further processing.

The second level controllers are two attitude controllers: a fixed-wing attitude controller and VTOL attitude controller. While the fixed-wing attitude controller directly computes the desired moment from its attitude error, the VTOL attitude controller will use either the transition or rotary-wing position controller attitude set point to compute the desired moment, depending on the current flight mode.

Depending on the current vehicle flight mode (i.e., rotary-wing mode, fixed-wing mode or transition mode), the VTOL mixer chooses different moment and thrust sources and maps them to different actuators. For example, in rotary-wing mode, the moment from the VTOL attitude controller and the thrust from the rotary-wing position controller are used to actuate the four lifting rotors. This results in an aircraft that will behave like a typical quadrotor UAV. In transition flight mode, the moment from the VTOL attitude controller and the thrust from the transition controller are synthesized to actuate the control surfaces such as ailerons, push motor, or the four lifting rotors all together. More specifically, during forward transition from rotary-wing mode to fixed-wing mode, the push motor speeds up to a prescribed RPM to provide forward thrust. Once the prescribed airspeed is reached, the fixed-wing mode will be triggered. During backward transition from fixed-wing mode to rotary-wing mode, the push motor slows down gradually to a stop. At the same time, the lifting rotors are turned on to control the vehicle’s attitude and altitude. Similarly, once the vehicle’s airspeed drops below some prescribed value, the rotary-wing mode will be triggered. Finally, in fixed-wing mode, moment from fixed-wing attitude controller and thrust from the fixed-wing position controller are used to actuate the control surfaces and push motor like a conventional fixed-wing airplane.

A. Position and Attitude Controller Implementation

In our scenario, the position controller including fixed-wing position controller, rotary-wing position controller, and transition controller. The fixed-wing position controller is adopted from [16] and the rotary-wing position controller from [17]. The transition controller will be presented in section III-B. The fixed-wing attitude controller is a PID controller adopted from [18]. The VTOL attitude controller is a cascaded controller similar to [1]. These controllers are all implemented on the existing framework of the Pixhawk autopilot software stack [18].

B. Transition Controller

Here we focus on introducing the transition controller. The key features of the transition controller in Fig. 5 are sending fixed attitude command, the pitch and roll commands are both set to 0, while the yaw is set to its current value at the beginning of transition. The push motor is set to its maximum power until the specified airspeed is reached.

The thrust command is determined by an altitude holding controller, which is used to hold the aircraft altitude at the value right before the transition. Recall that the rigid body altitude dynamic can be written as

\[
\ddot{h} = \frac{1}{m} \begin{bmatrix} r^T_3 (F_{aero} + F_T) + g \end{bmatrix}
\]

where \( r_3 \) denotes the third column of the rotation matrix \( R \in SO(3) \), which is the orientation of the body frame relative to the inertial frame (seen in Fig. 1), \( h_z \) is the altitude in the inertial frame, \( F_{aero} \in \mathbb{R}^3 \) and \( F_T = \begin{bmatrix} F_{Tx} & F_{Ty} & F_{Tz} \end{bmatrix}^T \in \mathbb{R}^3 \) are the aerodynamic force and motor thrust vector in body frame, respectively.

The reference altitude is described as \( h_d \), and the altitude error is described as \( h_e = h_d - h_z \). A simple altitude PID controller is used to calculate motor thrust as follows:

\[
r_3^T F_T + mg = k_p h_e + k_i \int h_e dt + k_d \frac{dh_e}{dt}
\]

The resulting thrust can be finally described as

\[
F_{Tz} = \frac{k_p h_e + k_i \int h_e dt + k_d \frac{dh_e}{dt} - mg \cdot r_{31}}{r_{31}}
\]

where \( r_{31} \) is the first entry of \( r_3 \in \mathbb{R}^3 \). It is worth noticing that the aerodynamic force \( F_{aero} \), though neglected in the controller design, can be compensated effectively by the integral action. The computed thrust and attitude commands are sent to both VTOL and fixed-wing attitude controller for moment computation. A VTOL Mixer, as discussed below, is finally used to distribute the required moment and thrust to proper actuators (i.e., control surfaces and lifting motors) depending on the current airspeed during transition.
where \( S \) is the total area including tails, \( \bar{c} \) is the mean aerodynamic chord (MAC), \( C_{m_0} \) is the pitch moment coefficient when \( \alpha = 0 \) and \( \delta_i = 0 \). \( C_{m_{\alpha}} \) and \( C_{m_{\delta}} \) are, respectively, the pitch moment derivatives with respect to attack angle and elevator deflection. As no rudder is used for this aircraft, the moment produced by all control surfaces can be further written as

