

Dual-Axis Tilting Quadrotor Aircraft

An investigation into the overactuatedness thereof



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Abstract

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The aim of this project is to design, simulate and control a novel quadrotor platform which can articulate all 6 Degrees of Freedom by vectoring the propellers' directional thrust. To achieve this the structure of the air-frame must redirect those thrust vectors to any desired orientation. This means it has to transform its configuration during flight, redirecting lift actuators whilst still maintaining stable attitude & position control in spite of such relative motion. In view of this required articulation the proposal is to add 2 (degrees) axes of extra actuation to each propeller. As a result each lift propeller can then be pitched or rolled relative to the body frame. This change, to what is an otherwise well understood and highly researched platform, produces an over-actuated control problem. Actuator allocation is the primary contribution of this paper with novel elements of non-linear (*state-space*) attitude control.

The structure of the dissertation first presents the design which the subsequent dynamics and control are derived with respect to. Following that, the kinematics associated with rigid bodies are derived. Any unique effects that could apply to the design like gyroscopic, inertial and aerodynamic responses are investigated and then incorporated into the dynamics. Position and control algorithms are first derived, then simulated and compared based on the plants' dynamics (*which include discretionary effects on the system*). The relative performance of the controllers are evaluated but regular performance metrics for attitude and position control are ill-suited for such a system. Some time is spent discussing the consequence of this and how the controllers are actually evaluated. Finally the design is built and tested using readily available RC components and conclusions drawn on the success or failure of the design.

The purpose of the investigation is the practicality and feasibility of such a design, most importantly whether the complexity of the mechanical design is a decent trade-off for the added degrees of control actuation. The outcome of the build is to ascertain if it's both economically (cost and control effort) feasible to use such a prototype to expand the range of a quadrotors' motion. The design and control treatment presented here are by no means optimal or the most exhaustive solutions, focus is placed on the system as a whole and not just one aspect of it.

This dissertation report is presented in a logical progression of concepts and information. In some cases the research and results were compiled differently from how they're listed.

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Chapter 1

Introduction

1.1 Foreword

1.1.1 A Brief Background to the Study

A popular topic for current control and automation research is that of quadrotor UAVs. Attitude control of a quadrotor poses a unique 6-DOF control problem, to be solved with an under-actuated 4-DOF system. As a result the ϕ pitch and θ roll plants aren't controllable. The attitude plant is often simplified around a stable operating point. The trimmed operation region is always at the inertial frames' origin; resulting in a zero-set point tracking problem. The highly coupled non-linear dynamics of a rigid body's translational and angular motions arise from gyroscopic torques [Section: 3.2.1] and Coriolis accelerations [Section: 3.2.2]. These effects are negligible around the origin¹, hence the origin trim point removes the systems' non-linear complexities. The control system can then reduce each state variable, $\vec{X}_b = [\phi \ \theta \ \psi \ x \ y \ z]^T$, to an isolated SISO plant.

As almost every recent quadrotor research paper will mention, the latest interest in the platform is because of recent emergences in availability of MEMS systems and low-cost microprocessors. Such advancements allow for real time state estimation and on-board control loop processing, all at a relatively low cost. Developmental progress in quadrotor and, to a lesser extent, the general UAV field has led to rapidly growing enthusiast community. Companies like HobbyKing [28] are now synonymous with providing custom made DIY hobbyist quadrotor kits, not just ready to fly commercial products like the DJI Phantom [18].

The avenues for potential application of both fixed wing and VTOL UAVs is expansive, supporting civil [51], agricultural [53] and security [36] industries. Quadrotor configurations provide a mechanically simple and low cost platform on which to test advanced aerospace control algorithms. Commercial drone use in industry is already emerging as a prolific sector; especially in Southern Africa. Subsequently following the 8th amendment of civil aviation laws [56], use of UAVs for commercial application has now been legalized and regulated. Any research into some non-trivial aspect of this field is therefore going to be extremely valuable.

Larger scale quadrotor, hexrotor and even octocopter UAVs are a popular intermediate choice for aerial cinematography due to their high payload capacity. Whilst still expensive, the cost of a commercial drone like the SteadiDrone Maverik [41] is far less than chartering a helicopter to achieve the same panoramic aerial scenes or on-site inspections. Another interesting application for UAVs is in the agricultural and cartography surveying sectors. One foreseeable issue which may hinder commercial drone sector progress is the inertial effects associated with large aerial bodies. When scaling up any

¹Expanded upon in Appendix:A

vehicle, its performance is adversely affected if actuation rates aren't proportionately scaled.

1.1.2 Research Questions & Hypotheses

The difficulty with quadrotor control is that fundamentally it's unstable and under-actuated, *which is empirically proven later with Layupanov Theorem in Chapter:4*. A quadrotor only has four controllable inputs, namely propeller rotational speeds $\Omega_{1,2,3,4}$, which are then abstracted² to virtual control inputs net torque, $\vec{\tau}_{net} = [\tau_\phi \ \tau_\theta \ \tau_\psi]^T$, and a perpendicular heave thrust $\vec{T}_{net} = \sum_{i=1}^4 T(\Omega_i)$. Those four inputs have to affect both the linear X-Y-Z positions and angular pitch, roll and yaw rotations, $\vec{\gamma} = [\phi \ \theta \ \psi]^T$. Pitch and roll torques, τ_ϕ & τ_θ are induced from differentials thrusts of each opposing propeller. Yaw torque, τ_ψ , is dependent on net aerodynamic torque about the rotational axes of each propeller (See Section:3.3.1). Aerodynamic torque is a non-linear and fluctuating source of control input and the body's yaw control is depreciated. As a result of the under-actuation the attitude control problem becomes a zero set point problem as any other attempt to track attitude cannot be achieved.

The aim of this project is to implement quadrotor attitude and position set point tracking by solving the problem of its inherent under-actuation. Inspired by Boeing/Bell Helicopters' V22 Osprey and the tilting articulation of its propellers, the prototype design proposed here introduces two additional actuators for each of the quadrotors' lift propellers. Specifically, adding rotations about the X and Y axes for each motor/propeller pair. The result is a vectored 3 dimensional thrust force rather than a bound perpendicular lift force. The control problem is then posed as the design of net forces, $\vec{F}_{net} = [F_x \ F_y \ F_z]^T$, and torques, $\vec{\tau}_{net} = [\tau_\phi \ \tau_\theta \ \tau_\psi]^T$, such that for any given trajectory, $X_d = [x \ y \ z \ \psi \ \theta \ \phi]^T$, the error state $X_e = X_d - X_b$ asymptotically tends to $\vec{0}$.

$$\lim_{t \rightarrow \infty} X_e = \vec{0} \quad \forall X \in \mathbb{R}^n \quad (1.1)$$

Where n is the degrees of freedom. The over-actuation brings about the need for a control allocation scheme which distributes the 6 commanded system inputs (net torques and forces) among the actuator set (12 actuators) in order to optimize some objective function secondary to that of Eq:1.1.

Part of the control research question is the multivariable treatment of the system, making no assumptions or simplifications to the non-linear dynamics involved in the quadrotors motion and its operational conditions. Standard linearizations applied to the quadrotors' control plant won't hold true for the more aggressive manoeuvres; they're dependent on small angle approximation. Stable control law design will need to expand and simulate the existing kinematic model of an aerial body and applying it to a quadrotors motion. Following this there must be design, development and control of the new actuator suite which is to be implemented on a quadrotor platform. Final key outcomes for the project are the simulation analysis and prototype construction of the proposed design and the conclusion drawn thereon.

Introducing relative motion within an unconstrained body will produce a lot of unwanted dynamics like inertial and gyroscopic responses, amongst others. A rotating propeller will respond to pitching much like a Control Moment Gyroscope [72] or a flywheel and produce a precipitating torque. A less trivial aspect to consider is the aerodynamic torque produced from the propellers' aerofoil profile. Such induced responses occur in planes perpendicular to whatever the propellers' rotation exists in. These aspects are normally compensated for due to a basic quadrotors' co-planar propeller rotation. It's anticipated that a plant dependent control solution will have to compensate for these dynamics, which if left unaccounted for could potentially cause instability.

²The abstraction of which is explored in Appendix:A

1.1.3 Significance of Study

Due to the huge popularity of quadrotor platforms as research tools, any work that improves the UAV & quadrotor general body of knowledge will prove to be valuable. With that being said, there is already a vast amount of existing research on linear and non-linear control techniques for regular quadrotor platforms. The attitude loop is the most common topic for control research, requiring an under-actuated solution and mostly linearized around the origin (See Appendix:A). Far less common is the application of optimal flight path and trajectory planning to quadrotor control. The uniqueness and difficulty of the quadrotor attitude control does not hold true for its position control, so standard techniques can be used for way point planning and the like once the attitude control problem has been solved.

The most significant aspect of this project is the attitude control, discussed later in Section:4.1. The over-actuation of the proposed design and, more critically, the manner in which the controllers' (virtual) output is distributed among those control effectors would appear to be the first of its kind. Otherwise known as control allocation, the requirements of the distribution algorithm(s) are outlined in Section:4.3. Dynamic set point attitude control for aerospace vehicles is not a subject heavily researched outside the field of satellite attitude control. Even papers which propose similarly complex mechanical over-actuation (expanded upon in next in the literature review, Section:1.2) hardly broach the topic of tracking attitude set points away from the origin.

Whilst the control plant (developed in Chapter:4) does indeed close both the position and attitude control loops, there is no consideration of trajectory generation nor flight path planning. Such topics are well discussed elsewhere in a far more concise and deliberate way than this project could ever hope to achieve. Once closed loop position and attitude control has been achieved, the control algorithms can be adjusted to account for higher order state derivative (acceleration, jerk and jounce) tracking needed for nodal way point planning. The heuristics involved with flight path planning are well documented elsewhere and their implementation is an academic task.

Where possible the system identification and control (design and allocation) for this project is kept both modular and generically applicable. The intention here is that its pertinence falls not only within the UAV field but to any aerospace or free body attitude control. Hopefully this investigation can be expanded upon with more in-depth research on one of the subsystems without compromising the functionality of the remainder of the whole plant.

Provisionally, an obvious outcome which the investigation could yield is improved yaw control of a quad copters attitude. However, if the express purpose was just to improve yaw control, it could be done with a dramatically more simple design. Furthermore, the project could provide greater insight into high bandwidth actuation and thus a faster control response for larger aerospace bodies. Any standard quadrotor uses differential thrust to develop a torque about its body which suffers a second order inertial response when the propellers accelerate or decelerate, $\tau_{simplified} = \mathbb{I}_f \dot{\omega}_i$. Prioritizing pitching the propellers' principle axis of rotation rather than changes to the propellers speed could potentially improve the virtual control response. This is entirely dependent on how the allocator block is prioritized (presented in Section:4.3).

1.1.4 Scope and Limitations

Scope

Critical to this project is the conceptualized design and prototyping of a novel actuation suite to be used on a quadrotor platform. The express purpose of which is to apply set point attitude tracking control to the body. Stemming from this is an investigation into the kinematics that are potentially influenced by the design and the structures' relative motion. In order to apply correct control theory

to achieve the attitude tracking on a physical prototype, the plant dynamics must first be identified so that responses can be approximated with confidence. Aspects of the mechanical design are covered next in Section 2.2 but, beyond the cursory investigation, there is no scope for materials analysis or stress testing of the design. To the detriment of the project, the design will either produce an over-engineered or catastrophically under-engineered solution. The scope focuses mainly on the control application and embedded systems design, not the structural integrity of a proposed frame given the forces it may undergo. Physical measurements are only made for critical kinematics, such as inertial measurements for the second order gyroscopic and inertial dynamic responses.

As mentioned in the antecedent, Section: 1.1.3, trajectory & flight path planning are not ubiquitous with this dissertation. Derivations for the differential equations which dictate a 6-DOF body's movement are wholly applicable to any dynamic (rigid or otherwise) aerospace body, although some particular standards are used [sic Z-Y-X Euler Aerospace Sequence, 2.1]. Similarly the control plant is stabilized with non-linear state space control techniques, aided and justified by Lyapunov theorem. Alternative solutions through Model Predictive Control or Quantitative Feedback Theory could provide more refined or effective controllers, they aren't presented and remain open to further investigation. Quadrotor attitude control is commonly stabilized with feedback linearizations, decoupling plant around a trim point so that SISO techniques can be applied. A derivation of such a linearization is included in Appendix:A but beyond that there are no further discussions. Any comparison between non-zero and zero-set point attitude control of quadrotor is difficult as the fundamental objectives are in stark contrast with each other.

Arguably the most important and indeed novel aspect of this project is the control allocation. The system has 12 plant inputs and 6 output variables to be controlled. There is then a family of actuator set $u \in \mathcal{U}$ solutions that exist for each commanded input. Such a plant is classified as over-actuated. Ergo, there must be some logical process as to how those 12 inputs are articulated to achieve the desired 6 movements. Appropriate techniques are first investigated in Section:4.3 and compared before a final solution is implemented in Section:5.4. It is by no means a comprehensive investigation of every possible allocation scheme but rather an analysis of the sub-set of problems and design of what is regarded as a logical and pertinent approach.

With regards to the actual prototype design, in Section 2.2, it's assumed that certain aspects are a given certainty. Particularly the state estimation, updated through a 4-camera positioning system fused with a 6-axis IMU through Kalman Filtering, is assumed to be precise and readily disposable at a consistent 50 Hz. Hence state estimation is included but is bereft of intricate detail, this is another topic which remains open to further investigation.

