Design, Modelling and Control of a Single Rotor UAV

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ABSTRACT

In this thesis, a novel Vertical Take-Off and Landing (VTOL) Single Rotor Unmanned Aerial Vehicle (SR-UAV) will be presented. The SR-UAV's design properties will be analysed in detail, with respect to technical novelties outlining the merits of such a conceptual approach. The system's model will be mathematically formulated, while a cascaded P-PI and PID-based control structure will be utilized in extensive simulation trials for the preliminary evaluation of the SR-UAV's attitude and translational performance. Further a prototype SR-UAV will be presented with a corresponding experimental evaluation of the established control scheme. Finally analytic discussions on the obtained results, as well as on the current design limitations and future research directions will also be depicted.

PREFACE

I would like to express my gratitude towards the faculty of the Control Engineering group at Luleå University of Technology who all freely offered their expertise and shared with me in their excitement for the field.

Thank you supervisor Professor George Nikolakopoulos, who's perspective and encouragement has left me in an appetite for further academic pursuits.

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Finally, thank to you the reader for showing an interest in my work and remember to rosbag everything.

- Christoffer Carholt

ABBREVIATION LIST

R	: Propeller radius
D_t	: Inner diameter of duct
δ_{tip}	: Blade tip clearance
L_d	: Diffuser length
θ_d	: Diffuser angle
r_{lip}	: Inlet/lip radius
L	: Length
C_l	: Coefficient of lift
ρ	: Air density
V	: True airspeed
A	: Surface area
μ	: Mean
σ^2	: Variance
CG	: Centre of Gravity
L	: z component of distance CG to centre of Control surface
r	: x,y component of distance CG to centre of Control surface
UAV	: Unmanned Aerial Vehicles
VTOL	: Vertical Take-Off and Landing
SR	: Single-Rotor
AoA	: Angle of Attack
ESC	: Electronic Speed Control
DOF	: Degrees of Freedom
RMSE	: Root mean square error
GS	: Ground Station
PLA	: Polylactide (Plastic)
IMU	: Inertial Measurement Unit

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CHAPTER 1

Introduction

1.1 Background information

The Unmanned Aerial Vehicle (UAV) refers to aircraft without a pilot on board. Instead the UAV is controlled either remotely through a pilot or at some degree of autonomy. UAVs are commonly found to be used in military operations, where they are used, e.g. for surveillance, with the intent to avoid threatening a pilot's life together with considerably reducing the logistic impact of the flight operations.

In recent years there has been an increased interest in recreational activities involving various types of UAVs, mainly in the form of traditional radio-controlled-fixed-wing aircrafts and rotor-based UAVs, such as helicopters and multicopters. Commercial and civil use of UAV's has been used in areas such as inspection[1], forest-fire surveillance [2], aerial photography/filming [3] and surveying/mapping [4], while there exists a wide range of UAV sizes, all from the so called nano-UAV's (mass < 0.025kg) to "High Altitude Long Endurance" UAV's (2500kg < mass < 5000kg). The size of the UAV proposed in this thesis can be identified as a Micro-UAV (mass < 5kg) [5].

Further for the purposes of this thesis, another feature of interest are those UAV's equipped with a Vertical Take-Off and Landing (VTOL) capabilities. The VTOL field of study has received a constant increase of research interest during the last decade [6, 7], mainly due to the important advantages of excluding the need for take-off runways, as well as their low cost design approach. Furthermore, in the general field of VTOLs, there have been multiple designs with the most dominant ones to be those of a) helicopters [8], b) multirotors [9] and c) tilt rotors/wings [10], each providing different mechanical merits in their translational and hovering capabilities. A different approach of a single rotor VTOL design has been researched in the past decades, which bases its operation on the operational principle of thrust vectoring via the utilization of a single propeller and control fins [11, 12]. This specific type of UAV has the merit of simplifying the design process, while keeping the development cost to a minimum, thus increasing their applicability in real life applications, while rendering them as a promising alternative aircraft solution to existing VTOL micro-UAV designs.

1.1.1 The Tail-Sitter concept

In the 1950s and 1960s experimental VTOL aircrafts such as the Convair XFY Pogo [13] seen in Figure. 1.1 (a) and the Lockheed XFV [14] in Figure. 1.1 (b) both intended for use by the United States Navy have been developed that possessed the ability of taking off and landing on their tail, then tilt horizontally for forward flight, commonly known as a tail-sitter [15]. However, their utilization have been proven impractical because of several issues, such as their difficulty in landing due to the pilots visual restriction, even if in the proposed tail-sitting SR-UAV designs this limitation is not encountered as the vehicle will be operated remotely at some degree of autonomy.

(a)

(b)

Figure 1.1: (a) The Convair XFY Pogo in vertical flight, (b) The Lockheed XFV sitting on it's tail.

Furthermore, the tail-sitter concept is seen in hobbyist RC-planes designed for 3D aerobatics, Figure. 1.2 (a), where the plane's thrust to weight ratio is greater than 1 and thus it is capable of hovering. UAV's such as the v-bat [16] demonstrates the same principle featuring VTOL and translational flight capabilities, Figure. 1.2 (b).

