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 propeller's 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, despite of such relative motion. In view of this required articulation the proposal is to add 2 axes (degrees) of extra actuation to each propeller. As a result each lift propeller can then be pitched or rolled relative to the body frame. This adaptation, to what is an otherwise well covered 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 and plant uncertainty compensation.

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 plant's 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 compromise 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 quadrotor's motion. The design and control treatment presented here are by no means optimal nor 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.

Acknowledgements

Nomenclature

Propeller Rotational Speed: $\Omega_i \quad [rpm]$
Rotational speed in RPS is used for Blade Element Theory Calculations in Chapter:3
Inertial Position: $\vec{P} = \begin{bmatrix} X_I & Y_I & Z_I \end{bmatrix}^T \quad \in \mathcal{F}^I$
Body Position: $\vec{E} = \begin{bmatrix} x & y & z \end{bmatrix}^T \quad \in \mathcal{F}^b$
Euler Angles: $\vec{\mathcal{E}} = \begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^T$

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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 directly controllable. The attitude plant is often simplified around a stable operating point. The trimmed operating region is always at the inertial frame's origin; resulting in a zero-set point tracking problem. The highly coupled non-linear dynamics of a rigid body's transnational and angular motions arise from gyroscopic torques [Section: 3.2.1] and Coriolis accelerations [Section: 3.2.2]. These effects are negligible around the origin[1], hence the origin trim point removes the system's nonlinearities. The control system can then reduce each state variable, $\vec{X}_b = \left[\phi\ \theta\ \psi\ x\ y\ z\right]^T$, to individual SISO plants.

As almost every recent quadrotor research paper mentions, the late interest in the platform is from recent emergences in availability of MEMS systems and low-cost microprocessors. Such advancements accomodate onboard state estimation and control algorithm processing in real time. Developmental progress in quadrotors and, to a lesser extent, UAVs in general has led to rapidly growing enthusiast communities. HobbyKing [34] is now synonymous with providing custom DIY hobbyist quadrotor kits, not just prebuilt commercial products like the DJI Phantom [21].

The avenue for potential application of both fixed wing and VTOL UAVs is expansive, supporting civil [62], agricultural [65] and security [46] industries. The quadrotor platform provides a mechanically simple 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 8^{th} amendment of civil aviation laws [68], commercial use of UAVs is now both legal and regulated. Research into any non-trivial aspect of the field will therefore be to extremely valuable to the field as a whole.

Large scale quadrotor, hexrotor and even octorotor UAVs are popular intermediate choices for aerial cinematography due to their high payload capacity. The cost of a commercial drone like the SteadiDrone Maverik [51] is far less than a chartered helicopter used for the same panoramic aerial scenes or on-site inspections. One foreseeable issue which may hinder commercial drone progress in the agricultural and civil sectors is the consequential inertial effects from scaling up the aerospace bodies. When scaling up any vehicle, its performance is adversely affected if actuation rates aren't proportionately scaled.

[1] Expanded upon in Appendix:A

1.1.2 Research Questions & Hypotheses

The difficulty with quadrotor control is that fundamentally it's unstable and under-actuated, *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 abstracted[2] 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, $P = [x \ y \ z]^T$, and angular pitch, roll and yaw rotations, $\mathcal{E} = [\phi \ \theta \ \psi]^T$. 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 responses are non-linear and fluctuating sources of control torques and as such the body's yaw control is depreciated. A result of the under-actuation is that the attitude control problem then becomes a zero set point problem, 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 Helicopter's V22 Osprey and the tilting articulation of its propellers, the prototype design proposed here introduces two additional actuators for each of the quadrotor's 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 heave thrust. The control problem is then posed as the design of net forces, $\vec{F}_{net} = [F_x \ F_y \ F_z]^T$, and torques, $\vec{\tau}_{net} = [\tau_\phi \ \tau_\theta \ \tau_\psi]^T$, for a general 6-DOF body 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 $\vec{0}$.

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

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 quadrotor's control plant won't hold true for the more aggressive manoeuvres; they're dependent on small angle approximations and negligible $2^n d$ order effects. Stable control law design will need to expand and simulate the existing kinematic model of an aerial body and apply it to a quadrotor's 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 for 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 [91] or a flywheel and produce a precipitating torque. A less trivial aspect to consider is the aerodynamic torque produced from the propeller's aerofoil profile. Such induced responses occur in planes perpendicular to whatever the propeller's rotation exists in. These aspects are normally compensated for due to a quadrotor's fundamental 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.

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

[2] The abstraction of which is explored in Appendix:A

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 controller's (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 bodies 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 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 stability of the remainder of the whole plant.

Provisionally, an obvious outcome which the investigation could yield is improved yaw control of a quadcopter's 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. Such actuation suffers a second order inertial response when the propellers accelerate or decelerate, $\tau_{simplified} = \mathbb{I}_f \, \dot{\omega}_i$. Prioritizing pitching the propeller's principle axis of rotation rather than changes to the propeller's 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 structure's 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 for input responses to be approximated with confidence. Aspects of the mechanical design are covered next in Section:2.1 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, Section:2.2]. Similarly the control plant is stabilized with non-linear state space control techniques, aided and justified by Lyupanov 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 one another.

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 $u \in \mathbb{U}$ 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 2.1, 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 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 that 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 structure's net weight is mostly dependent on the lift motors, often being the heaviest part of the vehicle (*batteries too*). A trade-off between net weight and actuator efficacy 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, reducing the possibility of unbounded scope creep, a limitation is self-imposed on the prototype design. Restricting the propeller diameter, and hence maximum thrust, will provide a constraint upon which all other design considerations must conform. Smaller propellers require a far greater rotational to produce a similar level of thrust as their larger diameter counterparts. Electing to use 3 blade $6X4.5$ inch small diameter propellers is going to reduce the overall dimensions of the prototype, but as a consequence will require very high RPM motor. Specifically a set of four Cobra-2208/2000KV [18] Brushless DC motors are be used for lift actuation. A direct consequence of this decision is that, provisionally based upon test data[3], the net thrust disposable for actuation is limited to around 950g, ≈ 9 N, per motor (see Section:3.3.1). 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 50-60% of the maximum available thrust, or roughly 2 Kg. Saturation conditions are detailed later in Section: 4.3.

Another aspect of limitations produced by design decisions made, mostly to reduce prototype costs and weight, is to use of 180° rotation servo motors. The servos are for individual motor's $\vec{X}_{M_i}$ and $\vec{Y}_{M_i}$ axial pitch and roll actuations respectively. The servos act in lieu of either continuous BLDC or stepper motors. Any non-servo rotations beyond 360° will require closed loop position control and, unlike servos, would need slip rings to transmit power throughout 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.

(a) Cobra CM2208/2000KV BLDC motor **(b)** Corona DS-339MG digital servo

Figure 1.1

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 samples at $330Hz$. The prototype's 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 needs to be processed by the μcontroller system. Particular attention is paid to the embedded system layout in Section:2.3.

[3]Official test data from [18] included in Appendix:C.2 and tested independently in Section:3.3.1

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 for research purposes.

Birotors

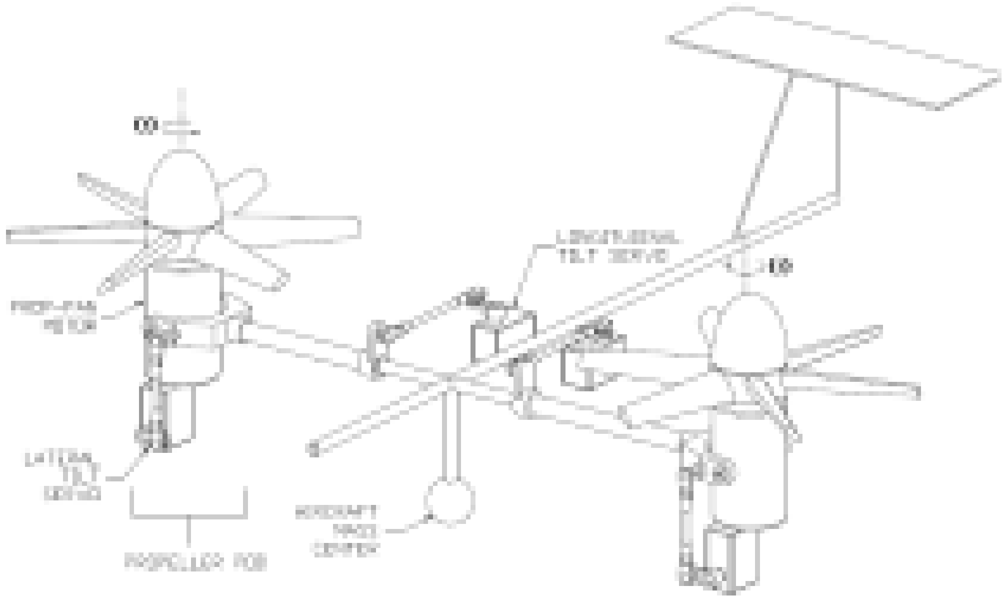


Figure 1.2: General structure for opposed tilting platform

Research into birotor vehicles (Fig:1.2)[4] with ancilliary lift propeller actuation is oft termed Opposed Active Tilting or *OAT*. Such a rotorcraft's mechanical design applies either a single *oblique* 45° tilting axis relative to the body; [8, 28, 42], or a *lateral* tilting axis, adjacent to the body; [15, 43, 64, 78]. 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, 27]. 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 the birotor's underactuation.

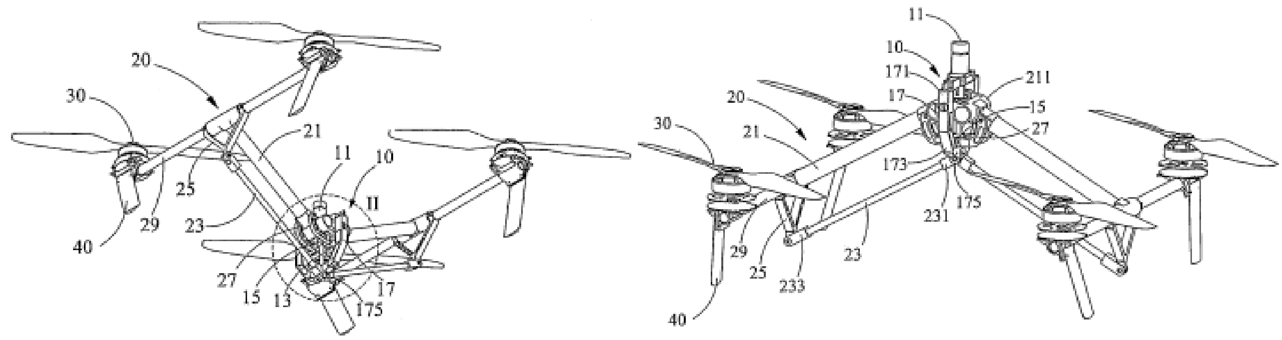
Birotor attitude control typically incorporates plant independent PD [8] and PID [64] controller schemes. Occasionally more computationally exhaustive and plant dependent Ideal and Adaptive backstepping controllers (*IBC* or *ABC*) are exploited, presented in [42, 78] and [43] respectively. The cross-coupling of a birotor vehicle's 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, [48], proposed a PID co-efficient selection algorithm for a bi-rotor control block. Using a Particle Swarm Optimization techinque, similar to [93], the coefficients were globally optimized around a given performance metric. However their performance criterion is a basic

[4]Image from G. Gress: [27]

ITAE† 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 here 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, [30, 70]. Alternative iterations like the Microraptor [73] and STARMAC [35] quadcopters have subsequently been built and tested. A plethora of literature exists around quadrotor kinematics & control [4, 11, 17, 52, 72], however dedicated rigid body 6-DOF dynamic papers [54, 66] provide better explanations of the kinematics. Often the plant's dynamics are simplified around an origin trim point and assumed to reduce into 6 SISO plants for each degree of freedom (Appendix:A). Lately research projects have begun to incorporate aerodynamic effects like drag and propeller BEM theory into the plant model [13, 35, 75]. Although mostly negligible under standard opperating conditions, the higher fidelity models offer more precision without linearisations or assumptions, [5, 35].



(a) Inspire 1 articulated upwards **(b)** Inspire 1 articulated downwards

Figure 1.3: DJI Inspire 1

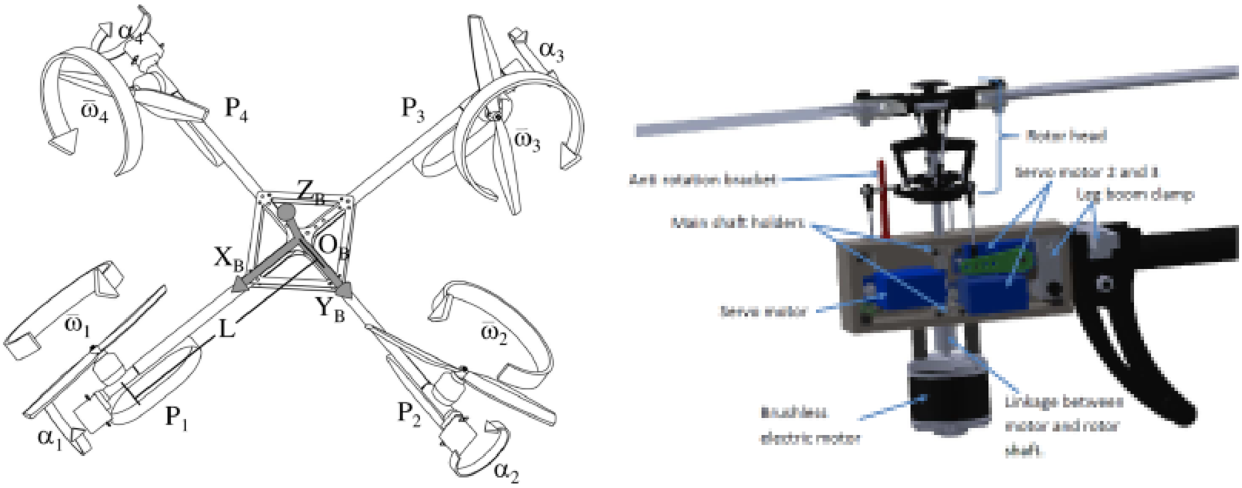
At the time of writing, the only commercial example of a transforming quadrotor is the DJI Inspire1 [20], made by Shenzen DJI Technologies (better known for the hugely successful DJI Phantom drone [21]). The Inspire can articulate its supporting arms up and down as shown in Fig:1.3 [5]. The aim of such 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 transformations which the frame can undergo is limited to just 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, [76, 77]. The authors M. Ryll et al.(2012, 2013) modified and tested a QuadroXL four rotor helicopter, propduced by MikroKopter [25], to actuate a single axis of tilting aligned with the frame's arms (Fig:1.4a)[6]. Their proposed control solution, discussed in detail next in 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) [59]. The latter remains simulated but as yet untested.

[5]Both images were sourced from the drone's patent, held by SZ DJI Tech Co [92]

[6]Image sourced from Modelling and Control of a Quadrotor UAV with tilting propellers, [76]

One approach to improving quadrotor flight response is to alter the manner in which the thrust is mechanically actuated, potentially improving the actuator bandwidth. Drawing from helicopter design, a project by Napsholm, (2013) [58], purported a quadrotor UAV prototype 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:1.4b). The cyclic-pitch swashplate used [60] could apply torques, τ_ϕ and τ_θ, about the propeller's 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.



