Design and control of an unmanned aerial vehicle for autonomous parcel delivery with transition from vertical take-off to forward flight

VertiKUL, a quadcopter tailsitter

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Abstract—This paper presents the design and control of VertiKUL, a Vertical Take-Off and Landing (VTOL) transitioning tailsitter Unmanned Aerial Vehicle (UAV), capable of hover flight and forward flight for the application of parcel delivery. Autonomous parcel delivery by air is proven technically feasible, reduces traffic congestion, delivery time and delivery cost. In contrast to existing transitioning UAVs, VertiKUL is not controlled by control surfaces, but exclusively by four propellers using differential thrust during hover flight, transition and forward flight. A numerical design method optimising range and payload is developed for initial sizing. A dynamic model is implemented in Simulink to evaluate different control strategies before conducting test flights. A unique mid-level control strategy enabling intuitive control of VertiKUL which requires no pilot skills is developed. Fluent transition from hover to forward flight is achieved through an autonomous control strategy. Attitude control based on quaternions instead of Euler-angles is implemented to avoid singularities. A high-level control system exclusively using GPS waypoints as input is developed enabling fully autonomous parcel delivery. The resulting design, VertiKUL, is built and tested.

Index Terms—VTOL, hybrid UAV, transition, parcel delivery, tailsitter, numerical design optimisation, autonomous navigation

1 INTRODUCTION

The past years UAVs have known an increase in interest and availability. They are widely used in civil applications and areas such as agricultural observation and aerial photography. Another interesting application is parcel delivery by air. For this purpose VertiKUL is designed. Figure 1 shows VertiKUL in hover flight. Its main design feature is the capability of transitioning from hover flight to forward flight. Manoeuvrability of a quadcopter and efficient forward flight of a conventional airplane are combined into one hybrid UAV. This is necessary for parcel delivery applications, where long distances are covered and tight landing spots are present. A high-level control system is designed to accommodate automated parcel delivery. For intuitive manual control of VertiKUL, a unique control strategy requiring no flying skills from the user is developed. In this thesis only technical aspects were considered, however economical and political considerations should still be investigated.

Figure 1: VertiKUL UAV during hover flight.
There are several ways to perform transitioning manoeuvres: thrust-vectoring, tilting-rotor, tilting-wing, etc. The most famous transitioning manned vehicles using thrust-vectoring and tilting-rotor are Harrier and V-22 Osprey respectively. Examples of unmanned tilt-rotor vehicles are Wingcopter and FireFLY6. These concepts involve significant extra mechanical complexity which increases cost, maintenance and risk of failure. The explicit choice is made to avoid the use of such tilting mechanisms. This means VertiKUL purely relies on differential thrust created by the four propellers to perform a transition and to control the UAV in both hover and forward flight. This concept can be regarded as tilting-body. Other examples of unmanned vehicles that transition using differential thrust only are Quadshot and ATMOS UAV (prototype). However, these UAVs still have tilting rotors or actuated control surfaces to control the vehicle in level flight. With respect to the absence of additional actuators few similar projects were found in literature.

The design of VertiKUL consist of a conceptual phase, in which different configurations are compared, and a numerical optimization design strategy for initial sizing. The final sizing and performance estimates are given in section 5. In section 3 a dynamical model of VertiKUL is derived. This model is implemented in Simulink. Using Simulink, a control strategy is developed and tested in simulation flights. The control of VertiKUL consists of a low-level, a mid-level and high-level controller which provide respectively acrobatic, intuitive and autonomous flight capabilities. The control strategy is explained in section 4. Section 5 presents the realization of VertiKUL. Based on test flights with different prototypes the design and control strategy are evaluated.

2 DESIGN OF VertiKUL VTOL UAV

VertiKUL has a unique fixed wing quadcopter hybrid design, capable of both VTOL and efficient forward flight. The design has the major innovation of having no additional control surfaces for attitude control and stability. This greatly reduces cost, maintenance and risk of failure. VertiKUL is capable of transporting a payload up to 1 kg and is optimised for range. The overall design process of VertiKUL is shown in figure 2. First, a configuration best meeting the requirements is designed. Next, initial sizing is done using a numerical approach optimising the range. After analysing, the proposed solution is designed in detail. Finally, tests with several prototypes are done to confirm the analyses and design.