1.1.2 Single-Rotors

Tail-Sitter UAVs have been successfully utilized in the cases of military surveillance missions and inspection of disaster sites, such as the damaged Fukushima Dai-Ichi nuclear power station,

(a)

(b)

Figure 1.2: (a) 3D flyer , (b) V-bat. Examples of tail-sitter UAVs

where the Single Rotor UAV, Honeywell RQ-16A T-Hawk, as seen in Figure. 1.3, was utilized to survey the the hazardous reactor area[17]. An advantage of the SR-UAVs, when compared to counter rotating propeller and multi-rotor based designs, is a reduction in complexity, i.e. no gearbox, less motors/propellers that in turn lead to less points of failure and a more economical solution [18]. In addition, a ducted propeller leads to a higher efficiency [19], while it is safer to operate and has a lower chance of human injuries during operation due to the portected rotor. On the contrary, an inherent issue that describes the SR-UAVs, is the fact that in such designs the propeller create a torque on angular acceleration of the vehicle, which leads to a rotation that needs to be counteracted to achieve a stable yaw [20].

Figure 1.3: T-hawk

1.2 Thesis Objective and Limitations

The overall objective of the project is to: a) develop a model prototype SR-UAV both regarding design features and the physical properties relating to the design. b) Propose and simulate a control structure for the SR-UAV using a graphical programming environment in order to make a preliminary evaluation of the proposed control structure. c) Construct a physical prototype using rapid prototyping tools such as a 3D-printer for the plastic construction and a CNC-mill for carbon fibre parts. d) Implement the proposed control structure on the prototype hardware to determine the flight characteristics and viability of the design and control structure.

CHAPTER 2

Design and Modelling

2.1 Design of the Single Rotor UAV

In Figure.2.1 a graphical representation of the proposed SR-UAV is presented with the main components of the SR-UAV highlighted. The airframe consists of an inner core, which holds the avionics and the carbon fibre support struts, which in turn connects the core with a fan duct and the four control fins. A structural support for the suspension rod, on which the control fins are rigidly fitted, was designed to act as landing struts. The SR-UAV design properties can be divided into three sub-systems, namely: a) the avionics, b) the propulsion, and c) the flight control, which further will be analysed in detail.

Figure 2.1: The SR-UAV with main components highlighted

2.1.1 Airframe

Figure 2.2 shows an overview of the SR-UAV's modelled airframe structure which acts as the systems mechanical foundation. In this approach four threaded rod studs located symmetrically

Figure 2.2: The airframe of the SR-UAV.

around the centre axis act as the mounting points for the core of the airframe. At the bottom of the studs there is a plastic structure for mounting four servo motors which will be acting as the actuators for the control fins. The top of the studs are fitted with a plastic motor mount that uses a thin carbon fibre plate as a firewall to contain heat generated by the motor so as to mitigate potential deformation of plastic parts. Carbon fibre rods were fitted in a plastic mount to the core and were designed to provide structural integrity of the SR-UAV and to support a duct. Further carbon fibre rods were fitted to the bottom servo mount to act as a suspension for the four control fins. Lightweight plastic landing struts acting as legs for the SR-UAV were designed to protect the control-fins during landing. They also provides mounting points for avionics and motion capture markers. For further analysis please refer to chapter 5.2.1 regarding the motion capture.

2.1.2 Propulsion system

The SR-UAV was designed to be actuated by an outrunner brushless DC motor of the type Turningy D2836/8 1100KV that drives the propeller in a pulling configuration powered by an 30A Turningy electronic speed controller (ESC).

Duct

A duct was proposed in this design in order to increase the thrust, while lowering the noise when operating at hover or at near hover states, as well as to increase the overall safety of operating the SR-UAV in populated areas, Figure 2.3. However, the proper placement of the

Figure 2.3: The duct of the SR-UAV.

duct is a mechanical detail of high importance in order to contribute in performance over the resulting increase in weight. The duct design was based on a dissertation [19], where analytical and wind-tunnel experiments were conducted in order to describe a general ideal duct profile in a hovering state. The parameters for the duct design is based on these results considering chosen propeller as seen in Figure. 2.4: where D_t is the inner diameter, δ_{tip} is the blade tip clearance, L_d is the diffuser length, θ_d is the diffuser angle and r_{lip} is the inlet or lip radius. The values of these parameters were chosen as suggested as in Table.2.1.

There are several reasons for implementing a ducted fan while the main advantages that apply to the adopted design are:

- Increase in thrust due to decrease in blade tip losses [21].

Figure 2.4: Shroud design parameters

Parameter	Expression derived in [19]	SR-UAV design value
δ_{tip}	$\leq 0.012R$	1mm
D_t	$R + 2\delta_{tip}$	256mm
L_d	$0.50D_t$	128mm
r_{lip}	$0.13D_t$	33mm
θ_d	$\approx 10^\circ$	10°

Table 2.1: Design parameters of duct

- Increased airflow over the propeller which leads to higher efficiency.
- The shielding of the blades and the reduced tip vortices both leads to a lower noise level.
- The duct potentially shields both the propeller and the environment from damage in case of a crash.
- The duct makes observers feel safer, when close to the SR-UAV during in operation.

These reasons must however to be defended against the weight and drag that the duct adds to the UAV, hence tests needs to be done in order to determine if a ducted approach is viable for the design. For further information regarding the viability of the duct refer to chapter 5.

