MAJOR PROJECT-II

DESIGN AND STABILITY ANALYSIS OF QUADROTORS TO BE USED IN PRECISION AGRICULTURE

Submitted in partial fulfilment of the requirement for the award of degree of

Master of Technology
In
Computational Design

Submitted by

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2K15/CDN/03

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DECLARATION

I, hereby declare that the work which is being presented in this dissertation, titled **"DESIGN AND ANALYSIS OF QUADROTOR FOR PRECISION AGRICULTURE"** towards the partial fulfilment of the requirements for the award of degree of **Master of Technology** with specialization in COMPUTATIONAL DESIGN from Delhi Technological University Delhi, is an authentic record of my own work carried out under the supervision of Mr. **Krovvidi Srinivas**, Assistant Professor, Mechanical Engineering Department, Delhi Technological University, Delhi.

The matter embodied in this dissertation record has not been submitted by me for the award ofany other degree.

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CERTIFICATE

This is to certify that the work embodied in the dissertation entitled "DESIGN AND ANALYSIS OF QUADROTOR FOR PRECISION AGRICULTURE" by ANANT GAURAV (2K15/CDN/03) in partial fulfilment for the award of degree of Master of Technology in COMPUTATIONAL DESIGN, is an authentic record of student's own work carried out under my guidance and supervision.

It is also certified that the report has not been submitted to any other institute/university for the award of any degree.

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I Anant Gaurav, student of M.Tech - Computational Design, registration number-2K15/CDN/03 is presenting a project report on **"Design and Analysis of Quadrotors for Precision Agriculture**" under the supervision of Krovvidi Srinivas (Assistant Professor), Department of Mechanical Engineering. He has encouraged me to undertake this enthralling topic and provided me with valuable suggestions, time and guidance which were vital for the completion of the project. I would also like to mention the deep gratitude towards Dr R.S Mishra, Head of the Department, Mechanical Engineering for his constant support and precious knowledge that she shared with me without which the project could not be completed.

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ABSTRACT

Quadrotors are currently one of the platforms under greater development in the academic world, because of their great mobility but also the potential to develop unmanned aircrafts capable of hovering. This project's goal was to build a small-scale aircraft from the fusion of the quadrotor and tiltrotor concepts, enabling it to move in all six degrees of freedom with the advantage of maintaining its central core levelled, regardless of its movement and speed, which also allows a reduction in drag by optimizing the surface facing the airflow. This possibility results from adding a tilting movement in two opposed rotors in two directions, other than their rotation. A few alternatives to the tilting rotors concept were explored, and the remaining components of the aircraft were fully explained. Since this is an original aircraft concept, all its motion possibilities were fully determined. An optimum rotor was designed for the aircraft and all the components needed for its construction and implementation were evaluated, selected or designed and constructed. The construction was done in laminated composites. Finally, analysis of servo's operation, flight performance and aerodynamic drag were conducted. This thesis contributed to the creation of this innovative platform for future works, especially control platforms, in the context of quadrotors with rotor tilting ability.

Keywords: Quadrotor, Tilting rotors, Laminated composites, Optimum rotor, QTR1

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CHAPTER 1: INTRODUCTION

1.1 Quadrotors

Quadcopter otherwise known as the quadrotor is the next generation of aviation devices having greater dynamic stability than the helicopters, Quadrotors are underactuated robots.. They are predominantly used in different areas like civilian purposes such as agriculture, logistics, military exercises, fire sensing and other important areas dealing with complexities such a weight and space constraints. This paper is focused on the dynamic stability and the design of quadcopter. It addresses all the aspects of quadcopter ranging from mechanical design, aerodynamics, materials to be used, applications to the electronics used, The aim of this project is to optimize the quadrotor for Agriculture purposes.

1.1.1.Tiltrotor

The tiltrotor came from the need of combining helicopter properties, such as VTOL, hover and high manoeuvrability, with the abilities of airplanes, long range, lower consumption and heavier payloads, and so is generally classified as a tiltrotor an aircraft that has a pair (or more) of its rotors mounted on rotating surfaces (shafts, nacelles). This way the rotor can be responsible solely for the forward thrust, like in a regular plane, when it is parallel to the wing, but can also contribute solely to the lifting motion,like an helicopter, when it is perpendicular to the wing. The tiltrotor aircrafts are generally capable of VTOL or at least STOL (short take-off and landing) with an in-between rotor angle.

1.2. Historical Overview

In the first years of the twentieth century, the goal of every aeronautical inventor was to lift a person from the ground with a heavier than air apparatus, and remain the maximum time possible airborne. According to Leishman [1] and as presented in section 1.1.1 the first quadrotor ever envisioned was the Gyroplane (figure 1.3). This pioneer quadrotor had rotors of 8:1 metres in diameter, each one consisting of four light fabric covered biplane-type blades, giving a total of thirty two separate lifting surfaces. The Gyroplane made a brief and low flight (reportedly 1:5 metres above ground), which was most certainly achieved by the ”ground effect”. A 578kg aircraft with its rotor design and the rudimentary technology available would need at least 50hp delivered, which was the limit of Gyroplane’s combustion engine [1]. Leishman also states that this result, due to the lack of controllability available, was assured ”by the assistance of several men, one at each corner of the cross-like structure, stabilizing and perhaps even lifting the machine”. Curiously a team from the University of Maryland, to compete for the Sykorsky prize1, built and flew what they called ”Gamera”[2], a human powered quadrotor, with a design inspired by, and similar to the Gyroplane. The first flight was attempted on May 12th, 2011 and it was a success.

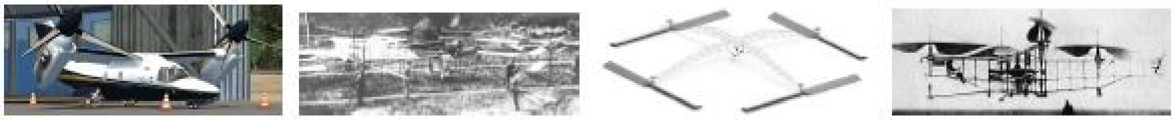


Figure 1.2: Wilco’s tiltrotor concept | Figure 1.3: Bréguet’s 1907 Gyroplane [1] | Figure 1.4: Maryland Univ. 2011 Gamera [2] | Figure 1.5: Oehmichen 2 [3]

Figure 0.1.1 Evolution of UAV

In 1920 Etienne Oehmichen, a French engineer and helicopter designer, created what became the first quadrotor able to perform a controlled and stable flight, the Oehmichen 2 [3]. With more than a thousand test flights completed, had a 1Km range, an autonomy of more than seven minutes, and could hover at about three metres above the ground. The Oehmichen 2, figure 1.5, had a cruciform steel-tube frame, and a rotor at the end of each arm, these rotors and a fifth centred, above the pilot, all of them on the horizontal plane were responsible for the stabilization and lifting of the aircraft. The Oehmichen 2 also had three smaller propellers for translational purposes, a frontal propeller for steering, much like the tail rotor of a helicopter, and two more propellers for forward propulsion, similar to a plane.
All this complexity in design made the quadrotor perfectly stable horizontally but still capable of manoeuvring with a considerable higher freedom than any machine of its time. Despite the success, Oehmichen was not totally pleased with his creation, due to the very low altitude it could reach, mostly due to the engine’s low capacities at he

time, rendering the ground effect as a major contributor for the lifting of the quadrotor.

About the same time Dr. George de Bothezat and Ivan Jerome sponsored by the Unites States Army Air Service, developed the ”de Bothezat” or ”Flying Octopus” (figure 1.6) whose first flight occurred in 1922. The ”de Bothezat” had four six-bladed rotors with 8:1 metres of diameter in a X-shaped, 20 metres structure and was capable of lifting up to five people at a maximum altitude of 5 metres. The X-shape differs from the regular quadrotor structure because the motors’ arms are not 90o apart [4]. Despite the complements by Thomas Edison who called the de Bothezat ”the first successful helicopter”, a favourable wind was necessary to achieve forwards flight and with the addition of its unresponsiveness, complexity of controls for the pilot and lack of power, the project was cancelled in 1924 [21]. It was not until 1930 that a significant fully controlled, without ground effect lifting bonus, hovering

flight was achieved, by Corradino d’Ascanio’s coaxial helicopter and quadrotors were forgotten until the late 1950’s due to major advancements in uni-axial helicopters. Meanwhile George Lehberger in May 1930 registered the first patent of a tiltrotor, but the concept was only developed in 1942 by Focke- Achgelis although a final model of that exact patent was never built.

1.3. Precision Agriculture

Goal of precision agriculture is to combine technology with agriculture to increase outcomes in agriculture, through database management of input variables and operation conditions, this data can be used for various reasons such as forecasting, inventory managements.

Figure 1.0.2 Smart Farming

In precision Agriculture we optimize the bests of Economics, Environmental data, Management strategies and technological advancements.

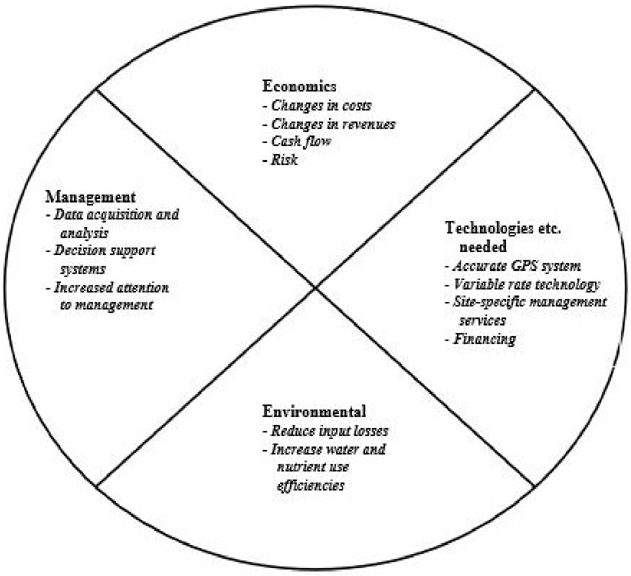


Fig 1.7 Economic, Management, Technological and Environmental Wings of Smart Farming

Farmers have already begun employing some high tech farming techniques and technologies in order to improve the efficiency of their day-to-day work. For example, sensors placed in fields allow farmers to obtain detailed maps of both the topography and resources in the area, as well as variables such as acidity and temperature of the soil. They can also access climate forecasts to predict weather patterns in the coming days and weeks.

Farmers can use their smartphones to remotely monitor their equipment, crops, and livestock, as well as obtain stats on their livestock feeding and produce. They can even use this technology to run statistical predictions for their crops and livestock.

And drones have become an invaluable tool for farmers to survey their lands and generate crop data.

As a concrete example, John Deere (one of the biggest names in farming equipment) has begun connecting its tractors to the Internet and has created a method to display data about farmers' crop yields. Similar to smart cars, the company is pioneering self-driving tractors, which would free up farmers to perform other tasks and further increase efficiency.

All of these techniques help make up precision farming or precision agriculture, the process of using satellite imagery and other technology (such as sensors) to observe and record data with the goal of improving production output while minimizing cost and preserving resources.

The farming industry will become arguably more important than ever before in the next few decades.

The world will need to produce 70% more food in 2050 than it did in 2006 in order to feed the growing population of the Earth, according to the UN Food and Agriculture Organization. To meet this demand, farmers and agricultural companies are turning to the Internet of Things for analytics and greater production capabilities.

Technological innovation in farming is nothing new. Handheld tools were the standards hundreds of years ago, and then the Industrial Revolution brought about the cotton gin. The 1800s brought about grain elevators, chemical fertilizers, and the first gas-powered tractor. Fast forward to the late 1900s, when farmers start using satellites to plan their work.

1.4. Objective and Requisites

In every quadrotor project there are two major aspects to be accounted for, the platform project and the aircraft's control. In this thesis only the platform project will be materialized, laying the foundations for 9 the implementation of a control via a correct and applicable conceptualized motion, through rotor tilting, and never forgetting the rotor's torque.

As said previously, the goal of this thesis is to improve Pedro's concept when possible, and build a quadrotor with tilting movements in two directions in a pair of opposing rotors. A structural analysis should be conducted and the design of an optimum rotor should be achieved. Finally a full determination of the possible movements of the aircraft shall be completed. The quadrotor itself, the QTR1, should be built with the following considerations, in accordance with Pedro's [18] and Raposo's [19] works:

1.5. Motivation

In a society where time is of the utmost relevance, mobility is the greatest asset anyone can desire. In overpopulated cities, even the shortest distances can become problematic. That is where airborne vehicles are at the vanguard, especially helicopters, which in situations of emergency are of most importance, either to save a life transporting a patient swiftly to a nearby hospital or even aiding in a fire-fight.