2.1 Configuration

VertiKUL has a fixed low wing configuration. Four fixed-pitch propellers provide lift during hover flight and thrust during level flight. They also provide attitude control by exerting moments on the frame using differential thrust. The payload is placed at the centre of gravity of VertiKUL to ensure the same flight characteristics for all payload masses.

![Figure 2: VertiKUL design process.](image-url)
Figure 3: VertiKUL design features.

Figure 3 shows the following design features:
- Fixed low wing tail sitter design
- Passive wing without control surfaces reducing complexity
- Four fixed-pitch propellers
- High capacity rechargeable lithium polymer batteries for long range
- Rear-end opening for payload insertion
- Winglets for directional stability and reduced drag during forward flight

2.2 Numerical design optimisation

In the numerical design optimisation, range is maximized with given constraints. The range of an electric propeller-driven aircraft can be expressed as:

\[
R = \frac{k \cdot m_{\text{bat}}}{g} \frac{C_L}{C_D} \cdot \eta_{\text{propulsion}} \cdot \text{technology level} \tag{1}
\]

- \( k \): gravimetric energy density battery [J/kg]
- \( m_{\text{bat}} \): mass fraction battery [-]
- \( C_L/C_D \): aerodynamic efficiency [-]
- \( \eta_{\text{propulsion}} \): propulsion group efficiency (ESC, motor, propeller) [-]

VertiKUL was designed following a numerical method written in Matlab. The proposed method combines models and databases of components and selects the best solution taking all constraints into account. Figure 4 shows the general design approach. The filtered solution set is shown in figure 5. The best solution for 1 kg payload forms the starting point for the detailed design of VertiKUL which is described in section 5.

Figure 5: Filtered solution set showing the best solutions for different payloads.
3 MODELLING AND SIMULATION

Figure 6 shows two reference frames to represent the attitude of VertiKUL. A first frame \( F_{\text{quad}}(E_x^q, E_y^q, E_z^q) \) is used to represent the UAV in quadcopter mode, when it’s in the hovering flight regime. A second frame \( F_{\text{plane}}(E_x^p, E_y^p, E_z^p) \) is used to represent the UAV in plane mode, when it’s in the forward flight regime. This way it is possible to think intuitively about VertiKUL’s attitude, i.e. roll, pitch and yaw, while in quadcopter mode as well as in plane mode. The origin of both frames coincides with the centre of gravity of VertiKUL. The attitude expressed in \( F_{\text{quad}} \) is represented by the Euler angles roll \( \phi_q \), pitch \( \theta_q \) and yaw \( \psi_q \). Expressed in \( F_{\text{plane}} \) the attitude is represented by \( \phi_p \), \( \theta_p \) and \( \psi_p \).

3.1 General Equations of Motion

The general equations of motion expressed in the quadcopter body frame \( F_{\text{quad}} \) are obtained based on Newton Euler formalism. They are presented mathematically in equation 2.

\[
\begin{bmatrix}
    m \ddot{q} \\
    0 \\
    q \dddot{\omega}
\end{bmatrix} +
\begin{bmatrix}
    q \dddot{\omega} \times m q \ddot{\omega} \\
    q \dddot{\omega} \times q \dddot{\omega}
\end{bmatrix} =
\begin{bmatrix}
    \sum q \dddot{F} \\
    \sum q \dddot{M}
\end{bmatrix}
\]

where \( q \ddot{\omega} \) and \( q \dddot{\omega} \) are the linear and angular velocities respectively. The external forces and moments are represented by \( q \dddot{F} \) and \( q \dddot{M} \). Index ‘q’ is used to indicate vectors are expressed in quadcopter body coordinates. External forces consist of gravity, aerodynamic and thrust forces. Similarly, external moments consist of aerodynamic and differential thrust moments.

Matrix equation 2 includes the translational and rotational equations of motion which are presented by equation 3 and 4 respectively.

