DESIGN, DEVELOPMENT, AND TUNING OF A GIMBALED COAXIAL UAV

A Thesis in Aerospace Engineering
by
Jacob Reddington

© 2021 Jacob Reddington

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

May 2021
The thesis of Jacob Reddington was reviewed and approved by the following:

Jacob W. Langelaan
Professor of Aerospace Engineering
Thesis Advisor

Joseph Horn
Professor of Aerospace Engineering

Eric Greenwood
Assistant Professor of Aerospace Engineering

Amy R. Pritchett
Professor of Aerospace Engineering
Head of the Department of Aerospace Engineering
Abstract

The GimbalHawk Unmanned Aerial Vehicle (UAV) serves as a proof-of-concept system in support of novel co-axial rotorcraft research at the Pennsylvania State University. Current UAVs are predominately configured as multirotor systems, but may not be suitable for all missions. While other configurations have also been developed, the co-axial tilting-head rotor configuration has been demonstrated in a small 1 kg UAV and a large 200 kg human-piloted vehicle, but scaling relationships for the CAT-HR need to be explored. This thesis outlines the design, construction, and development of the GimbalHawk UAV from concept exploration to field testing.

With objectives set on design, construction, and future scalability, co-axial motor and battery selection was an important design factor. Commercial-off-the-shelf (COTS) components were used to facilitate rapid development of a test vehicle. Additive manufacturing was critical in fabricating a gimbal to isolate the rotor system from the body and vector thrust. Carbon fiber blades and CNC adapters comprise the fixed-pitch rotor system. An open, cuboid frame is constructed of common lightweight materials to form the vehicle body. Servos are used to input pitch and roll commands. Thrust and yaw are controlled by varying each motor’s RPM.

Characterization of the test vehicle’s control and performance was achieved through flight tests with two different rotor blade systems. The 5.4 kg CAT-HR UAV maintained a piloted, stable hover profile. Performance derived from flight log data validates predicted hover performance estimates. Observed vehicle characteristics identified areas of future work including: control tuning, flight envelope expansion, system identification, IMU positioning, wind disturbance resistance, motor case temperature, and pusher propeller development.
# Table of Contents

List of Figures vi

List of Tables viii

List of Symbols ix

List of Abbreviations xii

Acknowledgments xiii

Chapter 1

Introduction 1

1.1 Coaxial Rotorcraft 2

1.2 Developments in Coaxial Rotorcraft UAVs 3

1.3 Objective and Contributions 5

1.4 Reader’s Guide 6

Chapter 2

Design of a CAT-HR UAV 8

2.1 Conceptual Design 8

2.1.1 Momentum Theory, Ideal Hover Power, and Figure of Merit 8

2.1.2 Hover Time and Takeoff Mass as Functions of Disc Loading 11

2.1.3 Net Power Draw in Steady Hover 13

2.1.4 Flight Endurance and Range 15

2.1.5 Longitudinal Equations of Motion 17

2.2 Preliminary Design 19

2.2.1 Airframe Definition 19

2.2.2 Major Component Selection 20

2.2.2.1 Power and Propulsion 20

2.2.2.2 Avionics 21

2.3 Detail Design 22

2.3.1 Fabricated and Modified Components 22

2.3.2 Design for Additive Manufacturing 22

2.3.2.1 Gimbal Plates 22
Chapter 3
Construction of the GimbalHawk UAV

3.1 Construction Process .................................................. 27
   3.1.1 Gimbal ................................................................. 27
   3.1.2 Fuselage ............................................................... 28
   3.1.3 Rotor System ......................................................... 30
   3.1.4 Landing Gear ......................................................... 30
   3.1.5 Electronics, Payload, and Systems Integration ................. 30
3.2 Component/System Mass Breakdown ................................ 32
3.3 Vehicle Assembly Process ............................................. 32

Chapter 4
Gimbaled Coaxial UAV Flight Operations ............................. 36

4.1 Initial Flight Testing ..................................................... 36
   4.1.1 Controller Structure and Flight Modes ............................ 36
   4.1.2 Flight Testing and Development .................................... 37
      4.1.2.1 Flight 1 ............................................................. 38
      4.1.2.2 Flight 2 ............................................................. 39
      4.1.2.3 Flight 3 ............................................................. 39
      4.1.2.4 Flight 4 ............................................................. 40
   4.1.3 Rotor Blade Change ................................................ 40

Chapter 5
Conclusions and Future Work ............................................. 47

5.1 Conclusions ............................................................... 47
5.2 Future Work .............................................................. 47
   5.2.1 Controller Tuning, Flight Envelope Expansion, and System Identification ............................................. 47
   5.2.2 IMU Positioning ....................................................... 48
   5.2.3 Wind Disturbance Resistance ....................................... 48
   5.2.4 Motor Case Temperature ............................................ 49
   5.2.5 Pusher Propeller ..................................................... 49

Appendix
Non-Default PX4 Parameters ........................................... 51

Bibliography ................................................................. 55
List of Figures

1.1 Unmanned Conventional Rotorcraft ............................... 2
1.2 SB-1 Defiant and S-97 Raider in Flight [1] ........................ 3
1.3 Unmanned Coaxial Rotorcraft ..................................... 4
1.4 Coaxial Helicopter Walkera 5#10 [2] .............................. 5
1.5 Coaxial Tilting-Head Rotorcraft ..................................... 5
1.6 GimbalHawk in Hover (Author Photo) .............................. 7

2.1 Hover Data for a Single KDE CF245-DP Rotor .................. 11
2.2 Conceptual Sizing for Coaxial sUAS as Function of Disc Loading as Payload Varies (0.5 kg, 1.0 kg, 2.0 kg). Top: Required Battery Mass (Solid Lines) and Total Vehicle Mass (Dashed Lines); Middle: Hover Power; Bottom: Rotor Radius .......................... 12
2.3 Expected Vehicle Performance ....................................... 16
2.4 Forces & Inertial/Body Reference Frames in Hover ............... 17
2.5 Simulink Diagram of Linearized Model ............................. 19
2.6 Maxxprod Himax CR6320A Contra-Rotating Motor (Author Photo) ... 20
2.7 Adapter Hub for KDE Blades (dimensions in mm) ................ 23
2.8 Lower Pitch Plate of Gimbal (dimensions in mm) .................. 24
2.9 Upper Roll Plate of Gimbal (dimensions in mm) .................. 25
2.10 Assembled Gimbal Schematic ........................................... 26

3.1 Gimbal Assembly with Roll Servo and Motor Installed (Author Photo) . 28
3.2 Assembled Fuselage (Author Photo) ........................................... 29
3.3 Rotor System ................................................................. 30
3.4 Landing Gear Assembly and Electronic Speed Controllers (Author Photo) 31
3.5 Electronics Compartment, Gimbal Pitch Plate, and Pitch Servo (Author Photo) ................................................................. 32
3.6 Remote Control Receiver, GPS Antenna, Compass, and Ground Plane (Author Photo) ................................................................. 33
3.7 Fully Assembled GimbalHawk (Author Photo) ........................................... 35

4.1 First Flight of the GimbalHawk (Author Photo) ........................................... 38
4.2 Acceleration Power Spectral Density ........................................... 41
4.3 Flight GPS Position: Wooden Propeller ........................................... 42
4.4 Flight GPS Position: KDE Rotor ........................................... 42
4.5 Total Power Usage and Throttle: Wooden Propeller ........................................... 43
4.6 Total Power Usage and Throttle: KDE Rotor ........................................... 43
4.7 Euler Angles and Body Rates: Wooden Propeller ........................................... 44
4.8 Euler Angles and Body Rates: KDE Rotor ........................................... 45
4.9 Normalized Pilot Stick Inputs: Wooden Propeller ........................................... 46
4.10 Normalized Pilot Stick Inputs: KDE Rotor ........................................... 46
List of Tables

2.1 KDE CF-245-DP Propeller Properties ........................................ 10
2.2 Vehicle Parameters ................................................................. 21
3.1 Component Mass Breakdown. ..................................................... 34
4.1 Mean Hover Power and Throttle ................................................. 41
Non-default PX4 parameters .......................................................... 51
List of Symbols

\begin{itemize}
  \item $A$ rotor disc area
  \item $\bar{c}$ blade chord
  \item $c_{d_0}$ minimum or zero-lift drag coefficient
  \item $c_{d,\text{blade}}$ average blade section drag coefficient
  \item $C_{D,\text{parasite}}$ parasite drag coefficient
  \item $\bar{c}_l$ mean blade section lift coefficient
  \item $C_T$ coefficient of thrust for each rotor
  \item $D_{\text{parasite}}$ parasite drag force
  \item $e$ gravimetric energy density
  \item $FM$ figure of merit
  \item $g$ acceleration due to gravity, $9.81 \text{m/s}^2$
  \item $I$ second moment of inertia of vehicle
  \item $I_{\text{motor}}$ motor current
  \item $I_0$ motor no-load current
  \item $K_Q$ motor torque constant
  \item $K_V$ motor speed constant
  \item $m$ vehicle mass
  \item $m_{\text{payload}}$ payload mass
  \item $m_{\text{battery}}$ battery mass
  \item $m_{\text{empty}}$ empty vehicle mass
\end{itemize}
\( N_b \) number of blades (for one rotor)

\( P_{aero,hover} \) total aerodynamic hover power

\( P_{batteryloss} \) battery power loss

\( P_{parasite} \) parasite drag power

\( P_{coreloss} \) core power loss

\( P_{hover} \) hover power

\( P_{climb} \) climb power

\( P_{hotel} \) power required to run avionics

\( P_{ideal} \) ideal (minimum) induced power

\( P_{ind,hover} \) induced hover power

\( P_{motorloss} \) motor power loss

\( P_{pathloss} \) path power loss

\( P_{profile,hover} \) profile hover power

\( q \) freestream dynamic pressure

\( r \) rotor radius

\( R_{battery} \) battery resistance

\( R_{path} \) path resistance

\( R_{winding} \) motor coil winding resistance

\( S \) body reference area

\( T \) thrust

\( w(\cdot) \) induced downwash

\( v_T \) rotor tip speed

\( z_t \) vehicle CG to gimbal axis arm, 0.103 m

\( \gamma \) flight path angle

\( \delta \) rotor tilt angle

\( \eta \) drivetrain efficiency
\( \theta \)  
body pitch angle

\( \kappa_{int} \)  
induced power interference factor for a coaxial rotor system

\( \kappa \)  
rotor induced power factor for a single rotor

\( \mu \)  
advance ratio

\( \rho \)  
air density

\( \sigma \)  
rotor solidity

\( \tau_{\text{motor}} \)  
motor torque

\( \omega \)  
body pitch angle

\( \Delta t \)  
hover time

\( \Omega \)  
rotational speed of the rotor
List of Abbreviations

\begin{enumerate}
\item \textit{BEC} battery elimination circuit
\item \textit{CAT – HR} co-axial tilting-head rotor
\item \textit{CG} center of gravity
\item \textit{COTS} commercially available off-the-shelf
\item \textit{ESC} electronic speed controller
\item \textit{IMU} inertial measurement unit
\item \textit{PMB} power management board
\item \textit{PX4} Pixhawk 4 flight controller
\item \textit{UAV} unmanned aerial vehicle
\end{enumerate}
Acknowledgments

I would like to thank my advisor, Jack Langelaan for the opportunity to work in the Air Vehicle Intelligence and Autonomy (AVIA) lab; his continued guidance in this project and my graduate studies; and the support he showed me and my family while here at Penn State. He and my AVIA colleagues, namely Junyi Geng, Nathan Kimmel, Tomás Opazo, Duncan Nicholson, Tyler Rosenberger, and Marc Volpe, have been exceedingly helpful throughout my project in listening and offering advice. Despite an unorthodox remote environment in which to conduct research and share resources, all of you were ever-available to illuminate a path when I hit a roadblock.