\[
\begin{bmatrix}
\frac{2M_{Tz}}{\rho V^2 S_1 (1 + C_{L_{1a}})} & 1 & -1 & 0 & \delta_1 \\
\frac{2M_{Ty}}{\rho V^2 S C_{m_{\delta}}} & 0 & 0 & -1 & \delta_2 \\
\end{bmatrix}
\]

\[
\delta_1 = \delta_2, \tag{8}
\]

where \( \alpha_1 \) and \( \alpha_2 \) are two different first order functions that relate to airspeed. The moment and thrust produced by the four lifting rotors can be represented as:

\[
\begin{bmatrix}
\frac{F_{z_{\alpha_i}}}{M_{rz}} \\
\frac{F_{y_{\alpha_i}}}{M_{ry}} \\
\frac{2M_{T_{\alpha_i}}}{\rho V^2 S_1 (1 + C_{L_{1a}})} \cos(\delta) \sin(\delta) \sin(\chi) + \frac{M_{T_{\alpha_i}}}{M_{T_{\gamma}}} \cos(\delta) d - \kappa \sin(\delta) \cos(\chi) \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 & 1 & T_1 \\
-1 & 1 & -1 & -1 & T_2 \\
-1 & 1 & 1 & -1 & T_3 \\
-1 & 1 & 1 & -1 & T_4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{F_{z_{\alpha_i}}}{M_{rz}} \\
\frac{F_{y_{\alpha_i}}}{M_{ry}} \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{2M_{T_{\alpha_i}}}{\rho V^2 S_1 (1 + C_{L_{1a}})} \cos(\delta) \sin(\delta) \sin(\chi) + \frac{M_{T_{\alpha_i}}}{M_{T_{\gamma}}} \cos(\delta) d - \kappa \sin(\delta) \cos(\chi) \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 & 1 & T_1 \\
-1 & 1 & -1 & -1 & T_2 \\
-1 & 1 & 1 & -1 & T_3 \\
-1 & 1 & 1 & -1 & T_4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{F_{z_{\alpha_i}}}{M_{rz}} \\
\frac{F_{y_{\alpha_i}}}{M_{ry}} \\
\end{bmatrix}
\begin{bmatrix}
\frac{2M_{T_{\alpha_i}}}{\rho V^2 S_1 (1 + C_{L_{1a}})} \cos(\delta) \sin(\delta) \sin(\chi) + \frac{M_{T_{\alpha_i}}}{M_{T_{\gamma}}} \cos(\delta) d - \kappa \sin(\delta) \cos(\chi) \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 & 1 & T_1 \\
-1 & 1 & -1 & -1 & T_2 \\
-1 & 1 & 1 & -1 & T_3 \\
-1 & 1 & 1 & -1 & T_4 \\
\end{bmatrix}
\]

\[
\frac{T_{i, \alpha_i}}{T_{i, \gamma}} = \frac{c_{t_{\alpha_i}}}{c_{t_{\gamma}}}, \quad (i = 1, 2, 3, 4). \tag{11}
\]

where \( d \) is the length of each motor to the aircraft center of mass, as seen in Fig. 6 and \( \chi \) is the azimuthal angle of the first rotor with respect to the lateral axis of the aircraft. \( \delta \) is the inclination angle of the four lifting rotors, as presented in the previous section. \( T_{i, \alpha_i} \) is the rotor thrust and \( \omega_i \) is the rotation speed of each rotor \((i = 1, 2, 3, 4)\). \( c_{t_{\alpha_i}} \) and \( c_{t_{\gamma}} \) are the propeller thrust coefficient and propeller torque coefficient, respectively. \( \kappa \) is the ratio of torque to thrust coefficient.