(a) Single rotation axis aligned with the frames arm

(b) Cyclic-pitch & swashplate mechanism

Figure 1.4

Irrespective of the strong initial design in the early stages of his project, it would appear that Napsholm's 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, being the most unique aspect, would be performed.

Finally, the most crucial research to mention is a project completed by Pau Segui Gasco [24], 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 design for their respective MSc dissertations. Shown in Fig:1.5[7], 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.

[7] Image from Development of a Dual Axis Tilt Rotorcraft UAV: Modelling, Simulation and Control [24]

Figure 1.5: Dual-axis tilt-rotor mechanism

1.2.2 Notable Quadrotor Control Implementations

Quadcopter Attitude Control

Attitude control of a 6-DOF body is best described by *The Attitude Control Problem* [86]. A rigid body that currently has an attitude state[8] $\vec{\mathcal{E}}_s$ and a desired state $\vec{\mathcal{E}}_d$, the problem is to then find a torque control law:

$$\mu\tau = h(\vec{\mathcal{E}}_s, \vec{\mathcal{E}}_d, \dot{\vec{\mathcal{E}}}_s, \dot{\vec{\mathcal{E}}}_d) \tag{1.2}$$

Such that both the angular position $lim\ \vec{\mathcal{E}}_s \rightarrow \vec{\mathcal{E}}_d$ and that angular rates $lim\ \dot{\vec{\mathcal{E}}}_s \rightarrow \dot{\vec{\mathcal{E}}}_d$ asymptotically stabilize as $t \rightarrow \infty$. A distinction must be made between angular rate vector, $\dot{\vec{\mathcal{E}}} = [\dot{\phi}\ \dot{\theta}\ \dot{\psi}]^T$ and the angular velocity vector $\vec{\omega}_b = [p\ q\ r]^T$. Depending on how the attitude is posed; with rotation matrices [45, 54, 66], quaternions [23, 26, 29, 45] or otherwise (Direct Cosine Matrix etc ...) the error sate[9] $\Delta\vec{\mathcal{E}} = \vec{\mathcal{E}}_d - \vec{\mathcal{E}}_s$ could then differ to a (hamilton) multiplicative 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, 53, 59, 74] without addressing the inherent singularity associated with such an attitude representation (sic Gimbal Lock, [79], Section:3.1.2). The alternative quaternion attitude representation, first implemented on a quadrotor UAV in 2006 [84], 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 [56] in $\mathbb{R}^3$ space.

Quadrotor plant dynamics, as mentioned previously, are often simplified; especially when represented with a 3-variable Euler angle set, $\vec{\mathcal{E}} = [\phi\ \theta\ \psi]^T$. 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 $\in \mathbb{R}^x$. 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 coupled cross-product 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 plant controlled with an appropriate technique. 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.

Commercial flight controllers (Arducopter [3], Openpilot [49][10], BetaFlight [7], etc ...) for custom fabricated UAV platforms all apply their own flavour of structured attitude controllers and state estima-

[8] Quaternion attitude states will replace Euler angles
[9] *The Attitude Control* [86] describes these conventionally different error states
[10] NOTE: OpenPilot's firmware stack is now maintained by LibrePilot

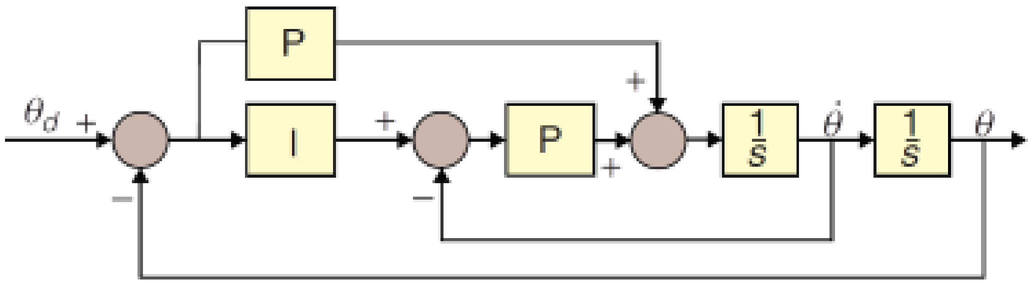


Figure 1.6: ArduCopter PI Euler angle attitude control loop

tion algorithms, based on onboard hardware sensor fusion. The article *Build Your Own Quadrotor* [50] 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:1.6)[11]. PI, PD and PID controllers are all easy and effective plant independent control solutions for general attitude plants. 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	[86]	[86]	2
PD	[1, 52]	[23, 59]	4
PID	[10, 12, 72, 76, 86]	[35, 74, 86]	8
Lead	[17, 70]	lead	2
IBC	[53, 78][12]	[53]	3
ABC	[6, 19, 43, 57]		4
LQR	[12]	LQR	1

Table 1.1: A breakdown of common attitude controllers

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 pratically 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 (with $u \in \mathbb{U}$, controller effort is then $||u||$ or the L_2 norm of the plant input). Although, in theory, solving the assocaited Ricatti cost function may produce an optimial, stable and efficient control law it needs exact plant matching. In practice, exact plant matching 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 [90](any of the examples in Table:1.1) builds on nominal IBC fundamentals by introducing an aditional disturbance state term in the LCF used for the backstepping iteration. The drawback with this form of Backstepping approach is that, from the Lyupanov 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 *apriori* information, some heuristic needs to be adopted with the approximation which usually involves some compromise. In one example, [19], the authors implemented a statistical $proj(.)$ operator based technique. Which, when used in adaptive control, the projection operator [14], $proj(.)$, ensures a derivative based estimator is bounded for adaptive regression approxmation [69].

[11]Image sourced from *Build your own Quadrotor* [50]

Although the control implementation isn't backstepping based, in [94], a sliding mode controller was used to compensate for the disturbances in an Unmanned Submersible Vehicle atttiude plant. The underwater current disturbances were 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 [55]; where the TSK system is more comprehensible than the latter. Statistical analysis and investigation of approximators without *apriori* knowledge of a system are well beyond the scope of this research 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] [59] and again in Gasco & Rihani [1, 24]) and PID controllers (Ryll et al.[2012,2013] [76,77]) 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 [39], 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[13], τ, has a linear multiplicative relationship with the input response, $g(x,t,\tau) \iff g(x,t)\tau$.

$$\dot{x} = f(x,t) + g(x,t)\tau \tag{1.3a}$$
$$y = l(x,t) \tag{1.3b}$$

With a state $x \in \mathbb{R}^n$ and $f(x,t)$ & $g(x,t)$ being the plant's dynamics and input response 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; that being $dim(x) = dim(\tau) \in \mathbb{R}^n$. In the case where the control input $\tau \in \mathbb{R}^m$, if $m > n$ the problem is then overactuated and a level of abstraction is needed; an asymptotically stabilizing 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 $\mathbb{R}^m \to \mathbb{R}^n$ for an actuator matrix $u \in \mathbb{U}^m$. An overactuated plant can be described as:

$$\dot{x} = f(x,t) + g(x,t)\nu_d,\ \nu_d \in \mathbb{R}^n \tag{1.4a}$$
$$\nu_c = B(x,t,u) \approx B(x,t)u,\ u \in \mathbb{U}^m,\ \nu_c \in \mathbb{R}^n \tag{1.4b}$$
$$y = x \tag{1.4c}$$

$B(x,t,u)$ is the effectiveness function which quantifies 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 plant's dynamics permit it, such that; $B(x,t) \in \mathbb{R}^{n\times m}$. For generic 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:

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

Which ensures the commanded input ν_c tracks the desired control input ν_d; $\nu_c \to \nu_d$ 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;

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

[13]Disambiguation: τ is not necessarily the torque input.

Those same authors Johansen and Tjnns [2004,2005,2008] proposed multiple control allocation solutions to a variety of systems. Following [39], in a subsequent paper [40], Johansen and Tjnns [2005] introduce a secondary cost function, driving the solution away from the norm quadratic programming direct or weighted inversion. Aiming to for optimal efficiency and not just actuator saturation. In a followup paper [41], the same authors proposed an online adaptive algorithm, using a Lyupanov energy approach to ensure the minimization adaptive law settles to a feasible solution.

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 [1,24], where the authors apply a weighted pseudo inverse (sic Moore Penrose Inverse [47]) allocation rule. A prerequisite for pseudo inversion is a multiplicative *linear* control effectiveness relationship for Eq:1.4b.

Segui et al. [2012] applied weighted inversio, relying on some very specific assumptions to achieve that linearity relationship in Eq:1.4b. 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:

$$\dot{\phi} \approx \frac{\phi}{t_{rise}} \tag{1.7}$$

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 represented or otherwise, is a topic well covered in the field of satellite attitude control; [38, 44, 88]. 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 [38], the authors Wang Jia, et al. [2010], proposed applying adaptive back-stepping to compensate for steady state errors of (asymmetric) inertial estimations. 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. Such an approach does assume any initial estimates are sufficiently close to true body values such that they will settle and stability can be ensured, however unacceptable the transition performance may be.

Satellite actuator suites mostly include additional redundant effectors, to ensure fault tollerance, and thus 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 [44]; the authors, Kristiansen et al. [2005], address the over-actuation with direct and well-matched inversion before applying quaternion based back-stepping for attitude control. A direct inversion solves to Eq:1.6 such that:

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

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

Where B is the 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 ${\tau_a}^b$ 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 Design

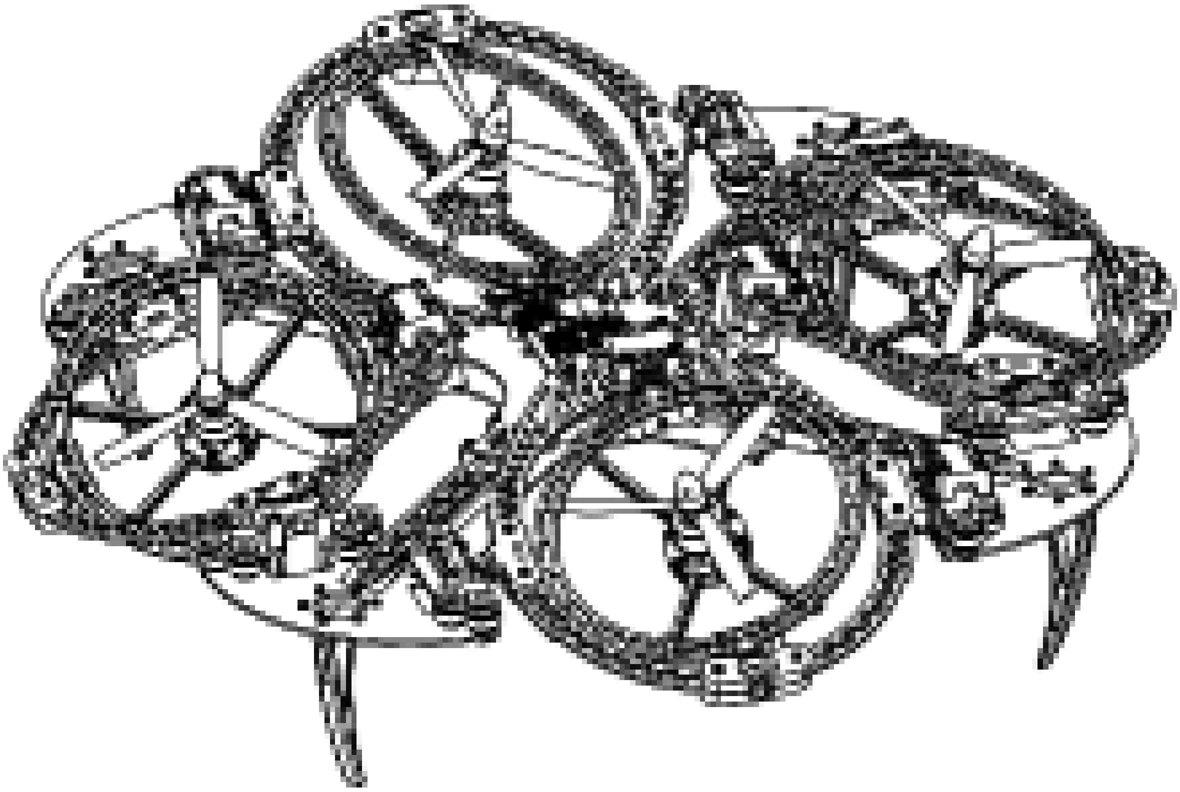
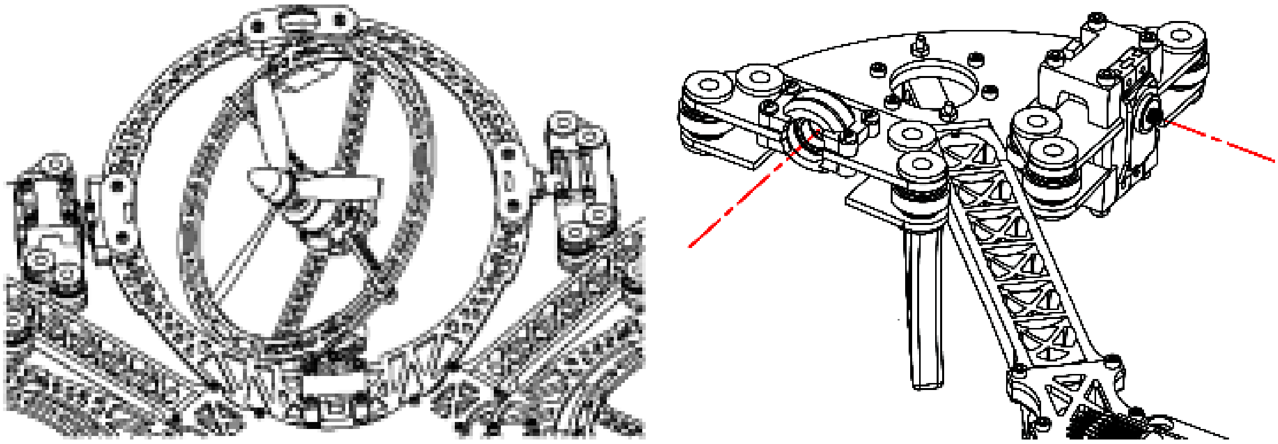


Figure 2.1: Isometric view of the prototype design

The final prototype (Fig:2.1) went through a series of different design iterations, all aimed at optimizing engineering time spent on construction and reducing the associated component costs thereof. A significant aspect of consideration for the design process was the net weight whose upper limit, as mentioned before, is inherently limited by the thrust produced from lift motors. Some of the more important design factors, like inertias & mass centers (Section:2.2.3), are discussed here in order to give context for the dynamics derived in the next chapter. The reference frame orientations which those dynamics are developed with respect to is then detailed as well. The actuator suite's functionality and transfer characteristics are also quantified. Finally a brief overview of the electrical systems layout is given with the components associated and their electrical characteristics listed. A review of the physical prototype realized and control loop implemented is detailed in Chapter:6 along with actual flight test results.