\[
m_{\text{tot}} q \ddot{\omega} = -q \dddot{\omega} \times m q \ddot{\omega} + q \dddot{\omega} + q \dddot{L}_{\text{wing}} + q \dddot{D}_{\text{prop,gyro}} + q \dddot{M}_{\text{drag}} + q \dddot{M}_{\text{winglet}} + q \dddot{M}_{\psi}
\]

where \( m_{\text{tot}} \) includes 1.6 kg battery mass and 1 kg payload. Gravity and collective thrust are defined using \( q \dddot{\omega} \) and \( q \dddot{T}_{\text{total}} \). Aerodynamic forces included in this model are lift and drag. Lift is represented by \( q \dddot{L}_{\text{wing}} \) and drag consists of wing drag \( q \dddot{D}_{\text{wing}} \) and body drag \( q \dddot{D}_{\text{body}} \). The lift and drag coefficients of the wing are estimated using Xfoil. The linear drag coefficient is determined experimentally. \( q \dddot{I} \) is the inertia matrix of VertiKUL with respect to its centre of gravity expressed in \( F_{\text{quad}} \). It is assumed the axes of \( F_{\text{quad}} \) are principal axes such that \( q \dddot{I} \) is a diagonal matrix with elements \( I_{xx}, I_{yy} \) and \( I_{zz} \). Angular body drag is represented by \( q \dddot{M}_{\text{drag}} \) and \( q \dddot{M}_{\text{prop,gyro}} \) denotes the propeller gyroscopic effect. Other angular aerodynamic effects included in this model are wing moment \( q \dddot{M}_{\text{winglet}} \), stabilizing moment \( q \dddot{M}_{\text{winglet}} \) due to the winglets and rolling moment \( q \dddot{M}_{\psi} \) due to small differences in lift and drag between the left and right wing. \( q \dddot{M}_{\theta} \), \( q \dddot{M}_{\psi} \) denote roll moment, pitch moment and yaw moment created by differential thrust of the propellers.
3.2 Propeller dynamics

In the simulation program a lag in collective and differential thrust is added to incorporate the effect of propeller inertia. This lag is represented by a first-order system with time constant $\tau$.

3.3 Quaternion representation

Although Euler angles provide an intuitive way to represent VertiKUL’s attitude it suffers from singularities at a pitch angle of $90^\circ$ or $-90^\circ$. Because in forward flight attitude control is done close to such a singularity ($\theta_q = -90^\circ$) the quaternion attitude representation is introduced. A quaternion is a set of four parameters and offers a singularity free mathematical representation of the attitude.

3.4 Simulation

The dynamical model is implemented in a Simulink simulation program to be able to test control strategies with a virtual UAV in simulation flights. Figure 7 shows the main components of the simulation program. The first two blocks represent the control which consists of a reference builder and a controller. The reference builder generates reference signals out of the user’s joystick input. Depending on the control mode the controller regulates the angular rates in low-level control, heading and altitude in mid-level control and finally position in high-level control. The third block represents the dynamic model and simulates the position and attitude at every time step. The forth block visualises the virtual UAV in a 3D environment using ‘Simulink 3D Animation’.

4 Control

VertiKUL can be controlled in a low-level, mid-level or high level mode which provide acrobatic, intuitive and autonomous flight capabilities respectively. As can be seen in figure 7, each mode has its own reference generator which translates user input into reference signals and controller. The reference generator and controller are designed using the Simulink program and are implemented on a Pixhawk autopilot to control VertiKUL. The developed Pixhawk’s firmware is based on ArduCopter source code and is called ArduVTOL. Figure 8 presents a diagram of the complete high-level control mode and shows how the high-level controller is built from the mid-level and low-level controller.

4.1 Low-level Control Mode

In low-level control mode the transmitter’s channels correspond to desired collective thrust $T$, roll rate $\dot{\phi}_d$, pitch rate $\dot{\theta}_d$ and yaw rate $\dot{\psi}_d$. The low-level controller consists of three separate PID-controllers that translates desired angular rates into actuator moments that need to be invoked by the propellers through differential thrust. Only experienced UAV pilots can fly in this low-level control mode.

4.2 Mid-level Control Mode

Because piloting VertiKUL in low-level mode requires a lot of practice a unique mid-level control mode is developed such that any user without experience can pilot VertiKUL safely and intuitively. A distinction is made between two flight modes. Quadcopter mode corresponds to VertiKUL hovering like a conventional quadcopter and plane mode corresponds to the forward flight regime. In mid-level control mode a smooth transition from hover to forward flight or back is commanded by a switch. During a transition to forward flight the control system ignores pilot input and decreases pitch gradually until the stall speed has been exceeded and optimal angle of attack has been reached. Transition back to hover can be performed faster because no forward speed needs to be built up.
In quadcopter mode the transmitter’s channels correspond to desired climb rate $\dot{h}_d$, roll angle $\phi_d$, pitch angle $\theta_d$ and yaw rate $\psi_d$. Desired altitude $h_d$ and yaw angle $\psi_d$ are obtained by integrating the desired climb rate and yaw rate input respectively. This way drift on altitude can be compensated and heading can be maintained, i.e. heading-lock. The altitude controller converts an altitude error into a supplementary climb rate which is added to the user’s commanded climb rate $\dot{h}_d$. This combined reference climb rate is converted into a reference climb acceleration which is regulated by a PI-controller that outputs a desired collective thrust. A feedforward term equal to VertiKUL’s weight is added.