It can be seen that the roll and pitch moment can be produced by either control surfaces, as shown in Eq. (8) or by motor differential thrust, as shown in Eq. (9). In our implementation, we assign a weighting factor \( \alpha \) to weight the contribution of the moment from the control surface and the motor differential thrust. That is, given the required roll moment \( L \), the moment from the control surface and the motor differential thrust are, respectively, \((1 - \alpha)L\) and \(\alpha L\). The way to allocate pitch moment is similar. The weighting factor \( \alpha \) is in between zero and one, depending on the
current flight mode. In fixed-wing mode, \( \alpha = 0 \), and the required moments are solely generated by control surfaces, the actuation signal of which are computed by inverting Eq. (8). Accordingly, the required thrust is mapped to the push motor. In rotary-wing mode, \( \alpha = 1 \), the required moment as well as thrust are solely generated by the four lifting rotors, the actuation signals of which are computed by inverting Eq. (9). In transition flight, the required moments are generated by the control surface with portion \( 1 - \alpha \) and by motor differential thrust with portion \( \alpha \). \( \alpha = 1 - (0.6 \frac{V}{V_T} + 0.2) \) is a function of airspeed \( V \), indicating that the effectiveness of the control surfaces increases as the airspeed \( V \) increases. \( V_T \) is a barrier speed that the aircraft has to exceed in order to switch to full fixed-wing mode. The total thrust produced by the four lifting rotors is computed from the altitude holding controller presented previously, while the push motor is set to a prescribed PWM to accelerate the aircraft in a horizontal direction. In practice, the parameters in Eq. (8) and Eq. (9) are not known, resulting a gain mismatch when inverting these two equations. By properly tuning the parameters of the flight controllers, these gain mismatches can be effectively mitigated, as shown in real flight tests.

IV. EXPERIMENTS

With the designed dual-system VTOL UAV along with its flight control system, intensive experiments are conducted to verify its aerodynamic performance, flight stability and system level autonomy. The first experiment is designed to verify the reliability of transition controller, the second experiment is to test the flight controller’s stability when the aircraft is under active pilot control, the third experiment is to test its range, endurance and the capacity of autonomous flight, and the fourth experiment is to determine the optimal flight speed.

A. Transition controller verification

Since the transition is a necessary maneuver of the hybrid VTOL UAV to achieve both vertical takeoff and level flight, we designed an experiment to verify the reliability of the transition controller presented in previous sections. The procedure of this experiment is as follows: the aircraft first takes off in manual mode. After reaching the desired altitude, the aircraft was switched to autonomous flight mode, where the quadrotor position controller took place and controlled the aircraft to a transition point. Once the transition point is reached, the aircraft initiated a transition maneuver and subsequently flew as a fixed-wing airplane.

Fig. 7 and 8 show the transition process. The upper figure in Fig. 7 indicates the flight states where 0 means quadrotor mode, 1 means transition mode and 2 means fixed wing flight mode. As mentioned in previous sections, after the transition maneuver is initiated, the push motor PWM increases linearly until the maximal value is reached, resulting an increased airspeed. During the transition process, the altitude increased by 1m due to the increased aerodynamic lift. After the airspeed reached the specified value, the flight state switched to fixed wing mode, and the push motor is controlled by a typical fixed-wing flight controller. Fig. 8 shows attitude response during the transition. It is worth noticing that the roll and yaw angles are set to relative large values after the transition due to the bank turn maneuvering. This results a slight altitude loss (i.e. 2m) and attitude error, which are caused by the low bandwidth of a typical fixed-wing controller. These errors, in practice, are acceptable in our outdoor environment.
B. Manual Flight Test

As the whole vehicle is a new system whose aerodynamic performance, robustness and system reliability remain to be verified, we designed a manual flight experiment for the purpose of determining the minimal airspeed, verifying the position controller and each chosen component of the whole systems such as video transmitter, telemetry, and AAT.

This experiment is designed as follows: First, the hybrid VTOL UAV takes off vertically in manual mode and lifts up to about 50 m. Then, the test pilot triggers a switch command to level flight mode. After the vehicle has fully transited to the fixed-wing mode, the test pilot will control the aircraft such that it can approximately track a circle. Finally, the hybrid VTOL UAV is switched to quadrotor mode and is landed.

The data log for circling flight is shown in Fig. 9, Fig. 10 and Fig. 11. The upper figure in Fig. 9 shows the altitude response. It can be seen that the actual altitude is well regulated around the desired value, with about 2.6 m peak to peak oscillation. This oscillation, in the same period of the flight trajectory, is caused by cross wind and lead to a similar oscillation in airspeed, as shown in the lower plot in Fig. 9. Fig. 10 shows the roll, pitch and yaw angle of the aircraft in manual mode where the attitude angle is directly controlled by pilot. Due to the presence of cross wind, the aircraft slowly drifts from its initial trajectory, the pilot thus intentionally adjusted roll angles respectively at 1 min, 1.2 min and 2 min to maintain its trajectory within the proper area. The resulting trajectory is shown in Fig. 11.