Limitations

The biggest constraint faced by the design is the net weight of the assembled frame. Lift forces required to keep the body aloft are obviously dependent on the all up weight. Conventional wisdom has it that steady state actuator rates ought to be far less than saturation conditions. For stability to be guaranteed at all feasible operating conditions, the actuators must have sufficient headroom to still effect the desired control inputs. Conversely the structures' net weight is mostly dependent on the lift motors, being the heaviest part of the vehicle. A trade-off between these two factors makes designing the prototype a balancing act of compromise; added actuation is needed to produce the desired thrust vectoring. That added actuation is going to increase the weight which then requires more thrust force to ensure the vehicle remains airborne. Larger motors then need stronger actuators to effect the relative motion and overcome the bodies inertial response. It's a compromise between the weight of the body and the strength/quality of the actuation.

To forego the deliberation detailed above, a self imposed limitation applied to the design is to only make use of a predetermined motor, specifically a set of four Turnigy DST-700 BLDC motors. The

Department of Electrical Engineering at University of Cape Town has a surplus of these from previous projects so it saves having to spec and purchase any new motors, which could lead to unbounded scope creep. A direct consequence of this decision is that the net thrust disposable for actuation is limited to around 700g, ≈ 6.9 N, per motor (see Section: 3.3.1). All other aspects of the prototype must adhere to this limitation. It's critical to ensure the control block doesn't induce over-saturation of the motor actuation, so the frame weight needs to be around 60-70% of the maximum available thrust. Saturation conditions are detailed later in Section: 4.3.

Another aspect of limitations produced by design decisions made, mostly to reduce prototype costs and complexity, is to use of 180° rotation servo motors. The servos are for individual motors' \vec{X}_{M_i} axis pitch and \vec{Y}_{M_i} axis roll actuations and act in lieu of BLDC or stepper motors. Any non-servo rotations beyond 360° require closed loop position control and, unlike servos, would need slip rings to transmit power despite rotational movement. However the logistics of implementing such a design whilst maintaining an acceptable weight is almost impossible. Such an implementation is going to dramatically scale up the size of the prototype to accommodate for weight increases. Commercial camera stabilizing gimbals already make use of similar configurations but the I/O requirements from the flight controller μC already constricts the amount of expansion available.

Discrete elements for the whole system can potentially limit performance but are going to be mitigated if possible. For example analogue servos have an associated 1ms deadband from their 20Hz refresh rate. That can be addressed by using faster, albeit more expensive, digital servos which sample at 330Hz. The prototypes' flight controller has to provide 12 PWM output compare channels for the 8 servos and 4 BLDC speed controllers. State updates from a ground control station and a fail safe 6Ch RC receiver module also need to be processed by the μC system. Particular attention is paid to the embedded system layout in Section:2.3.

1.2 Literature Review

1.2.1 Existing & Related Work

The field of transformable aerospace frames is not necessarily a new one, with many commercial examples having seen a lot of success over their operational life span. The most notable tilting-rotor vehicle is that of the Boeing/Bell V22 Osprey aircraft. First introduced in the field in 2007, the Osprey has the ability to pitch its two lift propellers forward to aid translational flight after vertically taking off or landing. In addition to this there have been a few papers published on similar tilting bi-rotor UAVs' (Fig: 1.1)³ for research purposes.

Birotors

Research into birotor vehicles (Fig: 1.1) with ancillary lift propeller actuation is oft termed Opposed Active Tilting, *OAT*. Such a rotorcrafts' mechanical design applies either a single *oblique* 45° tilting axis relative to the body; [8, 25, 32], or a *lateral* tilting axis, adjacent to the body; [15, 33, 52, 65]. Leading research is currently focussed on applying doubly actuated tilting axes to birotor UAVs. Dual axis Opposed Active Tilting or *dOAT* introduces vectored thrust with propeller pitch and roll motions to further expand the actuation suite, [2, 24]. A birotor is sometimes considered preferable to the multirotor platform due to its reduced controller effort. However the controller plant abstraction often detracts from the quality and effectiveness of its stability solution as a result of its underactuation.

Birotor attitude control typically incorporates plant independent PD [8] and PID [52] controller schemes. Occasionally more computationally exhaustive and plant dependent Ideal and Adaptive

³Image used from G. Gress: [24]

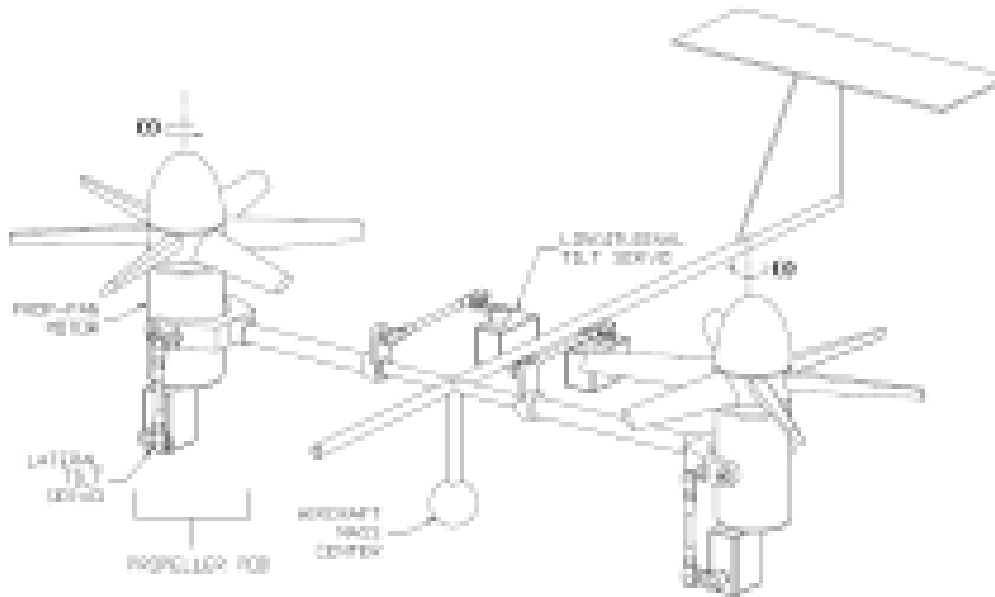


Figure 1.1: General Structure for Opposed Tilting Platform

backstepping controllers are exploited, presented in [32, 65] and [33] respectively. The coupling of a birotor vehicles' attitude system is more pronounced than that of a quadrotor, derived in Section: 3.2, and so feedback linearisation is almost always used. In an interesting progression from the norm, Lee et al, [38], proposed a PID co-efficient selection algorithm for a bi-rotor control block. Using a Particle Swarm Optimization technique, similar to [74], the coefficients were globally optimized around a cost function. However their performance metric criterion is a basic ITAE⁴ term and nothing more appropriate involving effects unique to flight systems. *PSO* algorithms iteratively search for a globally optimized solution and offer independent, derivative free optimization. Later on non-linear controller coefficient are also optimized using a *PSO* algorithm, shown in Section:5.1.

Quadrotors

Expanding on multirotor vehicles, the quadrotor UAV is a popular and well researched platform due to its mechanical simplicity. What would appear to be one of the first quadrotor research implementations, in 2002, is the X4-Flyer quadrotor, [27, 58]. Alternative iterations like the Microraptor [60] and STARMAC [29] quadcopters have been built and tested. A plethora of literature exists around quadrotor kinematics & control [4, 11, 16, 42, 59], however dedicated rigid body 6-DOF dynamic papers [44, 54] provide better explanations of the kinematics. Often the plants' dynamics are simplified around an origin trim point and assumed to reduce into 6 SISO plants for each degree of freedom, Section: 3.1 and Appendix: A. Lately research projects incorporate aerodynamic effects like drag and propeller BEM theory into the plant model [13, 29, 62]. Although commonly neglected under standard operating conditions, the higher fidelity models offer more precision without linearisations or assumptions, [5, 29].

The only commercial example of a transforming quadrotor is the DJI Inspire1 [19], made by Shenzhen DJI Technologies (better known for the popular DJI Phantom drone??). The Inspire can articulate its supporting arms up and down as shown in Fig:1.2⁵. The aim of such movements is to both alter the center of gravity and further expose a belly mounted camera gimbal for panoramic viewing angles. This transformation changes the moment of inertia about the body's center of gravity, in turn changing the inertial torque response induced by angular movements, an otherwise detrimental effect which makes researchers apprehensive of transformable aerospace frames. The range of "transformation" which the

⁴Integral Time Additive Error

⁵Both images were sourced from the drones' patent, held by SZ DJI Tech Co [73]

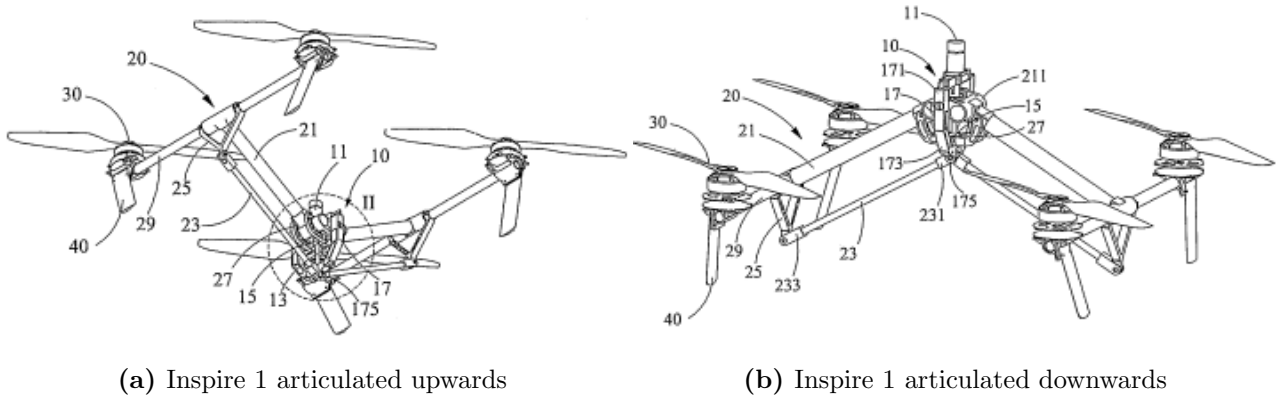


Figure 1.2: DJI Inspire 1

frame can undergo is just limited to articulating the arms up and down.

In a similar fashion to the progression seen in birotor state-of-the-art, quadrotor research is engaging the topics of single and dual axis tilting articulations. First conceptualized and implemented on a prototype related to an ongoing project covered in two reports, [63, 64]. The authors M. Ryll et al. (2012, 2013) modified and tested a QuadroXL four rotor helicopter, produced by MikroKopter [22], to actuate a single axis of tilt aligned with the frames arms (Fig:1.3a)⁶. Their proposed control solution, discussed in detail next in Sub-section:1.2.2, assumes no nominal linearised conditions around hover flight unlike a similar single axis tilting quadrotor prototype designed by Nemati, et al. (2012) [49]. The latter remains simulated but as yet untested.

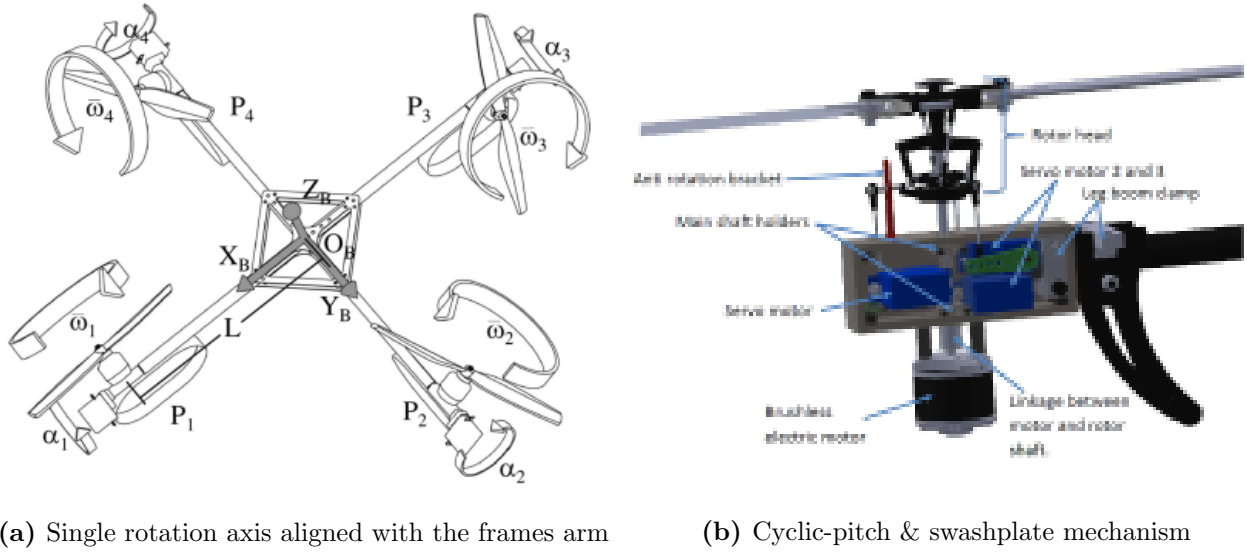


Figure 1.3

An approach to improving quadrotor flight response is to alter the manner in which the thrust is actuated. Drawing from helicopter design, a project by Napsholm, (2013) [48], purported a quadrotor UAV that used swashplates for varying the propeller pitch and generating torque moments. The aim was a design which wasn't dependent on speed control (*ESC*) power electronics to actuate variable thrust forces. Petrol motors were intended for use in place of BLDC motors. Furthermore, the design proposed a single axis of tilt actuation to each of the four motor modules. Whilst mechanically complex, Napsholm made use of existing RC helicopter components to design a rotor actuation bracket (Fig:1.3b). The cyclic-pitch swashplate used [50] could apply torques, τ_ϕ and τ_θ , about the propellers'

⁶Image sourced from Modelling and Control of a Quadrotor UAV with tilting propellers, [63]

hub, *principle axis of rotation*, by altering the blades angle of attack throughout its rotational cycle. The actuation rate of such a configuration is far faster than that of a differential torque produced rolling/pitching motion.