2.1.3 Avionics

From a conceptual point of view, an on-board flight computer system can be utilized to output five control signals, one to control the thrust of the motor and four for torque control via regulating the motion of the control fins. The microprocessor is used to run the angular rate control loop, while incorporating an Inertial Measurement Unit (IMU) as feedback. The flight computer is also intended to communicate with a ground-station that is executing the translational/position control loop, with position data feedback from a motion capture system, without the need of additional on-board sensors at this phase of design. The Li-Po battery pack is properly placed on the centre-axis so as to not contribute any imbalance.

Onboard Computer

A small onboard flight computer as seen in Figure. 2.5 called the KFly platform [9] was adopted to be used on the SR-UAV. This platform features a small form factor and a low weight, which is an important constraint in choosing the platform together with the computational power it brings. The Micro Controller Unit (MCU) driving the system is ST's

Figure 2.5: The KFly board.

STM32F405RGT6, an 32-bit ARM Cortex-M4F Central Processing Unit (CPU) featuring a Digital Signal Processing (DSP) core and an 32-bit single precision Floating Point Unit (FPU), all running at 168 MHz where most math operations have single cycle execution.

The main sensors on the KFly board which are used for control purposes are the following ones:

- Invensense's MPU-6050 MEMS Accelerometer and Gyroscope System on a Chip (SOC) for measuring acceleration and angular velocity, with a full scale range of $\pm 16g$ and ± 2000 degrees/s.
- Honeywell's HMC5983 Magnetometer for detecting North/South/East/West with 5 milli-Gauss resolution.

Communication

For the communication between the SR-UAV and the ground-station, two 2.4GHz X-Bee PRO S1 as seen in Figure. 2.6 (a) were used in order to send commands and control references wirelessly. Further a FR-Sky receiver, Figure. 2.6 (b), was used by the KFly for receiving manual inputs from a radio control.

(a)

(b)

Figure 2.6: a) X-Bee, b) FR-Sky receiver.

2.1.4 Flight Control System

The required torque is generated via the use of four control fins, which are located symmetrically around the center-axis of the main body. The reason behind the incorporation of a symmetrical airfoil is to get same behaviour at both positive and negative AoA. The fins were designed to be replaceable and therefore different profiles will be utilized in future experimental tests. Other possible conceptual considerations would include the use of a cambered airfoil, since the fins will be tilted to counteract the induced torque from the propeller, which will be addressed in future work as well.

Similarly to multirotors, forward flight is achieved by pitching in order to direct the acceleration vector as presented in Figure 2.8. The same principle is utilized to move sideways by the rolling action. In this thesis and for the preliminary evaluation of this novel concept, the flight envelope is constrained to small angles in roll and pitch, so as to limit the translational speed and keep the SR-UAV structurally bounded and closer to the hover state.

Figure 2.7: Control fins on the SR-UAV.

Figure 2.8: SR-UAV operation states: (a) Acceleration, (b) Hovering, and (c) Deceleration.

2.2 System Modelling

In this Section, the modelling analysis of the proposed SR-UAV is mathematically formulated. Given the geometrical representation of the exerted forces and the respective torques on the design presented in Fig. 2.9, the model of the system is derived by studying the Newton-Euler equations of a rigid body [22] as:

$$\begin{pmatrix} \mathbf{F} \\ \boldsymbol{\tau} \end{pmatrix} = \begin{pmatrix} m\mathbf{I}_{3 \times 3} & 0 \\ 0 & \mathbf{I}_{cm} \end{pmatrix} \begin{pmatrix} \mathbf{a}_{cm} \\ \dot{\boldsymbol{\omega}} \end{pmatrix} + \begin{pmatrix} 0 \\ \boldsymbol{\omega} \times (\mathbf{I}_{cm}\boldsymbol{\omega}) \end{pmatrix}, \quad (2.1)$$

where $\mathbf{F} = [F_x \ F_y \ F_z]^T \in \mathbb{R}^3$ is the force acting on the centre of mass, $\boldsymbol{\tau} = [\tau_x \ \tau_y \ \tau_z]^T \in \mathbb{R}^3$ is the torque around the centre of mass, $\boldsymbol{\omega} = [\omega_x \ \omega_y \ \omega_z]^T \in \mathbb{R}^3$ is the angular velocity, $\mathbf{a}_{cm} = [a_x \ a_y \ a_z]^T \in \mathbb{R}^3$ is the acceleration of the centre of mass, $\mathbf{I}_{3 \times 3}$ is the 3x3 identity matrix and $\mathbf{I}_{cm} = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \in \mathbb{R}^{3 \times 3}$ the inertia matrix. The left hand side of equation 2.1 can be expanded as:

$$\begin{pmatrix} F_x \\ F_y \\ F_z \\ \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} F_2 + F_4 \\ F_1 + F_3 \\ F_P \\ \tau_1 + \tau_3 \\ -\tau_2 - \tau_4 \\ -\tau_P + \tau_1 - \tau_2 - \tau_3 + \tau_4 \end{pmatrix} + m\mathbf{R}_g, \quad (2.2)$$

in relation to the acting force diagram in Fig. 2.9 where $\mathbf{R}_g = [g_x \ g_y \ g_z \ 0 \ 0 \ 0]^T \in \mathbb{R}^6$ is the gravitational acceleration exerted on the body frame and m is the mass. Additionally, the effect of the aerodynamic forces on the UAV's body is considered negligible, when operating in hover or near to hover states.