To all of my graduate course professors, thank you for your patience and understanding as I reentered formal academia after nearly a decade away. I could not have scraped away the rust without your assistance and instruction. I hope to replicate your efforts with my own cadets at West Point.

To all my classmates, particularly Joel Rachaprolu, Tyler Stephans, and Vitor Valente, thanks for burning the candle at both ends with me and reminding me of the importance to surround myself with people smarter than me.

To my military advisors, thank you for the professional guidance toward future goals in both academic and military career fields.

Last, but certainly not least, to my wife, Kaitlyn, family, and friends here in State College and around the world. You are my foundation that supports me in all my endeavours, and thanks for giving my heart wings.

Portions of this work were funded by the Office of Naval Research under grant number N00014-20-1-2052. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the Office of Naval Research.
Chapter 1
Introduction

Initially, the field of unmanned aerial vehicles (UAV) was dominated by fixed-wing applications, but intra-urban requirements have pressed the development of rotary-wing UAV platforms. The list of applications of autonomous rotorcraft, or drones, is ever expanding, and currently includes industrial inspection, surveying, mapping, emergency response, military, and recently, geoscience data collection [3].

Current generation small autonomous rotorcraft have in many cases converged to multirotor configurations. There are several advantages: mechanical simplicity (the only moving parts are motors); good controllability; reasonable scalability (10’s of grams to hundreds of kilograms take-off weight); and potential for redundancy (in the case of vehicles with more than four rotors) or even dynamically decoupled, omni-directional control [4]. Multirotors are currently in use on vehicles ranging from racing drones to package delivery vehicles to vehicles designed for exploration of other planets (such as the Dragonfly drone, recently selected as the next NASA New Frontiers mission [5]).

Notwithstanding the high forward speeds attained by racing quadrotors (in 2017 the DRL Racer X quadrotor reached a top speed of 179.6 mph\(^1\)), it is not completely clear that multirotors are suitable for all missions (for example, those that combine a requirement for high speed with significant endurance), and other VTOL-capable configurations may be better suited for such missions. In addition, multirotor platforms tend to have a higher disk loading for a given overall footprint, leading to higher required power.

Small conventional helicopters have also been developed for unmanned applications: see for example radio-controlled helicopters such as the Align T-Rex 450 [6], larger helicopters such as the Boeing Unmanned Little Bird H-6U [7], or the very small FLIR

\(^1\)https://techcrunch.com/2017/07/14/watch-this-racing-drone-set-the-guinness-world-record-for-fastest-drone/
Black Hornet [8] (See Figure 1.1). Building and characterizing other configurations may reveal other design families that better fit future missions.

1.1 Coaxial Rotorcraft

The design and successful demonstration of coaxial rotorcraft actually predates the success of the modern main rotor/tail rotor design. Jacob Ellehammer developed one of the first manned helicopters to hover under its own power in 1912. By 1930, Corradino d’Ascanio built a coaxial helicopter that held records for speed, altitude, and distance flown. From 1930-1936, Louis Breguet and René Dorand developed another coaxial rotorcraft that was arguably the first technically successful helicopter not just on the merits of the records it held, but also for its autorotation capability [9].

While the conventional configuration of the helicopter pioneered by Igor Sikorsky in the early 1940s gained popularity in rotorcraft design, coaxial rotorcraft design has its inherent advantages. One such advantage is the net size of the rotor area is reduced as both main rotor produce vertical thrust. This advantage has been exploited over the years by aircraft manufacturer Kamov with coaxial designs such as the Ka-8 and Ka-10 which demonstrated the ability to operate off naval ships in the late 1940s. Kamov continued development of its coaxial designs up through the 1990s, proliferating their operational service in many different countries [10].

Another advantage of the coaxial rotors is that in forward-flight, the aerodynamic lift load is carried by the two advancing blades on both sides of the aircraft, which virtually eliminates the negative effects of dynamic stall, or retreating blade stall. While
Compressibility at the tip of the advancing blades at high forward airspeeds is still a design consideration. Sikorsky successfully designed and tested a prototype coaxial helicopter to push the limits, so dubbed the advancing blade concept aircraft, or the XH-59A. Testing was conducted from 1972-1980, and resulted in a maximum level flight speed of 238 KTAS, confirming the advantage of the coaxial system [11]. Since then, Sikorsky has further developed the concept further in its S-97 Raider and S-100 SB-1 Defiant prototypes as seen in Figure 1.2. Some disadvantages of coaxial rotors include, but are not limited to a higher induced power requirement due to the wake interaction between the upper and lower rotor, and a more mechanically complex swashplate-rotor hub, resulting in higher likelihood of mechanical faults and high parasitic drag contributions in forward flight. Note also that either quite rigid rotors are required or significant rotor spacing is required to avoid blade strike due to blade flapping.

1.2 Developments in Coaxial Rotorcraft UAVs

Coaxial configurations have also been implemented in UAV platforms to accommodate various missions. The QH-50 Drone Anti-Submarine Helicopter, pictured in Figure 1.3, was developed as a UAV and fielded for use with the US Navy in 1962, was retrofitted
Figure 1.3. Unmanned Coaxial Rotorcraft

with television cameras with for observation and reconnaissance in the late 1960s, and eventually served as target drones for anti-aircraft and air defense system development until 1996. It was modified to be remotely piloted from a manned Model 2C Rotorcycle. Given the clandestine nature of its original mission, it was arguably the first unmanned helicopter, let alone a coaxial design [12].

The Canadair CL-227 Sentinel, or the "Peanut", was developed explicitly for battlefield surveillance and target acquisition. This UAV was a vertically-oriented, axi-symmetric, modular design with power, propeller, and control/payload sections. Though not widely proliferated, this vehicle demonstrated a different, yet highly stable and controllable configuration of a coaxial rotor system. Additionally, it shows some amount of scalability as the CL-227 was about 25% the size and weight of the QH-50 drone. On both the QH-50 and CL-227, control was effected via collective and cyclic pitch (and, in the case of the QH-50, yaw control was done using variable incidence end plates mounted on the rotor tips).

Coaxial rotorcraft designs with swashplates have been marketed, such as the Walkera 5#10 (Figure 1.4). Although with tail rotors to control yaw (rather than variable upper and lower rotor torque/thrust) and cyclic control on solely the lower rotor, stable coaxial rotor models have been developed weighing approximately 100 grams. Modeling and control of these micro helicopters has been shown [2]. The scalability of coaxial rotor vehicles both swashplate-controlled and multi-coaxial configurations has been analyzed [14], but other control configurations have been developed. Building and
characterizing other configurations may reveal other design families that better fit future missions.

1.3 Objective and Contributions

The objective of the work presented here is the design, construction, and flight demonstration of a mechanically simple coaxial rotorcraft. One such configuration is a co-
axial tilting-head rotor (CAT-HR). This configuration has been demonstrated in small scale [15] and in a scale large enough to be human-piloted [16] (see Figure 1.5). The CAT-HR has advantages: it is compact (the overall vehicle diameter is smaller than a multirotor with comparable disc loading); disc loading can be readily scaled by changing rotor diameter (without the need to also modify the structure to accommodate increased rotor diameter); and control does not require swashplates.

Notwithstanding the flight demonstration of both small and fairly large CAT-HRs, there are questions of scaling associated with this class of vehicle. Thus there were two main foci for the research conducted here: first, design, construction, and characterization of a small CAT-HR; second, development of scaling relationships in the vehicle and its drivetrain to determine the likely design envelope for this class of vehicle. Characterization includes vehicle performance as well as considerations of control. Specifically, control may become challenging for larger vehicles, as the bandwidth associated with actuators may approach the frequencies of rigid body modes of the vehicle.

As a motivating example, the research proposed here will focus on a vehicle capable of delivering a 1-2 kg payload over a distance of at least 2 km. This represents a vehicle capable of delivering a life-saving medical package, but can also encompass a vehicle carrying a fairly sophisticated EO-IR sensing payload.

The primary contribution of this thesis is a small coaxial rotor UAS (called “Gimbal-Hawk”) and initial flight test results (see Figure 1.6).

As flown, the vehicle has an overall footprint of 0.66 m x 0.66 m (due to the current landing gear, designed for robust landing) and a take-off mass of 5.4 kg. Hover endurance (based on measured total current draw and installed battery capacity) is 18 minutes.

1.4 Reader’s Guide

The remainder of this thesis is organized as follows. Chapter 2 describes conceptual and detail design of the GimbalHawk. Chapter 3 describes construction of the prototype vehicle, including a mass breakdown of the completed vehicle. Chapter 4 gives results of hover flight tests, and Chapter 5 presents concluding remarks.

2 This configuration could also be denoted 'heli-trike' to recognize the similarity of its configuration to the class of powered hang-gliders known as trikes.
Figure 1.6. GimbalHawk in Hover (Author Photo)
Chapter 2  
Design of a CAT-HR UAV

This chapter outlines the conceptual, preliminary, and detail design phases of the Gimbal-Hawk development responsible for individual component selection and implementation into the final project assembly.