Irrespective of the strong initial design in the early stages of his project, it would appear that Napsholms' research suffered due to time constraints. The introductory derivation on aerodynamic effects and deliberation over the design provide clear insight into the projects goals. However the control solution and system architecture, electronic and software, are significantly lacking. An introductory proposal of an MPC attitude control system detracted from the comprehensive dynamics discussed. The project ended before testing, simulation and results could be obtained. Unfortunately, despite the novel over-actuated design, there was no discussion given on how the allocation would be performed.

Finally, the most crucial research to mention is that of a project completed by Pau Segui Gasco [21], which was a dual presented MSc project with Yazan Al-Rihani [1]. At the time of writing, this would appear to be the only project published pertaining to *over-actuation* in aerospace bodies implemented on a quadrotor platform. The research was split between the two authors who completed the control/electronic design and the mechanical platform design for their respective dissertations. Shown in Fig:1.4⁷, the dual-axis articulation is achieved using an RC helicopter tail bracket and servo push-rod mechanism; reducing the mass of the articulated component but limiting the range of actuation. Considering the propellers as a spinning flywheel, the induced gyroscopic response can then be treated as an actuator plant. The commanded virtual control is then distributed by weighted inversion among the actuator set, Section: 1.2.2. The whole project justifies the extra actuation as redundancy but doesn't necessarily prove how such a redundancy could be beneficial.



Figure 1.4: Dual-axis tilt-rotor mechanism

1.2.2 Notable Quadrotor Control Implementations

Quadcopter Attitude Control

Attitude control of a 6-DOF body is a topic best described by *The Attitude Control Problem* [68]. A rigid body that currently has an attitude state \vec{E}_s and a desired state \vec{E}_d , the problem is to then find a torque control law:

$$\mu\tau = h(\vec{E}_s, \vec{E}_d, \vec{\omega}_s, \vec{\omega}_d) \quad (1.2)$$

Such that $\lim \vec{E}_s \rightarrow \vec{E}_d$ and $\lim \vec{\omega}_s \rightarrow \vec{\omega}_d$ asymptotically stabilize as $t \rightarrow \infty$. Depending on how the attitude is posed; with rotation matrices [35, 44, 54], quaternions [20, 23, 26, 35] or otherwise (Direct Cosine Matrix etc ...) the error state $\Delta\vec{E}^8 = \vec{E}_d - \vec{E}_s$ could then differ to a (hamilton) multiplicative

⁷Development of a Dual Axis Tilt Rotorcraft UAV: Modelling, Simulation and Control [21]

⁸*The Attitude Control* [68] describes these conventionally different error states

relationship. Note that here \vec{E} is not necessarily an Euler set but any attitude representative state variable. Simulation and modelling papers often rely on Euler angle based rotation matrices for attitude representation, [10, 11, 43, 49, 61] without addressing the inherent singularity associated with such an attitude representation [sic Gimbal Lock, [66], Section:3.1.2]. The alternative quaternion attitude representation, first implemented on a quadrotor UAV in 2006 [67], is often used in lieu of rotation matrices but has its own caveat of *unwinding*, (Section:3.1.4), as a result of quaternions dual-coverage [46].

Quadrotor plant dynamics, as mentioned before, are often simplified; especially when represented with a 3-variable Euler angle set, $\vec{Y} = [\phi \ \theta \ \psi]^T$. The coupled gyroscopic and Coriolis responses are both neglected when the angular velocity rate is small, $\vec{\omega}_b \approx 0$, and the inertial matrix is diagonal, $rk(\mathbb{I}_f) = x$ for $x \in \mathbb{R}^x$. The consequence of which is the ineffectual deterioration of both the gyroscopic term, $\vec{\tau}_{gyro} = -\vec{\omega}_b \times \mathbb{I}_b \vec{\omega}_b \approx 0$ and the Coriolis force term, $\vec{F}_{cor} = \vec{\omega}_b \times \vec{a}_b \approx 0$ in the bodies dynamics [Chapter:3 for context]. Once the cross-product coupled terms are no longer of consequence, the 6 degrees of freedom, $[x \ y \ z \ \phi \ \theta \ \psi]^T$, can each be treated as an individual SISO plants to be controlled with appropriate techniques. Quaternion represented attitude plants cannot easily be decomposed into individual single-input-single-output systems [quaternion dynamics in Section:3.1.3]. So a quaternion (combined four variable attitude state vector) is then used, $Q_b = [q_0 \ \vec{q}]^T$ for the abstracted major loop plant.

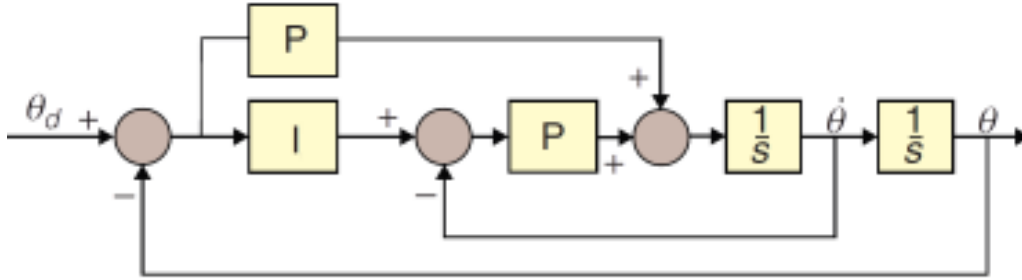


Figure 1.5: ArduCopter PI Euler Angle Attitude Control loop

Commercial flight controllers (Arducopter [3], Openpilot [39]⁹, BetaFlight [7], etc ...) for custom fabricated UAV platforms all apply their own structured attitude controllers and state estimation algorithms, based on onboard hardware sensor fusion. The article *Build Your Own Quadrotor* [40] summarizes the control structures implemented on a range of common flight controllers. The most popular of which, ArduCopter, implements a feed-forward PI compensation controller (Fig:1.5)¹⁰. PI, PD and PID controllers are all easy and effective plant independent control solutions for general attitude plants once the systems have been linearised. Table:1.1 collectively lists the common attitude control blocks (not exclusively quadrotors UAVs but MAVs too) and which projects they've been implemented in, after which a critique on the more unique adaptations is given.

Controller Type	Independent	Dependent	Total
PI	[68]	[68]	2
PD	[1, 42]	[20, 49]	4
PID	[10, 12, 59, 63, 68]	[29, 61, 68]	8
Lead	[16, 58]	lead	2
IBC	[43, 65] ¹¹	[43]	3
ABC	[6, 17, 33, 47]		4
LQR	[12]	LQR	1

Table 1.1: A Breakdown of common Attitude Controllers

⁹NOTE: OpenPilot's firmware branch is now maintained by LibrePilot

¹⁰Image sourced from *Build your own Quadrotor* [40]

In a collection of papers, written by Bouabdallah et al ... (2003,2004,2007) arguably the most prolific early quadrotor authors, a range of different control implementations are derived and reviewed. Their last paper (2007) [11] derived and practically tested an Integral Backstepping attitude controller on an OS4 quadrotor. It builds on their research from an earlier paper (2003) [12] wherein an analysis of PID vs LQR attitude controllers in the context of quadrotors is posed. LQR controllers aim to optimize the controller effort (that being $\|\mathbb{U}\|$ or the L_2 norm of the plant input) and although, in theory, solving the associated Ricatti cost function may produce an optimal, stable and efficient control law it needs exact plant matching. In practice, direct plant identification is difficult to achieve for a quadcopter or any aerospace body for that matter. The resultant controller in [12] achieved asymptotic stability but had poor steady state performance due to low confidence of the identified actuator dynamics and poor inertial measurements.

Adaptive Backstepping Control [71](any of the examples in Table:1.1) expands on nominal IBC fundamentals by introducing an added disturbance state term in the LCF used for the backstepping iteration. The drawback with this form of Backstepping approach is that, from the Lyapunov control theorem, a time derivative for the estimated disturbance (or an *update law*) is needed. Disturbance approximation has been investigated thoroughly but, for a signal without *a priori* information, some heuristic needs to be adopted with the approximation which usually involves compromise. In one example, [17], the authors implemented a statistical *proj(.)* operator based technique. When used in adaptive control the projection operator [14], *proj(.)*, ensures a derivative based estimator is bounded for adaptive regression approximation [57].

Although the control implementation isn't backstepping based, in [75], a sliding mode controller was used to compensate for the disturbances in an Unmanned Submersible Vehicle attitude plant. The underwater current disturbances are approximated using a fuzzy logic system, specifically a *zero-order TSK* fuzzy controller. The TSK system has been proven to act in the same way as an Artificial Neural Network approximator [45]; where the TSK system is more comprehensible than the latter. Statistical analysis and investigation of approximators without *a priori* knowledge of a system are well beyond the scope of what this project but are worth mentioning.

Single/Dual Axis Control & Allocation

The extra actuation introduced with single and dual axis articulation provides room for more control goals to be achieved as the order of actuation increases. Of the few papers published on tilting-axis quadrotors, PD controllers (Nemati et al.[2014] [49] and again in Gasco & Rihani [1, 21]) and PID controllers (Ryll et al.[2012,2013] [63, 64]) are the norm for control blocks. For either of these systems there needs to be an allocation rule to distribute a commanded input amongst the actuator set. In [31], Johansen et al.[2012] describes the control allocation problem for a dynamic plant:

Note in state space Equation:1.3a, it's assumed the plant input, τ , has a multiplicative relationship with the response, $g(x, t, \tau) \iff g(x, t)\tau$.

$$\dot{x} = f(x, t) + g(x, t)\tau \quad (1.3a)$$

$$y = l(x, t) \quad (1.3b)$$

With a state $x \in \mathbb{R}^n$ and $f(x, t)$ & $g(x, t)$ being the plants' dynamics and input responses respectively. In set point tracking, the output is then *tracking* the state $y = x$, and hence $y \in \mathbb{R}^n$. In an ideal well posed system the number of actuator inputs equals the number of controllable variable outputs; $\dim(x) = \dim(\tau) \in \mathbb{R}^n$. In the case where the input $\tau \in \mathbb{R}^m$, if $m > n$ the problem is then overactuated and a level of abstraction is needed; a virtual control input ν_d is designed by a control law $\nu_d = h(x_e, t)$ to affect dynamics. The goal is to then find a function that maps $\mathbb{R}^m \rightarrow \mathbb{R}^n$ for an actuator matrix $u \in \mathbb{U}^m$. An overactuated plant can be described as:

$$\dot{x} = f(x, t) + g(x, t)\nu_d, \quad \nu_d \in \mathbb{R}^n \quad (1.4a)$$

$$\nu_c = B(x, t, u) \approx B(x, t)u, \quad u \in \mathbb{U}^m, \quad \nu_c \in \mathbb{R}^n \quad (1.4b)$$

$$y = x \quad (1.4c)$$

$B(x, t, u)$ is the effectiveness function which formulates how the actuator inputs u relate to the virtual commanded input ν_c . $B(x, t, u)$ can be abstracted to a multiplicative relationship $B(x, t)u$ if the plants' dynamics permit it, such that; $B(x, t) \in \mathbb{R}^{n \times m}$. For setpoint tracking the control law will design a desired virtual control input ν_d , the allocation rule then has to solve u for ν_c such that a slack variable $s = \nu_c - \nu_d$ is minimized:

$$\min_{u \in \mathbb{R}^m, s \in \mathbb{R}^n} \|Q_s\| \quad \text{subject to } \nu_c - h(x_e, t) = \nu_c - \nu_d = s, \quad u \in \mathbb{U} \quad (1.5)$$

Which ensures the commanded input ν_c tracks the desired control input ν_d ; $\nu_c \rightarrow \nu_d$ as per some cost function of the slack variable Q_s . Mostly the L2 norm, $\|Q_s\|$, is used. In an overactuated system it then follows that there is a set of possible inputs for each ν_c . A unique actuator solution (rather than a family solution set) to Eq:1.5 needs a secondary objective function, $J(x, t, u)$. Eq:1.5 then becomes;

$$\min_{u \in \mathbb{R}^m, s \in \mathbb{R}^n} (\|Q_s\| + J(x, t, u)) \quad \text{subject to } \nu_c - h(x_e, t) = s, \quad u \in \mathbb{U} \quad (1.6)$$

Over-actuation is not something often applied to quadrotors and as a result rather than providing a comprehensive literature review of associated papers here (which are all mostly theoretical derivation), the contextual application and solutions to the above posed problems are expanded later in Section: 4.3.1. The only overactuated quadrotor (birotor dual-axis tilting makes the system critically actuated and so requires no allocation) literature which covers allocation of the given actuators is [1, 21], where the authors apply a weighted pseudo inverse (sic Moore Penrose Inverse [37]) allocation rule. A prerequisite for pseudo inversion is a multiplicative (*linear*) control effectiveness relationship for Eq:1.4b.

Segui et al. [2012] applied weighted inversion that relies on some very specific assumptions. For the net torque response, the authors assumed the extra actuators pitch and roll angular rates, $\dot{\phi}$ and $\dot{\theta}$ respectively, were proportionally related as follows:

$$\dot{\phi} \approx \frac{\phi}{t_{rise}} \quad (1.7)$$

In which t_{rise} is the actuators rise time to a set-point. As a result the gyroscopic first order torque $\tau_{gyro} = -\omega \times \mathbb{I}_f \omega$ and second order inertial torque $\tau = \mathbb{I} \dot{\omega}$ are then functions of position ϕ or θ and not their derivatives. The extent of that consequence is contrasted with the allocation solution in Section:4.3.