The Propeller force F_P is modelled as follows:

$$F_P = K_{force}u^2, \quad (2.3)$$

where K_{force} is the maximum force generated by the propeller and u the motor's input.

By assuming that the SR-UAV operates at small angles, the Angle of Attack (AoA) for each fin is equal to its corresponding fin angle θ_i where $i = 1, 2, 3, 4$ and the force generated by the fins can be described in terms of the lift equation as presented below:

$$L = \frac{1}{2}C_l\rho V^2A, \quad (2.4)$$

where C_l is the coefficient of lift, $\rho[kg/m^3]$ is the air density, $V[m/s]$ is the true airspeed and $A[m^2]$ is the surface area of the wing. All terms except V are assumed to be constant and can

Figure 2.9: Acting force diagram of the SRUAV's body frame. Where the distances $(OC) := L$, $(CB) := r$, and $(AE) := R$.

be simplified to the term K_{force} . The airspeed can in turn be expressed as proportional to the propeller force F_p and the component of the fin angle (θ) that lies in the X-Y-plane ($\sin(\theta)$). The force generated by each fin thus becomes:

$$F_i = \sin(\theta_i) K_{force} u^2. \quad (2.5)$$

The fin torque (τ_i) may now be described as the appropriate lever times the fin force (F_i) and the motor torque as a torque constant (K_{torque}) times the motor force. In this way, the kinematics of the system in the body frame is formulated:

$$\begin{pmatrix} F_x \\ F_y \\ F_z \\ \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & L & 0 & L & 0 \\ 0 & 0 & -L & 0 & -L \\ -K_{torque} & r & -r & -r & r \end{pmatrix} \begin{pmatrix} 1 \\ \sin(\theta_1) \\ \sin(\theta_2) \\ \sin(\theta_3) \\ \sin(\theta_4) \end{pmatrix} K_{force} u^2 + m \mathbf{R}_g. \quad (2.6)$$

Finally, the solution of the Newton-Euler equations in 2.1 with respect to the translational and angular accelerations yields the equations of motion:

$$\begin{pmatrix} a_x \\ a_y \\ a_z \\ \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{pmatrix} = \begin{pmatrix} (\sin(\theta_2) + \sin(\theta_4))K_{force}\frac{u^2}{m} \\ (\sin(\theta_1) + \sin(\theta_3))K_{force}\frac{u^2}{m} \\ K_{force}\frac{u^2}{m} \\ (\sin(\theta_2) + \sin(\theta_4))L \cdot K_{force}\frac{u^2}{I_{xx}} - \omega_x^2 \\ (\sin(\theta_1) + \sin(\theta_3))L \cdot K_{force}\frac{u^2}{I_{yy}} - \omega_y^2 \\ (-K_{torque} + \sin(\theta_1) - \sin(\theta_2) - \sin(\theta_3) + \sin(\theta_4))r \cdot K_{force}\frac{u^2}{I_{zz}} - \omega_z^2 \end{pmatrix} + \mathbf{R}_g, \quad (2.7)$$

which will be utilized in Chapter 4, where the equations of motion are acting as the body frame model of the SR-UAV, when performing simulation studies. Furthermore the model may be used for implementations of model based control, which is discussed in future work, in Chapter 6.

CHAPTER 3

SR-UAV based Control Scheme Development

In this Chapter, the control problem involving all the Degrees of Freedom (DOFs) for the SR-UAV, namely the translational $[x, y, z]^T$ and the attitude $[\phi_x, \phi_y, \phi_z]^T$, will be addressed.

3.1 Translation Control

An overview of the chosen control structure is presented in Figure 3.1. For controlling the

Figure 3.1: PID and cascaded P-PI structure for the respective control of the translation and attitude performance of the SR-UAV.

translational DOFs, the conventional Proportional–Integral–Derivative (PID) controller [23] was utilized due to its ease of implementation and the fact that loop tuning is possible in an intuitive ad hoc-fashion [24]. The PID controller is one of the most utilized model-free control algorithms with model-free being a good motivation for the choice of the PID controllers due to the uncertainty in the modelling. The PID controllers are featuring a feedback control ac-

tion $u(t)$, which utilizes the weighted sum of three control parameters, namely, a proportional term, an integral term, and a derivative term, and for the translational controllers it can be mathematically formulated as in:

$$u_i(t) = K_{P,i}e_i(t) + K_{I,i} \sum_{a=1}^b e_i(t_a)\Delta t + K_{D,i} \frac{e_i(t_b) - e_i(t_{b-1})}{\Delta t}, \quad (3.1)$$

where $K_{P,i}$ is the proportional gain, $K_{I,i}$ is the integral gain and $K_{D,i}$ is the derivative gain, with $i = 1, 2, 3$ the index for the corresponding translational controllers.

By an appropriate selection of the aforementioned control parameters, the controller's goal is to adjust the manipulated variable $u_i(t)$ and achieve minimization of the respective error signal $e_i(t) = (w_{i,ref} - w_i)$, where $(w_1, w_2, w_3) = (x, y, z)$, i.e. equivalence between the set-point value $x_{ref}, y_{ref}, z_{ref}$ and the process value x, y, z . The manipulated variables u_i define the control efforts of the PIDs, where $u_1 = \phi_{x,ref}$ and $u_2 = \phi_{y,ref}$ are the reference inputs for the attitude P-PI controllers, while $u_3 = \phi_{z,ref}$ is the motor control signal for the SR-UAV.