In plane mode only two transmitter channels are used to command climb and turning rate. Desired yaw angle $\psi_d$ and altitude $h_d$ are again obtained by integrating the their rates. With both transmitter sticks centred VertiKUL will maintain altitude and heading autonomously. Forward speed is not regulated. Two altitude control approaches are presented.

4.2.1 Thrust altitude control

A first approach uses the same controller as in quadcopter mode but with PI-gains optimized for forward flight. Also a feedforward term equal to steady-state thrust in forward flight or climb is added. This term is estimated from static equilibrium. Reference pitch, expressed in $\mathcal{F}_{\text{plane}}$, equals optimal angle of attack minus rigging angle and plus climb angle. The advantage of this strategy is that optimal angle of attack will always be maintained. This means that even with a different mass VertiKUL will fly most efficiently. A disadvantage are the possible variations in collective thrust. Also, during descend the thrust can drop significantly which reduces the angular controllability by differential thrust. Furthermore, when angle of attack becomes negative, thrust will amplify an altitude error instead of reducing it.

4.2.2 Pitch altitude control

In a second approach a PI-controller regulates the combined reference climb rate and outputs a reference pitch. This pitch is supplemented with the same feedforward as in the first approach. Thrust is now solely determined by the feedforward added in the first approach. This strategy ensures a smooth collective thrust output. Another advantage is that when losing altitude the pitch will be commanded to rise and VertiKUL approaches a safe hover regime where collective thrust will be able to compensate gravity. One disadvantage is that optimal angle of attack is not always ensured, especially not with changing weight. However, weight can be estimated during hover flight to optimize the feedforward terms.
\(\phi_d, \theta_d\) and \(\psi_d\) are regulated by a quaternion-based attitude controller which outputs reference angular rates expressed in \(F_{\text{plane}}\). Experimental evaluation of the mid-level control mode, using thrust altitude control, is presented in section 5.3.

### 4.3 High-level Control

A high-level control mode is designed to deliver packages fully autonomously. Instead of using a transmitter to control VertiKUL directly, waypoints are programmed into a mission plan. As can be seen in figure 8, a mission plan consists of a ‘take-off’ command, waypoints and a ‘land’ command. A mission scheduler provides the waypoint coordinates to the high-level controller at appropriate times. The navigation controller translates target coordinates (longitude, latitude and altitude) into reference signals sent to the mid-level controller and replaces the user’s input in the mid-level control mode. Based on the distance between current location and commanded waypoint the navigation controller uses three control strategies to guide VertiKUL to the waypoint.

#### 4.3.1 Forward flight navigation

When the distance to the waypoint is greater than 100 m a transition to forward flight is commanded. Altitude is regulated to match the desired altitude. Desired heading is calculated from the difference in longitude and latitude coordinates of desired and current position.

#### 4.3.2 Hover flight navigation

When the distance to the waypoint drops below 100 m, transition back to hover flight is commanded. A desired forward speed is proportional to the distance to the target and regulated using a PD-controller which outputs a desired pitch angle. Desired roll angle is kept zero. Desired yaw is calculated the same way as during forward flight navigation.

#### 4.3.3 Precision navigation

When the distance to the waypoint is smaller than 20 m desired yaw is kept constant. Roll and pitch are commanded separately to minimize the distance to the waypoint along the transverse- and longitudinal-axis of \(F_{\text{quad}}\) respectively.

Only discrete information on target position is used to navigate to the waypoints. The result of a simulation test flight in high-level control mode is shown in figure 9. Here the virtual UAV takes off to an altitude of 10 m. The navigation controller then receives a target waypoint of 500 m longitude and 1000 m latitude. A transition is initiated and after the transition the heading is changed. The target altitude is changed during flight. Changes to hover flight navigation and precision navigation are also indicated. Finally the virtual UAV lands.