Quadrotors can also play a very relevant role, because such as an helicopter, it has the ability to fly over any obstacle but it can also hover and land in a wide variety of locations, thus gaining a major advantage over fixed wing aircrafts. Moreover a quadrotor in relation to a helicopter adds some major advantages,

considering the same hypothetical dimensionality:

- Absence of tail rotor, hence making it more energy efficient, instead of the usual helicopter's tail yaw control;

- Division of the propelling mechanisms, from one to four, this way making the quadrotor safer in case of a malfunction in one of the motors, and in case of accident. The division also simplifies the mechanical complexity, enabling the absence of gearing between motors and rotors;
- Finally, and in accordance with the above arguments, a payload increase can be achieved.

This innovative rotor tilting concept in comparison with a standard quadrotor, by the substitution of two normal rotors for two tilting ones, adds the advantage of maintaining a payload totally stable in its interior, perpendicular to gravity, and independent of its motion or velocity, and thus contributing to a drag reduction, because in all translations the surface facing the airflow does not change, while for standard quadrotors, its velocity is proportional to the roll or pitch angle of all the quadrotor. Respecting all the topics cited above a design similar to figure 1.24 is achieved, in which a designer's concept of a quadrotor with two tilting rotors and capacity for an inboard pilot is illustrated. The small wings under the fixed rotors were designed so the rotors could retract into them for cruise flight. Such an apparatus could be a major asset aiding emergency crews, providing all the purposes of today's helicopters, plus, thanks to the tilting mechanism of two of its rotors, enabling total stability of its payload, reducing the flight drag and even allowing greater payloads through the existence of four motors. All these advantages of the quadrotors regarding regular helicopters could not come without some drawbacks, such as some weight penalty, which can be minimized by more energy efficient sources than the ones presently available, and lighter and stronger materials. Although this pilotable size aircraft would be an interesting new face in the aviation market, that goal is quite far-fetched, and a prototype should be created as a proof-of-concept. Since the ALIV is external to the IST, the main goal of this thesis is to design and build a prototype of this innovative concept, as well as fully define its motion and design an optimum rotor for the constructed aircraft, the QTR1.

1.6. Thesis Structure

In this chapter the key concepts used for this project, namely the quadrotor and tiltrotor are introduced. An historical overview and a state-of-the-art review of these concepts are conducted and the previous versions of the QTR1's concept, to be fully designed and constructed, are described. Lastly this chapter enlightens the motivation, objectives and requisites for the QTR1. Chapter 2 is focused on the preliminary design of the QTR1, its components maximum dimensions as well as their initially envisioned shapes are explained. A few swivel arm alternatives are introduced and a full motion determination is conducted with all possible movements of the QTR1 are fully explained. Chapter 3 is dedicated to the creation of an optimum rotor for the QTR1. The choice of its aerofoil and all the remaining crucial geometric or operational variables are acquired, using the blade element momentum theory and a genetic algorithm solver, with the intention of building the virtual three-dimensional model in a rapid prototyping process.

All QTR1 components that do not demand a precise design, or are very hard, or almost impossible to create, such as electronics, motors, and servos are selected in chapter 4, with a thorough and concise selection process for every component.

In chapter 5 all original designed components, and respective casts are depicted, and some dimensional decisions are sustained by a finite element method analysis.

The QTR1 constructed models are evaluated and a performance analysis to the forward flight and climbing motion are executed in chapter 6. The servo's maximum torque and the drag of both alternatives is also studied to determine which arm alternative is the most suited to accomplish the design goals more efficiently. Also the drag analysis will study the gains of adding a cover to the QTR1's central area.

The conclusions and a future work section close this thesis in chapter 7.

CHAPTER 2: LITERATURE REVIEW

2.1. Literature of Quadrotor

A.V. Javir (2015) [1] In this paper safety of the quadrotor is discussed, safe design of the quadrotor is done by designing a quadrotor model on a CAD software and doing its analysis on Ansys 15.0 Workbench, the thrust generated by the propellers to lift the system and its effect on the surrounding and the effect of vibration generated on the system itself.

Ahmad Khushairy Makhtar (2012) [2] This paper discusses the various different configurations of the quadcopter and provides a basis to chose a quadrotor model over other various model such as fixed wing type model. The pros mentioned in the paper are greater flight stability and VTOL feature. Addition to that its ability to hover closer to specified targets. Sometime however hovering is unstable, making the navigation difficult and use for precision usage. The purpose of this research was to fix this hover stability issue and fix the control system, but fully customisable to suit its users' needs. The results of the hardware implementation show that the quadcopter has a stable hover with an error of ±2 cm for a total flight time of 5 minutes with a total implementation cost of USD 24.

Hardik Modh (2014) [3] This paper takes the quadrotor from the engineering perspective and the problems associated with them in whole and also the the weight reduction of the complete system is the target. Our main goal is to design and fabricate a Quadrotor which can be used for various application in market, defense, commercial and infrastructure applications like Traffic obverse and control, disaster management operation, weather and height estimation, concourse management, Locating forest fire or frost conditions in farmlands, Weather forecasting, post natural disaster, Object identification and Reconnaissance. With the help of our project guides, we have the resources and technical knowledge to successfully complete this project. We chose the UAV Quadrotor for project because of its flexibility, high learning opportunity and potential of future research. The project tries to beyond the conventional ways of how we use quadrotors today, how we can incorporate it with daily usage, making it more robust, reliable and user friendly. This project will be definitely useful to implement new function of high weight lifting in the account of UAVs.

PRNewswire (Feb 1, 2010) [4]

Teal Group analysts already cover the UAV market in their ***World Missiles and UAV Briefing,*** which examines the UAV market on a program-by-program basis," said Zaloga. "The sector study examines the UAV market from a complementary perspective, namely national requirements, and includes both a comprehensive analysis of UAV system payloads and key UAV manufacturers. UAV market "continuing as one of the hottest areas of growth for defense and aerospace companies," said Philip Finnegan, third author of the new Teal Group UAV study. The new study will reflect the rapid growth of interest in the UAV business by increasing the number of companies covered to almost 30 U.S., European and Israeli companies, and reflect the fundamental reshaping of the industrial environment.

Paul Pounds, Robert Mahony (2005) [5]

A successful design must incorporate considerations including airfoil performance, ideal taper, blade stiffness, manufacturability and sensitivity to variation. It is possible to test a specified blade geometry in the simulator to determine steady-state thrust and speed at given conditions. A simple search algorithm can identify the optimal rotor geometry for an expected flight envelope. This process was used to develop blades for the ANU’s X-4 Flyer. The actual blades performed better than predicted and are each capable of lifting approximately 1.5 kg of weight. Efficient, small-scale fixed-pitch rotor blades are essential for miniature rotorcraft. Extremely thin blade sections are required for highly efficient rotor performance that leads to acceptable mission endurance. Such rotor blades are difficult to manufacture from sufficiently rigid material to avoid significant torsional deformation in operating conditions. In practice, it is necessary to trade-off manufacturing simplicity and mechanical rigidity of a blade design against aerodynamic performance. This paper presents a design methodology for this problem, based on development of a simulator for steady-state rotor performance along with a search algorithm to find the ideal taper and twist geometry for a specified motor torque. The approach is demonstrated on the design of rotors for a small scale quad-rotor unmanned aerial vehicle under development at the Australian National University. Experimental thrust tests indicate good correspondence with theoretical predications.

2.2. Literature Review of Precision Agriculture

Amir Abbas Bakhtiari (2013) [5] Precision farming is a data-based management and a way of agricultural production, which takes into account the in-field variability. Precision agricultural technologies, such as Global Positioning Systems,Geographic Information Systems, remote sensing, yield monitors, mapping, and guidance systems for variable rate application, made it possible to manage within-field variation on large scales. The objectives of this perusal are to collect information about precision farming technology and its opportunities, challenge and difficulty. It can be concluded by results of the study that there numerous opportunities and problems in adopting the precision farming across the world specially in south-asia which is mainly agriculture dependent and yield when compared to western world is low. Different mode of precisions can be used in the different parts of the world depending on the creativity of users.

NITI Ayog, Government of India [6] This paper aims on discussing important set of policy issues and challenges faced by Indian Agriculture and to come up with total solutions to bring about second Green Revolution and this time not concentrated to just some part of the name but rather to be pan India and maintain that levels of growth, maitaing the growth is also challenge. Five key issues are determined: measures necessary to raise productivity, policies ensuring remunerative prices for farmers, reforms necessary in the area of land leasing and titles, a mechanism to bring quick relief to farmers hit by natural disasters, and initiatives necessary to spread Green Revolution to eastern states. While measures that have been outlined are essential for rejuvenation of agriculture as well as ensuring a decent life for farmers, we must not lose sight of the fact that relief to farmers will remain incomplete without the creation of job opportunities for them in non-agricultural sectors. With industry and services able to grow much faster than agriculture—the fastest that agriculture has grown over a continuous ten-year period in the post independence era is 4.7% during the 1980s—the share of agriculture in the GDP will continue to decline. Already, this share is down to approximately 15% while it supports 49% of the workforce. In order that today's farmer families can share in the faster growth occurring in industry and services, it is essential that some of them be able to find good jobs in these sectors. As some of the farm families move out of agriculture, the opportunities for consolidating and enlarging land holdings will open up as well. In turn, this will allow greater use of modern machinery and farm techniques allowing productivity and wages to rise rapidly in agriculture as well. The following offers a summary of policy recommendation.

ALEX McBRATNEY (2015) [7] We have to be careful that we do not get stuck in a limited paradigm, such as zone management. Different kind of aim should be there for different kind of countries, developing or developed or based on there requirements, there should be no hard and fast rule for making a quadrotor . Challenges or conflicts in designing as per the requirements should be noted and resolved .Concerted and co-ordinated research effort is needed in the following six areas.

(1) Appropriate criteria for the economic assessment of PA.
(2) Recognition and quantification of temporal variation.
(3) Whole-farm focus.
(4) Crop quality assessment method
(5) Product tracking and quality assurance.

(6) Environmental auditing.

Amy T. Winstead and Shannon H. Norwood [8]

Evidence from the 2009 Alabama Precision Ag and Field Crops Conference indicated that sequential adoption of precision agriculture technologies exist, especially regarding yield monitors and GPS guidance. It was clear that precision agriculture technologies have been more readily adopted by farms with larger acreage rather than small-acre farms. It was also clear that users of precision agriculture technologies rely upon the university/Extension system for information.The perception of land value as a function of variable or uniform application indicates one incentive to adopt precision agriculture

1. **Mark W. Mueller et al. (2014) [5]** Here the analysis of quadrotor is done under a condition that each propeller gets out of service respectively. This paper has sequentially tried to establish the modalities/capabilities of the quadrotor in terms of its height, position, time of flight etc with limited no of propeller in operation, where one, two and three propellers get down and out. . The stability is analysed using the deviation or the tilt in the primary axis with respect to the stable position control axis, along with the changes in altitude are used to design the quadrocopter with proper validiation from experimental data.
2. **S. M. Mahbobur Rahman et al. (2014)** [6] In this paper study of fluid flow characteristics for the flow over a propeller used in vertical takeoff and landing (VTOL) radio controlled (RC) aircrafts. Simulation investigation has been conducted through SolidWorks flow simulation using a propeller model. Design can be modified
3. **Shlok Agarwal et al. (2014) [7]** In this paper structural design and manufacturing of twinrotor AVs has been detailed down. Individual component parts have been thoroughly describe and studied which would help in development of trirotor type unmanned aerial vehicle. Here the cost and dimension constraints are the main design feature that would would provide for practical applications. Thrust vector is directly explained and illustrated .

On the basis of rolling pitching and yawing a stable rotor design and propeller orientation has been proposed for the trirotor system.