2.1.1 Actuation

The novel component of the design is the manner of articulation for each concentric gimbal ring which forms the motor modules. The design objective is to produce a thrust vectoring actuation set for a quadrotor's control plant. The outcome was a module which independently redirects the thrust generated by the lift propellers (Fig:2.2a). Within each module are servos affixed onto sequential support rings to pitch and roll the substructure's axes. The gyroscope-like frame that surrounds each motor/propeller pair accommodates that relative movement. Aligned with each servo is a coaxial support bearing. The bearing and actuator servos have a mass disparity which results in an eccentric center of mass, 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:2.2.3.



(a) Motor module assembly **(b)** Motor frame damping support assemblies

Figure 2.2

Each motor module is positioned such that its produced thrust vector coincides with the intersection of its two rotational axes. As a result, there's only a perpendicular displacement co-planar to the body frames X-Y-Z origin (See Fig:2.7), $\vec{L}_{arm}$. That length directly affects the differential thrust torque $\tau_{diff} = \vec{L}_{arm} \times \vec{T}$. An off-center thrust vector line would make that arm displacement a non-orthogonal vector. The center of gravity of each module is time varying and depends on its servo rotational positions. It's more practical to ensure intersection of the thrust vector with the rotational center than to balance the masses undergoing rotation. A thrust varying torque is harder to approximate and compensate for than a gravitational torque, given the complexity with modeling a propeller's aerodynamic thrust (Section:3.3.1).

The primary body structure, similar to a traditional quadcopter '+' configuration, suspends each motor rotational assembly with silicon damping balls (Fig:2.2b). 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 module rings are 3D printed from CAD models using an Ultimaker V2+ [89]. 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.

The propellers rotational plane is not exactly the aligned with the plane made by the $\vec{X}_{M_i}$ and $\vec{Y}_{M_i}$ rotational servo axes (Fig:2.3). 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 by Cobra CM2208-2000KV Brushless DC motors. The thrust produced as a function of angular velocity (in RPS) for the propellers is derived in Section:3.3.1.

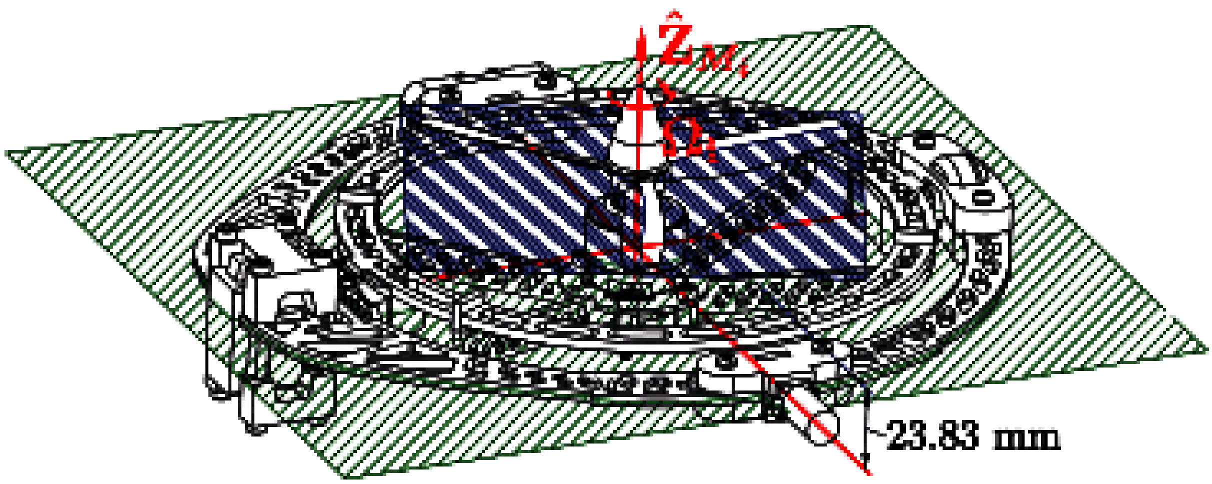
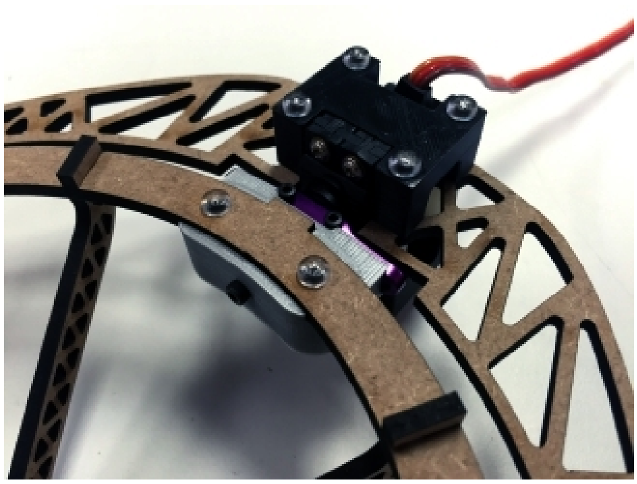


Figure 2.3: Difference between propeller and motor planes

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:2.3.1. 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 restriction 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.

(a) Cobra CM2208-2000KV BLDC Motor Module



(b) Corona DS-339MG Servo Bracket

Metal gear Corona DS-339MG digital servos are used for the two axes of rotation (Fig:2.4b). Each servo has a range of 180°, positioned such that a zero$^{\text{th}}$ offset aligns the motor modules, adjacent to the body frame, and has a ±90°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:2.3.1 using test data included in Appendix:C.

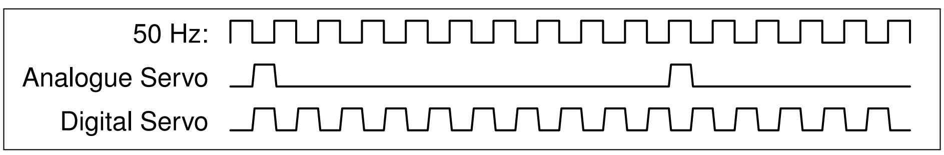


Table 2.1: Analogue & Digital Timing Signals

2.2 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 assumed to be obvious enough that they're omitted. 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 [29] and [66] provide an in depth and thorough explanation of rotation matrices and DCM attitude representation if such concepts are unfamiliar to the reader. Quaternions are introduced in Section:3.1.3.

2.2.1 Reference Frames Convention

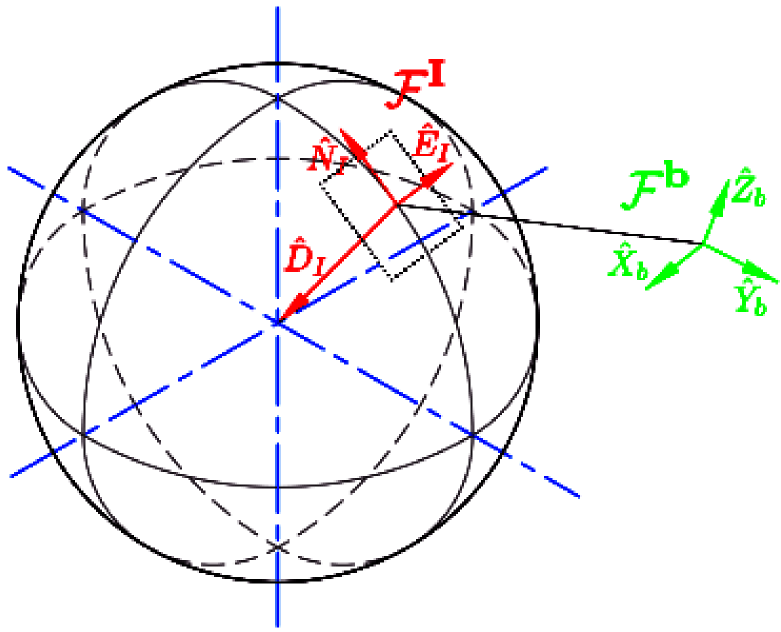


Figure 2.5: Inertial and Body Reference Frames

Euler (aerospace) frames are used for principle inertial and body coordinates (Fig:2.5). The inertial frame, $\mathcal{F}^I$, is aligned such that the $\hat{X}_I$ axis is in the $\hat{N}$orth direction, $\hat{Y}_I$ is in the $\hat{E}$ast direction and $\hat{Z}_I$ is in the $\hat{D}$ownward direction[1]. The body frame, $\mathcal{F}^b$, then has both $\hat{X}_b$ and $\hat{Y}_b$ aligned obliquely between two perpendicular arms of the quadrotor's body and the $\hat{Z}_b$ axis in the body's normal direction (Fig:2.8). The body frame's axes and their relation to the prototype design are highlighted next in Section:2.2.2. 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 or taken relative to.

Relative angular displacement between two frames is commonly measured by the three angle Euler set. The Euler angles $\vec{\mathcal{E}} = [\phi \;\; \theta \;\; \psi]^T$ represents rotations about the $\hat{X}$,$\hat{Y}$ and $\hat{Z}$ 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 by[2]:

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

Which, when $\hat{n}$ is either $\hat{X}$,$\hat{Y}$ or $\hat{Z}$ axes, can be simplified to produce the fundamental rotation matrices $\mathbb{R}_x(\phi)$,$\mathbb{R}_y(\theta)$ and $\mathbb{R}_z(\psi)$.

[1] In orbital sequences this would be toward the Earth's center. Sometimes referred to as the N$\hat{\text{E}}$D convention

[2] Derived and proven in *Quadrotor Dynamics and Control* [72]

Multiplication by a rotation matrix $\mathbb{R}(\cdot)$ applies a left-handed *rotation* operator, the resultant vector still exists in the same reference frame;

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

$$\vec{v}\,', \vec{v} \in \mathcal{F}^1 \tag{2.2b}$$

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 resultant vector's reference frame. Transformation is then 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 $\hat{X}$ axis is then:

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

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

The distinction between Eq:2.2 and Eq:2.3 is the directional sense of the angular operand ϕ, and hence the effect it has on the argument vector. The transformation or rotation of a vector from $\mathcal{F}^I$ to $\mathcal{F}^b$ is the product of three sequential operations about each axis. Each subsequent rotation is applied relative to a new intermediate frame and hence each Euler angle is taken relative to a specific intermediate frame. The sequence of axial rotation operations does indeed effect the Euler set. Any consequences of that chosen order is something discussed indepth in *Quaternions and Rotation Sequence*, [45]. 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:

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

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

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

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

$$\mathbb{R}_I^b = \left(\mathbb{R}_b^I\right)^{-1} = \left(\mathbb{R}_b^I\right)^T \tag{2.4e}$$

The relationship in Eq:2.4d is an inversion (*transpose*) of the rotation matrix. A rotation matrix's inverse can be used interchangeably with its negative counterpart 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 the rotation and transformation operations.

The body frame's angular velocity is taken relative to the inertial frame, represented by $\vec{\omega}_{b/I}$. Seeing that each Euler angle is measured with respect to an intermediary frame, a distinction must then be made between $\dot{\mathcal{E}}$ and $\vec{\omega}_b$. All three Euler angles need to be transformed to one common frame. Exploiting vehicle frames 1 & 2, $\mathcal{F}^{v1}$ & $\mathcal{F}^{v2}$, as intermediate frames to respectively describe post $\mathbb{R}_x(\phi)$ and $\mathbb{R}_y(\theta)$ operations.

$$\vec{\omega}_b = \frac{\delta}{\delta t_b}\mathcal{E} = \frac{\delta\phi}{\delta t}\mathbb{R}_{v2}^b(\phi)\begin{bmatrix}\phi\\0\\0\end{bmatrix} + \frac{\delta\theta}{\delta t}\mathbb{R}_{v2}^b(\phi)\mathbb{R}_{v1}^{v2}(\theta)\begin{bmatrix}0\\\theta\\0\end{bmatrix} + \frac{\delta\psi}{\delta t}\mathbb{R}_{v2}^b(\phi)\mathbb{R}_{v1}^{v2}(\theta)\mathbb{R}_I^{v1}(\psi)\begin{bmatrix}0\\0\\\psi\end{bmatrix} \tag{2.5a}$$

The vehicle frames in Eq:2.5a and the subsequent rotations between each frame don't necessarily have to be in that order. The equation could change depending on what rotation sequence was used.

Which then simplifies to the formal relationship between two rotating frames, with $\vec{\omega}_b = [p\ q\ r]^T$ in $rad.s^{-1}$:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -sin(\theta) \\ 0 & cos(\phi) & sin(\phi)cos(\theta) \\ 0 & -sin(\theta) & cos(\phi)sin(\theta) \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{2.5b}$$

$$\Rightarrow \vec{\omega}_b = \Psi(\mathcal{E})\dot{\mathcal{E}} \tag{2.5c}$$

$$\Psi(\mathcal{E}) = \begin{bmatrix} 1 & 0 & -sin(\theta) \\ 0 & cos(\phi) & sin(\phi)cos(\theta) \\ 0 & -sin(\theta) & cos(\phi)sin(\theta) \end{bmatrix} \tag{2.5d}$$

$$\Rightarrow \dot{\mathcal{E}} = \Psi^{-1}(\mathcal{E})\vec{\omega}_b = \Phi(\mathcal{E})\vec{\omega}_b \tag{2.5e}$$

$$\Phi(\mathcal{E}) = \begin{bmatrix} 1 & sin(\phi)tan(\theta) & cos(\phi)tan(\theta) \\ 0 & cos(\phi) & -sin(\phi) \\ 0 & sin(\phi)sec(\theta) & cos(\phi)sec(\theta) \end{bmatrix} \tag{2.5f}$$

The termed Euler matrix, $\Phi(\mathcal{E})$, contains a well known and problematic singularity at $\theta = \pm\pi$; because $sec(\theta) \rightarrow \infty$ as $\theta \rightarrow \pi$. The effect of the rotation matrix singularity is further explored later in Section:3.1.2. It's manifestation in the θ angle here is a direct consequence of the Z-Y-X sequence used. Each Euler angle can potentially suffer a singularity depending on how the rotations are sequenced. 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 in this Chapter.

Quaternion operations are similarly sequenced in the Z-Y-X order:

$$\mathbb{R}_I^b \iff Q_b^* \otimes (.) \otimes Q_b \tag{2.6a}$$

$$Q_b^* \triangleq Q_z^* Q_y^* Q_x^* \text{ and } Q_b \triangleq Q_x Q_y Q_z \tag{2.6b}$$

With $\otimes$ being the Hamilton product (or quaternion multiplication). Each quaternion, Q_i, is a unit quaternion about that $\hat{i}^{th}$ axis. It is important to note that a quaternion rotation operates on an argument vector with a zero quaternion scalar component. So then for some vector $\vec{v}$, the quaternion rotation operation in Eq:2.6a is equivalent to;

$$Q_{\vec{v}}\ ' = Q^* \otimes (Q_{\vec{v}}) \otimes Q \tag{2.7a}$$

$$\text{Where } Q_{\vec{v}} = \begin{bmatrix} 0 \\ \vec{v} \end{bmatrix},\ Q_{\vec{v}}\ ' = \begin{bmatrix} 0 \\ \vec{v}\ ' \end{bmatrix} \tag{2.7b}$$

The quaternion representation in Eq:2.7b ensures that the operation is entirely in $\mathbb{R}^4$ space. However it is usually omitted and as such, Eq:2.7a is then simply:

$$\vec{v}\ ' = Q^* \otimes (\vec{v}) \otimes Q \tag{2.8}$$

Quaternion dynamics, and the quaternion operator, are later expanded upon to replace the use of Euler angles and Rotation matrices as a convention for attitude representation later in Chapter:3

2.2.2 Motor Axis Layout

Fundamentally the whole structure, although treated as fixed and rigid in the kinematics, consists of multiple rigid bodies with relative rotations to one another, illustrated previously in the Design Section:2.1. Those rigid bodies are grouped into four inter-connected motor modules and a single body structure. Each module consists of two sequential gimbal rings, each with one degree of relative rotation between itself and the next subsequent ring. There needs to be distinct nomenclature used for describing these motor modules.