3.2 Attitude Control

Furthermore, a set of cascaded proportional-proportional-integral (P-PI) controllers (Figure.3.2) is utilized to control the SR-UAV's attitude. Similar to the PID, every cascaded P-PI features

Figure 3.2: Cascaded P-PI structure for attitude control.

an inner loop, containing the proportional and integral terms, and an outer loop featuring a proportional controller, which is placed in an outer loop. As it has been presented in [9], the use of a P^2 -controller was addressed. With such a cascade control formulation, the attitude of the quadrotors can be successfully controlled. In the case of the SR-UAV, the integral was added to accommodate the induced torque from the propellers. In this case, the PI and P controllers can be mathematically formulated as in:

$$u_j(t) = K_{P,j}e_j(t), \quad (3.2)$$

$$u_k(t) = K_{P,k}e_k(t) + K_{I,k} \sum_{a=1}^b e_j(t_a)\Delta t, \quad (3.3)$$

where in (3.2), $K_{p,j}$ is the proportional gain of the outer loop, $e_j(t)$ is the reference defined as $e_j(t) = ((u_2 - \phi_x), (u_3 - \phi_y), (\phi_{z,ref} - \phi_z))$, $\phi_{z,ref}$ is the reference yaw angle, which is independent of the translational controllers, and $j = 4, 5, 6$ is the index range used for identifying the outer loop controllers. The manipulated variable $u_j(t)$ serves as the input for the inner loop (3.3), where $K_{p,k}$ is the proportional gain of the inner loop, $K_{I,k}$ is the integral gain, and $k = 7, 8, 9$ is the index used for identifying the inner loop controllers. The reference $e_k(t)$ is defined as $e_k(t) = ((u_4 - \omega_x), (u_5 - \omega_y), (u_6 - \omega_z))$, where the manipulated variable $u_k(t)$ involves the control signals used for the control fins of the SR-UAV, which are given by:

$$\begin{aligned}\theta_1 &= u_7 + u_9 \\ \theta_2 &= -u_8 - u_9 \\ \theta_3 &= u_7 - u_9 \\ \theta_4 &= -u_8 + u_9,\end{aligned}\tag{3.4}$$

While equation (3.4) is executed by the signal mixer block (SM) in Fig. 3.1.

CHAPTER 4

Simulations Studies

The overall closed-loop system described in Chapter 3 was simulated in order to provide a preliminary evaluation of the behaviour of the proposed design as well as the efficiency of the utilized control structure. The simulations were executed with a sample-rate of 50Hz. White-noise was added to the outputs of the simulations in order to simulate the resolution of the proposed sensors. The added disturbance was of the form of a white-noise sequence $N(\mu, \sigma^2)$, where μ is the mean and σ^2 is the variance, in the position data $n_1 \in N(0, 1)mm$, in angle $n_2 \in N(0, 0.0087^2)rad$ and in angular rate $n_3 \in N(0, 0.17^2)rad/s$.

4.1 Design Parameters

For the simulation of the proposed SR-UAV and in order to extract the parameters needed for its preliminary evaluation, through the utilization of the aforementioned control scheme, the materials of all parts were properly selected. Specifically, all structural and support parts, i.e. the duct, the inner core of the body frame, the control fins, as well as the landing struts, have been properly designed to be 3D printed via polylactide (PLA) plastic for decreased weight and high endurance. A suitable choice for constructing the profile of the fins would be the airfoil type NACA0020. The last two digits in the NACA profile were chosen to get a relative thin profile but at the same time accommodate the radius of the suspension rod.

The parameters utilized in the simulated system of the SR-UAV, most of which were extracted through the corresponding Computer Aided Design (CAD), are presented in Table 4.1. Of these parameters: a) the lengths L and r , as well as the propeller radius R were user defined in the CAD design, b) the mass m and inertia parameters were extracted from the CAD design, and c) the maximum force K_{force} and torque K_{torque} constants were chosen for the purpose of the evaluation that will be presented in the next Sub-section.

At this point, it has to be noted that the user-defined parameters L and r were properly defined for the purposes of this preliminary evaluation, while R was selected via commercially available propeller dimensions. Further analysis on the effect of alternating the aforementioned

Table 4.1: Design parameters of the SR-UAV.

Parameter	Value	Units
L	0.106	<i>m</i>
r	0.084	<i>m</i>
R	$0.203 \cdot 10^{-4}$	<i>m</i>
m	0.393	<i>Kg</i>
I_{xx}	$3.7 \cdot 10^{-3}$	<i>Kg \cdot m^2</i>
I_{yy}	$3.7 \cdot 10^{-3}$	<i>Kg \cdot m^2</i>
I_{zz}	$2.1 \cdot 10^{-3}$	<i>Kg \cdot m^2</i>
I_{xy}, I_{xz}, I_{yz}	~ 0	<i>Kg \cdot m^2</i>
K_{force}	15	<i>N</i>
K_{torque}	0.5	<i>Nm</i>

Table 4.2: Control parameters for each DOF of the SR-UAV, where $i = 1, 2, 3$, $j = 4, 5, 6$, $k = 7, 8, 9$ are the index ranges for corresponding controller.