2.1 Conceptual Design

This phase of aircraft design focuses on the high level aspects of vehicle requirements. Semi-empirical analytic methods are used to assess the design, often involving simplified physical models with correction factors based on existing aircraft data [17]. This project aimed to focus on a novel control mechanism for a coaxial, contrarotating vehicle using a gimbaled rotor system to control vector thrust. As such the vehicle configuration was predetermined. Key design drivers are overall compactness, simplicity of control, and scalability.

2.1.1 Momentum Theory, Ideal Hover Power, and Figure of Merit

Based on preliminary requirements (1000g payload, 15 minutes endurance, minimum 2 km range, flight in 24 km/h [15 mph] wind) and an assumed battery gravimetric energy density of 150 Wh/kg (the energy density of commercially-available hobby grade lithium polymer batteries), initial sizing is determined based on methods outlined in Langelaan [18]. Beginning with ideal hover power for a single rotor, or the theoretical minimum power required to hover based on momentum theory,

\[ P_{\text{ideal}} = \sqrt{\frac{m^3 g^3}{2 \rho A}} \]  

(2.1)
where \( m \) is total vehicle mass, \( g \) is acceleration due to gravity, \( \rho \) is air density, and \( A \) is rotor disc area. The total hover power is then derived,

\[
P_{\text{hover}} = \frac{1}{FM} \sqrt{\frac{m^3 g^3}{2\rho A}}
\]  

(2.2)

where \( FM \) is figure of merit (essentially a rotor efficiency).

Given a coaxial rotor, the rotor disk area of upper and lower rotors are coincident, thus the total rotor area is computed using the equation of the area of a circle of rotor radius, \( r \). An expression for \( FM \) has been determined for a coaxial rotor configuration [19]:

\[
FM = \frac{1.2657 \left( \frac{C_T}{\kappa} \right) \left[ \left( \frac{C_T}{C_{T_l}} \right)^{\frac{3}{2}} + 1 \right]}{\kappa_{int} \kappa \frac{C_T}{\sqrt{2}} \left[ \left( \frac{C_T}{C_{T_l}} \right)^{\frac{3}{2}} + 1 \right] + \frac{\sigma c_d}{4}}
\]  

(2.3)

\( C_T(\cdot) \) is the coefficient of thrust for each rotor, \( \kappa \) is the induced power factor, \( \kappa_{int} \) is the interference-induced power factor, and the constant 1.2657 is the absolute minimum theoretical value of \( \kappa_{int} \), where the rotors operate at a torque balance and the lower rotor operates in the vena contracta of the upper rotor. \( C_{T_l} \) is determined by using momentum theory to derive the relationship in thrust for equal torque and non-dimensionalized:

\[
C_{T_l} = \frac{T}{\frac{1}{2} \rho A (\Omega r)^2}
\]  

(2.4)

Prior [14] referring to Leishman [9] states that the upper rotor generally operates at 20% higher thrust coefficient than the lower rotor in order to balance torque, hence \( \frac{C_{T_u}}{C_{T_l}} = 1.2 \).

To obtain an estimate for figure of merit that can be used to estimate hover power (and thus estimate hover endurance) some rotor data is needed. Using published data for a commercially available rotor (the KDE-CF245-DP), the static thrust coefficient, power coefficient, and figure of merit were determined, and thus the mean section lift coefficient in hover can be obtained.

The power coefficient is

\[
C_P = \frac{P}{\rho A v_T^3}
\]  

(2.5)
Table 2.1. KDE CF-245-DP Propeller Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius</td>
<td>$r$</td>
<td>0.311 m</td>
</tr>
<tr>
<td>mean chord</td>
<td>$\bar{c}$</td>
<td>0.041 m</td>
</tr>
<tr>
<td>solidity ratio</td>
<td>$\sigma$</td>
<td>0.084</td>
</tr>
<tr>
<td>thrust coefficient</td>
<td>$C_T$</td>
<td>0.0085</td>
</tr>
<tr>
<td>power coefficient</td>
<td>$C_P$</td>
<td>$9.53 \times 10^{-4}$</td>
</tr>
<tr>
<td>mean section lift coefficient</td>
<td>$\bar{c}_l$</td>
<td>0.6</td>
</tr>
<tr>
<td>figure of merit (single rotor)</td>
<td>$FM$</td>
<td>0.6 (if shaft speed $&gt; 2000$ rpm)</td>
</tr>
</tbody>
</table>

and the rotor solidity ratio is

$$\sigma = \frac{N_b \bar{c}}{\pi r} \quad (2.6)$$

Mean blade section lift coefficient in hover is

$$\bar{c}_l = \frac{6C_T}{\sigma} \quad (2.7)$$

Geometry and some derived parameters\(^1\) are tabulated in Table 2.1; static thrust, power, and calculated figure of merit for a single rotor are plotted in Figure 2.1 (for full sized helicopters, figures of merit between 0.7 and 0.75 are not uncommon). Note that figure of merit correlates strongly with chord Reynolds number. When $Re \gtrsim 125000$ (corresponding to shaft speeds greater than 2000 rpm), $FM \approx 0.6$. Blade section drag coefficients become very large for low Reynolds number and profile power becomes a large contributor to rotor total power.

Using Equation 2.3 and assuming that the upper and lower rotor are both operating at the same thrust coefficient the figure of merit for a coaxial rotor using KDE CF245 DP blades can be estimated. With $C_{T_l} = C_{T_u} = C_T$,

$$FM = \frac{1.2657\sqrt{2}C_T}{\kappa_{int}\kappa\sqrt{2C_T + \frac{c_{sd_0}}{4}}} \quad (2.8)$$

Using $C_T = 0.0085$, $c_{d_0} = 0.015$, and $\kappa_{int}\kappa = 1.4$, $FM = 0.89$ for the coaxial pair. Note that in general $C_{T_u} \neq C_{T_l}$; the upper and lower rotor will be operating at equal torque. However, the effect on calculated $FM$ is small. Sensitivity to $c_{d_0}$ is also small:

---

setting $c_{d_0} = 0.02$ (an increase of 33%) results in $FM = 0.88$. There is stronger sensitivity to $\kappa_{int} \kappa$: setting $\kappa_{int} \kappa = 1.5$ (an increase of 7%) gives $FM = 0.83$. This estimate of $FM$ was then used to determine hover performance as a function of disc loading.

### 2.1.2 Hover Time and Takeoff Mass as Functions of Disc Loading

The hover power can be used with battery parameters to estimate the takeoff mass and hover time of the project vehicle. The mass of the vehicle can be further defined as follows:

$$m = m_{payload} + m_{battery} + m_{empty}$$

(2.9)

And the energy available in the battery as $E = em_{battery}$, where $e$ is the gravimetric energy density of the battery. The hover time $\Delta t$ is a function of the required hover power and the total energy in the battery:

$$\Delta t = m_{battery}eFM \sqrt{\frac{2\rho A}{m^3 g^3}}$$

(2.10)
Removing $m^2g^2$ from the square root term and further rearranging:

$$
\Delta t = \frac{m_{\text{battery}}e}{g} FM \sqrt{\frac{2\rho A}{mg}} \frac{1}{m} 
$$

(2.11)

Rearranging to solve for battery mass required for an endurance $\Delta t$ is

$$
m_{\text{battery}} = \frac{\Delta t g}{FM \sqrt{\frac{mg}{2\rho A}}} \left( m_{\text{payload}} + m_{\text{empty}} \right) 
$$

(2.12)

The quantity $\frac{mg}{A}$ is the hover disc loading. Clearly the denominator above must be positive (to avoid nonsensical negative battery mass). Thus a given battery energy density, hover time, and figure of merit defines the maximum possible disc loading. A larger rotor (lower disc loading) leads to lower required battery mass for a given endurance.

Figure 2.2 shows sizing as a function of hover disc loading and payload for an assumed empty (i.e. no battery, no payload) mass of 3.5 kg and a desired hover endurance of 15 minutes. For comparison, the Robinson R22 light helicopter operates at a maximum disc loading of 130 N/m$^2$, the MD500E light helicopter operates at a maximum disc loading of
approximately 250 N/m² and the CH-53K King Stallion heavy-lift helicopter operates as a maximum disc loading of approximately 800 N/m². The low energy density of batteries compared with gasoline and Jet-A (current generation batteries have energy density about 1/70 of gasoline) requires significantly lower disc loading for a given endurance. For small electric-powered rotorcraft, useful disc loading is between 100 and 150 N/m² (similar to that of ultralight and light helicopters). At this disc loading, a battery of mass 1 to 2 kg will be required for 15 minutes hover endurance.

Note that for a given disc loading, the main impact of increasing payload is increased hover power and thus increased battery mass to achieve the desired hover endurance. Also note that reducing rotor radius below approximately 0.3 meters results in significantly higher disc loading and thus significantly higher hover power. Vehicles with rotor radii significantly smaller than 0.3 m will thus be more challenging to design (in the case of payloads of order 1 kg).

2.1.3 Net Power Draw in Steady Hover

Low order analysis of coaxial rotors is complicated by the interactions between rotors. Since the purpose of low order analysis is to enable a fast design cycle, several approximations will be used.

In hover, total aerodynamic (i.e. shaft) power includes induced power and profile power:

$$P_{aero,hover} = P_{ind,hover} + P_{profile,hover}$$ (2.13)

For a coaxial rotor pair,

$$P_{ind} = \kappa\kappa_{int}(T_{upper}w_{upper} + T_{lower}w_{lower})$$ (2.14)

where $w_{(\cdot)}$ is the induced downwash. To first order assume $T_{upper} = T_{lower}$. Using Glauert’s hypothesis to relate thrust and downwash,

$$T = 2\rho A\bar{\bar{v}}w$$ (2.15)

where $A$ is disc area and $\bar{\bar{v}} = \sqrt{(w - v_n \sin \alpha)^2 + (v_n \cos \alpha)^2}$. In hover, $v_n = 0$ and $w$ can be computed directly; in forward flight it is computed iteratively for a given thrust, airspeed, and angle of attack.
The profile power is

\[ P_{\text{profile}} = \rho A v_T^3 \frac{\sigma \bar{c}_{d,\text{blade}}}{8} \left( 1 + 3 \mu^2 \right) \]  

(2.16)

where \( v_T = \omega r \) is rotor tip speed, \( \bar{c}_{d,\text{blade}} \) is the average blade section drag coefficient, \( \sigma \) is rotor solidity ratio and \( \mu = \frac{\omega}{v_T} \) is advance ratio (note that in hover \( \mu = 0 \)).