4. **Mr. Kalpesh N. Shah et al. (2014) [8]** In thispaper payload capacity of UAVs is the area of research. Additional payloads on the accounts of design improvement leads to more functionality in a UAV. In order to do such, different basic design structures of UAVs were compared to developed enhanced payload capacities and choose a quadrotor. On rough estimate a quadrotor has a pay load capacity around 4 kg which gives it additional features for military and other applications. Calculation of aerodynamic drag-lift forces has been done. The stresses generated in the body of quadrotor is not more than 22.5 MPa in "Box" sectional chassis and 22.2 MPa in "C" Sectional chassis as per the practical testing. To validate these results, the stress analysis of two types of body of quadrotor ("Box" and "C" section) is carried out in ANSYS static structural solver. As per the Static Structural solver the stress generated are 15.4 MPa and 16.97 MPa in "Box" and "C" sectional chassis respectively.
5. **S. Subhas et al. (2012) [9]** The paper predominantly focuses on CFD analysis of the propeller, forsay ship propeller is used here for CFD. Cavitation and fluid dynamics solution are the parameter are the under consideration. Fluent solution have been implemented here such that the local pressure reduces below surrounding pressure in order to simulate cavitation result. The CFD result are used to establish the design criteria only after experimental validation of the result. The optimization of vibration in flow domain and burrs is done using the above analysis. Varriant boundary conditions, fluid computational domain and grid refinement is considered for improvement in mesh generation methods.
6. **John B. Brandt et al. (2011) [10]** In this paper a full scale research on propeller has been done which has earlier been done for aircraft but with growing needs of UAVs, it has highly become imperative to perform such analysis on it too. UAVs use propeller that operate under conditions of low Reynolds number ranging from 5000 to 100000 based on the propeller chord at 75% propeller blade station. Experiments were done at university of Illinios to evaluate the efficiency of propeller under these conditions. 9 to 11 inches

was the diameter range for set of 79 propellers under the test. In test conditions at constant rpm. of propeller varied velocities of wind tunnel were used to sweep over a vast range of advanced ratios until a zero thrust condition was reached i.e. windmill state. To study the effect of variable low Reynolds number over the propeller , a range of 1500 to 7500 rpm of propeller revolution, depending upon the nature of propeller was the velocity set used. The results of efficiency varied from 0.68 for best condition to 0.28 under worst possible scenario, implicated that propeller design has a huge impact over the aircraft and UAVs operations.

7. **W.Shawn Westmoreland et al. (2008) [11]** In this paper propeller modelling using CFD is done to simulate fluid flow condition over it. Research with the support NLOS-T (Non Line Of Sight Transportation) is published here. The NLOS-T is a conceptual vehicle that will be canister launched, deploy wings and control surface, and then fly to a destination within approximately 15-20 minute of the launch point. The scientific investigation was undertaken over the propeller i.e. spinning geometry of UAV, excluding the rest of air frame structure.
8. **Dr K.C. Wong et al. (2006) [12]** This paper includes the instrumentation of off-the-shelf Remote-Controlled flight platforms, the design development and operation of flight research platforms, innovative airframe concepts, of Micro Air Vehicles (MAVs), and exploring commercial applications for UAV.

9. **Bruno Herisse et al. (1998) [13]** In this paper a controller of nonlinear nature to control flight and touchdown operations of a vertical take-off and landing unmanned aerial vehicle is presented. The VTOL is a rigid body equipped with only a camera and IMU circuit which moves over textured flat plane. Stability of hovering flight and automatic landing of the unmanned aerial vehicle using optical flow feedback system is achieved. Results shows that the proposed control strategy is a successful one.
10. **AbdellahMokhtari et al. (2000) [14]** In this paper, a nonlinear quadrotor unmanned aerial vehicle is combined with a feedback linearised controller. The most unfavorable case of control is analysed by introducing Actuator saturation and by constrain on state output. Parameter uncertainities and

external disturbances causes performance issues of a controller which is shown through a simulation study. The results shows that the system becomes robust depending upon the selection of weighted functions.

11. **Peter G. Ifju et al. () []** This research shows the effects of windy environment and unsteady aerodynamics over the micro air vehicle. The introduction of flexible wing on this vehicle improves its flight stability and durability and its performance in adverse weather conditions. The flexible wing has a operating range wingspan of 18 inches to 5 inches. In addition with the concept of flexible wing, aerodynamic assessment, and flight data analysis, fabrication method are also shown in this research.
12. **T. A. Maitre et al. (1991) []** Circulation around **liftin**g body is modelled through a non linear function in this paper. The circulation potential is well defined inside the body and evaluation is made for the flow over the body. This method is well suited for the flow analysis over the propeller of UAVs which are consider to be extremely thin. This method is applied over non cavitating fluid flow condition in a marine propeller. Here the researcher deeply tried to solve the problem pertaining to Joukowski condition, problem of propeller mesh, wake region analysis and the influence of wake region over the hub is numerically analysed.
13. **Jonathon Bell et al. () []** This project has undertaken the task of designing and constructing a test rig for the purpose of experimental analysis of SUAVs coaxial rotor system. The focus is led on the importance to highlight aero mechanical components and variable that dictate the co-axial flight performance with the aim of optimizing the propulsion system to be used for HALO coaxial SUAVs manufactured by Middlesex university. The chief contribution of the paper is to design and optimize the co-axial configuration with respect to motor and propeller variation. Inter rotor spacing has been detailed out with the help of H/D ratio that is in between 0,41 to 0.65.

14. **Pierre Jean Bristeaue et al. () []** Here different models of quadrotor UAV have been studied. Aerodynamic effects of the propellers and their interaction with rigid body motion of the UAV has been modelled. The main assumptions are the twisting of the propellers in such a way that the local angle of attack is

constant along the blades in stationary flight and, secondly the local induced velocity is invariable along the blade, these conditions are used to optimize the hovering rotor and hence conclude that the dynamics of the UAV is prominently dependent on the flexibility propeller design (location of centre of gravity) thereby playing important role in designing close loop controller**.**

15. **S. NorouziGhazbi et al. (2016) [3]**This paper reviews and gives an overview of various works done on quadrotor with dynamic modelling and control features

Chapter 3: Off-the Shelf Components and Motion Control.

3.1. Propulsion Components

The propulsion system is the sole responsible for the lift of the QTR1, it is composed by a motor, a rotor and its necessary accessory components. As an example for electric brushless motors, an Electronic Speed Control (ESC) is required for every motor. The choice of rotor was already performed in chapter 3, however another rotor option will be necessary because the rapid prototyping process envisioned for the optimum rotor did not materialized, and so a four rotors set, two puller and two pushers should be considered as an alternative solution. For the motor selection, first it is necessary to decide what technology shall be selected, electric or petrol, and the choice is most obvious, considering the aim of the project. Petrol engines are usually high power engines, for heavy lift and short flights, and another problem is the mass of the fuel they must carry, and so the cheaper, cleaner and lighter electric alternative is the better option. In the electric 43 market, two new option arise, the brushed motors and the brushless ones. In general, brush-type direct current (DC) motors are commonly used when low system cost is a priority, while brushless motors are used to fulfil requirements such as maintenance-free operation, high speeds, and operation in explosive environments where sparking could be hazardous. On the other hand a brushless DC motor's main disadvantage is higher cost, which arises from two issues. First, brushless DC motors require complex electronic speed control to run. Brushed DC motors can be regulated by a comparatively simple controller, such as a rheostat (variable resistor). However, this reduces efficiency because power is wasted in the rheostat and again the choice becomes simple and the brushless alternative will be the selected one, like other working examples suggest [18, 11, 13, 15, 39, 40]. So three components need to be selected for the QTR1 propulsion system, a brushless motor, a compatible ESC and an inferior to 279.4mm (11in) rotor, available in the market in both pusher and puller configurations, for the positive and negative rotations needed for the torque annulment. For the motor selection the market provides a wide variety of choices available. The best course of action is to resort to existing functioning models for inspiration and the best alternative for inspiration is the open source quadrotor derivative, the Arducopter [15] that has similar properties, such as mass and span, to the QTR1's preliminary design. Although useful, using motors from other quadrotors blindly is absurd, and testing several motors and choose the one with best results cannot be considered here due to the budget ceiling, however FlyBrushless.com [41] provides a source for comparing different motor models. The motors for the QTR1 must be capable to provide the rotor with a thrust 4N for hovering, however the QTR1 must be capable of much more than that and so 8N to be able to account manoeuvring and incongruences from the queried results. Three 11.1V motors were the best options from all the other models analysed, and their properties are in table 4.1. In the table are shown the most important aspects of the brushless motors, such as the motor velocity constant (Kv) measured in rpm/V and displays the maximum angular velocity (Ω) the motor is capable of, e.g. an 11.1V motor with a Kv = 1000rpm/V as a maximum Ω = 11000rpm.

	Turnigy 2217 16turn 1050kv 23A Outrunner 	Hacker Style Brushless Outrunner 20-22L 	BP A2217-9 Brushless Outrunner Motor 
$K_v[rpm/V]$	1050	924	950
$i_{max}[A]$	18	17	18
Weight$[g]$	71	56	73.4
Dimensions (diameter×height)$[mm]$	36×28	32×28	34×27.8

Table 3-1 Motor Properties

Brushless DC motors also termed as BLDC motors are used in Quadcopters. These motors consist of a permanent magnet which rotates around a fixed armature. They offer several advantages over brushed DC motors which include more torque per weight, reduced noise, increased reliability, longer life time and increased efficiency.

Figure 3.0.3 Three Phase D.C. Motor

3.1.1. Motor calculations: The motors should be selected in such a way that it follows following thrust to weight relationship.

Ratio=Thrust / weight =ma / mg

Thus, vertical takeoff and vertical landing (VTOL) is possible only when,(a / g) > 1 or in other words, The total thrust to total weight ratio should be greater than 1 so that the quadcopter can accelerate in the upward direction. In this case, we assumed that

Total Thrust = 2*(Total Weight of the Quadrotor)

Therefore, Thrust Provided by Each Motors = Total Thrust/4

3.1.2. **Electronic Speed Controller**: Low voltage and current is provided by the microcontroller and this is not sufficient to drive motors. To drive the motors at specific speed, we require a motor driver to supply specific amount of voltage and current required by them and this work is done by Electronic speed controller.

3.1.3. **Propeller:** Propeller is a type of fan that converts rotational motion into thrust. Generally, propellers are classified on the basis of their diameter and pitch and are represented in terms of product of diameter and pitch. For e.g. 10 *4 449 × 255 7, 10*4.5, etc. The diameter of propeller indicates the virtual circle that the prop generates whereas the pitch indicates the amount of travel per single rotation of propeller. In order to counter motor torque, Quadcopter require two clockwise and two anticlockwise rotating propellers. All the propellers used in quadcopter should have same diameter and pitch. Many motors come with propeller specifications so as to have optimum power consumption. If propeller specifications are not mentioned on motor then we have to use trial and error method.

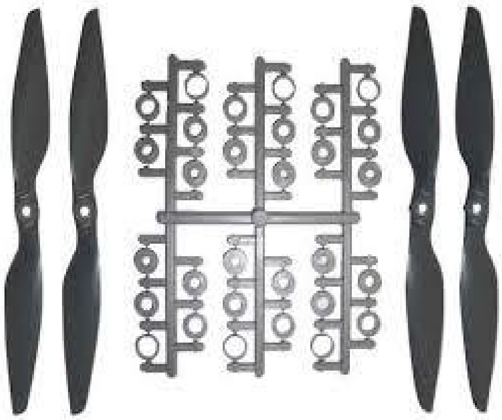


Figure 4.0.4 Propeller

3.1.4. Battery:

3.1.5. Flight Controller: To maintain balance, the quadcopter should continuously take measurements from the sensors and make adjustment accordingly to the speed of the rotors to keep the body level. Flying capabilities and cost are the two main factors to be considered while selecting flight controller. Flying capabilities consists of following basic factors-

- ***Gyro stabilization***: It is the ability to keep the copter stable and level under the pilot control.
- ***Self-leveling***: It is the ability to automatically adjust itself during any orientation so that the copter stays level.
- ***Altitude hold***: It is the ability to hover at a certain distance from ground without having to manually adjust the throttle.

3.2. Transmitter and Receiver

The Transmitter (Tx) and Receiver (Rx) system allows the Quadcopter to be remotely controlled through a wireless signal. The aircraft controls would typically include throttle, pitch, roll, yaw, and mode settings.2.4GHz TX and RX system is used for its better performance, because it will not experience signal conflicts from other radio frequency (RF) controllers. Receiver used is having 6C 2.4 Ghz system which perfectly bonded with the 2.4Ghz transmitter.

3.3. Physical Principles

Quadcopter is lifted up high in the air with the help of propellers. These propellers convert rotational motion into thrust and this can be explained with the help of Bernoulli's principle and Newton's third law. Every action has equal and opposite reaction.

i. **Bernoulli's Principle**: Bernoulli's principle states that for an inviscid flow of no conducting fluid, and increase in the speed of fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.

ii. **Newtons Second Law**: An air foil is the shape of the wing or blade as seen in the cross section, when moved through a fluid produces an aerodynamic force. Due to airfoil shape of the propeller, the air moves faster over the top than under the bottom which results in a greater pressure difference below the airfoil than above it. This pressure difference in turn produces the required thrust.