Satellite Attitude Control

Unconstrained attitude set-point tracking for 6-DOF bodies, quaternion based or otherwise, is a topic well covered in the field of satellite attitude control; [30, 34, 69]. The *status quo* for recent research is on non-linear adaptive attitude back-stepping control systems, wherein the adaptive update rule is the novel focus. Often plant uncertainty affects the inertia tensor of a satellite. In [30], the authors Wang Jia, et al. [2010], proposed applying adaptive back-stepping to compensate for steady state (asymmetric) inertial estimation errors. Alternatively, instead of deliberating on costly non-orbital prelaunch inertial measurements, [9] developed an algorithm for estimating the inertia tensor based on single axis controlled perturbations. However that does assume any initial estimates are sufficiently close to true body values such that they will settle and stability can be ensured.

Satellite actuator suites mostly include additional redundant effectors, to ensure fault tolerance and reliability, and hence require control allocation. Often the extra allocators are CMG actuators, driven by DC motors, to produce rotational torques. Fuel burning can only actuate for a certain period of time and so thrusters are scheduled to have a lower priority. Seen in the paper [34]; the authors, Kristiansen et al. [2005], addresses the over-actuation with direct and well-matched inversion before

applying quaternion based back-stepping for attitude control. A quadratic pseudo inverse solution to Eq:1.6 is:

$$u = B^\dagger(\tau_a^b - D\omega_{ib}^b) \quad (1.8a)$$

$$B^\dagger = B^T(BB^T)^{-1} \quad (1.8b)$$

Where B is the control effectiveness matrix and B^\dagger is such that $BB^\dagger = \mathbb{I}$. Specifically B^\dagger is the general *pseudo* inverse of B (more on inversions in Sec:4.3). It's assumed there's a multiplicative relationship between the input, $u \in \mathbb{U}$, and the input effectiveness matrix in Eq:1.4b. The controller designed actuator torque τ_a^b then dictates the input u as in Eq:1.8a. Much like the over-actuation previously discussed W.R.T quadcopters; the pseudo inversion method of control distribution applies quadratic optimization to the allocation slack cost function, Eq:1.5.

Chapter 2

Prototype Design

2.1 Conventions Used

The attitude conventions used for the system's dynamic derivations in the following Chapter:3 are first briefly discussed here. Often these aspects are omitted or assumed to be known already. It's important to clearly and unambiguously define a standard set of framing conventions to avoid uncertainty later. Rotation matrices are included but the focus remains on the *contrast* between a rotation and transformation operation. Both [26] and [54] provide an in depth and thorough explanation of rotation matrices and DCM attitude representation if such concepts are unfamiliar to the reader.

2.1.1 Reference Frames Convention

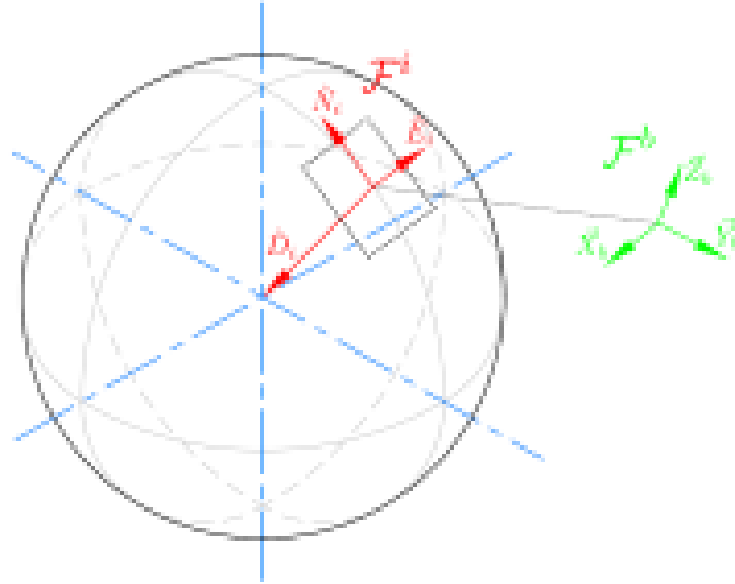


Figure 2.1: Inertial and Body Reference Frames

Euler (aerospace) frames are used for principle inertial and body coordinates (Fig:2.1). The inertial frame, F^i , is aligned such that the \vec{X}_i axis is in the \hat{N} orth direction, \vec{Y}_i is in the \hat{E} ast direction and \vec{Z}_i is in the \hat{D} ownward direction¹. The body frame, F^b , then has both \vec{X}_b and \vec{Y}_b aligned obliquely between two perpendicular arms of the quadrotor's body and the \vec{Z}_b axis in the body's normal direction (Fig:2.4). The body frame's axes and their relation to the prototype design are highlighted next in

¹In orbital sequences this would be toward the Earth's center. Sometimes referred to as the NED convention

Section:2.1.2. Frame superscripts i and b represent inertial and body frames respectively whilst vector subscripts imply the reference frame in which the vector's coordinates exists in.

Relative angular displacement between two frames is commonly measured by the three angle Euler set. The Euler angles $\Upsilon = [\phi \ \theta \ \psi]^T$ represents rotations about the \vec{X}, \vec{Y} and \vec{Z} axes respectively. Depending on how the rotation sequence is formulated, those angles can be used to construct rotation matrices which give relation to vectors or can transform coordinates. The generic equation to rotate a vector \vec{v} about a (normalized) axis \hat{n} by some angle μ is given by²:

$$\vec{v}' = (1 - \cos(\mu))(\vec{v} \cdot \hat{n})\hat{n} + \cos(\mu)\vec{v} + \sin(\mu)(\hat{n} \times \vec{v}) \quad (2.1)$$

Which, when \hat{n} is either \vec{X}, \vec{Y} or \vec{Z} axes, can be simplified to produce the fundamental rotation matrices $\mathbb{R}_x(\phi), \mathbb{R}_y(\theta)$ and $\mathbb{R}_z(\psi)$. Multiplication by a rotation matrix $\mathbb{R}(\cdot)$ applies a left-handed *rotation* operator, the resultant vector still exists in the same reference frame;

$$\vec{v}' = \mathbb{R}_x(\phi)\vec{v} \quad (2.2a)$$

$$\vec{v}', \vec{v} \in \mathcal{F}^1 \quad (2.2b)$$

No subscripts are used in Eq: 2.2 to indicate reference frame ownership because all vectors are in the same frame

A *transformation* changes the vectors reference frame. The transformation is a rotation by an angle of the difference between the resulting and principle reference frames. A transformation from frame \mathcal{F}^1 to \mathcal{F}^2 , differing by an angle of ϕ about the \vec{X} axis is then:

$$\vec{v}_2 = \mathbb{R}_x(-\phi)\vec{v}_1 \quad (2.3a)$$

$$\vec{v}_2 \in \mathcal{F}^2 \text{ and } \vec{v}_1 \in \mathcal{F}^1 \quad (2.3b)$$

The distinction between Eq:2.2 and Eq:2.3 is the sense of the angular operand ϕ , and hence the effect it has on the argument vector. The transformation of a vector from \mathcal{F}^i to \mathcal{F}^b is the product of three sequential operations about each axis. Because each subsequent rotation is applied relative to a new intermediate frame, the sequence of axial rotation operations will effect the Euler set. Any consequences of that chosen order is something well documented in *Quaternions and Rotation Sequence*, [35]. In this dissertation the Z-Y-X sequence is used. Hence a transformation of a vector \vec{v} from the inertial to the body frame is applied by:

$$\mathbb{R}_i^b \triangleq \mathbb{R}_z(\psi)\mathbb{R}_y(\theta)\mathbb{R}_x(\phi) \quad (2.4a)$$

$$\vec{v}_b = \mathbb{R}_i^b(-\psi, -\theta, -\phi)\vec{v}_i \quad (2.4b)$$

$$\Rightarrow \vec{v}_b = \mathbb{R}_z(-\psi)\mathbb{R}_y(-\theta)\mathbb{R}_x(-\phi)\vec{v}_i \quad (2.4c)$$

$$\mathbb{R}_z(-\psi)\mathbb{R}_y(-\theta)\mathbb{R}_x(-\phi) \iff \mathbb{R}_x(\phi)\mathbb{R}_y(\theta)\mathbb{R}_z(\psi) = \mathbb{R}_b^i \quad (2.4d)$$

The relation in Eq:2.4d is an inversion (*transpose*) of the rotation matrix. A rotation matrix's inverse can be used interchangeably to maintain a positive sense of the rotational angle. To ensure clarity throughout this paper's mathematics, a negative angular sense implies a *transformation* to a different reference frame. Where applicable, the order of rotation will indicate the sequence direction and an angular sign differentiates a rotation or transformation operation.

An inherent singularity does exists with such attitude representations. Indeed Quaternions are used for kinematics later in lieu of Euler angles. Euler angular attitude representation is, however, easily understood and well suited to the conventional distinctions made here. Quaternion operations are similarly sequenced in the ZYX order:

$$\mathbb{R}_i^b \iff Q_b^* \otimes (\cdot) \otimes Q_b \quad (2.5a)$$

$$Q_b^* \triangleq Q_z^* Q_y^* Q_x^* \text{ and } Q_b \triangleq Q_x Q_y Q_z \quad (2.5b)$$

With \otimes being the Hamilton product (or quaternion multiplier). Each quaternion, Q_i , is a unit quaternion about that \hat{i}^{th} axis. The operator and subsequent quaternion kinematics are defined later in Sec: 3.1.3.

²Derived and proven in *Quadrotor Dynamics and Control* [59]

2.1.2 Motor Axis Layout

Fundamentally the whole structure, although treated as rigid in the kinematics, consists of multiple bodies able to rotate relative to one another. Each propeller and motor pair is actuated by two servos. If the propeller, attached to the motors' rotor, has a rotational speed ω about the \vec{Z} stator axis, then two servos are aligned with \vec{Y} and \vec{X} axes to pitch and roll the propeller away from its principle rotational axis. Each of the four motors has their own reference frame, \mathcal{F}^{M_i} , aligned as in Fig:2.2.

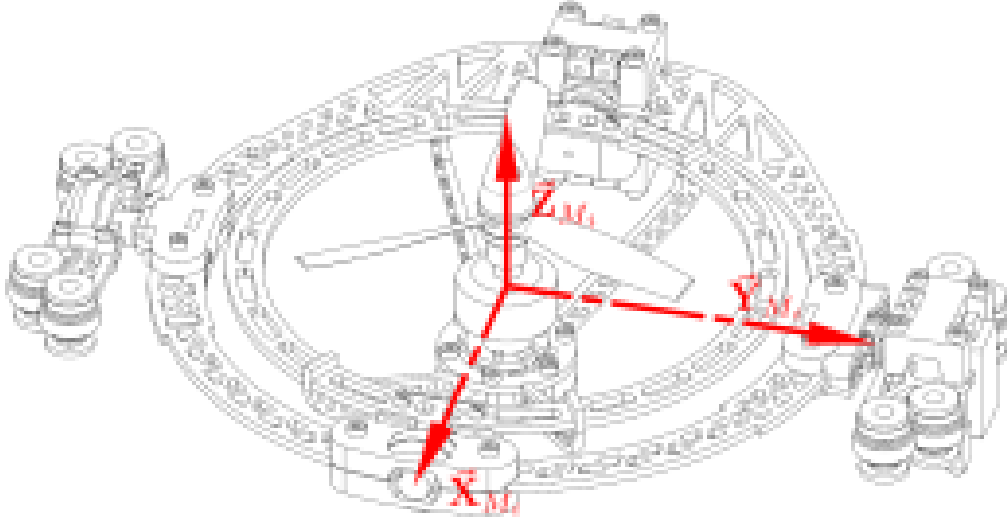


Figure 2.2: Aligned Motor Frame Axes

The motor frames, numbered 1 – 4, transform to the body frame first by an angle of λ_i about the \vec{X}_{M_i} axis. Then by η_i about the $\vec{Y}_{M'_i}$ axis in an intermediate M'_i frame. The second servo actuates η_i to produce a second intermediate frame M''_i , the servo is fixed in the M'_i frame. Finally there is a relative $\vec{Z}_{M''_i}$ rotation between \mathcal{F}^b and $\mathcal{F}^{M''_i}$. The layout of all four motor modules are such that the \vec{Z} axis transformation between the intermediate frame $\mathcal{F}^{M''_i}$ and \mathcal{F}^b are all constants; 0, 90°, 180° or 270°. Each modules' state is fully described by $[\Omega_i, \lambda_i, \eta_i]^T$ for $i \in [1 : 4]$.

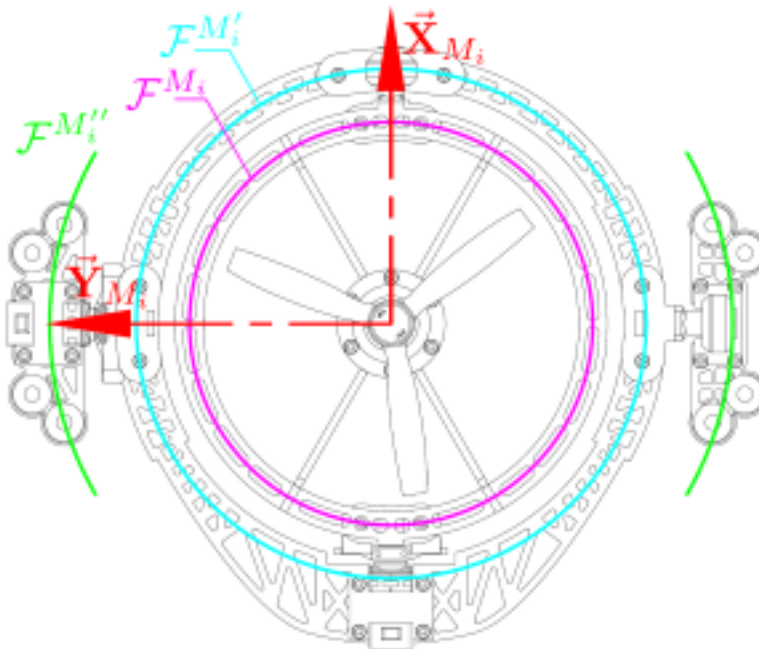


Figure 2.3: Intermediate Motor Frames

The four motor modules are aligned relative to the body's XYZ axes as show in Fig:2.4. Modules 1 and 3 have their X-axes respectively in the positive and negative X direction of the body frame. Similarly Modules 2 and 4 have their X-axes in the positive and negative Y directions of the body frame.