Tip speed in hover can be obtained from the thrust coefficient,

\[ v_T = \sqrt{\frac{T}{\rho AC_T}} \]  

(2.17)

and thrust coefficient is related to mean section lift coefficient (Equation 2.7). Thus for a coaxial rotor with thrust equally divided between upper and lower rotor,

\[ v_T \approx \sqrt{\frac{3mg}{\rho r N_b \bar{c} \bar{c}_l}} \]  

(2.18)

and now profile power can be computed using Equation 2.16.

The total power drawn from the battery includes aerodynamic (shaft) power and losses in the drive train.

Motor power loss includes \( I^2R \) loss in the coils as well as core losses. In the coaxial rotor system (2 motors), motor loss is

\[ P_{\text{motorloss}} = \sum_{i=1}^{2} \left( R_{\text{winding}} I_i^2 + P_{\text{coreloss}} \right) \]  

(2.19)

where \( P_{\text{coreloss}} \) is power dissipated in the core and the current through a motor is

\[ I_{\text{motor}} = \frac{\tau_{\text{motor}}}{K_Q} + I_0 \]  

(2.20)

where \( \tau_{\text{motor}} \) is motor torque, \( K_Q \) is the motor torque constant and \( I_0 \) is the motor no-load current. Motor torque can be obtained from shaft power and speed:

\[ \tau_{\text{motor}} = \frac{P_{\text{aero}}}{v_T} \]  

(2.21)

The motorpath loss is

\[ P_{\text{motorpathloss}} = \sum_{i=1}^{2} R_{\text{path},i} I_i^2 \]  

(2.22)
where $R_{\text{path},i}$ is the path resistance to the $i^{th}$ motor.

The battery loss is

$$P_{\text{battery loss}} = R_{\text{battery}} \left( \sum_{i=1}^{2} I_i \right)^2$$

(2.23)

Given the parameters of the as-constructed GimbalHawk (see chapters 3 and 4), the predicted total aerodynamic shaft power is 489 W and the current required is 39.6 A. Note that significant power will be dissipated in the motor windings, increasing the total power drawn from the windings above the aerodynamic power. Total power drawn from the battery is 885 W in hover.

### 2.1.4 Flight Endurance and Range

Vehicle performance for no load and a 2 kg payloads is shown in Figure 2.3. Given the fairly low blade Reynolds number and the non-optimized airfoils on lower-cost COTS rotors, mean blade lift coefficient is assumed to be high, leading to high predicted blade profile power. However, range well above 15 kilometers is still predicted even for the 2 kg payload.

Additional power requirements develop from climbing or forward flight. Gravitational power required depends on the vertical component of the velocity vector:

$$P_{\text{climb}} = mg v_a \sin \gamma$$

(2.24)

where $\gamma$ is the flight path angle measured relative to horizontal. For constant altitude flight, $P_{\text{climb}} = 0$.

The parasite drag force is

$$D_{\text{parasite}} = q S C_{D,\text{parasite}} = \frac{1}{2} \rho v_a^2 S C_{D,\text{parasite}}$$

(2.25)

where $q$ is freestream dynamic pressure, $S$ is body reference area, and $C_{D,\text{parasite}}$ is parasite drag coefficient; parasite drag power is then

$$P_{\text{parasite}} = D_{\text{parasite}} v_a$$

(2.26)

For hovering flight, $P_{\text{parasite}} = 0$. Additional control overhead is assumed to be 5% of the electrical power. $P_{\text{hotel}}$ (the power required to run avionics) is a assumed to be 5 W.
Figure 2.3. Expected Vehicle Performance
With the zero payload, the maximum range speed is 18.6 m/s and the total power drawn from the battery 565 W. Given a total battery energy of 285 Wh, flight time at this condition is 30 minutes and the total range is 33.7 km.

With an additional 2 kg payload the maximum range speed is 20 m/s and the total power drawn from the battery is 856 W. Given the total battery energy of 285 Wh, flight time at this condition is 20 minutes and the total range is 23.9 km.

Note that achieving these speeds will require careful flight testing for safe expansion of the flight envelope.

2.1.5 Longitudinal Equations of Motion

Examining longitudinal equations near hover is useful to assess the likelihood of controllability given the assumed inputs of total thrust and tilting of the rotor head. Further, a simplified physical model can give insights into overall controllability of the system. For this model, the following assumptions were made to simplify analysis: The rotor thrust, T, acts through the center of the gimbal axes. The rotor system is assumed to be weightless compared to the mass of the rest of the vehicle. The sensors are collocated with the vehicle CG. This model neglects drag. Roll axis (lateral) dynamics are the same based on a assumed vehicle symmetry.

From these assumptions and an understanding of the conceptual design a free body diagram can be drawn as seen in Figure 2.4.

From this drawing, the longitudinal equations of motion near hover in the inertial frame are derived:
\[ \sum F_x: \quad m\ddot{x} = -T \sin(\theta + \delta), \quad (2.27) \]
\[ \sum F_z: \quad m\ddot{z} = -T \cos(\theta + \delta) + mg, \quad (2.28) \]
\[ \sum M_\theta: \quad I\ddot{\theta} = T \sin(\delta) z_t \quad (2.29) \]

where \( \delta \) is the rotor tilt angle, \( g \) is the acceleration due to gravity, \( I \) is the second moment of inertia about the pitch axis, \( m \) is the vehicle mass, \( T \) is the thrust input, \( \theta \) is the body pitch angle, and \( z_t \) is the distance arm between vehicle CG and gimbal axes. Applying addition formulas, a small angle assumption for both angles, and linearizing the equations in a stable hover condition, the equations are further simplified:

\[ \sum F_x: \quad \ddot{x} = -\frac{T}{m} \delta, \quad (2.30) \]
\[ \sum F_z: \quad m\ddot{z} = -T + mg, \quad (2.31) \]
\[ \sum M_\theta: \quad I\ddot{\theta} = mg\delta z_t \quad (2.32) \]

If vertical acceleration is constrained to zero, \( T = mg \) and the lateral acceleration becomes \( \ddot{x} = -g \delta \). For some desired non-zero vertical acceleration, the desired total thrust can be computed from 2.31 and some desired lateral acceleration can be achieved by defining rotor tilt angle \( \delta \).

From the simplified equations, the following state-space system is constructed:

\[ x_1 = x \quad \dot{x}_1 = x_4 \quad (2.33) \]
\[ x_2 = z \quad \dot{x}_2 = x_5 \quad (2.34) \]
\[ x_3 = \theta \quad \dot{x}_3 = x_6 \quad (2.35) \]
\[ x_4 = \dot{x} \quad \dot{x}_4 = -\frac{T}{m} \delta \quad (2.36) \]
\[ x_5 = \dot{z} \quad \dot{x}_5 = g - \frac{T}{m} \quad (2.37) \]
\[ x_6 = \dot{\theta} \quad \dot{x}_6 = \frac{mgz_t}{I} \delta \quad (2.38) \]

Figure 2.5 shows the representation of these equations in a MatLab Simulink model that can be used to simulate a time response of the proposed system to predict aircraft motion. This model could be developed by accounting for earlier assumptions and through adding more degrees-of-freedom in order to more accurately predict the response of the
Figure 2.5. Simulink Diagram of Linearized Model

vehicle to different disturbances or control inputs. However, using system identification tools could be used to extract a model from the flight test data to also improve the model, as well as inform future decisions for project design [20].

2.2 Preliminary Design

Following selection of a general aircraft concept, which meets system level requirements, preliminary design seeks to determine and optimize major component elements that form the basis of the air vehicle system [17]. In support of design research considerations, some selected components were chosen to facilitate future scalability assessments.

2.2.1 Airframe Definition

Given the coaxial configuration and the design goal of manipulated thrust through the use of a gimbal, an open, cuboid airframe was adopted to keep the vehicle CG below the center of thrust and allow easy access to components. Tiers allowed for the separation and stacking of component compartments in this manner, and also allowed for variability in the size of each compartment based on individual component dimensions.
2.2.2 Major Component Selection

2.2.2.1 Power and Propulsion

The largest COTS coaxial, contra-rotating motor available at the beginning of project design was the Maxxprod Himax CR6320A pictured in Figure 2.6. Based on the specifications supplied by the manufacturer and considering the product’s intended use as propulsion for a fixed-wing model, a maximum current draw of 50 amps was assumed. This assumption drove the selection of a pair of Castle Creations Pheonix Edge 50 electronic speed controllers (ESC) to route power from the 8-cell power system to drive the motors. An integrated battery elimination circuit (BEC) is used to provide power for the pitch and roll servos. The ESCs are pictured in Figure 3.4 installed on the front of the fuselage. Based on a planned total vehicle weight 4-8 kg, two 4S LiPo 10 Ah batteries were selected and wired in series. The Turnigy Graphene batteries met the specified continuous draw for the motor.