Chapter 4: Motion Control

4.1. Motion Control

In a standard quadrotor, the control is achieved by varying symmetrically the thrust of opposite rotors, and every translation is obtained by roll or pitch angles. In the QTR1 configuration that is impossible and a more complex operation needs to be conducted and will be explained next. As previously reported, in the first version of the ALIV two separate control alternatives were attempted, neither of them fully functional in the real model, and thus this section serves as control guidelines for future implementation. It is important to emphasize that the main problem with both Raposo's [19] and Costa's [23] motion alternatives, was that neither of them really considered the rotor's torque effects due to the tilting of the motor-rotor couple, and thus unexpected adverse roll and pitch moments were created when that same tilt was conducted.

The control alternative chosen as a guideline is Severino's, because in longitudinal or lateral motion, the opposite rotors' symmetric rotation cancels the motor-rotor torque in all axis, and the main objective of any aircraft is to move. Of course the easy equilibrium that can be achieved from standard quadrotors decoupled motions is lost, and an alternative for rebalancing the QTR1 in the case of a gust or some unexpected rolling or pitching movement will be explained next, as well as the lateral or longitudinal motions, the yaw movement and the climb and descent motions. In Severino's alternative, rotors one and four had a negative rotation while rotors two and three rotated positively, in the ABC frame, where the z-axis points down and the motions directions described are in accordance with that fact. Rotors (and motors) two and four are the ones able to tilt. It is important to introduce a few notations in the ALIV for a better understanding of the motions themselves. Referring to figure 1.21 and respecting the numbering of the rotors, $\Theta 2$ and $\Theta 4$ will be the pitch of the rotors through

action of the first-servo. They are responsible for the forward motion, with the pitch of the swivel arm, positive according to the right hand rule. The roll of the rotors, resultant form the action of the secondservo, responsible for the lateral motion, will be depicted as ϴ2 and ϴ4. All these angles equal zero when the rotor points upwards, in the hovering position, in the opposite direction of the ABC frame's z-axis, nonetheless the angle's signals always respect the ABC frame. Each rotor's torque is represented by Qi with the corresponding subscript for every rotor or motor, the rotor's thrust is represented by Ti, both torque and thrust from the rotor are proportional to the motor's power output. This leads to a total of eight independent output variables, T^1; T^2; T^3; T^4; Ω^2; Θ^2; Θ^4 and Ω^4.

4.2. Levelled motions

In all levelled motions (all translations and rotation along z) the ALIV remains parallel to the ground. The simplest levelled motion in any quadrotor is hovering, where all rotors must provide the same thrust and accordingly the same torque. Since all the motors are similar the same power is delivered from all of them equally. For a hovering scenario the total thrust must match the weight of the QTR1 and that is accomplished by the following equations:

$$\sum F_z = 0 \Rightarrow 0 = -(T_1 + T_2 + T_3 + T_4) + mg|_{T_1=T_2=T_3=T_4} \quad (2.2a)$$

$$\sum M_z = 0 \Rightarrow 0 = Q_1 + Q_2 + Q_3 + Q_4|_{Q_1=-Q_2=-Q_3=Q_4} \quad (2.2b)$$

From now on T is defined as the thrust necessary for a rotor to lift a quarter of the QTR1's weight (T = mg/4) and Q as the torque necessary to produce the supra-cited thrust. Also the moments in x and y-axis produced by T equal to T b/2 are omitted but always present.

In the following examples a simplified ALIV is shown with the direction of rotation of the rotors, and viewed from above. The axis shown respects the ABC frame's axis directions and the rotors' turning directions also respect the descriptions above, appearing the opposite because z is pointing downwards.

The alteration or maintenance of the rotors' thrust in relation to T is displayed by mathematical signs (+;- or =), and the tilting of the rotors is represented by an arrow alongside the rotor illustrating the directional extra thrust provided by the rotor's tilting.

4.3. Climb motion

After hovering, climbing is the simplest of the QTR1's possible operations. As figure 2.8 suggests, by increasing evenly all motors' power the balance of the aircraft is maintained and the increased thrust when greater than the drag force results in upwards acceleration. The climb speed will depend of the thrust increase (_T) and all these aspects are described in the following expressions:

$$\sum F_z = ma_z \Rightarrow -ma_z = -4\left(\overline{T} + \Delta T\right) + mg + D_z\big|_{T_1=\overline{T}+\Delta T=T_2=T_3=T_4} \qquad (2.3a)$$

$$\sum M_z = 0 \Rightarrow 0 = Q_1 + Q_2 + Q_3 + Q_4\big|_{Q_1=-Q_2=-Q_3=Q_4} \qquad (2.3b)$$

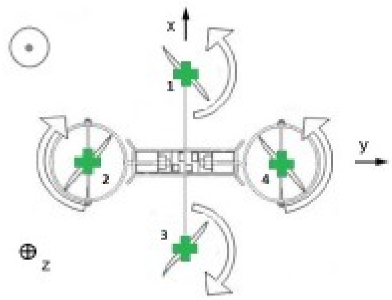


Figure 4.0.5 QTR1's Climb Motion Control

To descent it is only necessary to decrease the total thrust evenly: the higher the decrease the faster the descent. To maintain a steady climb or descent, with constant velocity, a_z must be null with $4\Delta T = Dz$ to maintain the z-axis velocity.

4.4. Forward motion

In forward levelled motion, the tilting of the rotors is responsible for the motion itself, through an increase in thrust and a pitching angle (Θ_i) of both rotors, two and four. The increase in thrust must be such that the lift (z-axis) component must remain as it was before tilting, for two reasons: to maintain the QTR1 levelled its total weight must remain equal to the lift, and secondly to maintain the torque in the z-axis null. The x-axis torque is symmetric in both tilted rotors and thus null, and the moment created through the forward thrust is symmetric for both rotors and thus cancelled. The distance between rotors (or motors), from now on is represented as l, and was defined previously as 600mm. The following equations rule the forward motion case:

$$\sum F_x = ma_x \Rightarrow ma_x = T_2 \sin\theta_2 + T_4 \sin\theta_4 - D_x|_{T_2 \sin\theta_2 = T_4 \sin\theta_4 = \Delta T, \theta_2 = \theta_4} \quad (2.4a)$$

$$\sum F_z = 0 \Rightarrow 0 = -(T_1 + T_2 \cos\theta_2 + T_3 + T_4 \cos\theta_4) + mg|_{T_1 = \overline{T} = T_2 \cos\theta_2 = T_3 = T_4 \cos\theta_4} \quad (2.4b)$$

$$\sum M_x = 0 \Rightarrow 0 = Q_2 \sin\theta_2 + Q_4 \sin\theta_4|_{Q_2 = -Q_4} \quad (2.4c)$$

$$\sum M_z = 0 \Rightarrow 0 = Q_1 + Q_2 \cos\theta_2 + Q_3 + Q_4 \cos\theta_4 + \frac{b}{2}(T_2 \sin\theta_2 - T_4 \sin\theta_4)\Big|_{Q_1 = \overline{Q} = -Q_3} \quad (2.4d)$$

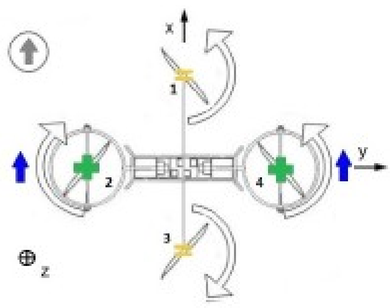


Figure 4.0.6 QTR1’s Forward Motion Control

For a forward motion, figure 2. Θ_i angles must be negative, according to the ABC frame; for a backwards motion it is only necessary to perform a positive shift in both rotors’ Θ_i. For a constant velocity with forward motion already achieved, ax must be zero, with 2T sinϴ= Dx to maintain a constant x-axis velocity.

4.5. Lateral motion

The lateral motion (figure 2.10) is almost identical to the forward one, but instead of a pitch angle in the rotors, a rolling (Θ_i) movement is necessary in the tilting rotors. The y-axis torque is symmetric in both tilted rotors and thus null. As in forward motion the increase in thrust must be such that the lift (z-axis) component must remain as it was before tilting, and the ruling equations for lateral motion are also similar to the previously shown forward motion case:

$$\sum F_y = ma_y \Rightarrow ma_y = T_2 \sin\phi_2 + T_4 \sin\phi_4 - D_y|_{T_2 \sin\phi_2 = T_4 \sin\phi_4 = \Delta T, \phi_2 = \phi_4} \quad (2.5a)$$

$$\sum F_z = 0 \Rightarrow 0 = -(T_1 + T_2\cos\phi_2 + T_3 + T_4\cos\phi_4) + mg|_{T_1 = \overline{T} = T_2\cos\phi_2 = T_3 = T_4\cos\phi_4} \quad (2.5b)$$

$$\sum M_y = 0 \Rightarrow 0 = Q_2\sin\phi_2 + Q_4\sin\phi_4|_{Q_2 = -Q_4} \quad (2.5c)$$

$$\sum M_z = 0 \Rightarrow 0 = Q_1 + Q_2\cos\phi_2 + Q_3 + Q_4\cos\phi_4|_{Q_1 = \overline{Q} = -Q_2\cos\phi_2 = -Q_3} \quad (2.5d)$$

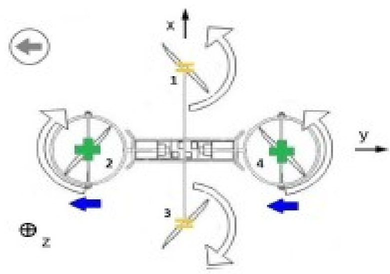


Figure 4.0.7 QTR1's Lateral Motion Control

To move left, as the figure 3 shows, the rotors' roll angles (Θ_i) must be negative, on the other hand to achieve a lateral motion to the right the roll of the moments must be positive. As for the previous examples, for a constant velocity a_y must be zero and 2T $\sin_{\emptyset}$ = Dy.

4.6. Yaw motion

The yaw motion is a little more complex than the previous motions described. In standard quadrotors the yaw motion is achieved by varying evenly and symmetrically each couple of rotors, but with these rotors' rotation configuration such a solution is impossible. So the yaw motion for the QTR1 is simply achieved through the increase of thrust in one rotor, and a pitch of that same rotor to increase the yaw speed by both alterations. This creates a slight backwards adverse motion, but the main goal is achieved nonetheless. Both yaw movements (positive and negative rotations) are shown in figure 2.11 and the 22 following equations describe the movement for a positive yaw. From now on rotational drag is considered negligible and _Ti is the increase in thrust of rotor i.

$$\sum F_x = ma_x \Rightarrow ma_x = T_4 \sin\theta_4 - D_x \tag{2.6a}$$

$$\sum F_z = 0 \Rightarrow 0 = -(T_1 + T_2 + T_3 + T_4 \cos\theta_4) + mg\big|_{T_1=T_2=T_3=T-\frac{\Delta T_4 \cos\theta_4}{3}} \tag{2.6b}$$

$$\sum M_x = 0 \Rightarrow 0 = Q_4 \sin\theta_4 - \left[T_4 \cos\theta_4 - \left(T - \frac{\Delta T_4 \cos\theta_4}{3}\right)\right]\frac{b}{2} \tag{2.6c}$$

$$\sum M_z = I_z\ddot{\psi} \Rightarrow I_z\ddot{\psi} = Q_1 + Q_2 + Q_3 + Q_4 \cos\theta_4 + T_4 \sin\theta_4 \frac{b}{2}\bigg|_{Q_1=-Q_2=-Q_3<Q_4\cos\theta_4} \tag{2.6d}$$

For small rotor pitching angles the acceleration in the x-axis is null, and thus the QTR1 remains in a stationary yaw motion. To obtain an equilibrium along the z-axis the tilted rotors increase in thrust is balanced by a decrease in the other three rotors thrust and thus maintaining the QTR1 levelled. In this case the y moments created by the lift of rotors one and three, usually T, in this case T–(ΔT4cos4)/3 is omitted because they cancel each other and that's the reason why in the ∑ Mx the expression is as shown.