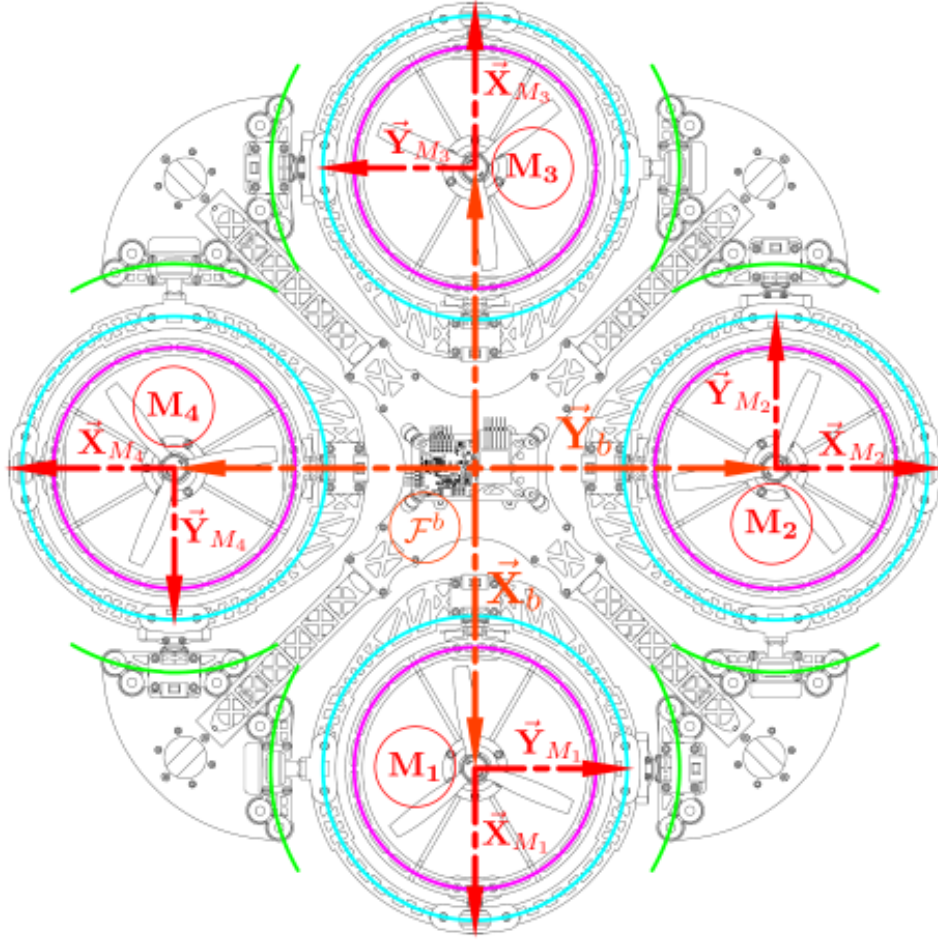


Figure 2.4: Body Frame Axes Layout

Not shown in Fig:2.4 is the relative Z axis position with respect to the structure. The Z height of the body's motion centroid such that its origin is co-planar with the four motor modules rotational centres. The centre of motion is not the center of mass, an aspect which is quantified in the following Section:2.2.2.

Transformation relationships from each of the motor frames to the body can be characterized as:

$$\vec{v}_b = \mathbb{R}_z(-\sigma_i)\mathbb{R}_y(-\eta_i)\mathbb{R}_z(-\lambda_i)\vec{v}_{M_i}, \quad \sigma_i \in [0, 90^\circ, 180^\circ, 270^\circ] \quad (2.6a)$$

$$\mathbb{R}_z = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ for } i \in [1, 2, 3, 4] \text{ respectively} \quad (2.6b)$$

The entire actuator space, including propeller speed Ω_i [rps], is then $(\in \mathbb{R}^{12})^3$, or rather $\mathbb{U} \in \mathbb{R}^{12}$. The actuator input set $u \in \mathbb{U}$ is then structured as:

$$u_{\in \mathbb{U}} = [\Omega_1 \ \lambda_1 \ \eta_1 \ \dots \ \Omega_4 \ \lambda_4 \ \eta_4]^T \quad (2.7)$$

³Disambiguation: An omission of axial subscript on the \mathbb{R} symbol implies a real space of the superscript dimension.

2.2 Design

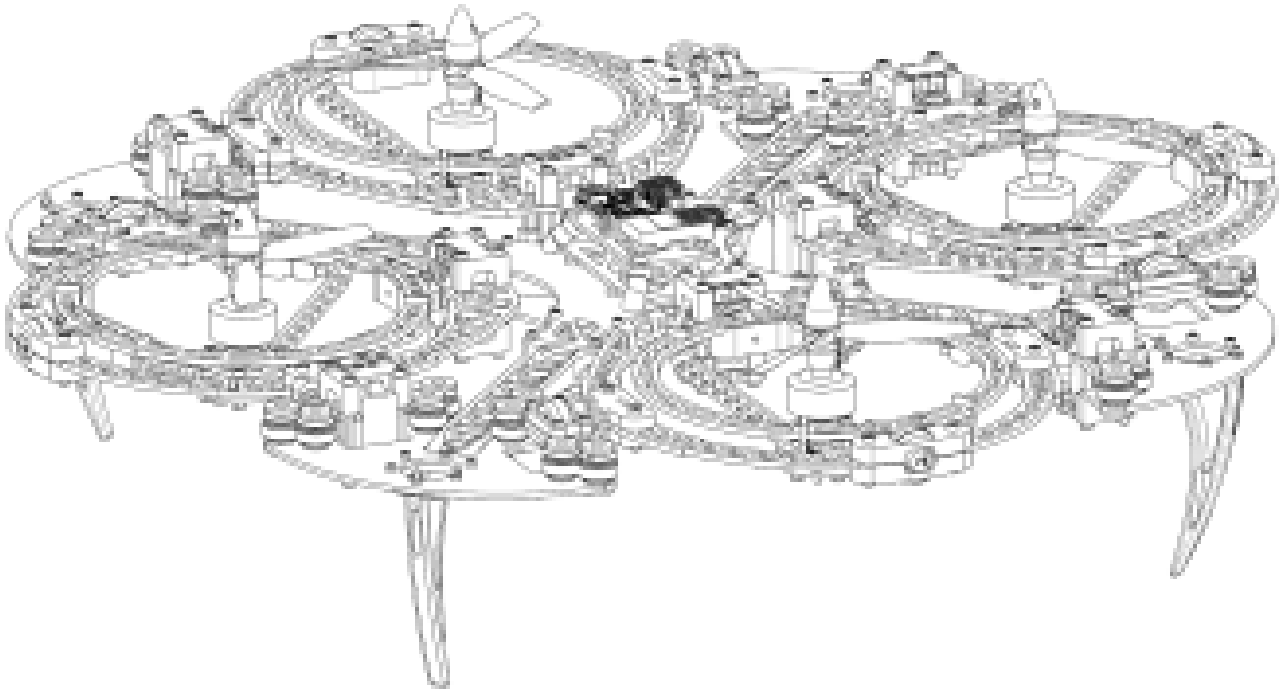


Figure 2.5: Isometric layout of the designed prototype

The actual prototype went through a series of different design iterations, all aimed at using as many off-the-shelf RC components as possible whilst attempting to optimize construction costs. A significant factor in the design was the net weight whose upper limit, as mentioned before, is inherently linked to the thrust produced by the motors used. Some of the more important design aspects, like inertias, are discussed here in order to give context to some of the dynamics derived in the next chapter. The actuator suite’s functionality and transfer characteristics are presented here. Finally a brief overview of the electrical systems layout is given with the components associated electrical characteristics listed. A review of the physical prototype realized and control loop implementation is detailed in Chapter:6 along with actual flight test results.

2.2.1 Actuation

The novel component of the design is articulation of each motor module, independently redirecting the thrust generated by each lift propeller. Within each module are servos affixed onto sequential rings to pitch and roll the substructure’s axes. The gyroscope-like frame that surrounds each motor/propeller pair accommodates the relative movement. Aligned with each servo is a coaxial support bearing. The coaxial bearing and actuator servos do have a mass disparity that results in an eccentric mass center, producing a gravitational torque arm. Unfortunately, due to weight constraints, counter balance measures cannot be introduced. Consequences from the center of mass variations must either be compensated for (*plant dependent solution*) or exploited in the dynamics (*additional non-linear actuator plants*). The precise effects are quantified numerically next in Section:2.2.2.

Each module is designed such that thrust vector produced coincides with the two rotational axes intersections (Fig:2.6a). There’s no perpendicular displacement of generated thrust vectors relative to the body’s X-Y-Z origin⁴. It’s more prudential to ensure intersection of the thrust vector with the rotational center than to balance the masses undergoing rotation. A thrust varying torque is harder

⁴Although the center of gravity does have a time varying position dependent on the 8 servos positions

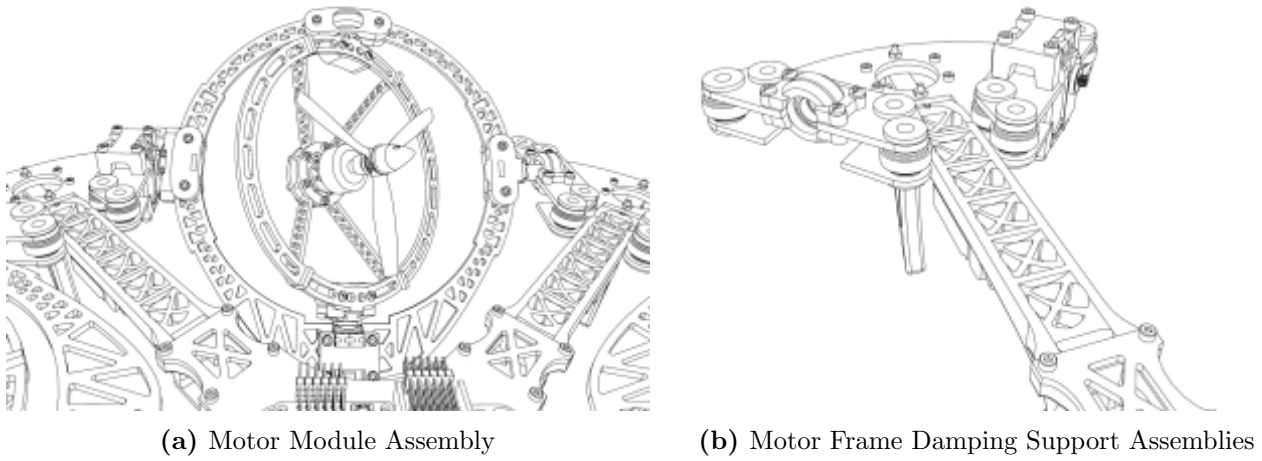


Figure 2.6: Motor Assembly

to compensate for than a gravitational torque given the complexity with modelling a propeller's aerodynamic thrust (Section:3.3.1).

The primary frame has silicon damping balls between brackets which attach to the motor gyroscope assembly (Fig:2.6b). For damping to be effective there has to be roughly equatable relative masses between the two damped bodies. A smaller damping assembly in the center of the frame houses all the electronics and power distribution circuitry. All the mounting brackets which affix the motor modules are 3D printed from CAD models using an Ultimaker V2+ [70]. There is a complete bill of materials for all parts used, including working drawings for each 3D printed bracket and the laser cut frame(s), in Appendix:B.