C. Fully Autonomous Flight and Flight Range Verification

As pointed out in section I, our primary goal is to develop a UAV which can take-off and land vertically and achieve a 30 km range in a fully autonomous way. Thus, this experiment is designed to verify whether our UAV can achieve this goal.

Due to the limited flight test area, we cannot let the vehicle fly straight forward for 30-kilometers. The compromised solution is to follow a circle trajectory and calculate the distance by airspeed and endurance time. In this experiment, we set the airspeed as 18 m/s (64.8 km/h). Then a minimal flight endurance of 27.78 min is required to meet 30 km of range. To verify this, a fully autonomous flight is performed on our unmanned aerial system, including auto take-off, transition and level flight.

The log data is shown in Fig. 12, Fig. 14, Fig. 13 and Fig. 15. In Fig. 12, the upper plot shows the aircraft airspeed, which oscillates in the same period of flight trajectory due to the presence of cross wind. This results an oscillation in current measurement (middle plot of Fig. 12), roll angle (upper plot of Fig. 13) and pitch angle (middle plot of Fig. 13). Moreover, it is seen that our vehicle can fly 32 min, satisfying the required endurance (i.e. 27.78 min).

Fig. 11. Trajectory of manual flight test
oscillating, which is, again, caused by the cross wind and in the same period of flight trajectory. Fig. 15 shows the resulting trajectory.

D. Optimal Flight Speed

Although the autonomous flight test presented above has already realized our goal, the range and endurance of the designed aircraft can be further improved by observing the following:

- From Fig. 13 we can know that in the flight range test, the vehicle has a constant banking angle of about 33.7 deg. This means that only 100% \cdot \cos 33.7^\circ = 83.2\% aerodynamic lift has been used to counterweigh the aircraft’s force of gravity. The flight range for straight level flight will be 1.2 times more.
- As we know, flight speed is crucial in determining the flight efficiency. As for our VTOL, 18 m/s may not be the optimal flight speed. Consequently, it is possible to extend the flight range if the aircraft flies at an optimal speed.

To find the optimal flight speed, another experiment is conducted. Similar to the second experiment, the aircraft is set to loiter around a specified point at different test speeds. Figure 16 shows the current of each case which oscillated due to disturbance. The average current and voltage are summarized in table VII.
The expected range can be predicted by

\[ R = \frac{t \cdot V}{I} = \frac{C}{I} \cdot \frac{V}{I} = \frac{V}{T} \cdot C. \]  

(12)

where \( R \) is the flight range, \( t \) is endurance time, \( C \) is battery capacity and \( I \) is the current drained from the battery. By assuming that the battery capacity \( C \) is constant, the flight range is proportional to the ratio of airspeed \( V \) to current \( I \). As seen in table VII, the ratio \( V/I \) is maximal when the flight speed is set at 17 m/s, the corresponding flight range will be \( \frac{2.97}{2.54} = 1.17 \) higher than the case where \( V = 18 \text{ m/s} \). Therefore, the flight range our aircraft can achieve is expected to be \( 1.2 \times 1.17 \times 30 \text{ km} = 42 \text{ km} \).

V. CONCLUSION AND FUTURE WORK

In this study, a hybrid VTOL UAV was developed and tested. The design requirement was achieving a flight range of 30 km. The work is based on a mini SkyHunter due to its size and payload capacity. On the basis of theoretical calculation, selection of the propulsion system and mechanical design proceeded. A flight control system was designed to realize transition, improve flight stability and achieve full autonomous flight. The designed flight control system consists of VTOL attitude controller, transition controller and VTOL mixer based on our special aerodynamic characteristics and mechanical design. Finally, experiments were designed to determine the aerodynamic performance, verify the controller’s stability and autonomy. As shown by these experiments, this prototype can meet the initial design goal.

In the future, we will optimize this prototype, in terms of aerodynamics design and controller improvement. Actual long distance experiments will be conducted to verify the range of the communication devices. Based on this hybrid VTOL UAV, several topics, such as precise landing, motion planning, and 3-D mapping will be investigated.

REFERENCES