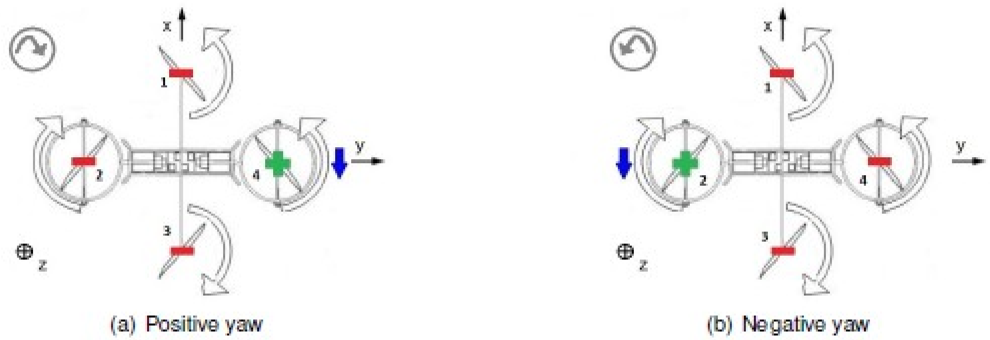


Figure 4.0.8 QTR1's Yaw Motion Control.

To rotate in the opposite direction, every alteration regarding an hovering status is mirrored (figure 4), and instead of altering rotor four thrust and roll angle, these alterations are made in rotor 2 and all the rotors thrust are decreased

4.7. Rebalancing operations

All the previous situations are necessary to complete every possible mission scenario, nonetheless they would only work if no oscillations occurred, and all components behaved as expected, but that does not happen, and so it is necessary to rebalance the QTR1 to a levelled position when it rolls or pitches in an unexpected and uncontrolled manner. In all the cases presented henceforth the NED frame will be used to fully correspond to translational motions; for rotations the ABC frame is used, and all rebalancing operations are transient and take only fractions of a second.

4.8. Roll rebalancing

For a positive roll tilt angle Ǿ of the QTR1 (meaning a negative roll rebalancing), the following equations serve as guidelines. For the rebalancing, a negative roll of the rotors is necessary (Ǿi) to cancel the lateral motion; in the following expressions _i should always be positive and so -Ǿi is used, the same applies for ϴ4. An increase in rotor four thrust is mandatory to create the roll rebalancing; to cancel the z torque created, that same rotor is pitched (negatively in the ABC frame). Finally rotors one and three need to increase their thrust to balance the QTR1's weight, and their increase must be equal, to cancel each other's torque.

$$\sum F_X = ma_X \Rightarrow ma_X = T_4 \sin\theta_4 \cos\phi_4 - D_X \tag{2.7a}$$

$$\sum F_Y = 0 \Rightarrow 0 = (T_1 + T_3)\sin\phi - T_2 \sin(\phi_2 - \phi) - T_4 \cos\theta_4 \sin(\phi_4 - \phi) \tag{2.7b}$$

$$\sum F_Z = 0 \Rightarrow 0 = -\left((T_1 + T_3)\cos\phi + T_2\cos(\phi_2 - \phi) + T_4\cos\theta_4\cos(\phi_4 - \phi)\right) + mg \tag{2.7c}$$

$$\sum M_x = I_x\ddot{\phi} \Rightarrow I_x\ddot{\phi} = Q_4\cos\phi_4\sin\theta_4 + \left[T_4\cos\theta_4\cos\phi_4 - (\overline{T} + \Delta T_2)\right]\frac{b}{2} \tag{2.7d}$$

$$\sum M_y = 0 \Rightarrow 0 = Q_2\sin\phi_2 + Q_4\cos\theta_4\sin\phi_4 \tag{2.7e}$$

$$\sum M_z = 0 \Rightarrow 0 = Q_1 + Q_2\cos\phi_2 + Q_3 + Q_4\cos\theta_4\cos\phi_4 - T_4\cos\phi_4\sin\theta_4\frac{b}{2} \tag{2.7f}$$

As for the adverse translations, for small rotor pitch angles the acceleration in the x-axis is null which results in 5 equations and 7 variables T1; T2; T3; T4; _2; _4 and _4, so to simplify the system it is defined that T2 = T and as said before with T1 = T3, the system has a total of 5 independent variables and is solvable. The second rotor's thrust is maintained and all the others are increased, the remaining variables are changed according to the speed in which the manoeuvre must be preformed, as well as the undesired initial roll angle. Figure 2.12(a) represents the scenario described above.

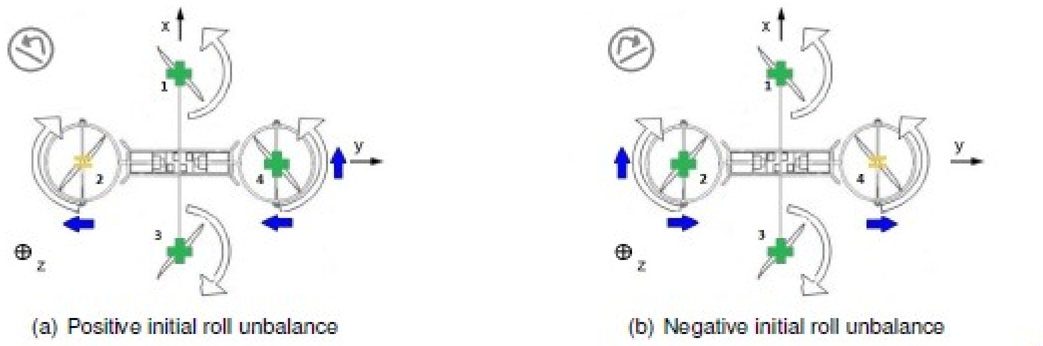


Figure 4.0.9 QTR1's Roll Rebalancing

To obtain the rebalancing from a negative initial roll angle it is just a matter of reversing the concept as figure 6(b) illustrates. Rolling the rotors in the opposite direction and this time pitching rotor two instead of rotor four in the same direction as before. Mathematically the negative initial roll is identical to the case described above and the real value of Ǿi is used. Ɵ2 is used instead of Ɵ4 and so it is just a question of switching all the 2 subscripts by 4 and vice-versa.

4.9. Pitch rebalancing

The pitch rebalancing is maybe the most complex manoeuvre of the QTR1, because all 8 output variables are used, yet the rebalancing is quite simple. Referring to figure 2.13(a), for a positive initial pitch angle, both tilting rotors are forced to move, they pitch (in the negative angle in the ABC frame) to cancel the backwards motion the unexpected roll creates and roll symmetrically to create a pitching moment and rebalance the quadrotor. The fixed arm's rotors speed (one and three) should be decreased but that would depend on the power available and that is not mandatory, their speed can be maintained, however the thrust in both rotors must remain equal. Rotors two and four should also have the same thrust between them as well as roll angle (_i), the pitch angle must be symmetric, -Ǿ2 = Ǿ4 because Ǿ4 is positive in the ABC frame in this situation. The following equations represent a positive initial pitch angle unbalance and are constructed in a way that Ɵi should always be positive, and so -Θi shall be used.

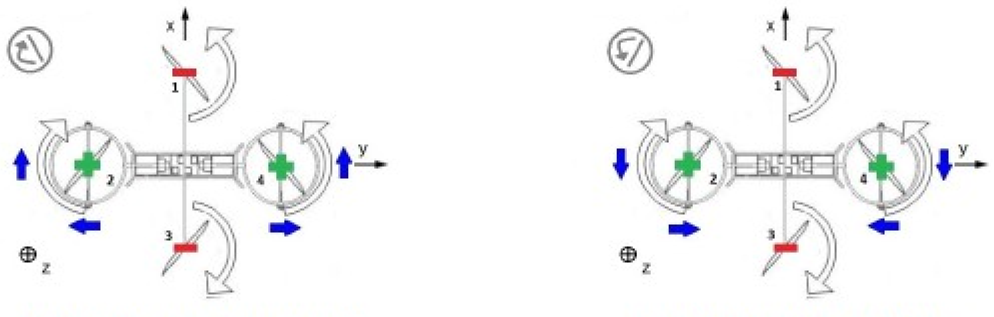
$$\sum F_X = 0 \Rightarrow 0 = (T_1 + T_3)\sin\theta - T_2\cos\phi_2\sin(\theta_2 - \theta) - T_2\cos\phi_4\sin(\theta_4 - \theta)|_{T_1=T_3, T_2=T_4} \quad (2.8a)$$

$$\sum F_Y = 0 \Rightarrow 0 = T_2\cos\theta_2\sin\phi_2 - T_4\cos\theta_4\sin\phi_4|_{\theta_2=\theta_4, -\phi_2=\phi_4} \quad (2.8b)$$

$$\sum F_Z = 0 \Rightarrow 0 = -((T_1 + T_3)\cos\theta + T_2\cos\phi_2\cos(\theta_2 - \theta) + T_4\cos\phi_4\cos(\theta_4 - \theta)) + mg \quad (2.8c)$$

$$\sum M_y = I_y\ddot{\theta} \Rightarrow I_y\ddot{\theta} = Q_2\cos\theta_2\sin\phi_2 + Q_4\cos\theta_4\sin\phi_4 \quad (2.8d)$$

$$\sum M_z = 0 \Rightarrow 0 = Q_1 + Q_2\cos\theta_2\cos\phi_2 + Q_3 + Q_4\cos\theta_4\cos\phi_4 + T_2\cos\phi_2\sin\theta_2\frac{b}{2} - T_4\cos\phi_4\sin\theta_4\frac{b}{2} \quad (2.8e)$$



(a) Positive initial pitch unbalance (b) Negative initial pitch unbalance

Figure 4.0.10 QTR1's Pitch motion control

In this case ∑Mx is omitted because all opposed thrusts and torques cancel each other, resulting in four independent variables that will be determined in relation to the initial pitch angle and the speed in which a levelled position needs to be reached. If the initial pitch angle is negative (figure 2.13(b)) it is only necessary to invert the tilting of the rotors, do an inwards roll and a backwards pitch, which mathematically is identical to equations 2.8, with a positive _i used. By making the rotors' roll angles null, it is interesting to note that the QTR1 can remain in hover with a pitch angle in a stable position, and thus with a mounted camera a wide variety of imagery is possible with the QTR1, because a rebalancing of the pitch angle or a transition to a desired pitch angle is the same operation, and then to remain in hover in that position, is just a case of making all equations in 2.8 equal zero by imposing Θ2 = Θ4 = 0 and thus the global pitch angle _ is maintained and the QTR1 maintains its position.

4.10. Combined motions

Up until now all possible motions were only shown isolated, however in a real flight situation more than one of the described manoeuvres may need to be executed at the same time, and that can be done simply by combining the wanted motions simultaneously. In the previous rebalancing subsection the autonomous QTR1's motions were described, those are the manoeuvres that the control should be responsible for, without any interference from the pilot, and should activate immediately when necessary, to rebalance the QTR1. In subsection 2.5.1 (levelled motions) the motions described were supposed to be controlled by the user, yet all of those motions are subjected to oscillations and so the control software needs to be aware of what the motion, or motions, the pilot desires and disable all other, applying the necessary compensations in case of unwanted and unexpected oscillations both for translations as for rotations.

Chapter 5: Methodology

5.1 Definition of Static Analysis

A static analysis calculates the effects of *steady* loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. A static analysis can, however, include *steady* inertia loads (such as gravity and rotational velocity), and time-varying loads that can be approximated as static equivalent loads (such as the static equivalent wind and seismic loads commonly defined in many building codes).

5.2 Loads in a Static Analysis

Static analysis is used to determine the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. *Steady* loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time. The kinds of loading that can be applied in a static analysis include:

- Externally applied forces and pressures
- Steady-state inertial forces (such as gravity or rotational velocity)
- Imposed (non-zero) displacements
- Temperatures (for thermal strain)
- Fluences (for nuclear swelling)

5.3 Linear vs. Nonlinear Static Analyses

A static analysis can be either linear or nonlinear. All types of nonlinearities are allowed- large deformations, plasticity, creep, stress stiffening, contact (gap) elements, hyperelastic elements, etc. This chapter focuses on linear static analyses, with brief references to nonlinearities.

5.4 Commands Used in a Static Analysis

You use the same set of commands to build a model and perform a static analysis that you use to do any other type of finite element analysis. Likewise, you choose similar options from the graphical user interface (GUI) to build and solve models no matter what type of analysis you are doing.

Section 2.7, "A Sample Static Analysis (Command or Batch Method)," shows you the sequence of commands you would issue (either manually or while running ANSYS as a batch job) to perform an example static analysis. Section 2.6, "A Sample Static Analysis (GUI Method)," shows you how to execute the same sample analysis using menu choices from the ANSYS GUI. (To learn how to use the commands and GUI selections for building models, read the *ANSYS Modeling and Meshing Guide*.)