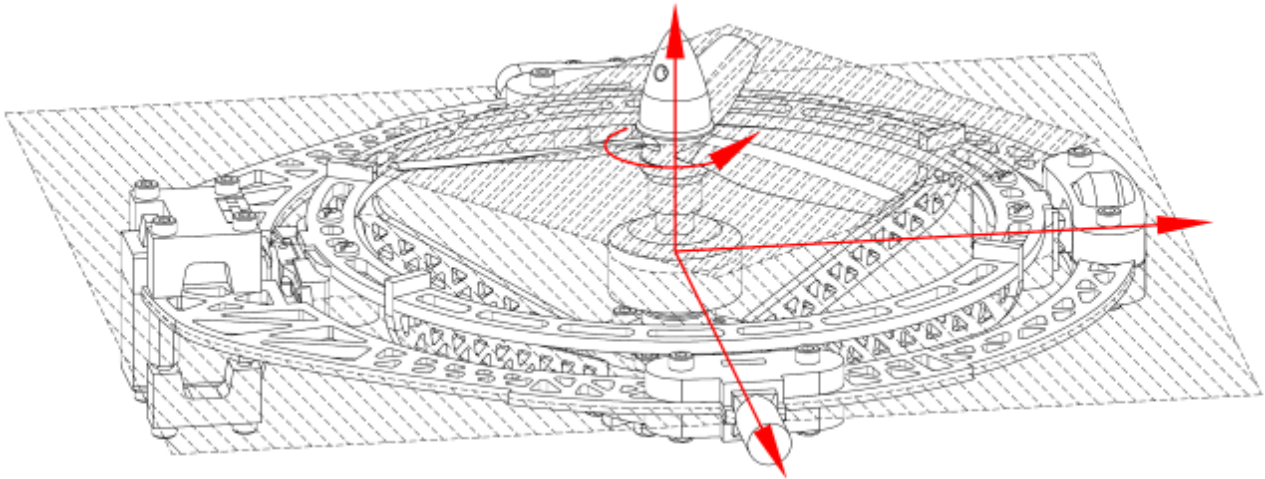
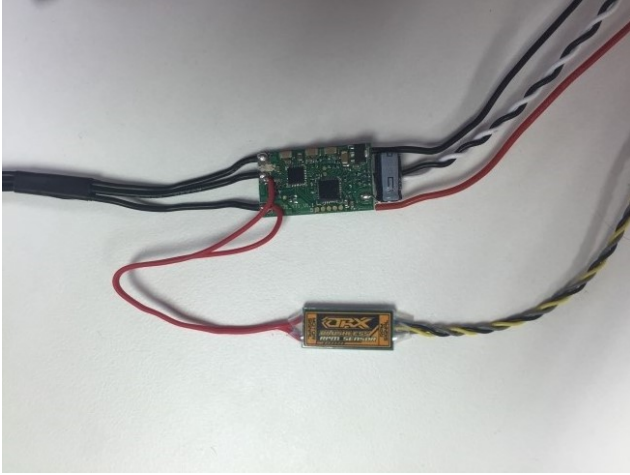


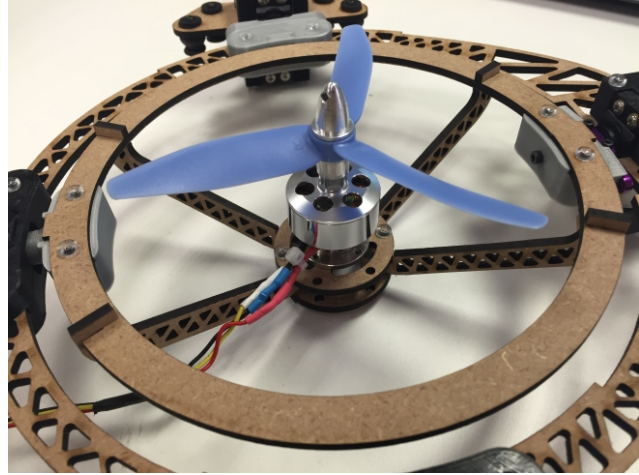
Figure 2.7: Difference between propeller and motor planes

The propellers rotational plane is not exactly aligned with the plane made by the \vec{X}_{M_i} and \vec{Y}_{M_i} rotational servo axes (Fig:2.7). The offset is approximately 28.2 mm and must be considered when evaluating pitch/roll gyroscopic torque responses later in Section:3.2.1. The propellers are 6 inch (6×4) 3-Blade plastic Gemfam propellers, powered Turnigy DST-700KV Outrunner Brushless DC motors. The thrust produced as a function of angular velocity (in RPS) for the propellers is derived in Section:3.3.1. The BLDC motors are controlled with Hobbywing XRotor 15A ESC modules with an inline Orange RPM Sensor. The transfer function for the combined unit is presented subsequently in Section:2.2.3. Power for the quadrotor is supplied not from a battery bank but from a power

tether. Tethered power will ensure consistent flight time and reduce the concern of payload strain on the available lift actuation. Power lines to both the BLDC motors and servos are both supplied conventionally, however an ideal construction would see slip-rings for each module's supply. Power transmission lines are affixed such that they don't impede rotation.



(a) BLDC ESC & RPM Sensor Assembly



(b) Turnigy DST-700KV BLDC Motor

Metal gear Corona DS-339MG digital servos are used for the two axes of rotation (Fig:2.9). Each servo has a range of 180° , positioned such that a zeroth offset aligns the motor modules adjacent to the body frame and has a $\pm 90^\circ$ range. A digital servo updates at 330 Hz, faster than a 50 Hz analogue servo equivalent (Table:2.1). This means the otherwise 20ms zero-order analogue sampling becomes a less significant 3.30ms zero-order holding time. Both the \vec{X}_{M_i} and \vec{Y}_{M_i} axis servos will be rotating a large loading mass and so their *open loop* plant dynamics are determined empirically in Section:2.2.3 using test data included in Appendix:C.

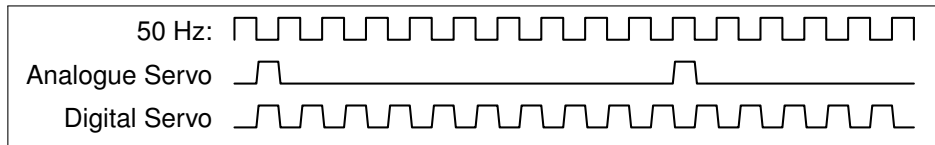


Table 2.1: Analogue & Digital Timing Signals

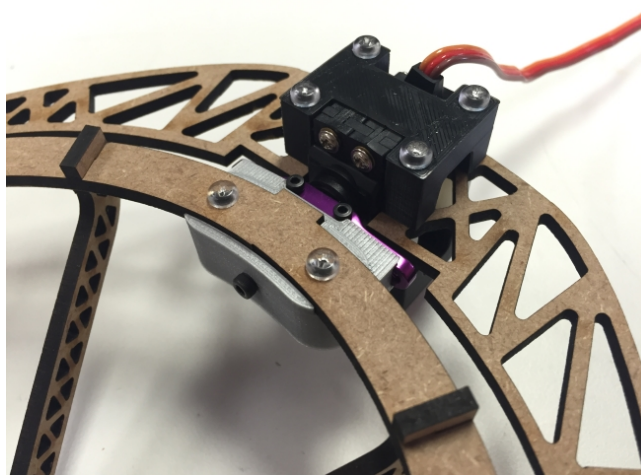


Figure 2.9: Corona Servo Bracket

2.2.2 Inertial Matrices & Mass

Although inertias are presented here rounded to either 2 or 0 decimal places, full floating point numbers are used in simulation and prototype software. Un-rounded inertias are included in Appendix:D. Similarly rotation matrices produce a more cumbersome results for Eq:2.92.12??, which are susceptible to singularities. Quaternion operators are used in practice.

Inertias

An undesirable side effect of the rigid body rotations the structure undergoes are the inertial responses produced from such movements. Given Newton's Second Law of rotational motion[†], the applied rotations are going to produce an equal but opposite reaction onto the principle inducing frame. Similarly a gyroscopic cross product from rotational velocities is also present. Such first and second order effects are often neglected given that angular rates are mostly small enough to approximate as zero, $\vec{\omega}_b \approx \vec{0}$. A dynamic set-point (non-zero) attitude tracking plant is, however, going to produce sizable time varying body angular velocities and accelerations. Unlike a traditionally actuated quadrotor, such effects have to be accounted for.

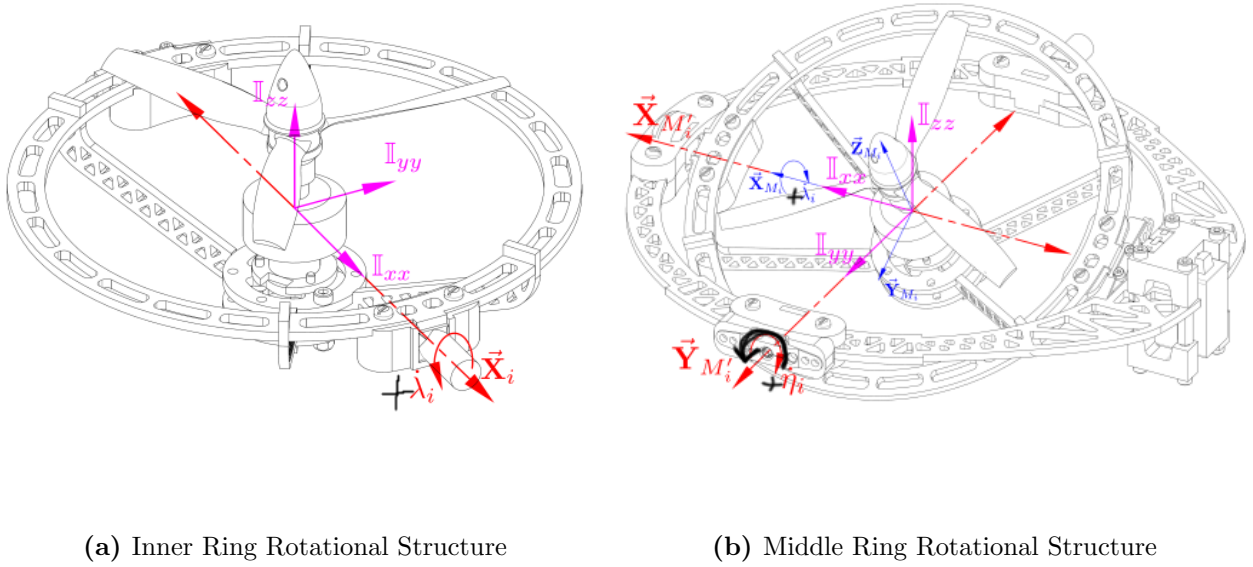


Figure 2.10: Inertial Measurement References

The manifestation of the aforementioned torques are explored in thorough detail in Section:3.2. Those effects are both dependent on the rotational body's inertial tensor⁵ about the respective rotational axes. The magnitude of those inertias are obviously a byproduct of the structure's design. Starting with the innermost assembly, in each Motor Frame \mathcal{F}^{M_i} , the inside ring structure is a 99g assembly (all components incorporated). The rotational center *roughly* coincides with the center its of mass ($C.M = [-1.40 \ -0.04 \ -1.94]^T$ [mm] relative to its rotational center). The inner ring being rotated by λ_i° about the \vec{X}_{M_i} axis then has an inertial matrix (centered as in Fig:2.10a):

$$\mathbb{I}_{M_i} = \begin{bmatrix} 588.84 & -0.28 & 0.25 \\ -0.28 & 1966.60 & 0.90 \\ 0.25 & 0.90 & 2141.78 \end{bmatrix} [g.cm^2] \quad (2.8a)$$

⁵All inertias are assumed asymmetrical and calculated in Solidworks with overridden masses to match physical prototype measurements in App:B

$$\approx \text{diag}(588, 1966, 2141) \times 10^{-7} \text{ [kg.m}^2\text{]} \quad (2.8b)$$

The effect of a rotating propeller on the inertia in Eq:2.8a is approximated by a solid disc and hence the inner ring's inertial products are regarded as negligible. The moment of inertia about that \vec{X}_{M_i} axis, pertinent to λ_i rotation, is then $\mathbb{I}_\lambda = 588.84 \times 10^{-7} \text{ [kg.m}^2\text{]}$.

The first λ_i actuating servo and bearing supports are affixed to the intermediate middle ring assembly (Fig:2.10b). The middle ring frame, $\mathcal{F}^{M'_i}$, is a 102g structure, excluding the inner most ring. Collectively the mass for both the inner and middle rings structures is $m_{\text{module}} = 201\text{g}$. That middle ring is rotated by η_i° about its \vec{Y}_{M_i} axis. The compound body's inertia about the axis of rotation, \vec{Y}_{M_i} , is a combination of both the middle ring's inertia and the inner ring's. The latter contribution being a function of the *rotation* (not transformation) angle λ_i° which, from the conservation of angular momentum theory [55]⁶, is:

$$\text{If } \mathbb{I}_{\text{middle}} = \begin{bmatrix} 3024.30 & 0.03 & 406.84 \\ 0.03 & 8791.16 & 0.01 \\ 406.87 & 0.01 & 11579.85 \end{bmatrix} \text{ [g.cm}^2\text{]} \quad (2.9a)$$

$$\mathbb{I}_{M'_i} = \mathbb{I}_{\text{middle}} + \mathbb{R}_X(\lambda_i)(\mathbb{I}_{\text{inner}})\mathbb{R}_X^{-1}(\lambda_i) \quad (2.9b)$$

$$\mathbb{I}_{M'_i}(\lambda) = \mathbb{I}_{\text{const}} + \mathbb{I}_{M_i}(\lambda) \quad (2.9c)$$

$$\approx \begin{bmatrix} 3609 & 0 & 407 \\ 0 & 10842 & 0 \\ 407 & 0 & 13630 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & -88c_{2\lambda} & 2c^2_\lambda - 91s_{2\lambda} \\ 0 & 2c^2_\lambda - 91s_{2\lambda} & 88c_{2\lambda} \end{bmatrix} \times 10^{-7} \text{ [kg.m}^2\text{]} \quad (2.9d)$$

With $\mathbb{I}_{\text{inner}} = \mathbb{I}_{M_i}$ being the inertia from Eq:2.8a, transformed by a rotation $\mathbb{R}_x(\lambda_i)$. The net inertia being a function of rotation angle, λ_i , and a constant inertia (Eq:2.9c) is then simplified⁷ to Eq:2.9d. It's important to note the non-zero product of inertia, \mathbb{I}_{yz} , which is going to result in a τ_z response. The inertia then encountered by an η_i rotation is:

$$\mathbb{I}_\eta(\lambda) \approx [0, 10842 - 88c_{2\lambda}, 2c^2_\lambda - 91s_{2\lambda}]^T \times 10^{-7} \text{ [kg.m}^2\text{]} \quad (2.10)$$

Variable inertias dependent on state input variables are the first of many non-trivial aspects unique to this aircraft's design. The resultant control solutions are thus decidedly plant dependent in their formulation. Secondly, the center of mass for the motor module's compound assembly isn't coincidental with either rotational axes intersection. As a result the effective center of mass for the entire structure is going to be time varying, dependent on the angular rotation which the motor modules have been effected by.