The motor package includes wooden propellers, aluminum cowling, and an aluminum
Table 2.2. Vehicle Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blades per rotor</td>
<td>$N_b$</td>
<td>2</td>
</tr>
<tr>
<td>Rotor radius</td>
<td>$r$</td>
<td>0.311 m</td>
</tr>
<tr>
<td>Rotor vertical separation</td>
<td></td>
<td>0.0254 m</td>
</tr>
<tr>
<td>Rotor mean chord</td>
<td>$\bar{c}$</td>
<td>0.041 m</td>
</tr>
<tr>
<td>Blade mean lift coefficient (in hover)</td>
<td>$\bar{c}_l$</td>
<td>0.6</td>
</tr>
<tr>
<td>Blade mean drag coefficient</td>
<td>$\bar{c}_{d,blade}$</td>
<td>0.015</td>
</tr>
<tr>
<td>Hover thrust coefficient</td>
<td>$C_T$</td>
<td>0.0113</td>
</tr>
<tr>
<td>Parasite drag coefficient</td>
<td>$C_{P_{parasite}}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Body frontal area</td>
<td>$S$</td>
<td>0.04 m²</td>
</tr>
<tr>
<td>Drivetrain efficiency</td>
<td>$\eta$</td>
<td>0.8</td>
</tr>
<tr>
<td>Nominal battery mass</td>
<td>$m_{battery}$</td>
<td>1.9 kg</td>
</tr>
<tr>
<td>Nominal battery voltage</td>
<td></td>
<td>29.6 V</td>
</tr>
<tr>
<td>Battery energy density</td>
<td>$e$</td>
<td>150 Wh/kg</td>
</tr>
<tr>
<td>Motor speed constant (Himax CR6320)</td>
<td>$K_V$</td>
<td>240 rpm/V</td>
</tr>
<tr>
<td>Motor mass (total)</td>
<td></td>
<td>1.25 kg</td>
</tr>
<tr>
<td>Structure mass</td>
<td></td>
<td>0.75 kg</td>
</tr>
<tr>
<td>Expected vehicle empty mass</td>
<td></td>
<td>3.5 kg</td>
</tr>
<tr>
<td>Mass including battery and 1.0 kg payload</td>
<td></td>
<td>6.4 kg</td>
</tr>
<tr>
<td>Mass including battery and 2.0 kg payload</td>
<td></td>
<td>7.4 kg</td>
</tr>
</tbody>
</table>

hub adapter for the lower motor/upper rotor axle. The wooden propellers were not optimized for weight and thrust in a hovering attitude, thus two counter-rotating pairs of 24.5 cm KDE Direct carbon fiber blades were selected for the rotor design, yielding approximately a 62.25 cm diameter rotor disks.

Using COTS components is somewhat limiting, but it permits rapid development of a proof of concept vehicle that will enable work on the key research tasks. Table 2.2 lists vehicle parameters assuming the use of a COTS drive system. Here the motor is intentionally oversized (the manufacturer claims 30 lb static thrust) to ensure that it can adequately spin a large rotor and to provide room for growth in vehicle size. Note that the use of COTS hardware also affected the rotor spacing: here the rotor spacing is 4% of the diameter, somewhat smaller than the Sikorsky X2 rotor spacing of 5.7% [14].

2.2.2.2 Avionics

A Pixhawk 4 (PX4) kit manufactured by Holybro and Futaba R3001SB radio receiver were selected as the GimbalHawk’s avionics package, which operates on the capable and developer-popular PX4 open-source autopilot system. The Holybro kit was chosen
primarily because its included power distribution board (PDB) could support up to 12S LiPo batteries and 120 A, more than adequate for the GimbalHawk’s 8S power system and anticipated maximum current draw. The R3001SB’s S.BUS functionality ensures radio control (R/C) compatibility with the autopilot so as to facilitate manual and assisted flight modes, which is vital in all stages of development and operation. A combined GPS/compass module supports location and heading determination, while a pair of telemetry radios facilitates real-time over-the-air communication between the vehicle and ground station. The selected avionics are pictured installed in Figures 3.5 and 3.6.

2.3 Detail Design

High level system requirements met in conceptual design, and major component selection and optimization completed in the preliminary design stages, the overall configuration was frozen so the final phase of detail design can refine component architecture prior to beginning vehicle construction [17]. This consists of developing bespoke or modified components to facilitate vehicle assembly and systems integration, including a means of adapting the motor for a rotor system and designing a gimbal to support all involved components for the CAT-HR thrust vectoring. Assembly is addressed in Chapter 3.

2.3.1 Fabricated and Modified Components

Implementing KDE Direct blades require hub adapters for their use with UAS motors. The blade manufacturer did not have adapters for sale to accommodate a 20 mm motor axis, thus necessitating the design of a hub. The designs were water jet cut out of $\frac{1}{4}$ inch steel plates. Figure 2.7 depicts the steel adapter hub for KDE blades, common on the top and bottom of each rotor assembly.

2.3.2 Design for Additive Manufacturing

Additive manufacturing, also known as 3-D printing, proved crucial in the development of the thrust-vectoring, gimbal design in this project.

2.3.2.1 Gimbal Plates

The gimbal was designed in two plates that nest to form the whole gimbal with the pitch plate, pictured in Figure 2.8, mounted to the fuselage, and the roll plate, pictured in
Figure 2.7. Adapter Hub for KDE Blades (dimensions in mm)

Figure 2.9 mounted to the motor. Two rectangular openings were included to mount the roll and pitch servos. Hitec HS-645MG servos were selected as they were suited to larger RC models requiring high-torque inputs. Command inputs are supplied via these servos, which pivot the gimbal-mounted motor. An assembled gimbal schematic is depicted in Figure 2.10 with pitch and roll section views to illustrate how the servos actuate commands.
Figure 2.8. Lower Pitch Plate of Gimbal (dimensions in mm)
Figure 2.9. Upper Roll Plate of Gimbal (dimensions in mm)
Figure 2.10. Assembled Gimbal Schematic
Chapter 3  
Construction of the GimbalHawk UAV

3.1 Construction Process

3.1.1 Gimbal

The roll plate fits within the pitch plate of the gimbal with a one mm gap on both sides between plates. Both the pitch and roll axes comprise of 5 mm 18-8 stainless steel, shoulder screws and M4 threaded inserts press-fit into the pre-printed holes of the roll plate. The roll axis attaches roll plate and two carbon steel, M5 ball joint rod ends. The rod ends are fastened to the motor mounting holes with steel, M5 nylon-insert locknuts. Figure 3.1 depicts the gimbal assembled with hardware isolated from the pitch plate.

The Hitec HS-645MG servos are attached to each plate with four M3 screws and double nuts to lock. Figure 3.1 shows the roll servo installed with with its control linkage. The linkage connects the servo horn to the rod end mounting the motor. The pitch control linkage is attached in a similar manner, but to a screw through the wall of the roll plate. Some of the roll plate was removed with a rotary tool due to impingement with the pitch servo. Both linkages have two steel clevises 2-56 connected by threaded rod. The clevis attached to each servo horn is unaltered. The clevis attached to the threaded rod end and screw required alteration due to the thickness of the threaded ends. The pins were bored out and replaced with 0.059 inch stainless steel wire. Additionally, the altered clevises were soldered to the threaded rod to prevent backing off.
3.1.2 Fuselage

The fuselage is constructed of 1/8 inch plywood, M4 steel threaded rod, nylon spacers, steel angle brackets, and M4 fasteners. Each tier shelf is 165 mm by 130 mm. The forward and aft panels are 140 mm wide by 180 mm tall. They were added to add stiffness to reduce twisting from yaw commands, and provide additional mounting surfaces for electronics. The forward and aft panels are attached to each shelf with two angle brackets and M4 fasteners. They are also attached to the pitch plate each with two M4 screws and press fit threaded inserts. The height of each compartment was set by nylon inserts encasing the threaded rod from the base of the fuselage to the pitch plate. The height of the electronics compartment is 50 mm set for clearance of the motor base to the top of the flight controller, and the height of the battery compartment is 105 mm set for ease of battery removal.
Figure 3.2. Assembled Fuselage (Author Photo)
3.1.3 Rotor System

The upper and lower rotor components are pictured both partially disassembled, and assembled/mounted to the motor in Figure 3.3. The lower rotor hub plate is fastened with four M4 screws to either the upper motor casing or the aluminum hub adapter. One M4 screw and two nuts for locking secure the upper rotor hub plate through each blade root to the lower hub plates. The hub adapter is secured to the lower motor axle via two set screws.

3.1.4 Landing Gear

The landing gear is constructed of 1/2 inch PVC pipe for its modularity and light weight. It can be seen in Figure 3.4. The assembly is symmetric about the fuselage x and y axes. Its cross-member is secured to the base of the fuselage with plastic pipe hanger strap. The gear is secured to each of the fuselage’s threaded rods at the top of the battery compartment with four 1-inch, rubber-lined suspension clamps. The base spans roughly 66 cm square.

3.1.5 Electronics, Payload, and Systems Integration

The GimbalHawk’s on-board electronics consisted of two flight batteries, a PM07 PDB, two ESCs, one coaxial motor unit (consisting of contrarotating upper and lower motors),
a radio control receiver, PX4 autopilot board, GPS/compass module, and telemetry radio. The flight batteries are mounted with hook-and-pile tape in the battery compartment, and in order to achieve the desired voltage, needed to be wired in series. The blue series wiring harness was fashioned with two XT-90 connectors, one XT-60 connector, and 12 AWG blue wire. The installed harness is pictured in Figure 3.7. The PMB then routes power to both ESCs and flight controller.

The PX4 is mounted with four screws on electronics compartment shelf centered on the x and y planes near the vehicle CG below the motors and above the batteries. The PMB is mounted to the right of the PX4 board with four screws. The telemetry radio is mounted with hook-and-pile tape to the left of, and is powered by, the PX4. Control input commands are passed from the PX4’s I/O-PWM-Out to PDB’s FMU-PWM-In ports. The PDB FMU pins, which are powered by the ESC’s BEC, relay command signals to both servos and ESCs. This layout is depicted in Figure 3.5, and the ESCs, mounted on the forward fuselage panel, are pictured in Figure 3.4.

The radio control receiver is powered by the PX4 and is mounted on the aft fuselage panel with hook-and-pile tape. The GPS/compass module is also powered by the PX4 and is mounted near the edge of the rotor disk on a cantilevered 10.5 cm ground plane. The ground plane is made of 1/8 inch plywood covered in aluminum tape. It is cantilevered with 1/4 inch aluminum tube; secured with four 1/4 inch, rubber-lined suspension clamps; and mounted to the top of the battery compartment. This configuration is displayed in Figure 3.6.
3.2 Component/System Mass Breakdown

Table 3.1 breaks down the GimbalHawk’s total mass by component and category.

3.3 Vehicle Assembly Process

The open cuboid design of the GimbalHawk allows for access to most components as required for assembly and disassembly. Flight batteries are easily removed/installed with hook-and-pile tape. In order to facilitate overhead access to the electronics compartment, the gimbal/motor/rotor assembly is easily remove by disconnecting the ESC-motor wire connectors, disconnecting the roll servo wire from the PDB, remove the pitch control linkage clevis from the pitch servo horn using retaining ring pliers, and removing the two pitch axis shoulder screws with a 2.5 mm Allen wrench. Rotor components and the fuselage fasteners can be further disassembled with a metric Allen wrench, 7 mm socket wrench, and a low-profile 7 mm open end wrench. The landing gear is assembled without glue to allow for easy disassembly. The fully assembled GimbalHawk is pictured.
in Figure 3.7. Preflight procedures include verifying component security and correct wiring configurations.
Table 3.1. Component Mass Breakdown.