For detailed, alphabetized descriptions of the ANSYS commands, see the *ANSYS Commands Reference*.

5.5 Overview of Steps in a Static Analysis

The procedure for a static analysis consists of three main steps:

1. Build the model.

2. Apply loads and obtain the solution.

3. Review the results.

5.5.1. Build the Model

To build the model, you specify the jobname and analysis title and then use the PREP7 processor to define the element types, element real constants, material properties, and the model geometry. These tasks are common to most analyses. The *ANSYS Modeling and Meshing Guide* explains them in detail.

5.5.1.1 Points to Remember

- You can use both linear and nonlinear structural elements.

Command(s):

ET

GUI:

Main Menu>Preprocessor>Element Type>Add/Edit/Delete

- Material properties can be linear or nonlinear, isotropic or orthotropic, and constant or temperature-dependent.

Command(s):

MP

GUI:

Main Menu>Preprocessor>Material Props>-Constant- Isotropic/Orthotropic

- You must define Young's modulus (EX) (or stiffness in some form).

- For inertia loads (such as gravity), you must define the data required for mass calculations, such as density (DENS).

- For thermal loads (temperatures), you must define the coefficient of thermal expansion (ALPX).

Note the following information about mesh density:

- Regions where stresses or strains are of interest require a relatively finer mesh than regions where only displacements are of interest.

- If you want to include nonlinearities, the mesh should be able to capture the effects of the nonlinearities. For example, plasticity requires a reasonable integration point density (and therefore a fine element mesh) in areas with high plastic deformation gradients.

5.5.2 Apply Loads and Obtain the Solution

Define the analysis type and options, apply loads, specify load step options, and begin the finite element solution.

5.5.2.1 Enter the ANSYS Solution Processor

Command(s):

/SOLU

GUI:

Main Menu>Solution

5.5.2.2. Define the Analysis Type and Options

Define the analysis type and analysis options. ANSYS offers these options for a static analysis:

Table 2-1 Analysis types and analysis options

Option	Command	GUI Path
New Analysis or Restart	ANTYPE	Main Menu>Solution>-Analysis Type-New Analysis
Analysis Type: Static	ANTYPE	Main Menu>Solution>-Analysis Type -New Analysis>Static
Large Deformation Effects	NLGEOM	Main Menu>Solution>Analysis Options
Stress Stiffening Effects	SSTIF	Main Menu>Solution>Analysis Options
Prestress Effects Calculation	PSTRES	Main Menu>Solution>Analysis Options
Newton-Raphson Option	NROPT	Main Menu>Solution>Analysis Options
Mass Matrix Formulation	LUMPM	Main Menu>Solution>Analysis Options
Equation Solver	EQSLV	Main Menu>Solution>Analysis Options
Fast Solution Option	EQSLV	Main Menu>Solution>Fast Sol'n Optn

Each of these options is explained in detail below.

Option: New Analysis (or Restart) [ANTYPE]

You will usually use New Analysis. Use Restart in these situations:

- If you have previously completed a static analysis, and you want to specify additional loads
- If you want to restart a failed nonlinear analysis.

Note-The files ***Jobname*.EMAT**, Jobname.ESAV, and ***Jobname*.DB** from the initial run must be available for the restart. Results will be appended to the initial results file, ***Jobname*.RST**, if it is available

Option: Analysis Type: Static [ANTYPE]

Choose static analysis type.

Option: Large Deformation Effects [NLGEOM]

Use this option if you expect large deflections (as in the case of a long, slender bar under bending) or large strains (as in a metal-forming problem). Large deflections and large strains are geometric nonlinearities and are described in Chapter 8. The default is OFF, assuming small deflections and small strains.

Option: Stress Stiffening Effects [SSTIF]

Use this option in either of the following situations:

- If, in a small deflection analysis, you expect the stresses in the structure to significantly increase or decrease its stiffness (for example, a thin circular shell under normal pressure)
- If you need stress stiffening to help convergence in a large deflection analysis.

The default is ON when **NLGEOM**, is ON and **SOLCONTROL**,is ON. Otherwise, it is OFF..

Option: Prestress Effects Calculation [PSTRES]

Use this option to perform a prestressed analysis on the same model, such as a prestressed modal analysis. The default is OFF.

Note-The stress stiffening effects and the prestress effect calculation both control the generation of the stress stiffness matrix, and therefore should not be used together in an analysis. If both are specified, the last option specified will override the previous setting.

Option: Newton-Raphson Option [NROPT]

Use this option only in a nonlinear analysis. This option specifies how often the tangent matrix is updated during solution. You can specify one of these values:

- Program-chosen (default)
- Full
- Modified
- Initial Stiffness

Option: Mass Matrix Formulation [LUMPM]

Use this option if you plan to apply inertial loads on the structure (such as gravity and spinning loads). You can specify one of these values:

- Default (depends on element type)
- Lumped Mass Approximation

Note- For a static analysis, the mass matrix formulation you use does not significantly affect the solution accuracy (assuming that the mesh is fine enough). However, if you want to do a prestressed dynamic analysis on the same model, the choice of mass matrix formulation may be important; see the appropriate dynamic analysis section for recommendations.

Option: Equation Solver [EQSLV]

Specify one of these solvers:

- Frontal solver (default for linear analysis)
- Jacobi Conjugate Gradient (JCG) solver
- JCG out-of-memory solver
- Incomplete Cholesky Conjugate Gradient (ICCG) solver
- Preconditioned Conjugate Gradient (PCG) solver

- PCG out-of-memory solver
- Sparse (SPAR) solver (default for nonlinear analysis when **SOLCONTROL** is ON)
- Iterative (auto-select; for linear static/full transient structural analyses only) (recommended)

If you choose the iterative solver, you can specify an accuracy level between 1 (fastest) and 5 (most accurate). If the model contains only PLANE2, SOLID45, SOLID92, SOLID95, SURF153, and SURF154 element types, this option will suppress the creation of ***Jobname.*EMAT** and ***Jobname.*EROT** files.

5.5.2.3. Apply Loads to the Model

Except for inertia loads, which are independent of the model, you can define loads either on the solid model (keypoints, lines, and areas) or on the finite element model (nodes and elements). You can also apply complex boundary conditions via TABLE type array parameters.

Table 2-2 summarizes the loads applicable to a static analysis.

Table 2-2 Loads applicable in a static analysis

Load Type	Category	Command Family	GUI Path
Displacement (UX, UY, UZ, ROTX, ROTY, ROTZ)	Constraints	D	Main Menu>Solution>-Loads-Apply>-Structural-Displacement
Force, Moment (FX, FY, FZ, MX, MY, MZ)	Forces	F	Main Menu>Solution>-Loads-Apply>-Structural-Force/Moment
Pressure (PRES)	Surface Loads	SF	Main Menu>Solution>-Loads-Apply>-Structural-Pressure
Temperature (TEMP) Fluence (FLUE)	Body Loads	BF	Main Menu>Solution>-Loads-Apply>-Structural-Temperature
Gravity, Spinning, etc.	Inertia Loads		Main Menu>Solution>-Loads-Apply>-Structural-Other

In an analysis, loads can be applied, removed, operated on, or listed.

Applying Loads Using Commands

Table 2-3 lists all the commands you can use to apply loads in a static analysis.

Applying Loads Using the GUI

All loading operations (except List; see below) are accessed through a series of cascading menus. From the Solution menu, you select the operation (apply, delete, etc.), then the load type (displacement, force, etc.), and then the object to which you are applying the load (keypoint, line, node, etc.).

For example, to apply a displacement load to a line, follow this GUI path:

GUI:

Main Menu>Solution>-Loads-Apply>-Structural-Displacement>On lines

Listing Loads

To list existing loads, follow this GUI path:

GUI:

Utility Menu>List>Loads>*load type*

Applying Loads Using TABLE Type Array Parameters

To apply loads using TABLE parameters, you use the same commands or menu paths as explained earlier in this section. However, instead of specifying an actual value for a particular load, you specify the name of a table array parameter.

Note-When defining loads via commands, you must enclose the table name in % symbols: %tabname%. For example, to specify a table of force values, you would issue a command similar to the following:

f,all,fx,%ftable%

In a structural analysis, you can define a one-dimensional table that varies with respect to time (TIME). When defining this table, enter TIME as the primary variable.

You can define a table array parameter via command or interactively. For more information on defining table array parameters, see the *APDL Programmer's Guide*.

Command(s):

DIM

GUI:

Utility Menu>Parameters>Array Parameters>Define/Edit

Verifying Boundary Conditions

If you use table array parameters to define boundary conditions, you may want to verify that the correct table and the correct values from the table were applied. You can do so in several ways:

- You can look in the Output window. If you apply tabular boundary conditions on finite element or solid model entities, the name of the table, not the numerical value, is echoed in the Output window.

- You can list boundary conditions. If you list the boundary conditions during /PREP7, table names are listed. However, if you list boundary conditions during any of the solution or post-processing phases at a particular entity or time point, the actual numerical value at the location or time is listed.

- You can look at the graphical display. Where tabular boundary conditions were applied, the table name and any appropriate symbols (face outlines, arrows, etc.) can be displayed using the standard ANSYS graphic display capabilities (**/PBC**, **/PSF**, etc.), provided that table numbering is on (**/PNUM**,TABNAM,ON).

- You can retrieve a value of a table parameter at any given combination of variables using the ***STAT** command (**Utility Menu>List>Other> Parameters**).

5.5.2.4. Load Types

Displacements (UX, UY, UZ, ROTX, ROTY, ROTZ)

These are DOF constraints usually specified at model boundaries to define rigid support points. They can also indicate symmetry boundary conditions and points of known motion. The directions implied by the labels are in the nodal coordinate system.

Forces (FX, FY, FZ) and moments (MX, MY, MZ)

These are concentrated loads usually specified on the model exterior. The directions implied by the labels are in the nodal coordinate system.

Pressures (PRES)

These are surface loads, also usually applied on the model exterior. Positive values of pressure act towards the element face (resulting in a compressive effect).

Temperatures (TEMP)

These are applied to study the effects of thermal expansion or contraction (that is, thermal stresses). The coefficient of thermal expansion must be defined if thermal strains are to be calculated. You can read in temperatures from a thermal analysis [**LDREAD**], or you can specify temperatures directly, using the **BF** family of commands.

Fluences (FLUE)

These are applied to study the effects of swelling (material enlargement due to neutron bombardment or other causes) or creep. They are used only if you input a swelling or creep equation.

Gravity, spinning, etc.

These are inertia loads that affect the entire structure. Density (or mass in some form) must be defined if inertia effects are to be included.

2.5.2.5 Specify Load Step Options

The following options are available for a static analysis:

Option	Command	GUI Path
General Options		
Time	TIME	Main Menu>Solution>-Load Step Opts-Time/Frequenc>Time & Time Step/Time & Substeps
Reference Temperature	TREF	Main Menu>Solution>-Load Step Opts-Other>Reference Temp
Mode Number	MODE	Main Menu>Solution>-Load Step Opts-Other>For Harmonic Ele
Nonlinear Options		
Number of Time Steps	NSUBST	Main Menu>Solution>-Load Step Opts-Time/Frequenc>Time & Substeps
Size of Time Steps	DELTIM	Main Menu>Solution>-Load Step Opts-Time/Frequenc>Time & Time Step
Stepped or Ramped Loads	KBC	Main Menu>Solution>-Load Step Opts-Time/Frequenc>Time & Time Step/Time & Substeps
Automatic Time Stepping	AUTOTS	Main Menu>Solution>-Load Step Opts-Time/Frequenc>Time & Time Step/Time & Substeps
Max. No. of Equilibrium Iterations	NEQIT	Main Menu>Solution>-Load Step Opts-Nonlinear> Equilibrium Iter
Convergence Tolerances	CNVTOL	Main Menu>Solution>-Load Step Opts-Nonlinear> Convergence Crit
Predictor-Corrector Option	PRED	Main Menu>Solution>-Load Step Opts-Nonlinear> Predictor
Line Search Option	LNSRCH	Main Menu>Solution>-Load Step Opts-Nonlinear>Line Search
Creep Criteria	CRPLIM	Main Menu>Solution>-Load Step Opts-Nonlinear>Creep Criterion
Solution Termination Options	NCNV	Main Menu>Solution>-Load Step Opts-Nonlinear>Criteria to Stop
Printed Output	OUTPR	Main Menu>Solution>-Load Step Opts-Output Ctrls>Solu Printout
Database and Results File Output	OUTRES	Main Menu>Solution>-Load Step Opts-Output Ctrls>DB/ Results File
Extrapolation of Results	ERESX	Main Menu>Solution>-Load Step Opts-Output Ctrls>Integration Pt

5.5.2.6. General Options

General options include the following:

- *Time* [**TIME**]

  This option specifies time at the end of the load step. The default value is 1.0 for the first load step. For subsequent load steps, the default is 1.0 plus the time specified for the previous load step.