Gain	Values		
$K_{P,i}$	0.04	0.04	1
$K_{I,i}$	0.001	0.001	1
$K_{D,i}$	0.1	0.1	0.5
$K_{P,j}$	1.3	1.3	2.5
$K_{P,k}$	0.02	0.02	0.02
$K_{I,k}$	0.02	0.02	0.02

parameters is considered as future work and will not be investigated further.

4.2 Control Parameters

The controller gains were tuned via trial-and-error sequences so as to minimise the settling time and the corresponding oscillations of the closed-loop system. The gains utilized for the simulation results, are listed in Table 4.2.

4.3 Simulation Results

A simulated response of the system via set-point reference signals for the closed-loop translational movement of the SR-UAV is presented in Figure. 4.1. Furthermore, in Figure. 4.2 the resulting attitude responses for the roll, pitch and yaw DOFs are being presented. In this case, the control goal is for the angle responses to track the reference signals (tracking problem).

Figure 4.1: Translational step-response of the SR-UAV.

From the obtained results, it is obvious that the responses in all the axes of motion, reveal successful set-point tracking, with small rising times for the set-point references and absence of intense transient phenomena for all the cases despite the effect of the added noise signals into the system, which has a larger impact on the angle reference signals $\phi_{x,ref}$ and $\phi_{y,ref}$.

Furthermore, these responses reveal that the SR-UAV possesses the design characteristics for achieving successful translational and attitude performance, combined with the utilization of the proposed P-PI and PID control scheme, which is proved to be a suitable choice for this system.

This can be further supported from the extracted Root Mean Square Errors (RMSE) of the aforementioned responses, presented in Table 4.3. This criterion reveals that low RMSE values of the closed-loop system remain in generally small values, especially for the cases of the z axis, where the error is kept in the order of 0.001 m, and the ϕ_i signals that remain to the order of 0.001 rad. The oscillations in x and y , as well as the larger RMSE value, reveal the limitations of the control structure into counteracting the effect induced by the noise.

In Figure. 4.3 a graph showing the tracking performance of the suggested modeling and control scheme for a helix path following simulation is depicted for a simulation time of 150s. From the obtained results it is obvious that the system is capable of following a path with

Figure 4.2: Attitude response induced by a translational step of the SR-UAV.

Table 4.3: The root mean square error (RMSE) of the steady state error in the step-response simulation

D.O.F	RMSE
x	0.1065 m
y	0.1417 m
z	0.0013 m
ϕ_x	0.0114 rad
ϕ_y	0.0130 rad
ϕ_z	0.0042 rad

similar oscillations, as in the case of step responses, while the control scheme can track a rather fast 3-dimensional varied set-point. In this type of simulations, it has been also noted that the slower this variation is (bigger the helix is) the better the achievable tracking can be. as it has been indicated in Table 4.4, the RMSE of the presented tracking response reveals no significant change in the ϕ_x, ϕ_y, ϕ_z and z over the steady state of the step response. Finally, in Figure. 4.4 the simulated motor and servomotor signals are presented as the helix trajectory is followed.

Figure 4.3: The SR-UAV system's response, while tracking a helix-shaped trajectory.

Table 4.4: The root mean square error (RMSE) of the helix simulation

D.O.F	RMSE
x	0.7326 m
y	0.6777 m
z	0.0013 m
ϕ_x	0.0125 rad
ϕ_y	0.0125 rad
ϕ_z	0.0039 rad

Figure 4.4: The SR-UAV control signals for the first 10s, while tracking a helix-shaped trajectory.

CHAPTER 5

Experimental Evaluations

5.1 SR-UAV construction

All plastic parts were made using a 3D-printer of the type Ultimaker 2 [25]. The plastic used was Polylactic acid (PLA) with low infill for decreased weight. Table 5.1 features a list of the non-plastic parts used to construct the SR-UAV and was used in the experimental evaluations.

Table 5.1: Part List of the SR-UAV.

Description	Quantity
1000mAh 4S Li-Po Battery	1
RC - receiver	1
X-Bee Pro s1	1
APC style Propeller 9x3.8	1
Turnigy TSS - 10MG Servo motor	4
Turnigy 1100KV DC-motor	1
Turnigy Plush 30amp ESC	1
Kfly flight system	1
120x5mm Carbon Fibre tube	8
70x5mm Carbon Fibre tube	4
150x5mm Carbon Fibre tube	4
150mm m3 studding	4

5.1.1 Final Design Parameters

Two configurations of the SR-UAV were made in order to evaluate the performance of the design and control.

A) UnDucted Configuration

In Figure 5.1 the unducted configuration of the SR-UAV is presented while in Table 5.2 the specific design parameters are presented.

Figure 5.1: The SR-UAV configured without Duct.

Table 5.2: Design parameters of the unducted configuration SR-UAV.

Design Parameter	Value
Total Weight	0.534 Kg

B) Ducted Configuration

In Figure 5.2 the ducted configuration of the SR-UAV is presented while in Table 5.3 the specific design parameters are presented.

Figure 5.2: The SR-UAV configured with Duct.

Table 5.3: Design parameters of the ducted configuration SR-UAV.