<table>
<thead>
<tr>
<th>Component/Category</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor &amp; wiring (from spec.)</td>
<td>1050</td>
</tr>
<tr>
<td>Landing gear assembly</td>
<td>791</td>
</tr>
<tr>
<td>Fuselage &amp; Fasteners (est.)</td>
<td>763</td>
</tr>
<tr>
<td>Rotors &amp; hub</td>
<td>300</td>
</tr>
<tr>
<td>Electronic Speed Control (×2) (from spec.)</td>
<td>154</td>
</tr>
<tr>
<td>Servo (×2) (from spec.)</td>
<td>110</td>
</tr>
<tr>
<td>PDB &amp; wiring (est.)</td>
<td>100</td>
</tr>
<tr>
<td>Gimbal &amp; control links</td>
<td>70</td>
</tr>
<tr>
<td>Series battery wiring adapter</td>
<td>53</td>
</tr>
<tr>
<td>GPS Compass</td>
<td>33</td>
</tr>
<tr>
<td>Telemetry radio</td>
<td>26</td>
</tr>
<tr>
<td>PX4 (from spec.)</td>
<td>24</td>
</tr>
<tr>
<td>R/C RX</td>
<td>6</td>
</tr>
<tr>
<td><strong>Empty Mass</strong></td>
<td><strong>3480</strong></td>
</tr>
<tr>
<td>Flight battery (×2)</td>
<td>1900</td>
</tr>
<tr>
<td><strong>Takeoff Mass</strong></td>
<td><strong>5380</strong></td>
</tr>
</tbody>
</table>
Figure 3.7. Fully Assembled GimbalHawk (Author Photo)
Chapter 4  
Gimbaled Coaxial UAV Flight Operations

This chapter presents the GimbalHawk’s operational history, wherein the proceeding chapters culminate and form the basis for final conclusions and future work.

4.1 Initial Flight Testing

Prior to flight testing, it was important to ensure that the control architecture was properly understood and configured.

4.1.1 Controller Structure and Flight Modes

The most widespread control technique implemented across the entire spectrum of aircraft is a proportional, integral, and derivative (PID) feedback control. The PX4 installed on the GimbalHawk uses this form of control in a layered approach. There are three nested loops comprised of the rate, attitude, and velocity & position controllers, in that order from lowest to highest level [21]. Each loop has its own sets of control gains for each respective control input to output response. QGroundControl’s software package was used to program the vehicle configuration and parameters into the controller. The available coaxial airframe reference is based on the ESky Big Lama R/C helicopter, wherein the accelerometers and gyros are located on the body of the UAV forward of the main rotor shaft and motors. Note that the ESky Big Lama uses a swashplate design to apply cyclic inputs to the lower rotor; in the case of the GimbalHawk, the pitch and roll channels were mapped directly to the pitch and roll servos of the gimbal, respectively.

The vehicle was programmed with three preset flight modes. Stabilized flight mode
maps pilot stick inputs to commanded bank angle, pitch angle, yaw rate, and total thrust. This was the only mode flown during the flight tests. Altitude hold mode (where pilot stick input maps to commanded climb rate) and position hold mode (where pilot inputs map to lateral and vertical velocity) require a well-tuned stabilized mode to operate safely. An emergency kill switch was also programmed into channel 10 of the RC controller.

Not all of the flight modes utilize all of the previously described control loops. In the stabilized mode for example, the pilot functions as the outermost loop in setting and adjusting stick commands to maintain a desired velocity or position. The inner loops meanwhile command pitch, roll, and yaw to maintain the referenced horizon and heading at takeoff. Given these relationships, it is important to start by tuning the rate controller first as it affects all selectable modes of flight control, moving to outer loop gains as the flight envelope of the vehicle is expanded.

The mechanical simplicity of a multicopter allows for thrust vectoring by manipulating the speeds of the individual motors to achieve the commanded flight profile. Given its simplicity and variability, there are many available supported airframe references on which to configure a vehicle with a PX4, some even specifically tuned for COTS frames. Given the novel control mechanism some vehicle parameters needed to be changed to make the GimbalHawk controllable.

4.1.2 Flight Testing and Development

All flight tests were conducted on a paved surface with a slight southern sloping grade. The tests were conducted in an area surrounded by trees and buildings to limit any flyaway conditions. The flight data was logged on the PX4’s on-board storage, but also monitored on a MacBook Pro laptop with QGroundControl via the telemetry radio.

Preflight checks were conducted to ensure that rotors spin in the correct direction. The yaw for this vehicle is controlled by varying the speed of each motor, which varies the torque to track a reference yaw command. If the signals are switched, any small error is yaw will cause the vehicle to spin out of control. Thus, it is also vitally important to ensure that the rotation of each motor matches the airframe reference and the motor’s ESC signal corresponding to each rotor is connected to the correct output on the PMB.

Prior to the first flight, rotors were removed and the vehicle armed to determine if the control response mirrored the pilots RC inputs. The pitch axis on RC channel 2 was reversed due to the way in which the control linkages were rigged. As such, the RC2_REV parameter was set to -1 to reverse the channel. Additionally, with the system armed and motors static, tilt tests of the body were conducted to verify proper
control stabilization response to disturbance in roll and pitch. Prior to any changes to location and orientation of the vehicle components, the control response was reversed. For example, pitching body nose down resulted in pitch servo commands to pitch the rotors more nose down.

4.1.2.1 Flight 1

The first successful flight (see Figure 4.1) was achieved. The initial test objective was to achieve stable hover. The ambient temperature was 26 °C and the reported winds were
5 knots from the NE. During this event, it was observed that the body of the vehicle hovered in a nose-high, right-bank bank attitude. Pilot control was required to counteract a constant forward and left drift. From this observation, ESCs and servos were moved to shift the CG of the body closer to directly below the gimbal axes. The magnetometer and GPS antenna was repositioned further aft to improve signal and reduce rotor downwash on the GPS ground plane. As a result the orientation of the magnetometer relative to the airframe was changed, and this was set in the PX4 CAL_MAG0_ROT parameter.

4.1.2.2 Flight 2

One of the subsequent test flights occurred on August 26, 2020 to observe hover stability and control following vehicle reconfiguration. The ambient temperature 26.5°C and winds were reported at 10 knots from the W. In this test, the roll attitude had been centered, but the pitch was still 10° nose-high. As such, forward drift was still present and needed pilot stick correction. Of note, the GPS ground plane had not yet been moved further aft out of the rotor downwash for this test. The rotors were made out of wooden propellers designed for use with the MaxxProd motor for fixed-wing RC use.

On post-flight, it was discovered that the motor casing was very hot to the touch. Risk was considered for future tests and determined not a significant factor given future modifications and dropping ambient temperatures. Subsequent analysis of motor current showed roughly 23A current going to each motor. Given the motor winding resistance of 0.35 Ω, the power dissipated in each motor is approximately 190 W, which will cause significant heating.

4.1.2.3 Flight 3

The ambient temperature was 21 °C and winds reported calm. In an attempt to cancel out the drift in a hover, an additional step was added to the preflight checks. With battery power connected, emergency kill switch engaged, and PX4 safety switch off, the vehicle was suspended by hand from the rotors to place the body and IMU in its hovering attitude. The Level Horizon calibration was then completed via QGroundControl on the telemetry computer. This set ultimately eliminated the forward drift present in previous tests allowing for a hands-free hover in the stabilized flight mode. Additionally, the GPS ground plane was cantilevered further aft at the edge of the rotor disk for this test.

As the vehicle was at a stable hover, pilot commanded impulse response tests were initiated. Body oscillations were observed. Some attempts were made to tune the response by increasing the proportional gain on the pitch and roll rate were increased.
slightly, but more flight tests would be required in order to sufficiently damp the observed response.

4.1.2.4 Flight 4

The decision was made to redesign the rotor system to take advantage of COTS carbon fiber blades with a better twist ratio, yielding a more uniform inflow for efficient hovering performance. The ambient temperature 6.5°C and winds were reported at 10 gusting up to 15 knots from the N. It should also be noted that the winds coming from the North are the least obstructed at the flight test site. During this test with the wind conditions, it was observed that the servos are back-drivable due to wind, or other environmental disturbances.

4.1.3 Rotor Blade Change

Figures 4.3 through 4.10 depict the performance of the GimbalHawk with wooden propellers compared against the carbon fiber rotors. The plotted data is from separate flight logs, collected from flights 2 and 4.

Rotor speed was confirmed at approximately 3240 RPM based on observed vibration data (See Figure 4.2), where RPM is extrapolated from the rotor noise near 54 Hz. The acceleration power spectral density plots were generated by uploading the vehicle flight logs to the PX4 online flight review tool\(^1\).

Referencing Figures 4.3 and 4.4, it is demonstrated that modifications enabled controlled hovering flight in a more confined footprint. The start of the data for the flight 2 with the wooden propellers began in southwestern quadrant, but did not achieve takeoff until ground-taxiing to the northeast. Temporary hands-free hover was possible, despite wind disturbances on the flight 4. Also, ease of maneuverability from pilot stick commands notably improved.

Between the two flights, no alteration was made to the hover throttle settings, nor any further tuning of the controller gains. The implementation of the KDE rotors alone resulted in a 31.2% decrease in total vehicle current and a 27.2% decrease in throttle for the same hovering flight mode (see Figures 4.5 and 4.6).

Noting the weather differences between the two flight test samples, the flight log data suggests that the KDE rotor configuration with suspended level horizon calibration performed better. Figures 4.7 and 4.8 depict the Euler angles and body angular rates

\(^1\text{https://review.px4.io/}\)
over the same time span and respective vertical axis scales. While they appear similar, the larger magnitude pitch and roll deviations on the KDE rotor flight data correspond to the under-damped body oscillations that were observed in earlier flights due to responses to pilot commands. By contrast, the magnitude of angular position and rate noise is more constant and uncorrelated.