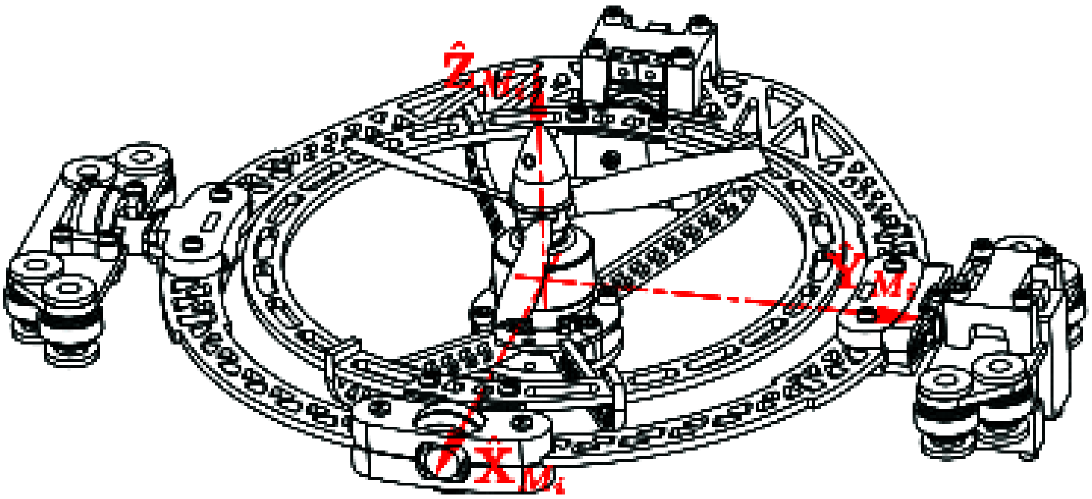


Figure 2.6: Aligned Motor Frame Axes

Every propeller/motor pair is actuated by two servos. The i^{th} propeller, directly driven by the motor's rotor, has a rotational speed ω_i $[rpm]$ about the $\hat{Z}$ stator axis. Two servos are aligned *at rest* with $\hat{Y}$ and $\hat{X}$ axes to pitch and roll the propeller away from its principle rotational axis. Each motors has its own reference frame, $\mathcal{F}^{M_i}$, aligned in Fig:2.6 and highlighted with the rotational rings in Fig:2.7.

Motor frames, numbered $1-4$, transform to the body frame first by an angle of λ_i° about the $\hat{X}_{M_i}$ axis. Then by α_i° about the $\hat{Y}_{M_i'}$ axis in an intermediate M_i' frame. The first servo actuates λ_i, rotating $\mathcal{F}^{M_i}$ to an intermediate $\mathcal{F}^{M_i'}$ frame. Secondly, the next servo actuates α_i to produce a second intermediate frame M_i''. That second servo is affixed in the M_i'' frame. Lastly there's a relative orthogonal rotation about $\hat{Z}_{M_i''}$ between $\mathcal{F}^b$ and $\mathcal{F}^{M_i''}$. Each module's actuation state is fully described by $[\Omega_i,\ \lambda_i,\ \alpha_i]^T$ for $i \in [1:4]$. The four motor modules are aligned relative to the body's XYZ axes as shown in Fig:2.8. Modules 1 and 3 have their X-axes in the positive and negative $\hat{X}$ directions of the body frame respectively. Similarly Modules 2 and 4 have their X-axes in the positive and negative $\hat{Y}$ directions of the body frame.

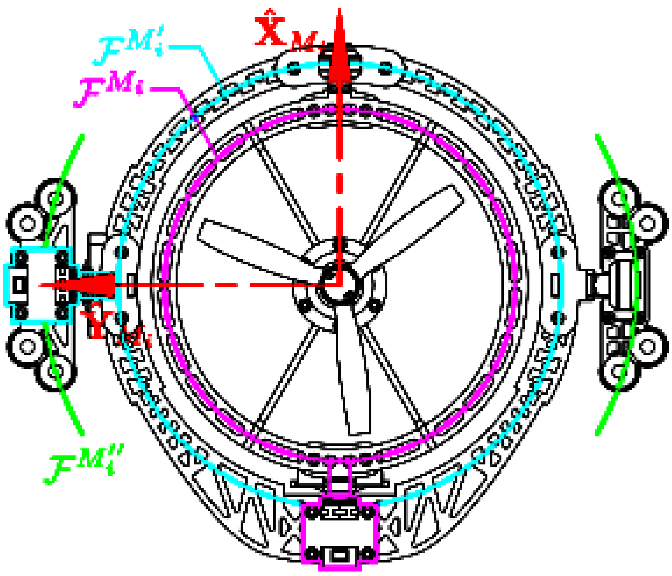


Figure 2.7: Intermediate Motor Frames

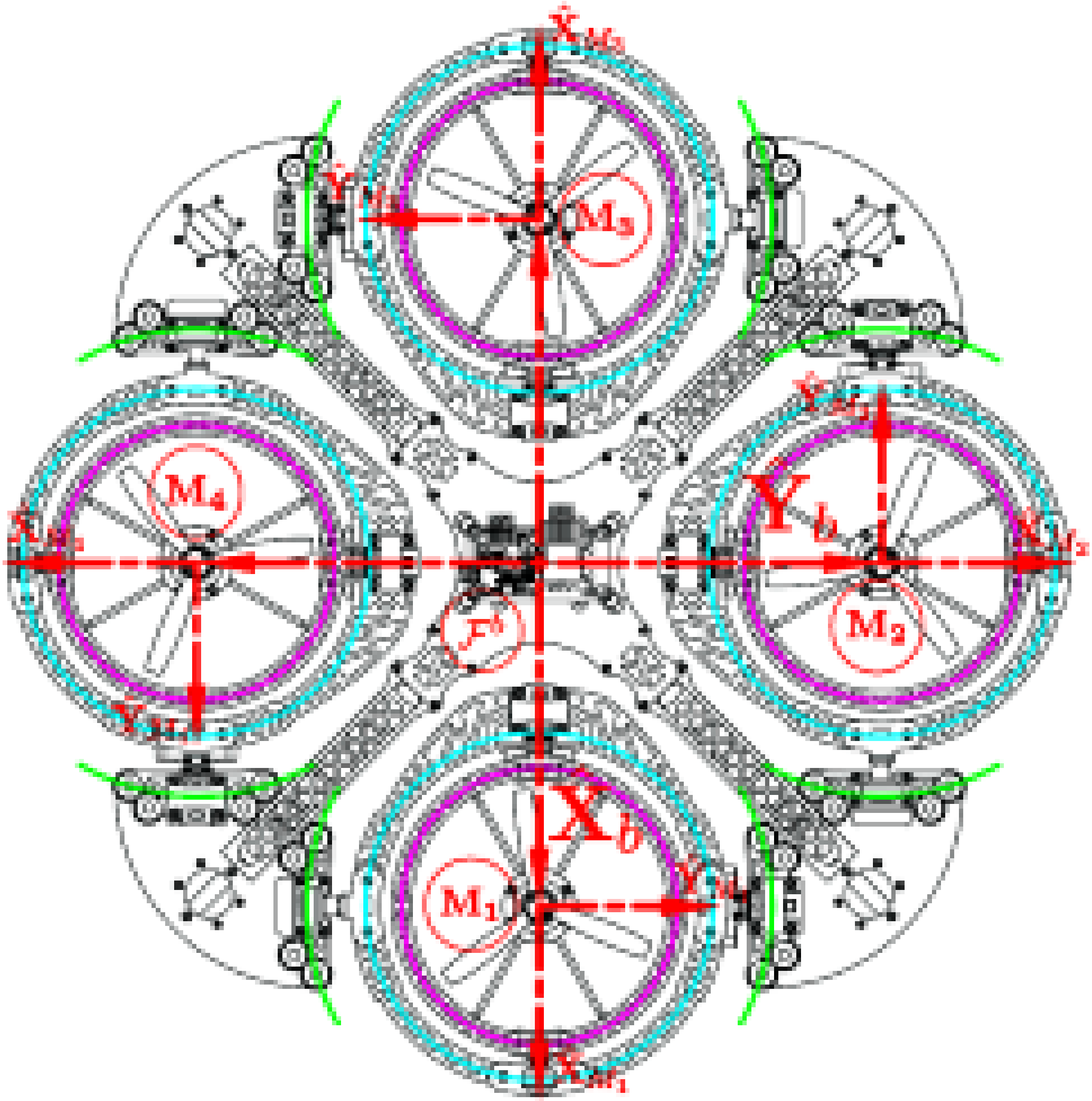


Figure 2.8: Body Frame Axes Layout

Not shown in Fig:2.8 is the relative $\hat{Z}$ axis position with respect to the structure. The $\hat{Z}$ height of the body's motion centroid is such that its origin is co-planar with the four motor modules rotational centres. The centre of motion is <u>not</u> the center of mass, an aspect which is quantified next in Section:2.2.3.

Transformation relationships from each of the motor frames to the body frame is characterized as:

$$\vec{v}_b = \mathbb{R}_z(-\sigma_i)\mathbb{R}_y(-\alpha_i)\mathbb{R}_x(-\lambda_i)\vec{v}_{M_i}, \;\; \sigma_i \in [0, 90°, 180°, 270°] \tag{2.9a}$$

$$\mathbb{R}_z = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ for } i \in [1, 2, 3, 4] \text{ respectively} \tag{2.9b}$$

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:

$$u_{\in \mathbb{U}} = \left[\Omega_1 \; \lambda_1 \; \alpha_1 \; \ldots \; \Omega_4 \; \lambda_4 \; \alpha_4\right]^T \tag{2.10}$$

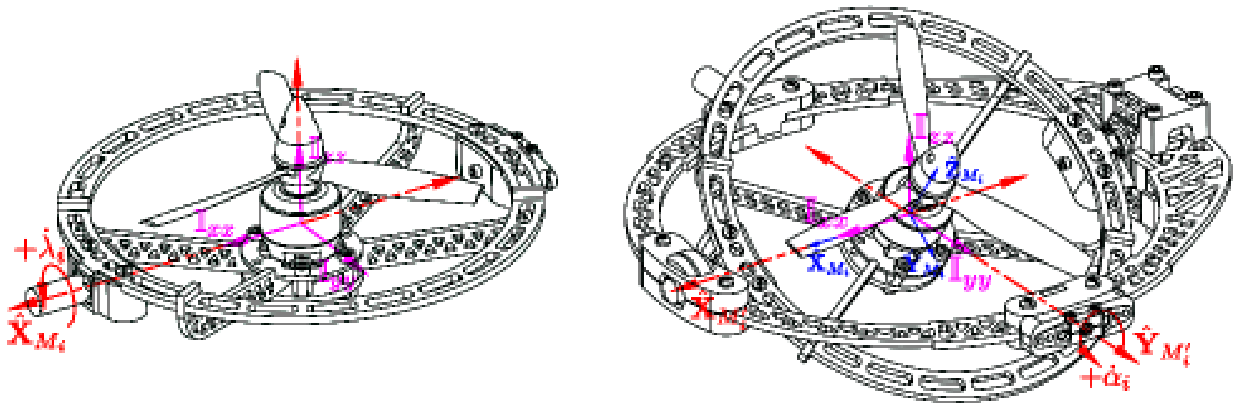
[3]Disambiguation: An omission of axial subscript on the $\mathbb{R}$ symbol implies a real space of the superscript dimension.

2.2.3 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:2.12,2.15,2.17, which are all susceptible to singularities. Quaternion transformations between rotating reference frames are used in practice.

Inertias

An undesirable side effect of the relative rigid body rotations within the structure are the inertial responses produced associated with such movements. Given Newton's Second Law of Rotational Motion†, each applied rotation is 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 the angular rates which they're dependent on 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 sizeable time varying body angular velocities and accelerations. Unlike a traditionally actuated quadrotor, such effects have to be accounted for.



(a) Inner Ring Rotational Structure **(b)** Middle Ring Rotational Structure

Figure 2.9: 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 tensor[4] about each respective rotational axis. The magnitude of those inertias are obviously a by-product of the structure's design. Starting with the innermost assembly, in each Motor Frame $\mathcal{F}^{M_i}$, the inside ring structure is a 92g assembly (all components incorporated). The rotational center *roughly* coincides with the center of its mass ($C.M = [-1.44\ -0.01\ 5.81]^T\ \ [mm]$ relative to its rotational center). The inner ring being rotated by $\lambda_i{}^\circ$ about the $\hat{X}_{M_i}$ axis then has an inertial matrix (centered and aligned with axes as in Fig:2.9a):

$$\mathbb{I}_{M_i} = \begin{bmatrix} 530.88 & -32.29 & 7.46 \\ -32.29 & 1855.74 & 0.00 \\ 7.46 & 0.00 & 2088.87 \end{bmatrix} \quad [g.cm^2] \tag{2.11a}$$

$$\approx diag\big(531,\ 1856,\ 2089\big) \times 10^{-7} \quad [kg.m^2] \tag{2.11b}$$

The effect of rapidly spinning propellers on the inertia in Eq:2.11a is approximated well by a solid disc, hence the inner ring's inertial components are regarded as constant. The moment of inertia about that $\hat{X}_{M_i}$ rotational axis, pertinent to a λ_i rotation, is then $\mathbb{I}_\lambda \approx 530.88 \times 10^{-7}\ \ [kg.m^2]$.

[4] All inertias are assumed symmetrical and calculated in Solidworks with overridden masses to match physical prototype measurements, all those values are included in Appendix:B

The first λ_i actuating servo and bearing supports are affixed to the intermediate middle ring assembly (Fig:2.9b). 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 $m_{module} = 201g$. The middle ring is rotated by $\eta_i°$ about its $\hat{Y}_{M_i}$ axis. The compound body's inertia about that axis of rotation, $\hat{Y}_{M_i}$, 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 $\lambda_i°$ which, from the conservation of angular momentum theory [83][5], is:

$$\text{If } \mathbb{I}_{middle} = \begin{bmatrix} 3024.30 & 0.03 & 406.84 \\ 0.03 & 8791.16 & 0.01 \\ 406.87 & 0.01 & 11579.85 \end{bmatrix} \quad [g.cm^2] \tag{2.12a}$$

$$\mathbb{I}_{M_i'} = \mathbb{I}_{middle} + \mathbb{R}_X(\lambda_i)\big(\mathbb{I}_{inner}\big)\mathbb{R}_X^{-1}(\lambda_i) \tag{2.12b}$$

$$\mathbb{I}_{M_i'}(\lambda_i) = \mathbb{I}_{const} + \mathbb{I}_{M_i}(\lambda_i) \tag{2.12c}$$

$$\approx \begin{bmatrix} 3609 & 0 & 407 \\ 0 & 10842 & 0 \\ 407 & 0 & 13630 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & -88c_{2\lambda} & 2c^2{}_\lambda - 91s_{2\lambda} \\ 0 & 2c^2{}_\lambda - 91s_{2\lambda} & 88c_{2\lambda} \end{bmatrix} \times 10^{-7} \quad [kg.m^2] \tag{2.12d}$$

With $\mathbb{I}_{inner} = \mathbb{I}_{M_i}$ being the inertia from Eq:2.11a, transformed by a rotation $\mathbb{R}_x(\lambda_i)$. The net inertia is then a function of the rotation angle λ_i and a constant inertia (Eq:2.12c) which is then simplified[6] to Eq:2.12d. 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:

$$\mathbb{I}_\eta(\lambda) \approx [0,\ 10842 - 88c_{2\lambda},\ 2c^2{}_\lambda - 91s_{2\lambda}]^T \times 10^{-7} \quad [kg.m^2] \tag{2.13}$$

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 a function of the angular rotational position of each motor module and time varying.