Design Parameter	Value
Duct Weight	0.275 Kg
Total Weight	0.801 Kg

5.2 Experimental Setup

An overview of the experimental setup is shown in Figure 5.3.

5.2.1 Motion Capture System

For retrieving the absolute position and updating the position controllers the VICON motion capture system of the Field Robotics (FROST) Lab was used. By placing reflective markers on the SR-UAV and capturing the reflection of infra red light generated near the lens of the cameras the 3 spacial degrees of freedom are triangulated. The system provides a resolution of $< 1mm$.

Figure 5.3: Overview of the experiment setup.

5.2.2 Ground-Station

The ground-station (GS) was in the experimental setup a personal laptop running a Linux operating system namely Ubuntu 14.04 LTS connected via Ethernet to the VICON server and a XBee(chapter 2.1.3) radio transmitter for communications with the SR-UAV.

Robot Operating System

To communicate between the SR-UAV, the motion capture system as well as performing computations such as the position control-loops, the Robotic Operating System (ROS) was used. ROS provides a structured communications layer above the host operating systems[26] and contains the API's to utilise nodes created by others and create your own. Software or command-line scripts may be used to communicate with ROS-nodes over the network. These ROS-nodes are processes that executes computations and by the use of topics and services handles node to node communication. Topics lets nodes publish or subscribe anonymously to messages sent over the network with corresponding topic name, where the message is of a predefined data-structure. Similarly services handles message communication between nodes. Instead of publishing and subscribing nodes only receive data when a query is made from a requesting

node. In Figure 5.4 the experimental setup is shown featuring the ROS communication used to update the position reference and change settings on the SR-UAV.

Figure 5.4: Overview of the ROS communication.

5.2.3 Test Jigs

6 DOF

A test jig was constructed using four tripods connected via suspension strings to the SR-UAV as seen in Figure 5.5. The jig allows for the control-parameters to be tuned safely in 6 DOF.

Figure 5.5: The SR-UAV fitted to the 6 DOF test jig.

1 DOF

A second jig was constructed to limit the SR-UAV to only allow for 1 DOF in height. In this jig two 10 mm carbon fibre rods were fitted to a plywood base which then constrained the motion of the SR-UAV to be parallel to the rod axis. As seen in Figure 5.6, tensed string was used to keep the carbon fibre rods perpendicular to the base. Before experiments involving the 1 DOF jig was conducted an oil based lubricant was applied to the rods to reduce friction between the carbon fibre and plastic slider.

Figure 5.6: The SR-UAV fitted to the 1 DOF test jig.

5.3 Experimental Results

The experiments were conducted in several stages. Following are the results of each step in the experimental evaluation.

5.3.1 Signal Mixing and Avionics

A static-test of the Avionics and the signal mixing was done in order to confirm correct behaviour of the low level control, Figure 5.7.

Torque generated by rolling and pitching manoeuvres were measured in an ad-hoc fashion for two different control surfaces. In Figure 5.8 the: a) revised and b) original NACA0014, control surfaces are presented. The revised control surface features a larger surface area which proved to generate more torque and thus increasing the controllability of the SR-UAV. In Chapter 6 further improvements and alternative methods of torque manipulation are discussed.

Figure 5.7: Static test of the avionics.

(a)

(b)

Figure 5.8: Tested control surfaces, (a) revised and (b) NACA0014.

5.3.2 Hover Test

A test to determine the SR-UAV's ability to hover was performed. The main purpose of this test was to determine the minimum percentage of power needed to sustain flight. This experiment used the 6-DOF test jig and utilizing angular-rate control via RC-control. One draw back regarding the 6-DOF test jig uncovered during this experiment was that the yaw motion was restricted due to tension in the strings and thus limiting the degrees of freedom of the test to 5. Another problem similarly occurred due to the tension in the strings when maximum tension in one string was reached and thus applying a jerk to the motion of the SR-UAV creating a

big disturbance to the system limiting the conclusions available to draw by the experiment. The SR-UAV was proven hard to control in angular-rate mode due to several possible reasons such as, the coupled nature of roll, pitch and yaw, the speed at which the angular rate need to be updated may be over the capability of a human pilot. Further tuning of the control parameters might prove the SR-UAV easier to control in angular-rate mode. The result of the hovering experiments concluded: a) the ducted version does not take off, b) the un-ducted version sustains flight at 70% of the motor power, and c) angular-rate control is not sufficient to achieve stable flight and higher level control should be investigated.

5.3.3 Evaluation of Translational Position Controller

The position controller was evaluated in height (z), utilizing the 1-DOF test jig. Figure 5.9, shows the tracking performance of a step response to the height of $0.5m$ at $Time = 3s$. The experiment was ended at the $Time = 34s$ mark by sending a new height reference of $0m$ to the SR-UAV. At this point the SR-UAV was caught to dampen the fall.

It is shown that tracking is possible, however due to the way the SR-UAV interacts with the test jig, friction force is present and a smooth step response is not achieved. What can be gathered from the data is: a) The SR-UAV sustains hover at 80% of the motor power in the 1-DOF test jig. b) The SR-UAV can track a height reference.

Figure 5.9: Experimental evaluation of PID in height only.