Suspending the vehicle from its rotor system while conducting the level horizon calibration clearly helped to center pitch and roll hover control forces (see Figures 4.9 and 4.10). The yaw control remained steady in both angular position, angular rate, and
Figure 4.3. Flight GPS Position: Wooden Propeller

Figure 4.4. Flight GPS Position: KDE Rotor
Figure 4.5. Total Power Usage and Throttle: Wooden Propeller

Figure 4.6. Total Power Usage and Throttle: KDE Rotor
pilot control inputs irrespective of vehicle configuration, indicating the pre-programmed airframe reference yaw control architecture and associate parameters were adequately tuned for hover.
Figure 4.8. Euler Angles and Body Rates: KDE Rotor
Figure 4.9. Normalized Pilot Stick Inputs: Wooden Propeller

Figure 4.10. Normalized Pilot Stick Inputs: KDE Rotor
This chapter presents the main outcomes in the design and development of the Gimbal-Hawk. Prospective continued effort is also suggested based on issues that arose during this iteration of project work.

5.1 Conclusions

This vehicle demonstrated a proof-of-concept for a CAT-HR UAV using commercially available drive-train/rotor combinations and open-source software. Initial system design yielded a vehicle capable of hovering flight. Continued system development through reconfiguration and programming improved the stability, control, and overall performance of the GimbalHawk. Construction with additive manufacturing for the gimbal components assures ease of interchanging various motors, servos, and rotor systems.

5.2 Future Work

A number of modifications were identified during construction and flight testing that are needed to improve flight performance and continue experimentation toward researching scalability of a CAT-HR configured UAV.

5.2.1 Controller Tuning, Flight Envelope Expansion, and System Identification

Further tuning of the current configuration is required to improve stability of the vehicle in the stabilized/manual mode while hovering. Flight in an indoor facility is recommended to eliminate environmental disturbances. An experienced pilot is also recommended to
accomplish this task. When properly tuned, the vehicle should be able to hold a stable position without correction for several seconds [21].

Once properly tuned, the operating envelope can be tested against the design goals of delivering a 1 kg payload over 2 km, 15 minute endurance, and flight in 15 mph winds. In addition, frequency-domain methods of system identification can be used to extract a physical model to improve lower order models. The US Army/NASA CIFER program has been shown to be very useful in the development of UAV programs. The extracted system identification model can then be used to design, rapidly construct, and tune scaled CAT-HR vehicles [20].

5.2.2 IMU Positioning

If the observed oscillations are not sufficiently stabilized with controller tuning, perhaps re-positioning the flight controller, and thus the IMU, would help. Strapping the PX4 in the same reference frame as the rotor system would put the sensors in the same frame as the servo inputs. Remaining changes to pitch and roll angular rates would be due to either vibrations or the body/fuselage response to the commanded inputs. However, when pitch and roll changes are commanded, the accelerometers will sense an acceleration due to the commanded input unless the IMU is exactly centered in the gimbal axes. Unfortunately, as it is currently configured, the motor is in the center of the gimbal rotation, which is also roughly the predicted CG of the total rotor system.

Similar to the Schuler tuning problems of early gyroscopes, in terms of keeping the North and East accelerometers horizontal, one would need to tune out the commanded pitch and roll angles. If the servo angles are known, then it is possible to re-reference the accelerometer axes in-flight, assuming the data rates support the computations. Once ‘tuned’, the difference between the updated setpoint for each axis and the accelerometer’s signal should be the accelerations felt on the vehicle. In that effort, using single degree-of-freedom gyroscopes on each gimbal axis may be simpler than moving the whole controller, but would require incorporating the new signals into the PX4 controller.

5.2.3 Wind Disturbance Resistance

During flight testing with the KDE rotor modification, it was observed that the pitch and roll servos are back-drivable during higher winds and gust conditions. Backdrivability is common in servos, but, if stability is the goal, the torque applied by the wind on the servo by its effects on the rotor disk should not be enough to over power the servo.
There are a few possible modifications that could improve performance in windy conditions. The simplest would be to modify the control linkages to the control arm on each servo. Currently, the quiklink clevises are connected further out on each servo arm. While this increases the moment of the rotor/motor system on the servo, it also gives the servo a wider range control authority in that axis. Thus, a compromise between backdrivability and control range for each axis could be made for future experimentation.

A second modification would be to install an alternate BEC for both servos, or reprogram the ESC BEC for a higher voltage. The installed servos are capable of operating up to 6 V, but are currently limited to 5 V supplied by the BEC by either ESC. Increasing the voltage could improve each servo’s torque by 20%, but could also mean adding mass to the vehicles empty weight. There is available mounting surface area near the ESC or on the shelf of the electronics compartment for an higher-voltage BEC.

Lastly, larger servos could be selected to replace the current servos, but this would require a redesign of the gimbal components as each servo is encased tightly by the gimbal plate walls. If redesigning the gimbal, one may also opt to drive the gimbal axes directly, which may be required as the vehicle configuration is scaled up or down. Again, the main cost here would be a larger incurred vehicle empty weight.

In either case, the test environment should be more controlled to precisely test the flight envelope due to wind disturbance. If indoor flight tests are possible, consider using a fan and anemometer to expose and observe the vehicle’s response.

5.2.4 Motor Case Temperature

Post-flight assessment during flight testing revealed a case temperature that was hot to the touch. The motor manufacturer published a maximum case temperature of 65°C and advises that insufficient cooling could cause the motors to overheat and fail. The motor is located directly below the induced flow of the rotor system, but may require additional means of cooling. After installing the KDE blade rotor system, the temperature of the case was not recorded. Future consideration of at least a means of monitoring the case temperature in flight is advised to prevent an in-flight motor failure.

5.2.5 Pusher Propeller

It may be possible to enable more efficient high speed forward flight with the addition of a tractor or pusher propeller, such as seen on the Sikorsky Raider and Defiant aircraft. Conventional and most coaxial rotor helicopters have utilized the thrust generated by
the main rotor as both a lifting and propulsive forces required to maintain trimmed, level forward flight. An auxiliary propeller could be implemented to provide the necessary propulsive force for forward flight, thus permitting further optimization of the main rotors for high speed flight.
Appendix
Non-Default PX4 Parameters