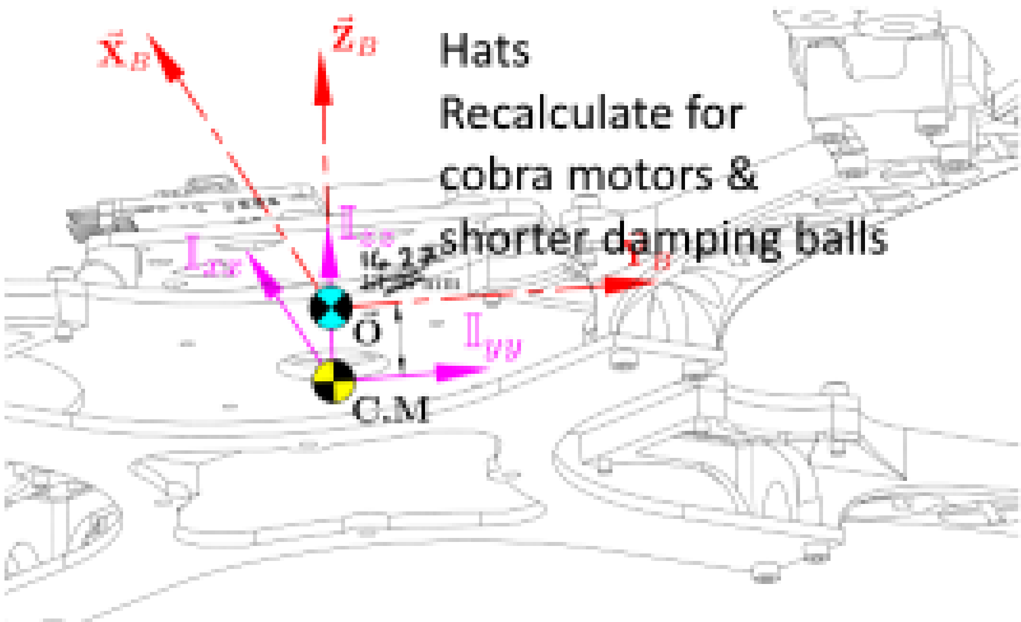


Figure 2.10: Body Frame Center of Mass

[5] $\mathbb{R}_x$ is a full rank and square, so an inverse $\mathbb{R}_X^{-1}$ always exists

[6] Eq:2.12d is rounded to no decimal places, seeing that its units are already $\times 10^{-7}$

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:2.10) coincides with the XY directional axes and lies $\Delta Z = -14.27\ mm$ 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.

The body's weight, including all four damping assemblies, totals to 814.7 g. The body's net inertia (*sans* motor modules) $\mathbb{I}_{body}$, about its center of mass is (Fig:2.10)

$$\mathbb{I}_{body} = \begin{bmatrix} 182018.63 & -0.44 & -80.30 \\ -0.44 & 181896.17 & -17.75 \\ -80.30 & -17.75 & 360077.58 \end{bmatrix} \ [g.cm^2] \text{ or } \times 10^{-7}\ [kg.m^2] \tag{2.14a}$$

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

$$\mathbb{I}_{body}{}' = \mathbb{I}_{body} + m(\vec{d}\cdot\vec{d} + \vec{d}\otimes\vec{d}^T) \approx \mathbb{I}_{body} + md^2 \tag{2.14b}$$

Here $\otimes$ represents the Hamilton product of two 3X3 matrices, it's used again later in Chapter:3 to indicate the quaternion multiplication operator.

$$\underset{\vec{\mathbf{O}}}{\mathbb{I}_{body}{}'} = \begin{bmatrix} 183677.51 & -0.42 & -4.45 \\ -0.42 & 183555.03 & -10.41 \\ -4.45 & -10.41 & 360077.62 \end{bmatrix} \times 10^{-7}\ [kg.m^2] \tag{2.14c}$$

Net inertia for the compound assembly, $\mathbb{I}_b$[7], about the 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: 2.9. Reiterating that the the origin is co-planar to the modules' center of rotation, each motor module's inertia, $\mathbb{I}_{M_i'}$[8], is further rotated by $\alpha_i°$ about $\hat{Y}_{M_i}$ and finally an orthogonal $\hat{Z}$ rotation onto $\mathcal{F}^b$. Still measured with respect to their individual centers, $\vec{\mathbf{M}}_i$, but re-orientated to align with $||\vec{\mathbf{O}}_b$. Contribution of each motor module's inertia, with $\mathbb{R}_Z$ being the same as Eq:2.9b, is then:

$$\mathbb{I}_{i^{th} motor} = \mathbb{R}_Z(\sigma_i)\mathbb{R}_Y(\alpha_i)\big(\mathbb{I}_{M_i'}\big)\mathbb{R}_Y^{-1}(\alpha_i)\mathbb{R}_Z^{-1}(\sigma_i) \tag{2.15a}$$

Expanding to Inner and Middle Ring components:

$$= \mathbb{R}_Z\mathbb{R}_Y(\alpha)\big(\mathbb{I}_{middle}\big)\mathbb{R}_Y^{-1}(\alpha)\mathbb{R}_Z^{-1} + \mathbb{R}_Z\mathbb{R}_Y(\alpha)\mathbb{R}_X(\lambda)\big(\mathbb{I}_{inner}\big)\mathbb{R}_X^{-1}(\lambda)\mathbb{R}_Y^{-1}(\alpha)\mathbb{R}_Z^{-1} \tag{2.15b}$$

$$\text{With axes } \hat{X} \in \mathcal{F}^{M_i},\ \ \hat{Y} \in \mathcal{F}^{M_i'},\ \ \hat{Z} \in \mathcal{F}^{M_i''} \tag{2.15c}$$

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

Each module's rotational center is spaced equally relative to $\vec{\mathbf{O}}_b$ with a parallel axis arm $\vec{L}_{arm} = \begin{bmatrix}195.16 & 0 & 0\end{bmatrix}^T\ [mm]$ (Fig:2.11). The net inertial equation about $\vec{\mathbf{O}}_b$, dependent on the actuator suite $\mathbb{U}$ positions, can be calculated as:

$$\underset{u\in\mathbb{U}}{\mathbb{I}_b(u)} = \mathbb{I}_{body} + \sum_{i=1}^{4}\mathbb{M}_i\ \ [kg.m^2] \tag{2.16a}$$

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

[8] As defined in Eq:2.12d

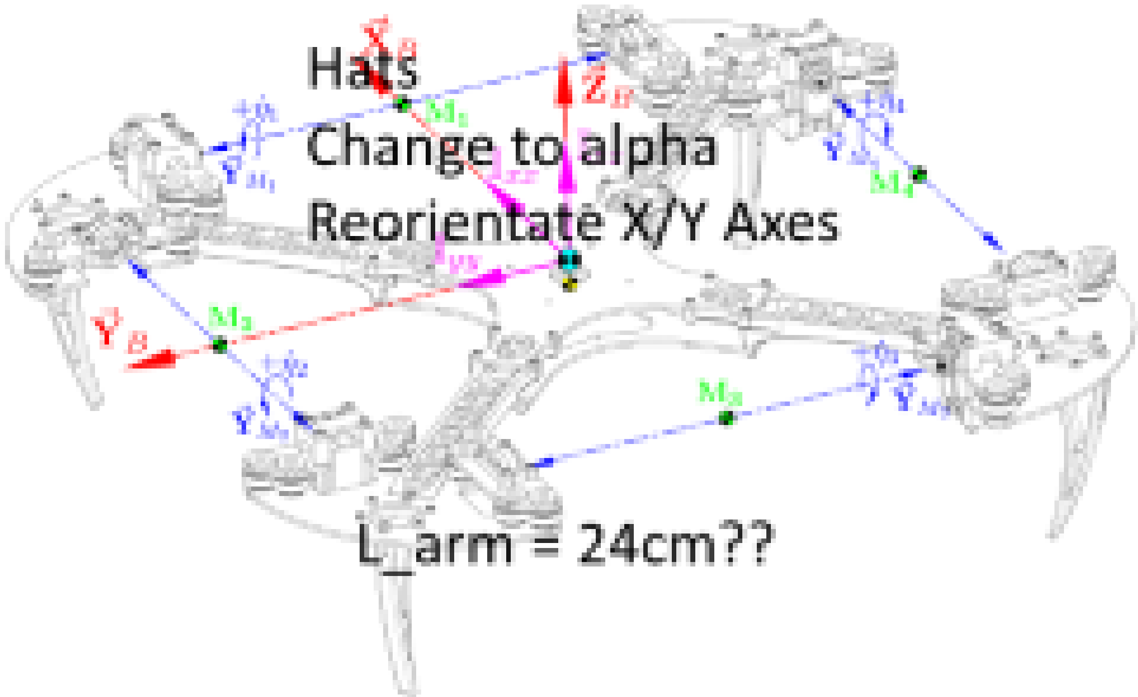


Figure 2.11: Inertial Center & Mass Center

$$\mathbb{M}_i = \mathbb{I}_{i^{th}motor} + m_{module}\big(\vec{L}\cdot\vec{L} - \vec{L}\otimes\vec{L}\big) \tag{2.16b}$$

Although Eq:2.16 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 from their respective center of masses and then finally 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 will improve the reliability of the produced inertial equations. It is perhaps more intuitive to consider each sub-body's contribution individually, despite having been derived as combined inertial systems previously.

$$\underset{u\in\mathbb{U}}{\mathbb{I}_b(u)} = \mathbb{I}_{body} + \sum_{i=1}^{4}\mathbb{M}_{inner} + \sum_{i=1}^{4}\mathbb{M}_{middle} \tag{2.17}$$

The relative movement pertinent to Eq:2.11 and Eq:2.12 are conceptually separated from that affecting Eq:2.16. For each inner ring, W.R.T its center of mass measured relative to its center of rotation, different from Eq:2.11a, the inner ring's inertia is calculated as;

$$m_{inner} = 99 \quad [g] \tag{2.18a}$$

$$\underset{C.M}{\mathbb{I}_{inner}} = \begin{bmatrix} 585.11 & -0.34 & -2.44 \\ -0.34 & 1960.93 & 0.81 \\ -2.44 & 0.81 & 2139.84 \end{bmatrix} \quad [g.cm^2] \tag{2.18b}$$

$$C.M_{inner} = \begin{bmatrix} 1.400 & -0.043 & -1.942 \end{bmatrix}^T \quad [mm] \tag{2.18c}$$

$$C.M_{inner}{}' = \mathbb{R}_Z\mathbb{R}_Y\mathbb{R}_X\big(C.M_{inner}\big) \tag{2.18d}$$

$$\underset{\parallel\,\vec{\mathbf{o}}}{\mathbb{I}_{inner}} = \mathbb{R}_Z\mathbb{R}_Y(\alpha)\mathbb{R}_X(\lambda)\big(\mathbb{I}_{inner}\big)\mathbb{R}_X^{-1}(\lambda)\mathbb{R}_Y^{-1}(\alpha)\mathbb{R}_Z^{-1} \tag{2.18e}$$

$$\Delta L = \vec{L}_{arm} - C.M_{inner}{}' \tag{2.18f}$$

$$\mathbb{M}_{inner} = \underset{\vec{\mathbf{o}}}{\mathbb{I}_{inner}} = \underset{\parallel\,\vec{\mathbf{o}}}{\mathbb{I}_{inner}} + m_{inner}\big((\Delta L\cdot\Delta L)\mathbb{I}_{3x3} - \Delta L\otimes\Delta L\big) \tag{2.18g}$$

Similarly for the middle rings:

$$m_{middle} = 102 \quad [g] \tag{2.19a}$$

$$\underset{C.M}{\mathbb{I}_{middle}} = \begin{bmatrix} 2996.57 & 179.32 & 232.71 \\ 179.32 & 6524.84 & 13.87 \\ 232.71 & 13.87 & 9312.733 \end{bmatrix} \quad [g.cm^2] \tag{2.19b}$$

$$C.M_{middle} = \begin{bmatrix} 47.00 & 3.74 & -3.63 \end{bmatrix}^T \quad [mm] \tag{2.19c}$$

$$C.M_{middle}{}' = \mathbb{R}_Z \mathbb{R}_Y \big(C.M_{middle}\big) \tag{2.19d}$$

$$\underset{||\vec{\mathbf{O}}}{\mathbb{I}_{middle}} = \mathbb{R}_Z \mathbb{R}_Y(\alpha)\big(\mathbb{I}_{middle}\big)\mathbb{R}_Y^{-1}(\alpha)\mathbb{R}_Z^{-1} \tag{2.19e}$$

$$\Delta L = \vec{L}_{arm} - C.M_{middle}{}' \tag{2.19f}$$

$$\mathbb{M}_{middle} = \underset{\vec{\mathbf{O}}}{\mathbb{I}_{middle}} = \underset{||\vec{\mathbf{O}}}{\mathbb{I}_{middle}} + m_{middle}\big((\Delta L \cdot \Delta L)\mathbb{I}_{3x3} - \Delta L \otimes \Delta L\big) \tag{2.19g}$$

Unless otherwise specified; any inertia $\mathbb{I}_b$, irrespective of arguments, will refer to an instantaneous calculated solution to Eq:2.17 given a particular $u \in \mathbb{U}$. The purpose of the derivations Eq:2.18 & Eq:2.19 is twofold; highlighting both the inertial contributions and the variable center of masses for each sub-body. Seeing that the origin of the motion frame $\mathcal{F}^b$ and the net body's center of mass aren't coincidental, it's important to quantify the equation for the varying center of mass. If, for a collection of n bodies, with each body's center $\vec{X}_i$ and a mass m_i, the net center of mass is:

$$C.M = \frac{\sum_{i=1}^n m_i.\vec{X}_i}{\sum_{i=1}^n m_i} \tag{2.20a}$$

So then, with $\vec{X}_{inner}$ & $\vec{X}_{middle}$ being defined in Eq:2.18d & Eq:2.19d respectively, the body has a center of mass†:

$$= \frac{m_{body}.\vec{X}_{body} + \sum m_{inner}.\vec{X}_{inner} + \sum m_{middle}.\vec{X}_{middle}}{m_{body} + \sum m_{inner} + \sum m_{middle}} \tag{2.20b}$$

Making the resultant gravitational torque[9] about the origin $\vec{\mathbf{O}}$ at any given moment:

$$\Delta C.G = \vec{\mathbf{O}} - C.M \tag{2.20c}$$

$$\tau_g = \Delta C.G \times \vec{G}_b \quad [N.m], \tau_g \in \mathcal{F}^b \tag{2.20d}$$