Note-Although time has no physical meaning in a static analysis (except in the case of creep, viscoplasticity, or other rate-dependent material behavior), it is used as a convenient way of referring to load steps and substeps (see Chapter 2 of the *ANSYS Basic Analysis Procedures Guide*).

- *Reference temperature* [**TREF**]

  This option is used for thermal strain calculations. Reference temperature can be made material-dependent with the **MP**,REFT command.

- *Mode number* [**MODE**]

  This option is used for axisymmetric harmonic elements.

5.5.2.7. Nonlinear Options

Nonlinear options are used only if nonlinearities are present (plasticity, contact elements, creep, etc.) and include the options listed below. For more details on these options and on nonlinear analyses in general, see Chapter 8.

- *Number of time steps* [**NSUBST**]
- *Size of time steps* [**DELTIM**]
- *Stepped or ramped loads* [**KBC**]

Note-Step-applied loads usually have valid physical significance only in rate-dependent analyses (for example, creep, viscoplasticity).

- *Automatic time stepping* [**AUTOTS**]
- *Maximum number of equilibrium iterations* [**NEQIT**]
- *Convergence tolerances* [**CNVTOL**]
- *Predictor-corrector option* [**PRED**]
- *Line search option* [**LNSRCH**]
- *Creep criteria* [**CRPLIM**]
- *Solution termination options* [**NCNV**]
- *Printed output* [**OUTPR**]

  Use this option to include any results data on the output file (***Jobname*.OUT**).

- *Database and results file output* [**OUTRES**]

  This option controls the data on the results file (***Jobname*.RST**).

- *Extrapolation of results* [**ERESX**]

  Use this option to review element integration point results by copying them to the nodes instead of extrapolating them (default).

Caution: By default, only 1000 results sets can be written to the results file. If this number is exceeded (based on your **OUTRES** specification), the program will terminate with an error. Use the command **/CONFIG**,NRES to increase the limit (see the *ANSYS Basic Analysis Procedures Guide*).

4. Save a back-up copy of the database to a named file. You can then retrieve your model by re-entering the ANSYS program and issuing **RESUME**.

Command(s):

SAVE

GUI:

Utility Menu>File>Save as

5. Start solution calculations.

Command(s):

SOLVE

GUI:

Main Menu>Solution>-Solve-Current LS

6. Repeat steps 3 to 5 for any additional loading conditions (load steps). (Other methods for multiple load steps are described in Chapter 2 of the *ANSYS Basic Analysis Procedures Guide*.)

7. Leave SOLUTION.

Command(s):

<u>FINISH</u>

GUI:

Close the Solution menu.

5.5.3. Review the Results

Results from a static analysis are written to the structural results file, ***Jobname.*****RST**. They consist of the following data:

- Primary data:
  - Nodal displacements (UX, UY, UZ, ROTX, ROTY, ROTZ)
- Derived data:
  - Nodal and element stresses
  - Nodal and element strains
  - Element forces
  - Nodal reaction forces
  - etc.

5.5.3.1 Postprocessors

You can review these results using POST1, the general postprocessor, and POST26, the time-history processor.

- POST1 is used to review results over the entire model at specific substeps (time-points). Some typical POST1 operations are explained below.
- POST26 is used in nonlinear static analyses to track specific result items over the applied load history. See Chapter 8 for the use of POST26 in a nonlinear

static analysis. For a complete description of all postprocessing functions, see Chapter 4 of the *ANSYS Basic Analysis Procedures Guide*.

5.5.3.2 Points to Remember

- To review results in POST1 or POST26, the database must contain the same model for which the solution was calculated.
- The results file (***Jobname*.RST**) must be available.

5.5.3.3 Reviewing Results Data

1. Read in the database from the database file**.**

Command(s):

RESUME

GUI:

Utility Menu>File>Resume from

2. Read in the desired set of results. Identify the data set by load step and substep numbers or by time. (If you specify a time value for which no results are available, the ANSYS program will perform linear interpolation on all the data to calculate the results at that time.)

Command(s):

SET

GUI:

Main Menu>General Postproc>-Read Results-By Load Step

3. Perform the necessary POST1 operations. Typical static analysis POST1 operations are explained below.

5.5.3.4 Option: Display Deformed Shape

Command(s):

PLDISP

GUI:

Main Menu>General Postproc>Plot Results>Deformed Shape

The *KUND* field on **PLDISP** gives you the option of overlaying the undeformed shape on the display.

5.5.3.5 Option: List Reaction Forces and Moments

Command(s):

PRRSOL

GUI:

Main Menu>General Postproc>List Results>Reaction Solu

The **PRRSOL** command lists reaction forces and moments at the constrained nodes.

To display reaction forces, issue **/PBC**,RFOR,,1 and then request a node or element display [**NPLOT** or **EPLOT**]. (Use RMOM instead of RFOR for reaction moments.)

5.5.3.6. Option: List Nodal Forces and Moments

Command(s):

PRESOL,F (or M)

GUI:

Main Menu>General Postproc>List Results>Element Solution

You can list the sum of all nodal forces and moments for a selected set of nodes. Select a set of nodes and use this feature to find out the total force acting on those nodes:

Command(s):

FSUM

GUI:

Main Menu>General Postproc>Nodal Calcs>Total Force Sum

You can also check the total force and total moment at each selected node. For a body in equilibrium, the total load is zero at all nodes except where an applied load or reaction load exists.

Command(s):

NFORCE

GUI:

Main Menu>General Postproc>Nodal Calcs>Sum @ Each Node

5.5.3.7. Option: Line Element Results

Command(s):

ETABLE

GUI:

Main Menu>General Postproc>Element Table>Define Table

For line elements, such as beams, spars, and pipes, use this option to gain access to derived data (stresses, strains, etc.). Results data are identified by a combination of a label and a sequence number or component name on the **ETABLE** command. See the **ETABLE** discussion in Chapter 5 of the *ANSYS Basic Analysis Procedures Guide* for details.

Chapter 6: Design and Construction

6.1 Designing as a Process

The design in any project is an iterative process, where all elements must be combined to achieve a catalytic effect and a perfectly working system. In this process many alternatives for every components are made, and by any means the parts created for this project are absolutely adequate for their role, in theoretical or practical construction terms. Being a first version prototype, the objective was to create a study platform, with space for improvement, but at the same time that worked according to the predetermined requisites, and this final prototype will be discussed ahead; first it is important to introduce both the technical and practical theories behind the laminate composites manufacturing.

6.2. Theoretical principles

6.2.1. Laminated composites

Composite materials exist everywhere, even trees are composites, and can be described as any material composed of at least two elements working together to produce material properties that are different to the properties of each element per se. In practice, most composites consist of a bulk material, called the matrix, and a reinforcement, usually in fibre form, added to increase the strength and stiffness of the matrix. Resin systems such as epoxies and polyesters have limited use for the manufacture of structures on their own, since their mechanical properties are not very high when compared to, for example, most metals. However, they have desirable properties, most notably their ability to be easily formed into complex shapes, and these examples are usually used on laminated composites as matrix. For the fibre role extremely high tensile and compressive strength materials are used such as glass, aramid or carbon, yet fibres alone can only exhibit tensile properties along the fibre's length, and by combining the two totally different material types, exceptional properties can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and also protects the fibres from damage caused by abrasion and impact. The major advantages that composite materials present are high strengths and stiffnesses, ease of moulding into complex shapes, high environmental resistance and low densities, making the composites superior to metals for many applications. Both glass and HT carbon fibre plain woven fabrics are available for this project; however in the 57 previous chapter it was determined that the carbon fibre is superior to the glass fibre in every aspect, and because of that it will be the selected material for the parts' construction. The matrix available is epoxy resin and both elements' properties are described in table

6.2.2. Finite Element Method (FEM)

The finite element method [48] was first developed by Hrennikoff in 1941 where a continuous domain discretized into a mesh of sub-domains, called elements, to solve a complex elasticity and structural analysis. The FEM is a numerical technique for finding approximate solutions of partial differential or integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the partial differential equations into an approximating system of ordinary differential equations, which are then numerically integrated. Due to the discretization of the closed system the most important areas (or volumes in three dimensions) of the system can have a greater refinement of the mesh, while non-important sections can have a coarser mesh, resulting in more precise solutions with less computational effort comparing this method with any other available. The FEM software used from henceforth is ANSYS R which for laminate composite structural or dynamic analysis suggest the use of SHELL181, a four-node element with six degrees of freedom at each node, three translations and three rotations, perfect for modelling composite shells, and governed by the Mindlin-Reissner shell theory [49]. For the arms' simulation the BEAM188, a cubic two-node beam element (in 3-D), with six degrees of freedom, and based on the Timoshenko [50] beam theory which includes shear-deformation effects, is suitable for analysing slender to moderately thick beam structures such as the QTR1's arms. Finally a multipoint constraint element, to apply kinematic constraints between nodes is necessary, to simulate connections and to apply forces and moments in a point that does not belong to a structure, and yet the effects from that same force or moment are transmitted to the structure. For this role the MPC184 will be used, an element that behaves as a rigid link/beam.

6.3. Laminated composite manufacturing process

To maximise the performance of composite materials, during the cure process an increase in the fibre to resin ratio and removal of all voids is required, and can be achieved by subjecting the material to elevated pressures and temperatures. The best technology to accomplish both requisites is the autoclave, an oven-like structure capable of maintaining high temperatures and pressures during several hours for a perfect cure of the laminate. Many other techniques for composite manufacturing exist being the autoclave the most commonly used in the industry, even to build Formula 1 chassis, however for this project such an advanced technology is not available and the alternative used here is the wet lay-up followed by vacuum bagging. In the wet lay-up process the epoxy resin is impregnated by hand into the woven fibres and placed in a cast. Then the finished wet laminate is placed inside a vacuum bag. Since true vacuum is very hard to achieve, a compressor is used as a vacuum pump and the part is covered by a slim plastic pierced film and a cotton blanket to reduce drastically the in-bag pressure in order to reduce the excess of resin and prevent voids in the final piece. For the cure process' completion it is necessary to maintain the part in the vacuum bag for approximately six hours. After that the part is ready to any final cutting or material removal process needed for its final completion. The casts are made in extruded polystyrene foam modelled with a computer numerical control (CNC) foam machine, and after the cast in foam is completed, it is cover with duct tape, to prevent the extruded polystyrene from reacting with the epoxy 60 resin and consequently melt.

6.4 Structural project

The final design of every component is made based in SolidWorks® and later analysed on an ANSYS® model of the part to be constructed, with a safety factor of 2, which means the Tsai-Wu failure criteria must be inferior to 0.5. The maximum deflection (wmax) must be below 5mm for integrity and tolerance reasons. The components were envisioned based on the preliminary design assumptions as well as in the dimensions of the off-the-shelf components selected.