Parameters Table

The final GimbalHawk firmware configuration used the following non-default parameters within the PX4 autopilot suite. Airframe type was set as Coaxial Helicopter, vehicle was set as Esky (Big) Lama v4, and firmware version was 1.10.1 on the PX4 board.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT_A_PER_V</td>
<td>Current per volt (A/V)</td>
<td>36.36751556</td>
</tr>
<tr>
<td>BAT_CNT_V_CURR</td>
<td>ADC current scaling</td>
<td>0.00080566</td>
</tr>
<tr>
<td>BAT_CNT_V_VOLT</td>
<td>ADC voltage scaling</td>
<td>0.00080566</td>
</tr>
<tr>
<td>BAT_N_CELLS</td>
<td>Number of cells</td>
<td>8</td>
</tr>
<tr>
<td>BAT_V_DIV</td>
<td>Battery voltage divider</td>
<td>17.96882820</td>
</tr>
<tr>
<td>CAL_ACC0_ID</td>
<td>Calibration Accelerometer ID</td>
<td>3866634</td>
</tr>
<tr>
<td>CAL_ACC0_XOFF</td>
<td>Acc X-axis Offset</td>
<td>1.708</td>
</tr>
<tr>
<td>CAL_ACC0_XSCALE</td>
<td>Acc X-axis scaling factor</td>
<td>0.9229</td>
</tr>
<tr>
<td>CAL_ACC0_YOFF</td>
<td>Acc Y-axis Offset</td>
<td>0.126</td>
</tr>
<tr>
<td>CAL_ACC0_YSCALE</td>
<td>Acc Y-axis scaling factor</td>
<td>0.9987</td>
</tr>
<tr>
<td>CAL_ACC0_ZOFF</td>
<td>Acc Z-axis Offset</td>
<td>0.0914 kg</td>
</tr>
<tr>
<td>CAL_ACC0_ZSCALE</td>
<td>Acc Z-axis scaling factor</td>
<td>0.9882</td>
</tr>
<tr>
<td>CAL_ACC1_ID</td>
<td>Calibration Accelerometer ID</td>
<td>4260618</td>
</tr>
<tr>
<td>CAL_ACC1_XOFF</td>
<td>Acc X-axis Offset</td>
<td>0.656</td>
</tr>
<tr>
<td>CAL_ACC1_XSCALE</td>
<td>Acc X-axis scaling factor</td>
<td>0.984</td>
</tr>
<tr>
<td>CAL_ACC1_YOFF</td>
<td>Acc Y-axis Offset</td>
<td>-0.053</td>
</tr>
<tr>
<td>Parameter Name</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>CAL_ACC1_YSCALE</td>
<td>Acc Y-axis scaling factor</td>
<td>0.979</td>
</tr>
<tr>
<td>CAL_ACC1_ZOFF</td>
<td>Acc Z-axis Offset</td>
<td>0.286</td>
</tr>
<tr>
<td>CAL_ACC1_ZSCALE</td>
<td>Acc Z-axis scaling factor</td>
<td>0.984</td>
</tr>
<tr>
<td>CAL_ACC_PRIME</td>
<td>Primary Acc</td>
<td>3866634</td>
</tr>
<tr>
<td>CAL_GYRO00_ID</td>
<td>Calibration Gyro ID</td>
<td>3932170</td>
</tr>
<tr>
<td>CAL_GYRO00_XOFF</td>
<td>Gyro X-axis Offset</td>
<td>0.071</td>
</tr>
<tr>
<td>CAL_GYRO00_YOFF</td>
<td>Gyro Y-axis Offset</td>
<td>-0.013</td>
</tr>
<tr>
<td>CAL_GYRO00_ZOFF</td>
<td>Gyro Z-axis Offset</td>
<td>-0.006</td>
</tr>
<tr>
<td>CAL_GYRO1_ID</td>
<td>Calibration Gyro ID</td>
<td>4325898</td>
</tr>
<tr>
<td>CAL_GYRO1_XOFF</td>
<td>Gyro X-axis Offset</td>
<td>-0.001</td>
</tr>
<tr>
<td>CAL_GYRO1_YOFF</td>
<td>Gyro Y-axis Offset</td>
<td>0.002</td>
</tr>
<tr>
<td>CAL_GYRO1_ZOFF</td>
<td>Gyro Z-axis Offset</td>
<td>-0.006</td>
</tr>
<tr>
<td>CAL_GYRO_PRIME</td>
<td>Primary Gyro</td>
<td>3932170</td>
</tr>
<tr>
<td>CAL_MAG0_ID</td>
<td>Calibration Magnetometer ID</td>
<td>396809</td>
</tr>
<tr>
<td>CAL_MAG0_ROT</td>
<td>Mag 0 Rotation vs Airframe</td>
<td>Yaw 180°</td>
</tr>
<tr>
<td>CAL_MAG0_XOFF</td>
<td>Mag X-axis Offset</td>
<td>-0.006</td>
</tr>
<tr>
<td>CAL_MAG0_XSCALE</td>
<td>Mag X-axis scaling factor</td>
<td>0.961</td>
</tr>
<tr>
<td>CAL_MAG0_YOFF</td>
<td>Mag Y-axis Offset</td>
<td>-0.009</td>
</tr>
<tr>
<td>CAL_MAG0_YSCALE</td>
<td>Mag Y-axis scaling factor</td>
<td>1.025</td>
</tr>
<tr>
<td>CAL_MAG0_ZOFF</td>
<td>Mag Z-axis Offset</td>
<td>-0.235</td>
</tr>
<tr>
<td>CAL_MAG0_ZSCALE</td>
<td>Mag Z-axis scaling factor</td>
<td>1.054</td>
</tr>
<tr>
<td>CAL_MAG1_ID</td>
<td>Calibration Magnetometer ID</td>
<td>396825</td>
</tr>
<tr>
<td>CAL_MAG1_XOFF</td>
<td>Mag X-axis Offset</td>
<td>-0.014</td>
</tr>
<tr>
<td>CAL_MAG1_XSCALE</td>
<td>Mag X-axis scaling factor</td>
<td>1.023</td>
</tr>
<tr>
<td>CAL_MAG1_YOFF</td>
<td>Mag Y-axis Offset</td>
<td>-0.169</td>
</tr>
<tr>
<td>CAL_MAG1_YSCALE</td>
<td>Mag Y-axis scaling factor</td>
<td>0.986</td>
</tr>
<tr>
<td>CAL_MAG1_ZOFF</td>
<td>Mag Z-axis Offset</td>
<td>-0.656</td>
</tr>
<tr>
<td>CAL_MAG1_ZSCALE</td>
<td>Mag Z-axis scaling factor</td>
<td>1.005</td>
</tr>
<tr>
<td>CAL_MAG_PRIME</td>
<td>Primary Mag</td>
<td>396809</td>
</tr>
<tr>
<td>COM_FLTMODE1</td>
<td>1st flight mode slot</td>
<td>Position</td>
</tr>
<tr>
<td>COM_FLTMODE4</td>
<td>4th flight mode slot</td>
<td>Altitude</td>
</tr>
<tr>
<td>COM_FLTMODE6</td>
<td>6th flight mode slot</td>
<td>Stabilized</td>
</tr>
<tr>
<td>EKF2_MAGBIAS_ID</td>
<td>Bias Mag ID</td>
<td>396809</td>
</tr>
<tr>
<td>EKF2_MAGDECL</td>
<td>Magnetic declination (°)</td>
<td>-10.6</td>
</tr>
<tr>
<td>Parameter Name</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MAV_TYPE</td>
<td>MAVLink airframe type</td>
<td>Coaxial Heli</td>
</tr>
<tr>
<td>MC_PITCHRATE_D</td>
<td>Pitch rate D gain</td>
<td>0.0050</td>
</tr>
<tr>
<td>MC_PITCHRATE_I</td>
<td>Pitch rate I gain</td>
<td>0.050</td>
</tr>
<tr>
<td>MC_PITCH_P</td>
<td>Pitch P gain (rad/s)</td>
<td>5.00</td>
</tr>
<tr>
<td>MC_ROLLRATE_D</td>
<td>Roll rate D gain</td>
<td>0.0050</td>
</tr>
<tr>
<td>MC_ROLLRATE_I</td>
<td>Roll rate I gain</td>
<td>0.050</td>
</tr>
<tr>
<td>MC_ROLLRATE_P</td>
<td>Roll rate P gain</td>
<td>0.170</td>
</tr>
<tr>
<td>MC_ROLL_P</td>
<td>Roll P gain (rad/s)</td>
<td>5.00</td>
</tr>
<tr>
<td>MC_YAWRATE_P</td>
<td>Yaw rate P gain</td>
<td>0.10</td>
</tr>
<tr>
<td>MC_YAW_P</td>
<td>Yaw P gain (rad/s)</td>
<td>2.00</td>
</tr>
<tr>
<td>MPC_MANTHR_MIN</td>
<td>Min. manual thrust (%)</td>
<td>0.00</td>
</tr>
<tr>
<td>NAV_ACC_RAD</td>
<td>Acceptance Radius (m)</td>
<td>2.0</td>
</tr>
<tr>
<td>PWM_MAX</td>
<td>Max. PWM for main outputs (µs)</td>
<td>1950</td>
</tr>
<tr>
<td>PWM_MIN</td>
<td>Min. PWM for main outputs</td>
<td>1075</td>
</tr>
<tr>
<td>RC10_MAX</td>
<td>RC channel 10 maximum (µs)</td>
<td>2064.000</td>
</tr>
<tr>
<td>RC10_MIN</td>
<td>RC channel 10 minimum (µs)</td>
<td>1106.000</td>
</tr>
<tr>
<td>RC10_TRIM</td>
<td>RC channel 10 trim (µs)</td>
<td>1514.000</td>
</tr>
<tr>
<td>RC1_MAX</td>
<td>RC channel 1 maximum (µs)</td>
<td>1924.000</td>
</tr>
<tr>
<td>RC1_MIN</td>
<td>RC channel 1 minimum (µs)</td>
<td>1106.000</td>
</tr>
<tr>
<td>RC1_TRIM</td>
<td>RC channel 1 trim (µs)</td>
<td>1523.000</td>
</tr>
<tr>
<td>RC2_MAX</td>
<td>RC channel 2 maximum (µs)</td>
<td>1924.000</td>
</tr>
<tr>
<td>RC2_MIN</td>
<td>RC channel 2 minimum (µs)</td>
<td>1104.000</td>
</tr>
<tr>
<td>RC2_REV</td>
<td>RC channel 2 reverse</td>
<td>-1 (Reverse)</td>
</tr>
<tr>
<td>RC2_TRIM</td>
<td>RC channel 2 trim (µs)</td>
<td>1514.000</td>
</tr>
<tr>
<td>RC3_MAX</td>
<td>RC channel 3 maximum (µs)</td>
<td>1924.000</td>
</tr>
<tr>
<td>RC3_MIN</td>
<td>RC channel 3 minimum (µs)</td>
<td>1104.000</td>
</tr>
<tr>
<td>RC3_TRIM</td>
<td>RC channel 3 trim (µs)</td>
<td>1104.000</td>
</tr>
<tr>
<td>RC4_MAX</td>
<td>RC channel 4 maximum (µs)</td>
<td>1924.000</td>
</tr>
<tr>
<td>RC4_MIN</td>
<td>RC channel 4 minimum (µs)</td>
<td>1104.000</td>
</tr>
<tr>
<td>RC4_TRIM</td>
<td>RC channel 4 trim (µs)</td>
<td>1512.000</td>
</tr>
<tr>
<td>RC5_MAX</td>
<td>RC channel 5 maximum (µs)</td>
<td>2064.000</td>
</tr>
<tr>
<td>RC5_MIN</td>
<td>RC channel 5 minimum (µs)</td>
<td>964.000</td>
</tr>
<tr>
<td>RC5_TRIM</td>
<td>RC channel 5 trim (µs)</td>
<td>1514.000</td>
</tr>
<tr>
<td>RC7_MAX</td>
<td>RC channel 7 maximum (µs)</td>
<td>2064.000</td>
</tr>
<tr>
<td>Parameter Name</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>RC7_MIN</td>
<td>RC channel 7 minimum (µs)</td>
<td>964.000</td>
</tr>
<tr>
<td>RC7_TRIM</td>
<td>RC channel 7 trim (µs)</td>
<td>1514.000</td>
</tr>
<tr>
<td>RC8_MAX</td>
<td>RC channel 8 maximum (µs)</td>
<td>2064.000</td>
</tr>
<tr>
<td>RC8_MIN</td>
<td>RC channel 8 minimum (µs)</td>
<td>964.000</td>
</tr>
<tr>
<td>RC8_TRIM</td>
<td>RC channel 8 trim (µs)</td>
<td>1514.000</td>
</tr>
<tr>
<td>RC9_MAX</td>
<td>RC channel 9 maximum (µs)</td>
<td>2064.000</td>
</tr>
<tr>
<td>RC9_MIN</td>
<td>RC channel 9 minimum (µs)</td>
<td>964.000</td>
</tr>
<tr>
<td>RC9_TRIM</td>
<td>RC channel 9 trim (µs)</td>
<td>1514.000</td>
</tr>
<tr>
<td>RC_CHAN_CNT</td>
<td>RC Channel Count</td>
<td>18</td>
</tr>
<tr>
<td>RC_MAP_FLTMODE</td>
<td>Single channel flight mode selection</td>
<td>Channel 7</td>
</tr>
<tr>
<td>RC_MAP_KILL_SW</td>
<td>Kill switch channel</td>
<td>Channel 10</td>
</tr>
<tr>
<td>RC_MAP_PITCH</td>
<td>Pitch Control channel</td>
<td>Channel 2</td>
</tr>
<tr>
<td>RC_MAP_ROLL</td>
<td>Roll Control channel</td>
<td>Channel 1</td>
</tr>
<tr>
<td>RC_MAP_THROTTLE</td>
<td>Throttle Control channel</td>
<td>Channel 3</td>
</tr>
<tr>
<td>RC_MAP_YAW</td>
<td>Pitch Control channel</td>
<td>Channel 4</td>
</tr>
<tr>
<td>RTL_DESCEND_ALT</td>
<td>Return mode loiter altitude (m)</td>
<td>10.0</td>
</tr>
<tr>
<td>RTL_RETURN_ALT</td>
<td>Return to launch transit altitude (m)</td>
<td>30.0</td>
</tr>
<tr>
<td>SENS_BOARD_X_OFF</td>
<td>Board rotation X (Roll) offset (°)</td>
<td>-1.484</td>
</tr>
<tr>
<td>SENS_BOARD_Y_OFF</td>
<td>Board rotation Y (Pitch) offset (°)</td>
<td>-0.658</td>
</tr>
<tr>
<td>SYS_AUTOSTART</td>
<td>Auto-start script index</td>
<td>15001</td>
</tr>
<tr>
<td>SYS_RESTART_TYPE</td>
<td>Restart Type</td>
<td>0 (Survives)</td>
</tr>
</tbody>
</table>