[9] With $\vec{G}_b = \mathbb{R}_I^b \vec{F}_g \quad [N]$

2.3 System Layout

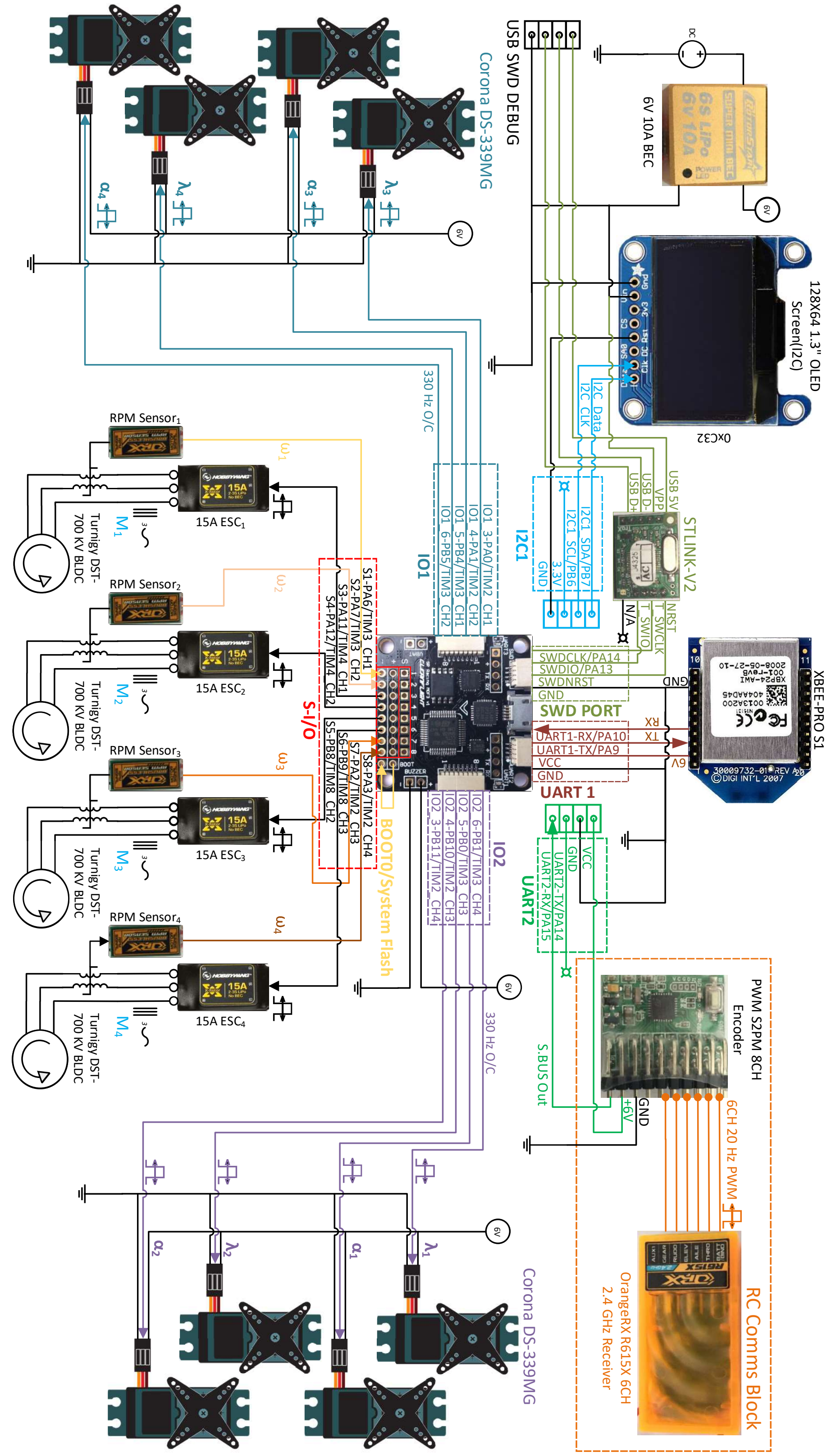
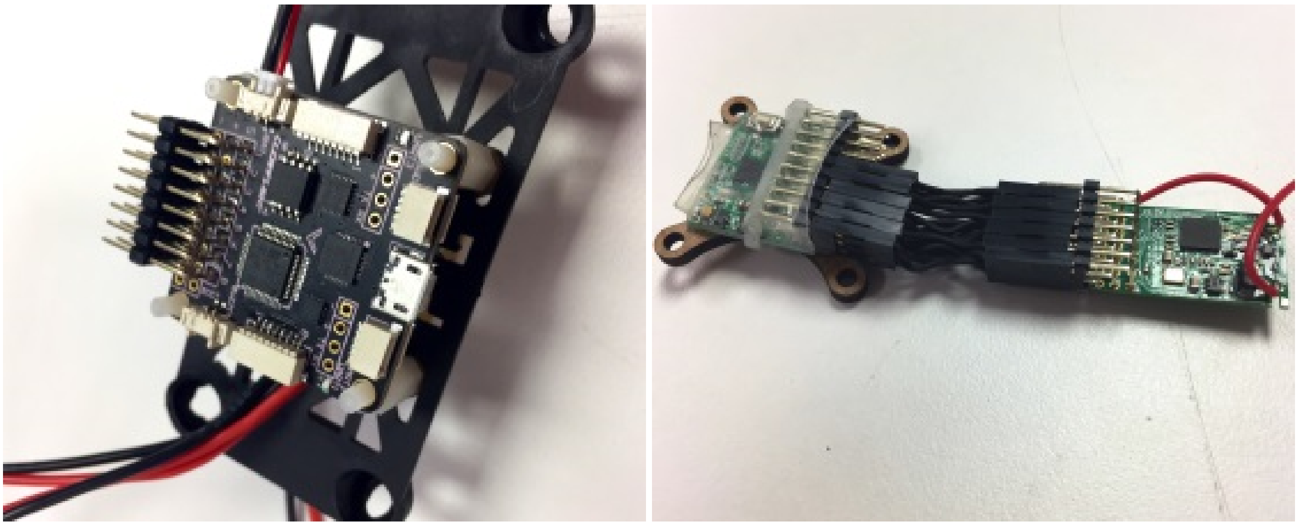


Figure 2.12: Hardware Schematic Diagram

An abstracted hardware diagram for the (electronic) system layout is shown in Fig:2.3. It's an illustration for the connection of different electronic peripherals used to aid the on-board control system. The structure of the autopilot system and control loops are addressed in a later Chapter:6. This description aims to provide a brief overview of the specific modules used, their purpose and how they're interfaced. No code structure or control loops are considered yet...



(a) SPRacing F3 Deluxe Flight Controller **(b)** SBUS Converter & 6CH Receiver Modules

Figure 2.13

The entire system is constructed around an ARM STM32F303 [82] based μcontroller. The microprocessor board is a commercial flight control board, specifically an SPRacing F3 Deluxe [16][10], which has had its bootloader removed and custom firmware, unique to this project, burnt to it. That software is later described in Chapter:6; the I/O for all the peripherals are detailed here however. The flight-controller has onboard peripherls: an I2C MPU-6050 [36] 6-axis gyroscope & accelerometer with a connected HMC5883 [22] magnetometer compass, an SPI MS5611 [80] barometer and similarly 64 Mb of SPI flash memory. The connections of which are listed in App:B.2.

The combination of above sensors fused for state estimation and their associated algorithms are dealt with in Section:5.3 in Chapter:5.

Figure 2.14: S.BUS Data Stream

Two wireless communication peripherals are used. First the system relays full state information, for a complete 6-DOF autopilot system, from a ground control station using 2.4 GHz XBEE S1 module(s) [37], USART connected. Secondly, an augmented pilot control input system, fail safe and secondary to the autopilot loop, is transmitted through 6 Channel 2.4 GHz R/F comms. The 6 CH received signals, otherwise permeated as six individual 20 KHz PWM signals via an OrangeRx R615x [63] receiver, are encoded into a single line S.BUS data stream.

[10] CleanFlight opensource software is regularly used for the F3 but hardware specifications are not openly avaiable. The reverse engineered electrical schematic for the board is included in Appendix:B.2

The S.BUS encoder [33] implements a USART derivative communications standard, Fig:2.14 shows the sampled data stream used to ascertain the following parameters:

- 8-Bit data bytes
- 25 Bytes per transmissions
- Bytes are:
  - MSB First
  - 1 start bit
  - 2 stop bits
  - Even parity bit
  - Inverted
  - 100000 baud (bps)
- 14 ms idle time between transmissions
- Up to 16 channels encoded
- Each channel is 11 bits of data
- Channel data is little endian prioritized

The received information of the transmitted 6 channels is filtered through an Infinite-Impulse Response filter. The filters frequency response is as follows: $y_n = y_{n-1}$. Any referenced signals received are all post filtered data. Filtering for state estimates is separately performed on the Ground Control Station computer.

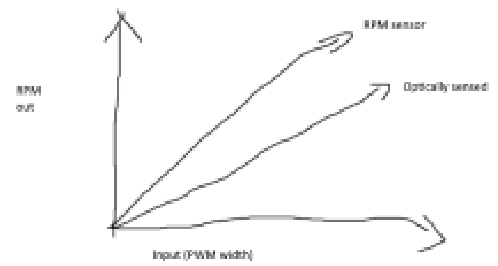
Each of the eight digital servo actuators are driven individually from 330 Hz PWM timer output compare channels, pulses range from 1ms - 2ms to linearly control the rotary position. The exact transfer function is empirically determined next in Subsection:2.3.1. The four 15A brushless DC speed controllers (ESCs) are each driven from a 20 Hz PWM timer channel output, similarly with 1ms - 2ms pulse widths. There are a total of 12 PWM output compare signals drawn from the μcontroller. Servos are powered by a regulated 6V DC 10A power supply [32] whilst the ESCs switch unregulated 15.1 V DC from an externally tethered power supply. The DC supply could potentially be drawn from an on-board battery bank but that would add significant weight to an already heavy platform.

There's no integrated feedback for instantaneous RPM values from the Electronic Speed Controllers. Using discrete OrangeRX BLDC RPM sensors [31], measuring the phase of back Emf induced across two of the three motor phases, the exact RPM can be ascertained. The signal produced by the RPM sensors varies the period, proportional to the rotational speed of the motor, of a square wave with a constant 50% duty cycle. The RPM sensor's output signal is calibrated to a *rate* gain, the linear relationship is shown in Fig:2.15a. Knowing exact RPM rates means the subsequent thrust and aerodynamic torques for the control plant inputs can be calculated.

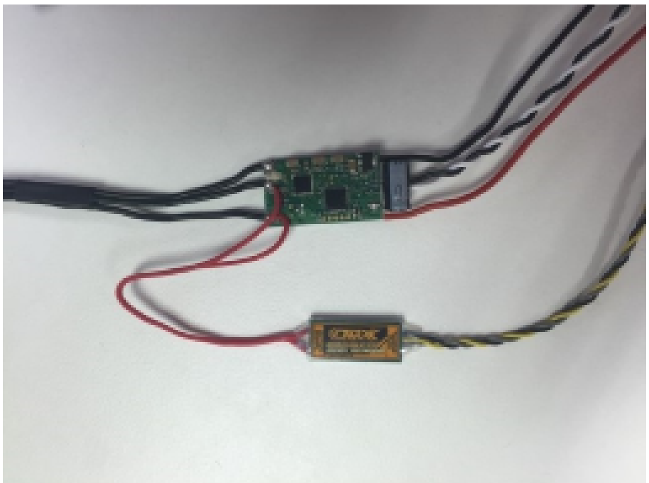
Any STM32 μcontroller is programmed through a dedicated debugging device. The ST-Link V2 [81] is the current proprietary device which, itself, is a specially programmed STM32F10 chip (Fig:2.15b). The chip connects to the dedicated Serial Wire Debugging ports of the target STM (*SWD-CLK*, *SWD-IO* & *SWD-NRST*) and is interfaced via regular USBD+ and USBD- data lines.

2.3.1 Actuator Transfer Functions

Thaar be transfer functions here...



(a) RPM sensor gain



(b) ESC & Inline RPM Sensor

Figure 2.15

Chapter 3

Kinematics & Dynamics

The body's dynamics are first solved as rigid, with appropriate equations derived for generic 6-DOF motion. There after, non-linear aerodynamic and inertial effects, unique to multi-body relative rotations, are presented and included in the plant's model. Finally a consolidated, quaternion based plant model is presented which is used for the later control plant development next in Chapter:4.

3.1 Rigid Body Dynamics

3.1.1 Lagrange Derivation

Fundamentally any body, rigid or otherwise, can undergo two kinds of movements, namely rotational and translation motions. Often a Lagrangian [71, 85] approach for combined angular and translational movements is used to derive the differential equations of motion for each degree of freedom. The Lagrangian principle ensures that translational, rotational and potential energies are conserved throughout the system's trajectory progression. When combined with Euler-Rotational equations, the Euler-Lagrangian [87] formulation fully defines the aerospace 6-DOF equation set.

Lagrangian formulation is regarded as especially useful in non-cartesian (*spherical etc...*) co-ordinate frames and multi-body systems. With that being said, a cartesian co-ordinate system was already defined in Section:2.2.2, rigid body dynamics in a cartesian co-ordinate frame do lend themselves to Newtonian mechanics. The Newtonain-Euler or Euler-Lagrange formulations produce the same result. The Lagrangian operator, $\mathcal{L}$, is a term made up of the difference between kinetic and potential energies, T and U respectively. Considering some generalized path co-ordinates $\mathbf{r}(t)$, for both linear $\mathcal{E}$ and angular η relative positions;

$$\mathbf{r}(t) = \begin{bmatrix} \mathcal{E} & \eta \end{bmatrix}^T \tag{3.1}$$

The co-ordinates in Eq:3.1 are generalized here, despite being symbols commonly used to represent linear and angular positions. The generalized co-ordinates are later be refined as Cartesian body co-ordinates with respect to the inertial frame. The Lagrangian, by definition, is then:

$$\mathcal{L}(\mathbf{r}, \dot{\mathbf{r}}, t) = T(\mathbf{r}, \dot{\mathbf{r}}) - U(\mathbf{r}, \dot{\mathbf{r}}) \tag{3.2a}$$

Introducing generic kinetic (angular & linear) and potential energies, the latter being only gravitational potential energy in this case;

$$\mathcal{L} = \frac{1}{2}\dot{\mathcal{E}}^T(m)\dot{\mathcal{E}} + \frac{1}{2}\dot{\eta}^T(\mathbb{I})\dot{\eta} - mgz \tag{3.2b}$$

Noting that $\mathbb{I}$ is the inertial tensor aligned w.r.t to whichever generalized coordinates are being used. The Euler-Lagrange formulation equates partial derivatives of the Lagrangian to any generalized forces, $\mathbf{V}$, acting on the system.