![Figure 9: Simulation of high-level control.](image)

### 5 Realisation and testing

The design of a non-conventional aircraft requires a trail-and-error approach where functionality increases with every iteration. It is after all not possible to base the design on already existing aircraft. Therefore, six fully functional prototypes are built and tested (figure 10). Based on the result of the numerical design optimisation approach described in section 2 the final VertiKUL prototype is built. Table 1 shows its design parameters and performance.

#### 5.1 Stability

For VertiKUL to be longitudinally stable, the centre of gravity lies with a distance of 5\% of the mean aerodynamic chord in front of the aerodynamic centre. Figure 11 shows the internal component arrangement.
Winglets and wing sweep are added for directional stability. For structural reasons, the wing has no dihedral. However, winglet dihedral is used to accommodate for roll stability. As can be seen in figure 10, VertiKUL has inclined propellers. Thus sacrificing thrust but gaining sideways force for better yaw control.

5.2 General structure

Mainly carbon rods are used in the wing and fuselage for strength. A laser-cut multiplex structure is built around the carbon frame for payload and avionics support. The hull is made out of kraft paper reinforced polystyrene, cut with hot wire. A strong yet light sandwich structure from polystyrene and balsa wood is used for the wing and stabilisers.

5.3 Test flights

To validate the mid-level controller, ArduVTOL source code is tested and evaluated with prototypes X2000 and X3000.

5.3.1 Transition flight

Figure 13 shows commanded and measured pitch angle, GPS ground speed and commanded and measured altitude during the test flight. During transition, angle of attack decreases gradually until a pitch set point is reached and forward speed increases while keeping altitude constant. During forward, climbing and descending flight altitude is regulated with thrust. While climbing with a constant climb rate, pitch angle increases. Transition to hover occurs fast and with little overshoot in pitch angle. Figure 12 shows VertiKUL during transition.

Figure 10: The different prototypes built during the thesis.

Figure 11: VertiKUL internal component arrangement.

Figure 12: VertiKUL during transition.
5.3.2 Turning flight

Figure 14 shows the 3D circular flight path. A clockwise 360° turn is done in mid-level control mode. Altitude and turning rate stay constant through differential thrust regulation as can be seen in figure 15. Because no GPS signal was used for control, wind caused drifting. The end point of the circle therefore shifted relative to the starting point in the direction of the wind.
6 CONCLUSIONS AND FUTURE WORK

In this paper the design and control of VertiKUL was described. For initial sizing of VertiKUL, a numerical design approach optimising range was developed. In the dynamic model only the relevant aerodynamic effects were considered. However, estimating realistic aerodynamic coefficients proved to be difficult. Two control strategies for altitude regulation in mid-level control mode were proposed. By regulating the altitude with pitch angle, a smooth thrust output is ensured. Also, when losing altitude the pitch will be commanded to rise and VertiKUL approaches a safer hover regime. However, only test flights using the thrust strategy were conducted up till now. Sufficient duration of transition appeared to be necessary to ensure stall speed is exceeded. Six fully functional prototypes were built and successful transitional flight was achieved. It was possible to perform transition and forward flight without using additional actuators and control surfaces. Intuitive mid-level control was demonstrated with autonomous transitional, turning, climbing and descending flight. In test flights, wind gusts turned out to have a big influence on hover stability. To overcome this problem, heading lock in quadcopter mode was relaxed and propellers were inclined for better yaw control.

This paper proved the technical feasibility of parcel delivery by air. However, other fields still need to be investigated. Most important are obstacle avoidance, public safety regulations, political and economical aspects. Also technical improvements can be made. The numerical design program can be expanded for more general configurations and with updated component models. Also, it would be interesting to replace the simulation model in Simulink by a more advanced flight simulator, for example X-Plane. CFD analysis and wind tunnel tests can be done for a more precise estimation of the aerodynamic coefficients. To evaluate control strategies, test flights were performed at high angle of attack. However, to evaluate forward flight efficiency, tests at optimal angle of attack should still be done. Also, pitch-regulated altitude control still needs to be evaluated in test flights. The stability advantage of a reflex profile should be re-evaluated because they suffer from low $C_{L,max}$ values. Lower stall speeds can be obtained with non-reflex profiles, making transition possible at lower speeds. Also, the use of multi-blade propellers should be investigated because propeller diameter is restricted by VertiKUL’s configuration type. To reduce wind disturbances in hover flight, wing area can be reduced when using part of the propeller thrust for lift during forward flight.