The second η_i rotating servo joins the complete motor module (both the inner and middle ring assemblies) to the body structure. The inertial volume of the servo and bearing supports contribute then to the body's inertia, whose value excludes any of the four motor modules. Consisting of servo and bearing damping brackets, the "damping" assembly collectively weighs 84g and suspends the motor modules from the body frame with a set of silicon damping balls. The body assembly's center of mass (Fig:2.11) coincides with the XY directional axes and lies $\Delta Z = -14.27 \text{ mm}$ below the Body Frame's origin of motion, $\vec{O} \in \mathcal{F}^b$.

Note: the origin which all motion is calculated with respect to is co-planar to the motor module's rotational centers, not the net center of mass.

⁶ \mathbb{R}_x is a full rank and square, so an inverse \mathbb{R}_x^{-1} always exists

⁷Eq:2.9d is rounded to no decimal places, seeing that its units are already $\times 10^{-7}$

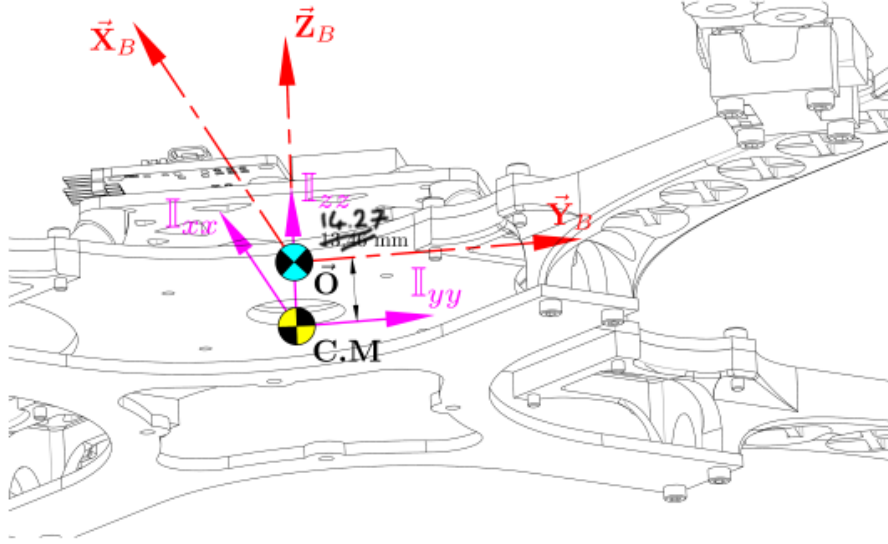


Figure 2.11: Body Frame Center of Mass

The body's weight, including all four damping assemblies, totals to 814.7g. The body's net inertia (*sans* motor modules) \mathbb{I}_{body} , about its center of mass is:

$$\mathbb{I}_{body} = \begin{bmatrix} 182018.63 & -0.44 & -80.30 \\ -0.44 & 181896.17 & -17.75 \\ -80.30 & -17.75 & 360077.58 \end{bmatrix} [g.cm^2] \text{ or } \times 10^{-7} [kg.m^2] \quad (2.11a)$$

Using the Parallel Axis theorem[†], that same net body inertia about the body frame's origin, \vec{O}_b , is:

$$\mathbb{I}_{body}' = \mathbb{I}_{body} + m(\vec{d} \cdot \vec{d} + \vec{d} \otimes \vec{d}^T) \approx \mathbb{I}_{body} + m\vec{d}^2 \quad (2.11b)$$

Here \otimes represents the Hamilton product of two 3X3 matrices, used later in Chapter:3 to indicate the quaternion operator.

$$\mathbb{I}_{body}' = \begin{bmatrix} 183677.51 & -0.42 & -4.45 \\ -0.42 & 183555.03 & -10.41 \\ -4.45 & -10.41 & 360077.62 \end{bmatrix} \times 10^{-7} [kg.m^2] \quad (2.11c)$$

Net inertia for the compound assembly, \mathbb{I}_b ⁸, about that origin \vec{O}_b is a combination of all the relative attached bodies. That being; the four motor modules, transformed and then translated to the center of motion, and the body structure itself. That transformation is analogous to that of Eq: 2.6. Reiterating that the origin is co-planar to the modules center of rotation, each motor modules inertia, \mathbb{I}_{M_i}' ⁹, is further rotated by $\mathbb{R}_Y(\eta_i)$ and finally a \vec{Z} orthogonal rotation onto \mathcal{F}^b . Still measured with respect to their individual centers, \vec{M}_i , but re-orientated to align with \vec{O}_b . Contribution of each motor module's inertia, with \mathbb{R}_Z being the same as Eq:2.6b, is then:

$$\mathbb{I}_{ith_{motor}} = \mathbb{R}_Z(\sigma_i) \mathbb{R}_Y(\eta_i) (\mathbb{I}_{M_i}') \mathbb{R}_Y^{-1}(\eta_i) \mathbb{R}_Z^{-1}(\sigma_i) \quad (2.12a)$$

Expanding to Inner Ring and Middle Ring components:

$$= \mathbb{R}_Z \mathbb{R}_Y(\eta) (\mathbb{I}_{middle}) \mathbb{R}_Y^{-1}(\eta) \mathbb{R}_Z^{-1} + \mathbb{R}_Z \mathbb{R}_Y(\eta) \mathbb{R}_X(\lambda) (\mathbb{I}_{inner}) \mathbb{R}_X^{-1}(\lambda) \mathbb{R}_Y^{-1}(\eta) \mathbb{R}_Z^{-1} \quad (2.12b)$$

$$\text{With axes } \vec{X} \in \mathcal{F}^{M_i}, \vec{Y} \in \mathcal{F}^{M_i'}, \vec{Z} \in \mathcal{F}^{M_i''} \quad (2.12c)$$

It's at this stage that, despite the simplifications, the symbolic inertial equation becomes overly cumbersome to include with numeric values... For the sake of brevity, exact calculated inertia values for the input dependent plant are omitted.

⁸Disambiguation: \mathbb{I}_b is net body frame's inertia, different from \mathbb{I}_{body} which is the inertia for *just* the body structure

⁹As defined in Eq:2.9d

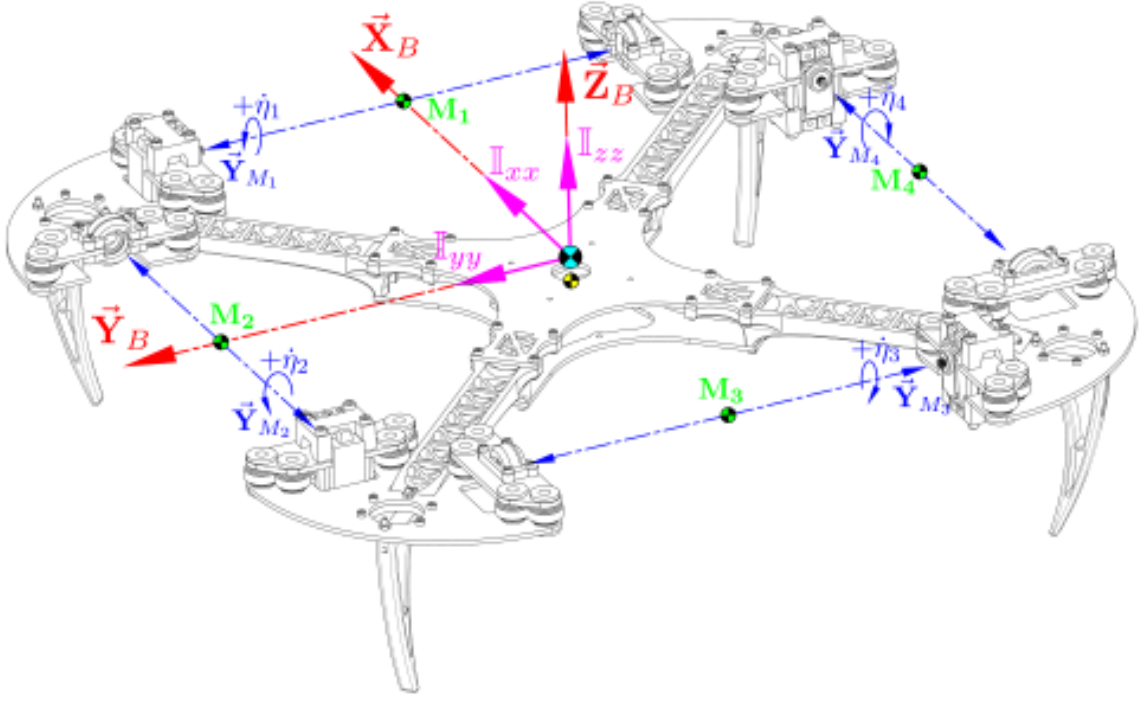


Figure 2.12: Inertial Center & Mass Center

Each module's rotational center is spaced equally relative to $\vec{\mathbf{O}}_b$ with a parallel axis arm $\vec{L}_{arm} = [195.16100]^T$ [mm] (Fig:2.12). The net inertial equation about $\vec{\mathbf{O}}_b$, dependent on a the actuator suite \mathbb{U} positions, can be calculated as:

$$\mathbb{I}_b(u) = \mathbb{I}_{body} + \sum_{i=1}^4 \mathbb{M}_i \text{ [kg.m}^2\text{]} \quad (2.13a)$$

$$\mathbb{M}_i = \mathbb{I}_{i^{th}motor} + m_{module}(\vec{L} \cdot \vec{L} - \vec{L} \otimes \vec{L}) \quad (2.13b)$$

Although Eq:2.13 does indeed produce the net body's inertia, the transformations to calculate \mathbb{M}_i are compounded. Inertias are first translated to the center of rotation and then to the body frame's origin. Subsequent transformations are successively going to deteriorate the floating point precision of the resultant inertial tensor. Transforming inertial tensors about each sub-body's center of mass directly to the body frame origin is going to improve results. Similarly, it is more intuitive for the reader to consider each sub-body's contribution separately, despite having been derived as compound inertial systems previously. The relative movement pertinent to Eq:2.8 and Eq:2.9 are conceptually separated from that affecting Eq:2.13.

It was found that each subsequent parallel axis translation further deteriorates the inertial value when compared to a true integral inertia. The net contributions used are translations of inertias from each respective center of mass to the origin $\vec{\mathbf{O}} \in \mathcal{F}^b$.

$$\mathbb{M}_i = \mathbb{M}_{inner} + \mathbb{M}_{middle} \quad (2.14a)$$

For each inner ring, W.R.T its center of mass, different from Eq:2.8a;

$$\mathbb{I}_{inner}^{C.M} = \begin{bmatrix} 585.11 & -0.34 & -2.44 \\ -0.34 & 1960.93 & 0.81 \\ -2.44 & 0.81 & 2139.84 \end{bmatrix} \quad (2.14b)$$

$$C.M_{inner} = [1.400 \quad -0.043 \quad -1.942]^T \text{ [mm]} \quad (2.14c)$$

$$\mathbb{I}_{inner} \parallel \vec{\mathbf{O}} = \mathbb{R}_Z \mathbb{R}_y(\eta) \mathbb{R}_x(\lambda) (\mathbb{I}_{inner}) \mathbb{R}_x^{-1}(\lambda) \mathbb{R}_y^{-1}(\eta) \mathbb{R}_Z^{-1} \quad (2.14d)$$

$$\mathbb{M}_{inner} = \mathbb{I}_{inner} = \mathbb{I}_{inner} + m_{\parallel \vec{\mathbf{O}}}((\Delta L \cdot \Delta L)\mathbb{I}_{3 \times 3} - \Delta L \times \Delta L^T) \quad (2.14e)$$

Similarly for each middle ring:

$$\mathbb{I}_{middle}^{C.M} = \begin{bmatrix} 2996.57 & 179.32 & 232.71 \\ 179.32 & 6524.84 & 13.87 \\ 232.71 & 13.87 & 9312.733 \end{bmatrix} \quad (2.15a)$$

$$C.M_{middle} = [47.00 \quad 3.74 \quad -3.63]^T \quad [mm] \quad (2.15b)$$

$$\mathbb{I}_{middle} = \mathbb{I}_{middle}^{C.M} + m_{middle}((\Delta_{C.M} \cdot \Delta_{C.M})\mathbb{I}_{3 \times 3} - \Delta_{C.M} \cdot \Delta_{C.M}^T) \quad (2.15c)$$

$$\mathbb{I}_{middle}^{\parallel \vec{\mathbf{O}}} = \mathbb{R}_Z \mathbb{R}_y(\eta)(\mathbb{I}_{middle})\mathbb{R}_y^{-1}(\eta)\mathbb{R}_Z^{-1} \quad (2.15d)$$

$$\mathbb{M}_i = \mathbb{I}_{middle}^{\parallel \vec{\mathbf{O}}} + m_{middle}((\Delta_L \cdot \Delta_L)\mathbb{I}_{3 \times 3} - \Delta_L \cdot \Delta_L^T) \quad (2.15e)$$

The above equations begin to deviate from the true inertial value, the deviations stem from subsequent transformations.

$$\mathbb{M}_i = \mathbb{R}(\sigma_i, \eta_i)(\mathbb{I}_{middle} + \mathbb{R}_X(\lambda_i)(\mathbb{I}_{inner})\mathbb{R}_X^{-1}(\lambda_i))\mathbb{R}^{-1}(\sigma_i, \eta_i) + L_i m_i^2 \quad (2.16a)$$

$$\sigma_i = [0^\circ, 90^\circ, 180^\circ, 270^\circ] \text{ for } i = [1 : 4] \quad (2.16b)$$

Unless otherwise stated, any inertia \mathbb{I}_b , irrespective of the arguments listed, refers to Eq:??.