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\mathbf{r}}}\right) - \frac{\delta L}{\delta \mathbf{r}} = \mathbf{V} = \begin{bmatrix} F \\ \tau \end{bmatrix} \tag{3.3}$$

Taking the partial derivatives of Eq:3.2b with respect to its path co-ordinates $\mathbf{r}$:

$$\frac{\delta L}{\delta \mathbf{r}} = \begin{bmatrix} mg \\ 0 \end{bmatrix} \tag{3.4a}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\mathbf{r}}}\right) = \begin{bmatrix} m\frac{d}{dt}\dot{\mathcal{E}} & \mathbb{I}\frac{d}{dt}\dot{\eta} \end{bmatrix}^T \tag{3.4b}$$

In any generalized coordinate system a rotating vector's time derivative [?, 67] is given by:

$$\frac{d\vec{f}}{dt_a} = \frac{d\vec{f}}{dt_b} + \vec{\omega}_{a/b} \times \vec{f} \tag{3.5}$$

So applying the Reynolds Transportation Theorem (Eq:3.5) to the partial derivatives in Eq:3.4b and further defining the generalized co-ordinates as cartesian body coordinates with respect to inertial origin. Noting that in Eq:3.4b the place holders used for linear and angular positions are in a specific frame, $[\dot{\mathcal{E}} \quad \dot{\eta}]^T \in \mathcal{F}^b$, and hence $\equiv [\nu \quad \omega]^T$. It then follows that Lagrangian will change:

$$\mathcal{L} = \frac{1}{2}\nu^T(m)\nu + \frac{1}{2}\omega^T(\mathbb{I})\omega - mg_b z \tag{3.6a}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\mathbf{r}}}\right) = \begin{bmatrix} m\frac{d}{dt}\nu & \mathbb{I}\frac{d}{dt}\omega \end{bmatrix}^T \tag{3.6b}$$

$$\rightarrow m\frac{d}{dt}\nu_b = m\dot{\nu} + \vec{\omega}_{I/b} \times \nu \tag{3.6c}$$

$$\rightarrow \mathbb{I}_b\frac{d}{dt}\omega_b = \mathbb{I}_b\dot{\omega} + \omega_{I/b} \times \mathbb{I}_b\omega \tag{3.6d}$$

Which, when reintroduced to the Euler-Langrage formulation Eq:3.3, results in the familiar Newton-Euler equations for linear and angular movements, in the body frame;

$$F = m\dot{\nu} + \omega_b \times m\nu - m\mathbb{R}_I^b g \tag{3.7a}$$

$$\tau = \mathbb{I}_b\dot{\omega}_b + \omega_b \times \mathbb{I}_b\omega \tag{3.7b}$$

It's important to recall that $\omega_b \neq \dot{\eta}$ where $\eta = [\phi \ \theta \ \psi]^T$, seeing that Euler Angles are defined in sequentially rotated reference frames. So the four differential equations often used to completely describe the entire state derivatives are:

$$\dot{\mathcal{E}} = \mathbb{R}_b^I\nu \qquad \in \mathcal{F}^I \tag{3.8a}$$

$$F = m\dot{\nu} + \omega_b \times m\nu - m\mathbb{R}_I^b g \qquad \in \mathcal{F}^b \tag{3.8b}$$

$$\dot{\eta} = \Psi(\eta)\omega_b \qquad \in \mathcal{F}^{v2}, \mathcal{F}^{v1}, \mathcal{F}^I \tag{3.8c}$$

$$\tau = \mathbb{I}_b\omega_b + \omega_b \times \mathbb{I}_b\omega \qquad \in \mathcal{F}^b \tag{3.8d}$$

The set of state equations Eq:3.8 could be reduced to a set of two equations, only in their respective reference frames of the state variables which they describe. The non-linear form of those equations substitutes $\dot{\eta} = \Phi(\eta)\omega_b$ in the Lagrangian derivative, Eq:3.4b.

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\mathbf{r}}}\right) = \begin{bmatrix} m\frac{d}{dt}\nu & \mathbb{I}\frac{d}{dt}\dot{\eta} \end{bmatrix} = \begin{bmatrix} m\frac{d}{dt}\nu & \mathbb{I}\frac{d}{dt}\Phi(\eta)\omega_b \end{bmatrix} \tag{3.9}$$

This only changes the angular component, and so applying the chain rule:

$$\mathbb{I}\frac{d}{dt}\Phi(\eta)\dot{\omega}_b = \mathbb{I}\big(\dot{\Phi(\eta)}\omega_b + \Phi(\eta)\dot{\omega}_b\big) \tag{3.10}$$

Drawing from [61] and recognizing that $\mathbb{I}$ must be transformed to common axes, $J = \Psi(\eta)^T\mathbb{I}\Psi(\eta)$. The controllable differential equations in Eq:3.7, then in the inertial frame for force and intermediate Euler frames for each angle becomes:

$$M(\eta)\ddot{\eta} + C(\eta,\dot{\eta})\dot{\eta} = \Psi(\eta)\tau \tag{3.11a}$$

$$M(\eta) = \Psi(\eta)^T\mathbb{I}\Psi(\eta) \tag{3.11b}$$

$$C(\eta,\dot{\eta}) = -\Psi(\eta)\mathbb{I}\dot{\Psi(\eta)} + \Psi(\eta)^T sk(\Psi(\eta)\dot{\eta})\mathbb{I}\Psi(\eta) \tag{3.11c}$$

Equation 3.11 fully describes the state derivative $\ddot{\eta}$ in its own frame(s). The two differential equations which dictate the entire bodies motion are:

$$F = m\dot{\mathcal{E}} + \mathbb{R}_b^I\omega_b \times m\dot{\mathcal{E}} - mg \qquad \in \mathcal{F}^I \tag{3.12a}$$

$$\Psi(\eta)\tau = M(\eta)\ddot{\eta} + C(\eta,\dot{\eta}) \qquad \in \mathcal{F}^{v2}, \mathcal{F}^{v1}, \mathcal{F}^I \tag{3.12b}$$

The generalized forces effecting the system, F and τ, are the system's controllable inputs and are going to be directly related to the actuator effectiveness terms. In the general case, which is expanded upon in Section:3.3, the control inputs are effected as follows:

$$\mu F = \sum \vec{T_i} \tag{3.13a}$$

$$\mu\tau = \sum \vec{l_i} \times \vec{T_i} \tag{3.13b}$$

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

Chapter 7

Conclusion

- Lagrange dynmaics for multibody system could have produced a more concise model etc ...

Appendix A

Standard Quadrotor Dynamics

Appendix B

Design Bill of Materials

B.1 Parts List

Part Name	No. 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
Cobra 2208 2000KV Brushlesss DC	4	44.2
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

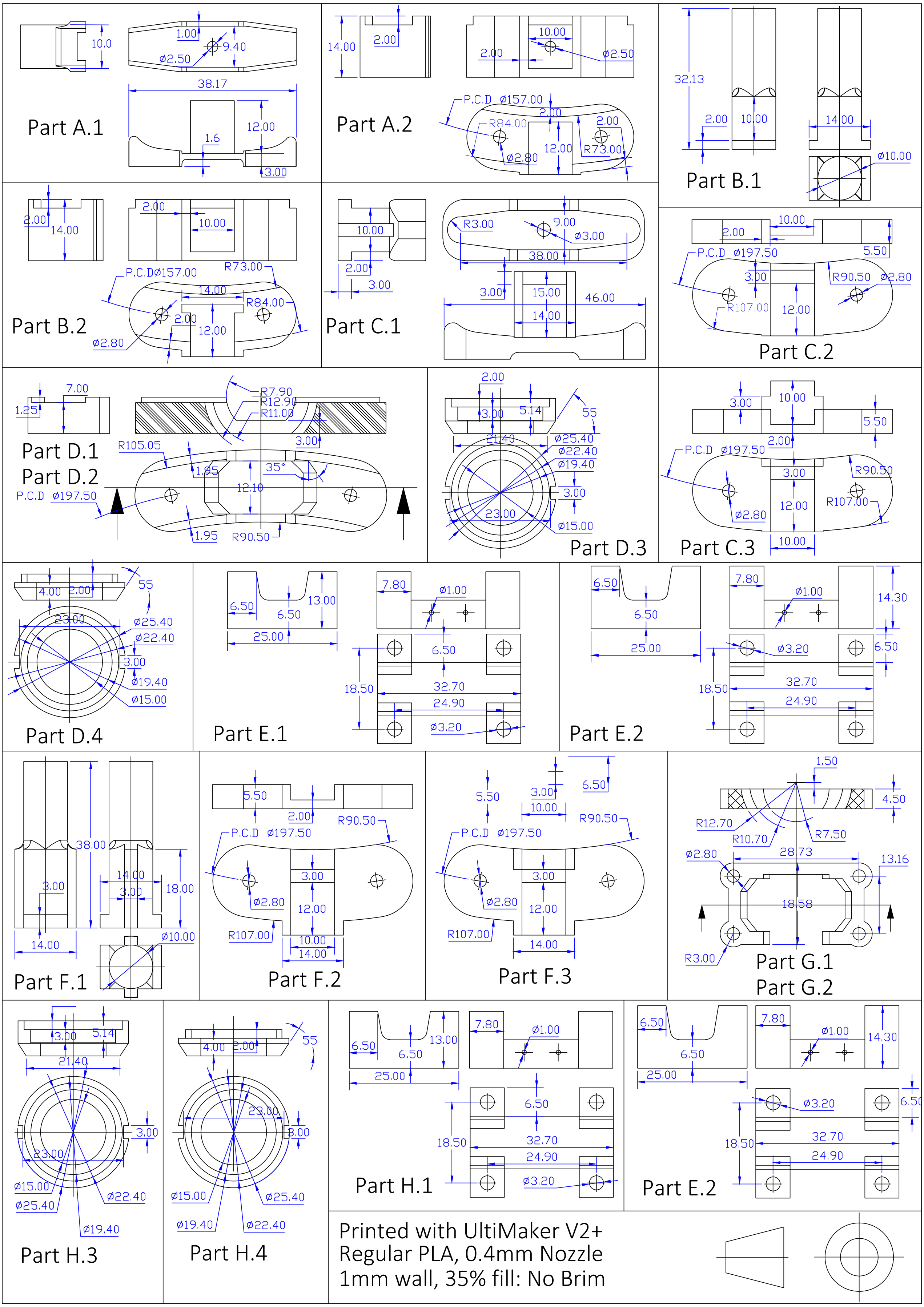


Table B.2: 3D Printed Parts

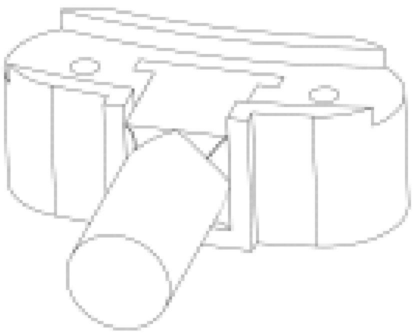
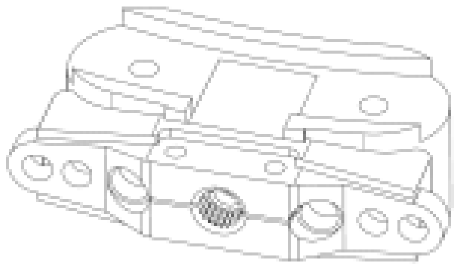
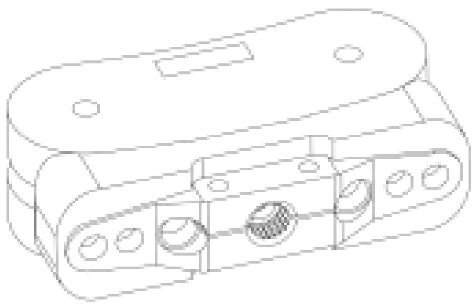
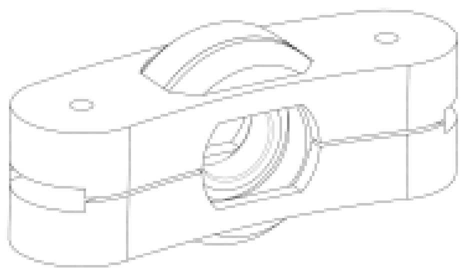
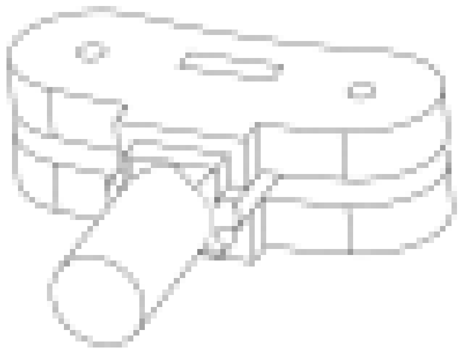
Bracket Assemblies 2	
 **Figure B.1:** Bearing Bracket Inner Ring Assembly Parts: A.1, A.2	 **Figure B.2:** Servo Bracket Inner Ring Assembly Parts: B.1, B.2, M3 Servo Horn
 **Figure B.3:** Servo Bracket Middle Ring Assembly Parts: C.1, C.2, C.3, M3 Servo Horn	 **Figure B.4:** Bearing Holder Middle Ring Assembly Parts: D.1, D.2, D.3, D.4, 18-10 Bearing
 **Figure B.5:** Servo Mount Middle Ring Assembly Parts: E.1, E.2, Corona Servo & Fasteners	 **Figure B.6:** Bearing Shaft Middle Ring Assembly Parts: F.1, F.2, F.3

Table B.3: Inner & Middle Ring Assemblies

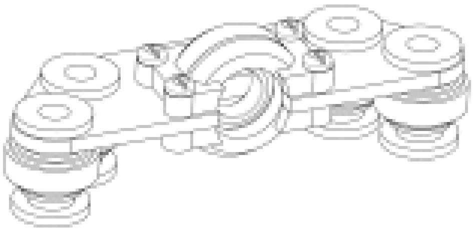
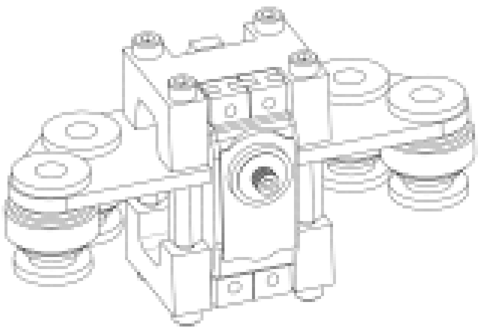
Bracket Assemblies 2	
 **Figure B.7:** Bearing Holder Damping Assembly Parts: G.1, G.2, G.3, G.4, 18-10 Bearing, 80g Damping Balls, Bearing Holder Damping Bracket	 **Figure B.8:** Servo Mount Damping Assembly Parts: H.1, H.2, Corona Servo & Fasteners, 80g Damping Balls, Servo Mount Damping Bracket