Conclusions and Future work

In this thesis, the design, modelling and control of a SR-UAV was presented. The conceptual design stages of the SR-UAV were analysed in detail, with respect to the advantages of utilizing a single rotor-based structure for the development of a low-cost and safe UAV with VTOL capabilities. The model was mathematically formulated for the hovering case, which was utilized in the simulation of the closed-loop system, with a control system based in cascaded P-PI and PID controllers to undertake the problem of translational and attitude control. Furthermore the design was tested in a lab setting where the height control was evaluated experimentally and the overall experimental setup was shown to produce tracking of the input set-point. In this chapter a discussion on the overall results and suggestions for future work for each of the main topics of this thesis will be covered in detail.

6.1 Design and Modelling

Regarding the design it has been shown that the concept is valid and that control of a tail-sitting single rotor based UAV is possible. The four control surfaces has been show to be able to control the attitude of the SR-UAV in simulations and the height-control was shown to work in practical trials. However there are several problems related to the design that was uncovered during the experimental evaluation that further development of the SR-UAV could overcome. It is therefore suggested that the design should be revised to reach the goal of achieving stable hovering and improve on the structural integrity of the SR-UAV. Following is the main design points at issue and suggestions on how to overcome them:

- The overall weight of the SR-UAV is such that the thrust to weight is less then desired. When overcoming this problem there are two approaches that are suggested by the author: a) decrease the overall weight of the SR-UAV or, b) Increase the thrust generated by the propeller. The first approach of decreasing the weight might not be feasible due to the necessity of keeping the SR-UAVs structural integrity. A suggestion is therefore to make a general study in the choice of motor propeller configuration such as a more

favourable thrust to weight ratio is reached.

- Tying in to the previous item, an observation that was made during the experimental trials is the duct and the negative impact the duct imposed on the thrust to weight. The theory covered in chapter 2.1.2, suggest that a duct will benefit the design. However the weight of the 3D-printed PLA duct added too much weight and a revisit to the design of the duct is suggested. Other ways of constructing a duct prototype may include vacuum forming or a foam based duct.
- The design of the landing struts may be revisited due to the lack of strength and with the ease they will be damaged. Making the landing struts longer will also improve on the airflow over the control surfaces during take-off and landing, which was observed to be a problem when the control surfaces were to close the ground.
- The joining between the servomotors and the control surfaces is another point for further improvement. A small slack in the joint induced a small oscillation on the control surfaces when under the turbulent flow of the propeller. The amplitude of the oscillations could be greatly reduced with a more rigid linkage.

To fully understand the dynamics of the SR-UAV a Computational Fluid Dynamics (CFD) analysis of the airflow is suggested to optimize the profile of the control surfaces with respect to the generated torque and the size of the fins themselves. A comprehensive CFD analysis will also help provide deeper understanding of the effect of the duct performance and the choice of propeller and motor specifications. To validate these findings wind-tunnel evaluation would be useful in improving the design decisions and further improve the model of the SR-UAV.

6.2 Control structure

The simulated responses revealed that the SR-UAV possessed the design characteristics for achieving successful translational and attitude tracking, combined with the utilization of the proposed P-PID and PID control scheme, which was proved to be a choice that can lead such a system to smooth and accurate tracking performances. Following is a discussion on the implemented control structure and what improvements are suggested in refining said control:

- In the experimental evaluation the success was limited and further tuning of the control parameters are needed. When an experienced human test pilot was involved in the low level control loop (angular rate control only) of the SR-UAV it was shown very hard to control. This might suggest that a higher level control is required for radio control of the SR-UAV.
- When the height control was evaluated it was shown that tracking is possible for the experimental setup given an input set-point. The results from these trials were negatively affected by factors as stated in Chapter 5.3. However due to the fragility of the UAV

design, tests outside of the jigs were limited. If improvements were made to combat this, more extensive trials and tuning of the control parameters can be made.

- Improvements to the control structure are possible and two different directions may be considered for further improvements. The first way is to improve and modify the cascaded PID approach. This can for example be done by including conditions for Bumpless operation for which the output signals will not change when changing the set-point of the regulators and suddenly 'bumping' to a different value. The other way for further development is to implement a different control structure. Enhanced performance might be gained from using a controller such as the Model Predictive Control structure which makes use of known system dynamics and predicts future behaviour of the system and thus can adjust accordingly, as opposed to the current structure where a reactive scheme is used.

6.3 Final Remarks

There are several areas that can and should be studied on the subject of single rotor UAVs that are not featured in this thesis, to fully understand the flight dynamics of the system and to improve upon them.

- To fully benefit from the Single-Rotor concept, when stable flight around hovering is achieved, horizontal flight should be investigated and be made a priority. In this case the lift requirement should be investigated and the need for wings determined as seen in the introduction regarding tail-sitters. The usefulness of horizontal flight is the higher maximum velocity and the inclusion of fixed wings can greatly improve on the flight time due to the lift generated by the wings themselves.
- An investigation on the payload where the SR-UAV is made to carry a camera or other sensors, may be included in further research depending on what tasks the SR-UAV is made to perform. In the case of an on board camera and utilizing recent research in Computer vision the system may be fully autonomous running the positional control on the UAV's flight computer.
- Other novel ideas for controlling the attitude torques may be investigated such as the utilization of Reaction Wheels or Control Moment Gyroscopes.

This work has led to an article that has been accepted into the 24th Mediterranean Conference on Control and Automation where parts of the modelling and control chapters were presented [27].

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