Mass & Center of Gravity

Seeing as the servo and bearings in $\mathcal{F}^{M'_i}$ are unbalanced, the center of gravity isn't coincidental with the center of rotation. The offset position of the center of gravity is going to produce a gravitational torque arm about the motor modules axes.

2.2.3 Actuator Transfer Functions

2.2.4 Overall Aspects

Vibration Damping

Landing Skids

Motors & ESCs

2.3 System Layout

2.3.1 Electrical Design

2.3.2 Component Characteristics

Chapter 3

Kinematics & Dynamics

3.1 Rigid Body Dynamics

3.1.1 Lagrange Derivation

3.1.2 Rotation Matrix Peculiarities

3.1.3 Quaternion Dynamics

3.1.4 The Unwinding Problem

3.2 Non-linearities

3.2.1 Gyroscopic Torques

3.2.2 Coriolis Acceleration

3.2.3 Inertial Matrix

3.3 Aerodynamics

3.3.1 Thrust Forces & Propeller Torques

3.3.2 Drag

3.3.3 Conning & Flapping

3.3.4 Vortex Ring State

3.4 Consolidated Model

Chapter 4

Control Treatment

Control Plant & Discussion

Control Plant Inputs

Model Dependent & Independent Controllers

4.1 Attitude Control

4.1.1 The Attitude Control Problem

4.1.2 Quaternion Based Controllers

PD Controller

Auxilliary Plant Controller

PID Controller

4.1.3 Non-linear Controllers

Ideal Back-stepping Controller

Adaptive Back-stepping Controller

Lyupanov Derived Ideal Controller

4.2 Position Control

4.2.1 Backstepping Position Controller

4.3 Controller Allocation

4.3.1 Non-linear Plant Control Allocation

4.3.2 Pseudo Inverse Allocator

Chapter 5

Simulations & Results

5.1 Controller Tuning

5.1.1 Partical Swarm Based Optimization

5.1.2 Performance Metric

5.1.3 Global & Local Minima

5.1.4 Fmincon Differences

5.2 Simulation Block

5.3 State Estimation

5.4 Optimized Controller Comparisons

5.4.1 Allocator Performance

5.4.2 Attitude Control Results

5.4.3 Autopilot Outcome

Chapter 6

Prototype Flight Results

Appendix A

Standard Quadrotor Dynamics

Appendix B

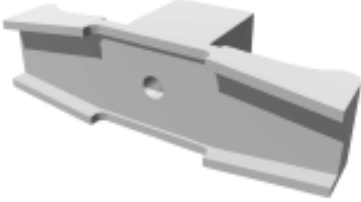
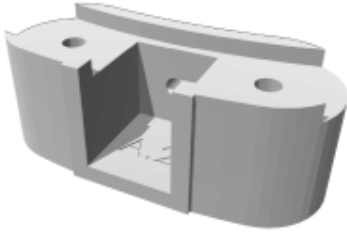

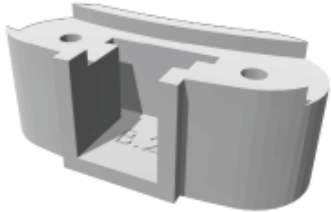
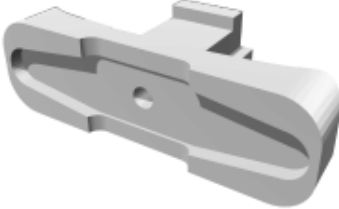
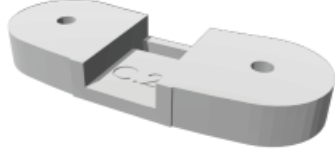

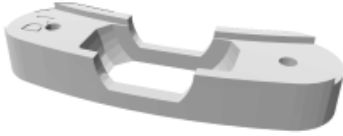

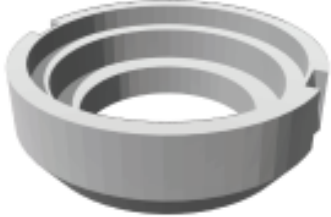

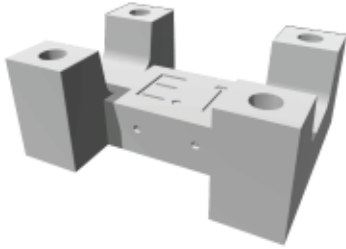
Design Bill of Materials

B.1 Parts List

Part Name	Amount Used	Unit Weight[g]
Electronics		
SPRacing F3 Deluxe Flight Controller	1	6
OrangeRx 615X 2.4 GHz 6CH Receiver	1	9.8
Signal Converter SBUS-PPM-PWM	1	5.0
STLink-V2 Debugger	1	N/A
RotorStar Super Mini S-BEC 10A	1	30
128x96" OLED Display	1	N/A
XBee-Pro S1	2	N/A
HobbyWing XRotor 15A Opto ESC	4	10.5
OrangeRX RPM Sensor	4	6
HobbyKing Multi-Rotor Power Distribution Board	1	7.6
Motors		
Corona DS-339MG	8	32
Turnigy DST-700KV Brushlesss DC	4	65
Frame Components		
APM Flight Controller Damping Platform	1	16
HobbyKing SK450 Replacement Arm (2 pcs)	2	N/A
SK450 Extended Landing Skid	1	93
Alloy Servo Arm (FUTABA)	8	N/A
10X18X6 Radial Ball Bearing	8	N/A
80g Damping Ball	32	N/A
Plastic Retainers for Damping Balls	32	N/A
3/5mm Aluminum Prop Adapter	4	N/A
6x4.5 Gemfam 3-Blade Propeller	4	N/A
M3 6mm Hex Nylon Spacer	8	N/A
M3 16mm Hex Nylon Spacer	32	N/A
M3 25mm Nylon Screw	128	N/A
M2.5x10mm Socket Head Cap Screw	36	N/A
M2.5x25mm Socket Head Cap Screw	20	N/A
M2.5 A-Lok Nut	16	N/A

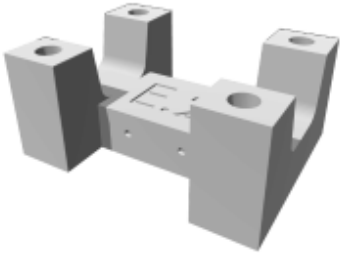

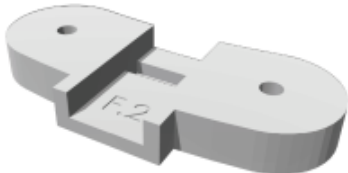
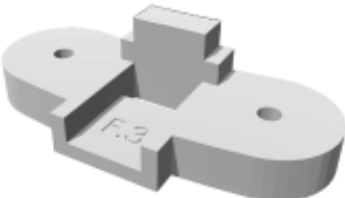
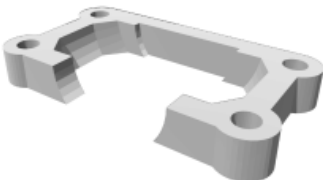


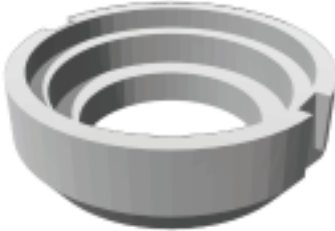
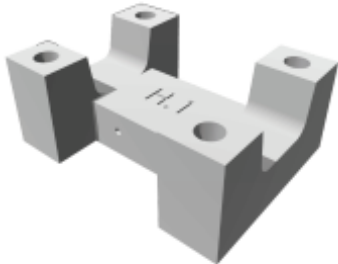
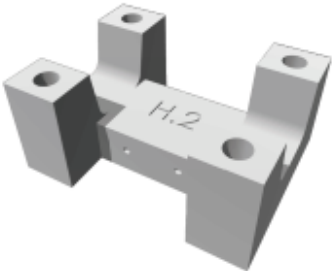
Table B.1: Parts List

B.2 3D Printed Parts

Custom Printed CAD Designs		
 <p>Figure B.1: Part A.1</p>	 <p>Figure B.2: Part A.2</p>	 <p>Figure B.3: Part B.1</p>
 <p>Figure B.4: Part B.2</p>	 <p>Figure B.5: Part C.1</p>	 <p>Figure B.6: Part C.2</p>
 <p>Figure B.7: Part C.3</p>	 <p>Figure B.8: Part D.1</p>	 <p>Figure B.9: Part D.2</p>
 <p>Figure B.10: Part D.3</p>	 <p>Figure B.11: Part D.4</p>	 <p>Figure B.12: Part E.1</p>

B.3 Lasercut Components

B.4 Assembly

 <p>A 3D model of a mechanical part, Part E.2, featuring a central rectangular block with two vertical rectangular protrusions on its top surface and two circular holes on its front face.</p>	 <p>A 3D model of a mechanical part, Part F.1, consisting of a tall, cylindrical central section mounted on a rectangular base with a T-shaped cross-section.</p>	 <p>A 3D model of a mechanical part, Part F.2, showing a U-shaped component with two circular holes on its outer edges and a central rectangular slot.</p>
Figure B.13: Part E.2	Figure B.14: Part F.1	Figure B.15: Part F.2
 <p>A 3D model of a mechanical part, Part F.3, which is a U-shaped component with two circular holes and a central rectangular slot, similar to Part F.2 but with a different internal profile.</p>	 <p>A 3D model of a mechanical part, Part G.1, showing a complex, curved bracket-like structure with multiple mounting points and holes.</p>	 <p>A 3D model of a mechanical part, Part G.2, which is a curved bracket-like structure with multiple mounting points and holes, similar to Part G.1 but with a different internal profile.</p>
Figure B.16: Part F.3	Figure B.17: Part G.1	Figure B.18: Part G.2
 <p>A 3D model of a mechanical part, Part G.3, showing a circular flange with a central hole and a raised outer rim.</p>	 <p>A 3D model of a mechanical part, Part G.4, which is a circular flange with a central hole and a raised outer rim, similar to Part G.3 but with a different internal profile.</p>	 <p>A 3D model of a mechanical part, Part H.1, featuring a central rectangular block with two vertical rectangular protrusions on its top surface and two circular holes on its front face, similar to Part E.2.</p>
Figure B.19: Part G.3	Figure B.20: Part G.4	Figure B.21: Part H.1
 <p>A 3D model of a mechanical part, Part H.2, featuring a central rectangular block with two vertical rectangular protrusions on its top surface and two circular holes on its front face, similar to Part E.2.</p>		
Figure B.22: Part H.2		

Appendix C

System ID Test Data

Appendix D

Full Equations

D.1 Inertias

$$\approx \begin{bmatrix} 3613.144 & 0.025 & 406.81 \\ 0.025 & 9774.160 & 0.4626 \\ 406.81 & 0.4626 & 12650.72 \end{bmatrix} \quad (\text{D.1a})$$

$$\begin{bmatrix} 0 & -0.249s\lambda - 0.276c\lambda & 0.249c\lambda - 0.276s\lambda \\ -0.249s\lambda - 0.276c\lambda & -0.448s2\lambda - 2142.67s\lambda + 983c\lambda & 983s2\lambda - 2142.67s\lambda + 0.448c2\lambda \\ 0.249c\lambda - 0.276s\lambda & 983s2\lambda - 2142.67s\lambda + 0.448c2\lambda & 1967.497s\lambda + 1070.88c2\lambda + 0.448s2\lambda \end{bmatrix} \quad (\text{D.1b})$$

$$= \begin{bmatrix} 814c_\eta s_\eta + 3613c_\eta^2 + 11580s_\eta^2 + 2142c_\lambda^2 s_\eta^2 + 1967s_\eta^2 s_\lambda^2 + 2c_\lambda s_\eta^2 s_\lambda - c_\eta s_\eta s_\lambda \\ 2c_\lambda^2 s_\lambda - s_\lambda - 175c_\lambda s_\eta s_\lambda \\ 4967s_{2\eta} + 814c_\eta^2 - c_\eta^2 s_\lambda + 175c_\eta c_\lambda^2 s_\eta + 2c_\eta c_\lambda s_\eta s_\lambda \\ 2c_\lambda^2 s_\eta - s_\eta - 175c_\lambda s_\eta s_\lambda \\ 10933 - 175c_\lambda^2 - s_{2\lambda} \\ 2c_\eta c_\lambda^2 - c_\eta - 175c_\eta c_\lambda s_\lambda \\ 4967s_{2\eta} + 814c_\eta^2 - c_\eta^2 s_\lambda + 175c_\eta c_\lambda^2 s_\eta + 2c_\eta c_\lambda s_\eta s_\lambda - 407 \\ 2c_\eta c_\lambda^2 - c_\eta - 175c_\eta c_\lambda s_\lambda \\ 9933c_\eta^2 - 814c_\eta s_\eta + 175c_\eta^2 c_\lambda^2 + 2c_\eta^2 c_\lambda s_\lambda + c_\eta s_\eta s_\lambda \end{bmatrix} \quad (\text{D.1c})$$

$$= \mathbb{R}_Z \begin{bmatrix} c_{\eta_i} & 0 & s_{\eta_i} \\ 0 & 1 & 0 \\ -s_{\eta_i} & 0 & c_{\eta_i} \end{bmatrix} (\mathbb{I}_{M'_i}) \begin{bmatrix} c_{\eta_i} & 0 & -s_{\eta_i} \\ 0 & 1 & 0 \\ s_{\eta_i} & 0 & c_{\eta_i} \end{bmatrix} \mathbb{R}_Z^{-1} \quad (\text{D.1d})$$

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