Table B.4: Damping Assemblies

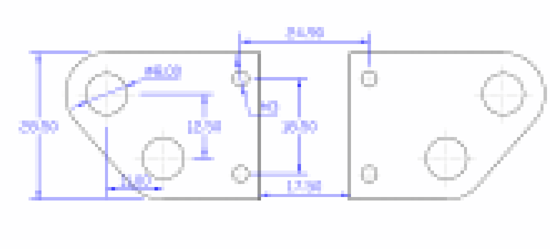
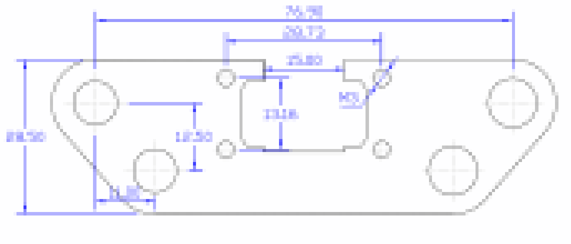
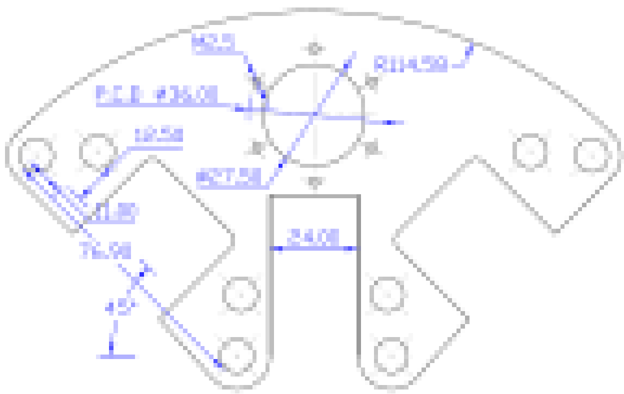
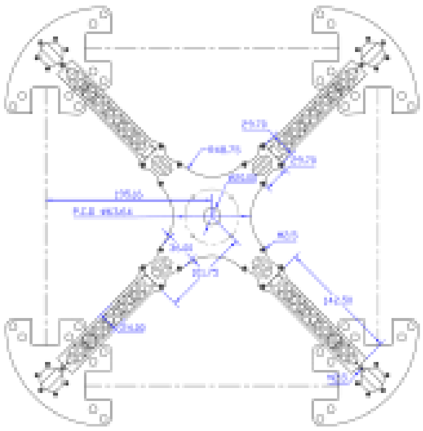
Laser Cut Brackets	
 **Figure B.9:** Servo Mount Damping Bracket	 **Figure B.10:** Bearing Holder Damping Bracket
 **Figure B.11:** Arm Mount Damping Bracket	 **Figure B.12:** Frame Brackets

Table B.5: Laser Cut Damping Brackets

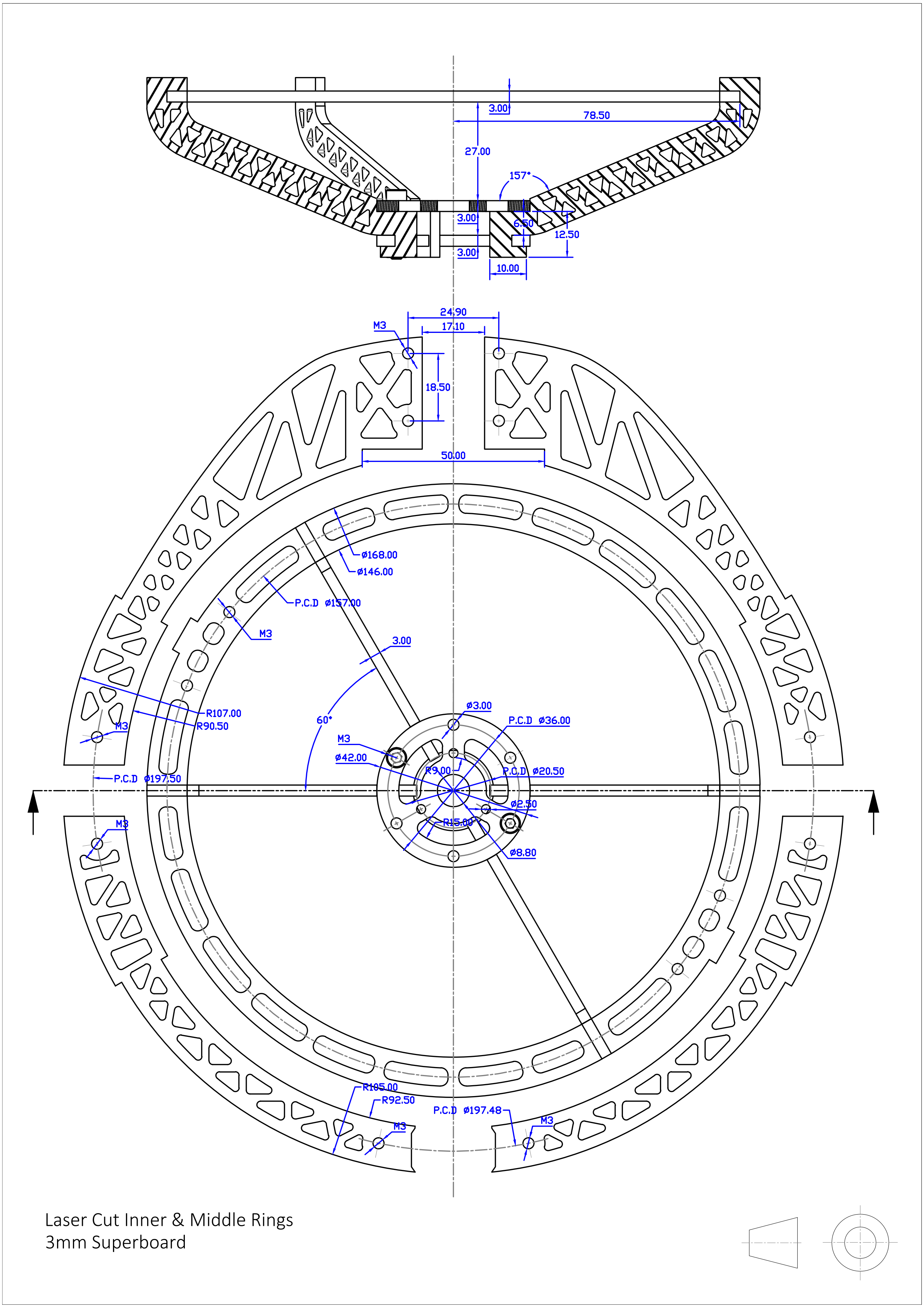


Table B.6: Laser Cut Parts

B.2 F3 Deluxe Schematic Diagram

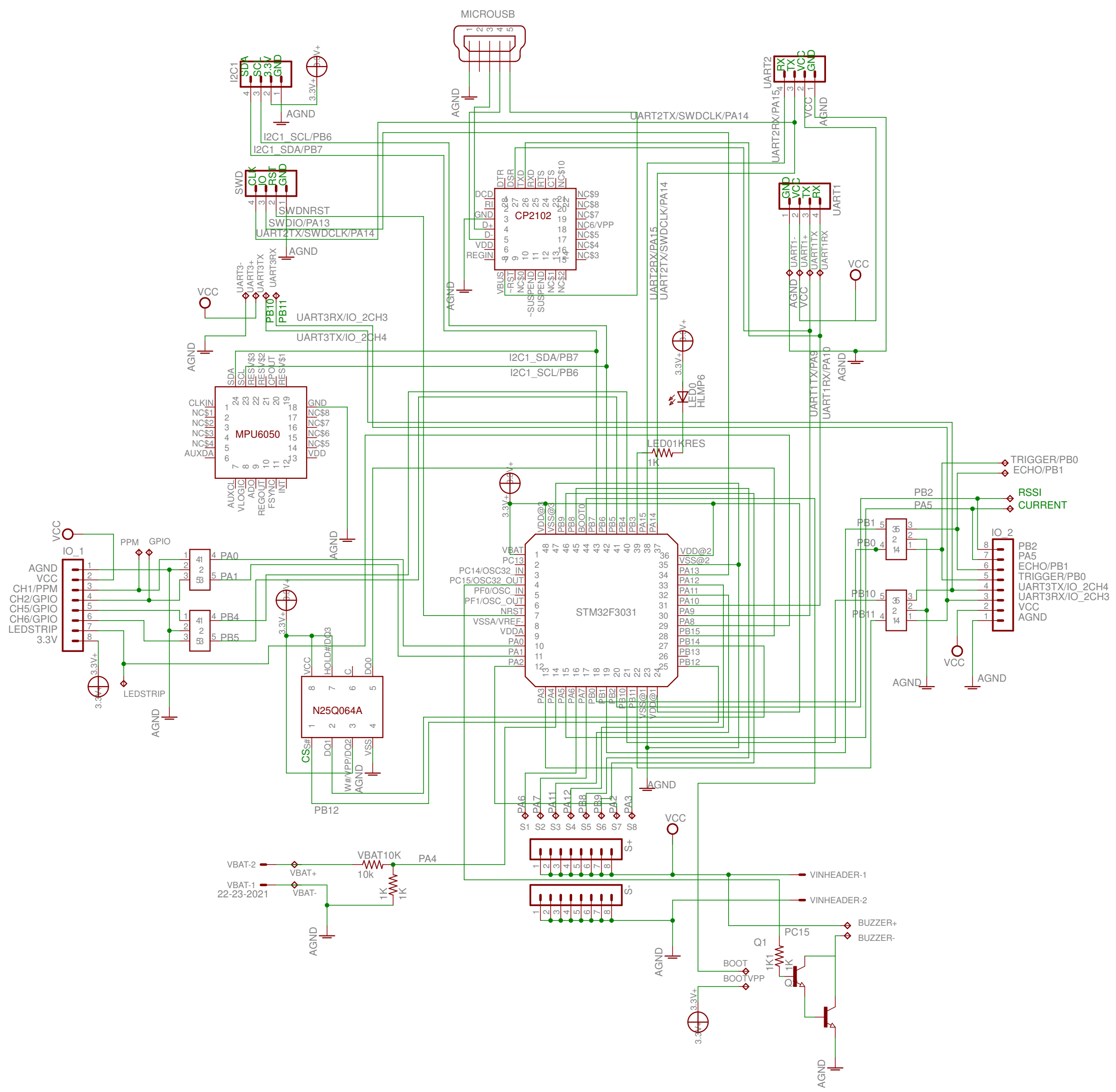


Figure B.13: F3 Deluxe Flight Controller Hardware Schematic

Appendix C

System ID Test Data

C.1 Servo Data

C.2 Cobra CM2208-200KV

Cobra CM-2208/20 Motor Propeller Data

Magnets	Motor Wind	Motor Kv	No-Load Current	Motor Resistance	I Max	P Max (3S)
14-Pole	20-Turn Delta	2000 RPM/Volt	Io = 0.77 Amps @ 10v	Rm = 0.076 Ohms	20 Amps	220 W

Stator	Outside Diameter	Body Length	Total Shaft Length	Shaft Diameter	Motor Weight
12-Slot	27.7 mm, 1.091 in.	24.0 mm, 0.945 in.	45.2 mm, 1.780 in.	3.17 mm, 0.125 in.	44.2 gm, 1.56 oz

Test Data From Sample Motor	Input Io Value	6.0 V	8.0 V	10.0V	12.0V	Measured Kv value	Measured Rm Value
		0.59 A	0.67 A	0.77 A	0.87 A	1988 RPM/Volt @ 10v	0.076 Ohms

Prop Manf.	Prop Size	Li-Po Cells	Input Voltage	Motor Amps	Input Watts	Prop RPM	Pitch Speed in MPH	Thrust Grams	Thrust Ounces	Thrust Eff. Grams/W
APC	5.25x4.75-E	3	11.1	13.34	148.1	17,507	78.7	451	15.91	3.05
APC	5.5x4.5-E	3	11.1	13.67	151.7	17,388	74.1	456	16.08	3.01
APC	6x4-E	3	11.1	14.87	165.1	17,003	64.4	630	22.22	3.82
APC	7x4-SF	3	11.1	21.82	242.2	13,985	53.0	840	29.63	3.47
APC	7x5-E	3	11.1	24.02	266.6	13,272	62.8	797	28.11	2.99
FC	5x4.5	3	11.1	8.66	96.1	19,061	81.2	428	15.10	4.45
FC	5x4.5x3	3	11.1	12.38	137.4	17,825	76.0	534	18.84	3.89
FC	6x4.5	3	11.1	15.47	171.7	16,792	71.6	721	25.43	4.20
GemFan	5x3	3	11.1	6.67	74.0	19,801	56.3	374	13.19	5.05
HQ	5x4	3	11.1	7.13	79.1	18,182	68.9	373	13.16	4.71
HQ	5x4x3	3	11.1	9.25	102.7	17,401	65.9	449	15.84	4.37
HQ	5x4.5-BN	3	11.1	11.17	124.0	16,902	72.0	487	17.18	3.93
HQ	6x3	3	11.1	7.34	81.5	18,128	51.5	419	14.78	5.14
HQ	6x4.5	3	11.1	13.53	150.2	16,206	69.1	645	22.75	4.29
HQ	6x4.5x3	3	11.1	17.60	195.4	15,137	64.5	762	26.88	3.90
HQ	7x4	3	11.1	20.71	229.9	14,250	54.0	850	29.98	3.70
HQ	7x4.5	3	11.1	20.31	225.4	14,351	61.2	865	30.51	3.84

Prop Manf.	Prop Size	Li-Po Cells	Input Voltage	Motor Amps	Input Watts	Prop RPM	Pitch Speed in MPH	Thrust Grams	Thrust Ounces	Thrust Eff. Grams/W
APC	5.25x4.75-E	4	14.8	17.29	255.9	20,560	92.5	603	21.27	2.36
APC	5.5x4.5-E	4	14.8	17.87	264.5	20,436	87.1	635	22.40	2.40
APC	6x4-E	4	14.8	20.15	298.2	19,829	75.1	837	29.52	2.81
FC	5x4.5	4	14.8	10.89	161.2	22,511	95.9	588	20.74	3.65
FC	5x4.5x3	4	14.8	16.43	243.2	20,828	88.8	718	25.33	2.95
FC	6x4.5	4	14.8	20.09	297.3	19,809	84.4	998	35.20	3.36
HQ	4x4.5-BN	4	14.8	10.45	154.7	22,661	96.6	477	16.83	3.08
HQ	5x3	4	14.8	6.88	101.8	23,580	67.0	442	15.59	4.34
HQ	5x4	4	14.8	10.22	151.3	22,739	86.1	589	20.78	3.89
HQ	5x4x3	4	14.8	13.26	196.2	21,763	82.4	710	25.04	3.62
HQ	5x4.5-BN	4	14.8	16.10	238.3	20,899	89.1	744	26.24	3.12
HQ	6x3	4	14.8	11.06	163.7	22,512	64.0	679	23.95	4.15
HQ	6x4.5	4	14.8	19.62	290.4	19,948	85.0	982	34.64	3.38

Figure C.1: Official Test Results for Cobra Motors

Appendix D

Full Equations

D.1 Inertias

$$\approx \begin{bmatrix} 3613.144 & 0.025 & 406.81 \\ 0.025 & 9774.160 & 0.4626 \\ 406.81 & 0.4626 & 12650.72 \end{bmatrix} \tag{D.1a}$$

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

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

$$= \mathbb{R}_Z \begin{bmatrix} c_{\eta_i} & 0 & s_{\eta_i} \\ 0 & 1 & 0 \\ -s_{\eta_i} & 0 & c_{\eta_i} \end{bmatrix} \left(\mathbb{I}_{M_i'}\right) \begin{bmatrix} c_{\eta_i} & 0 & -s_{\eta_i} \\ 0 & 1 & 0 \\ s_{\eta_i} & 0 & c_{\eta_i} \end{bmatrix} \mathbb{R}_Z^{-1} \tag{D.1d}$$

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