6.4.1. Original Model

For convenience purpose, we are going to call the quadrotor at the initial level of the design as the original quadrotor. To which changes in designs are made to suit the final requirements of the project. In the Fig the dimensions of the original QTR1 is shown.

$$Wm = 4\,Kg \times 9.81 \qquad \text{(i)}$$

$$P = \frac{4\,kg \times 2 \times 9.81}{4} \qquad \text{(ii)}$$

$$P = ¿\, gravity \frac{Mass\ of\ Model \times F.O.S. \times Acceleration\ due\ ¿}{No.\ of\ Rotors}$$

Permissible Weight for the Model, W_m	40N
Weight of Structure W_s	8N
Weight for Accessories W_a	32N

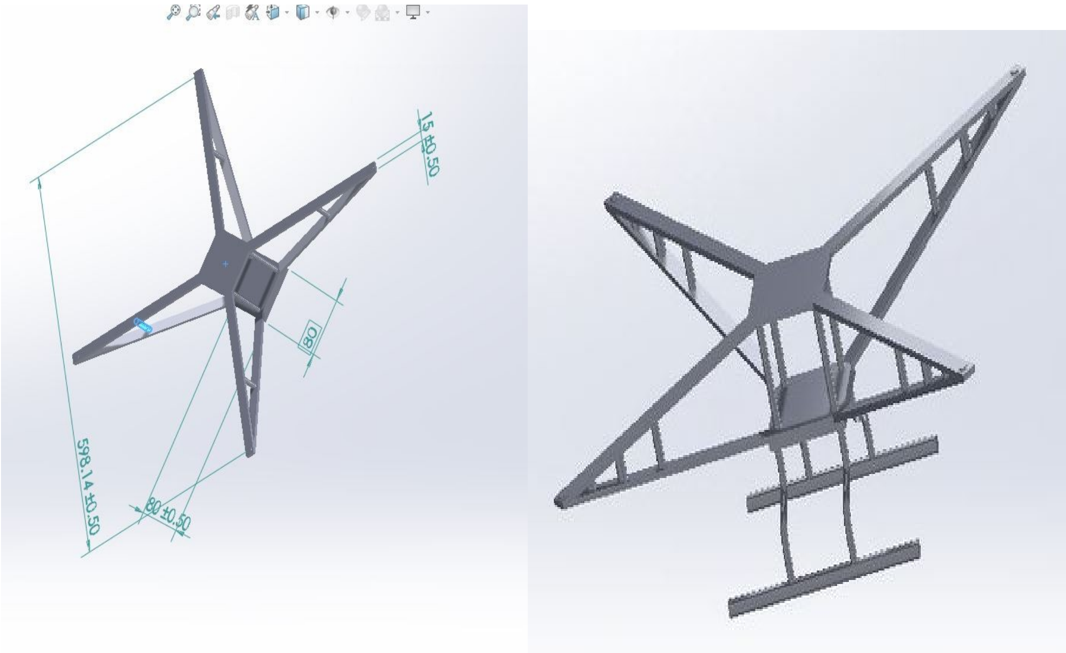


Fig 6.0.11 Dimensions of Original Quadrotor

Structural Analysis Result of the Original Quadrotor.

Figure 6.0.12 Stress Analysis Original Quadrotor

Figure 6.0.13 Total Deformation in the Original Model

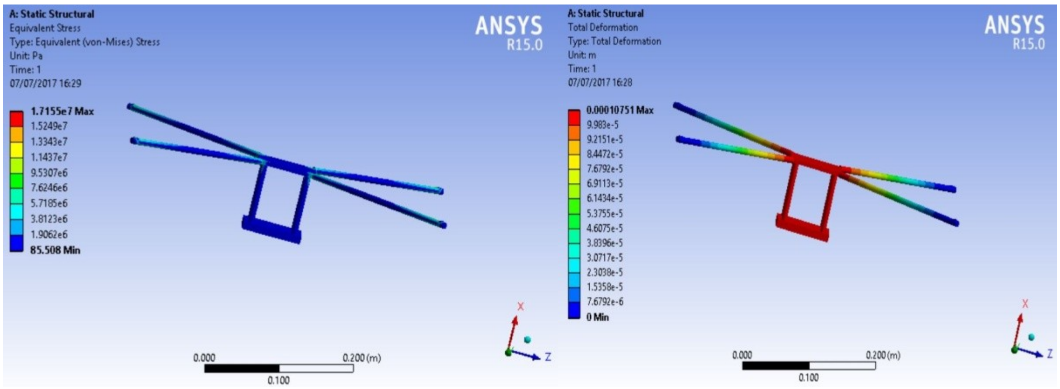


Fig 6.0.14 Stress Analysis Original Quadrotor 2 0.15 Deformation in Original Quadrotor 2

As it can be seen that the structure is deforming under the self load, the payload and the application of the thrust by the propellers, the design needs to optimize both for minimizing the weight and increasing the strength or infact increasing the strength to weight ratio.

Deflection limits

Deflection in beams is a major issue in structural design. Engineers adopt deflection limits which suit the nature of the building. For example, according to AS 1170.1 Minimum design loads on structures (known as the SAA Loading Code):

maximum allowable deflection = span ÷ 300

This means that to calculate the deflection in a beam which spans 6,000 mm, divide 6,000 by 300.

6,000 ÷ 300 = 20

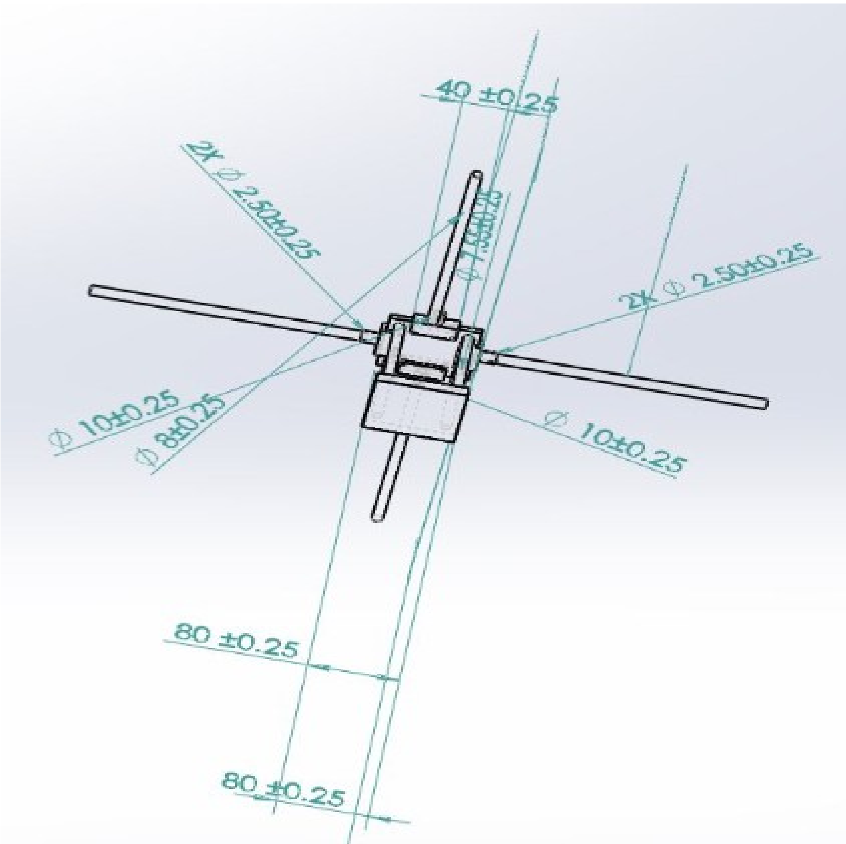
So a span of 6,000 mm has a maximum allowable deflection of 20 mm.

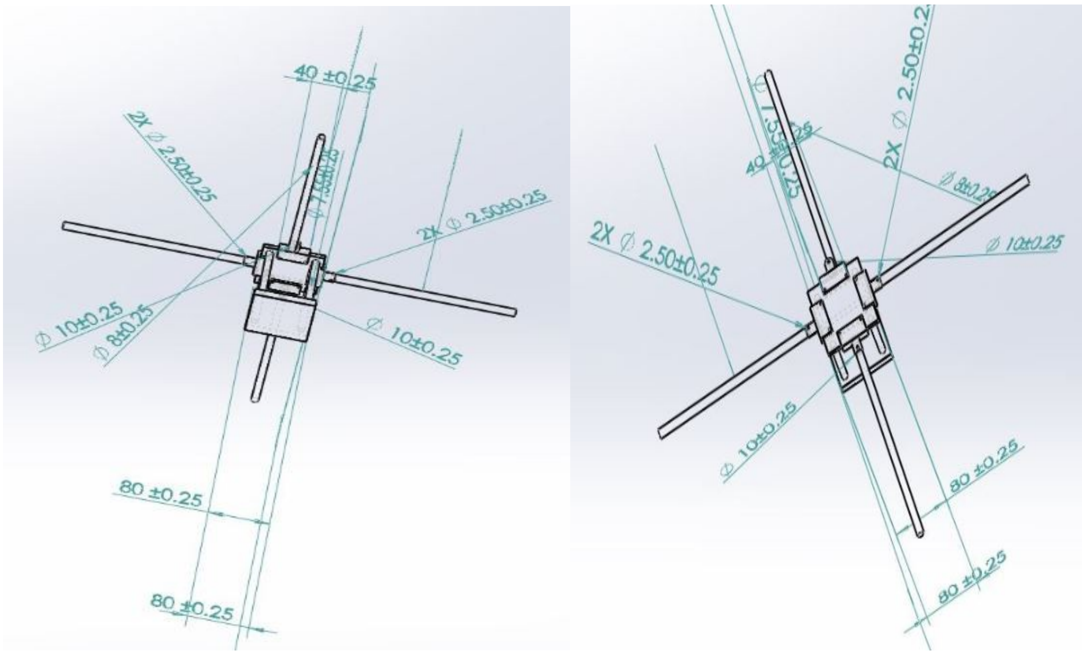
The final design of every component is made based in SolidWorksR and later analysed on an ANSYSR model of the part to be constructed, with a safety factor of 2, which means the Tsai-Wu failure criteria (eq. 5.1) must be inferior to 0:5. The maximum deflection (wmax) must be below 5mm for integrity and tolerance reasons. The components were envisioned based on the preliminary design assumptions as well as in the dimensions of the off-the-shelf components selected

6.4.2 Design Modifications to the Original Model.

The Approach to be taken for this is now design and static structural analysis on individual parts parts. We break down the parts into simpler groups.

A. Landing Gear
B. Swivel Arm and Rod
C. Embracing Plates
D. Central Area.
E. Rod





6.4.2.1. Landing gear

The landing gear design must respect the assumptions made in chapter 2 to be the lowermost position, also to prevent any tilting as well as sustain large accelerations on hard landings. The Landing Gear is designed here on the and from the assumptions and designs of all parts done so far, it was establish that the uppermost section of the landing gear will have 80mm, the width is 20mm and the total height is 122.5mm to have a 20mm margin for a 90º U-arm tilt, and the second coming from a structural FEM analysis, as well as the size of the carbon rod skis coming from tilted pitch landings.

The final dimension of the landing gear to be determined is its thickness. And is determined again by a FEM analysis, however this time the study must account for hard landings and a factor representing the acceleration increase, commonly known as G must be multiplied to the total weight of the QTR1 (1:6kg), and the final the landing thickness gear must withstand. The boundary conditions will be simply supported in the landing gear’s legs edge but free to move away form each other, and the 16N are applied in the 40mm upper straight section. By definition of the conservation of momentum, simplifying using the equations of motion, for no drag and no initial velocity:

with h as the initial altitude of the QTR1, and _t the time of impact, that according to Fuchs and Jackson can be considered 0:15s. So for a 25m free fall, a reasonably high climb and neglecting the drag effect, the total G will be 15:051. Before construction is necessary to determine the cast used. The cast consists on a 120/170/80mm, with a 30º cut in both sides of the 120/170mm section. In the edge of this cut, where it intersects the 120/80mm lower face, two foam 5mm rods are placed to create the skis attachment. Finally the 80mm follow the same rule as the arm's did, to create both legs at the same time and cut out the excess without worries.

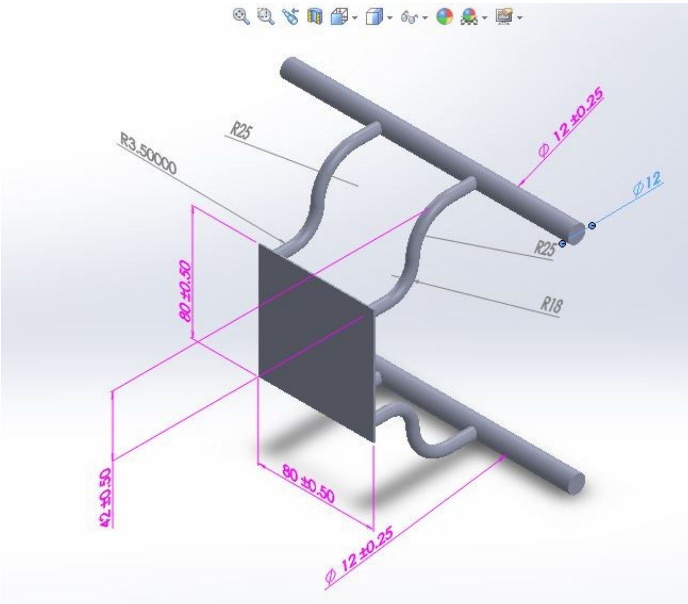


Figure 6.0.16 Dimension of a Landing Gear

Considering this factor and a total weight applied of 8N, because the landing gear is composed of two legs, and just one is analysed, because all loads and stress are symmetric. Table 5.9 is obtain to show the evolution of the design requisites with the thickness and becomes explicit that the best option is to create the landing gear with three millimetre [0=90=45=-45=90=0]3layup.

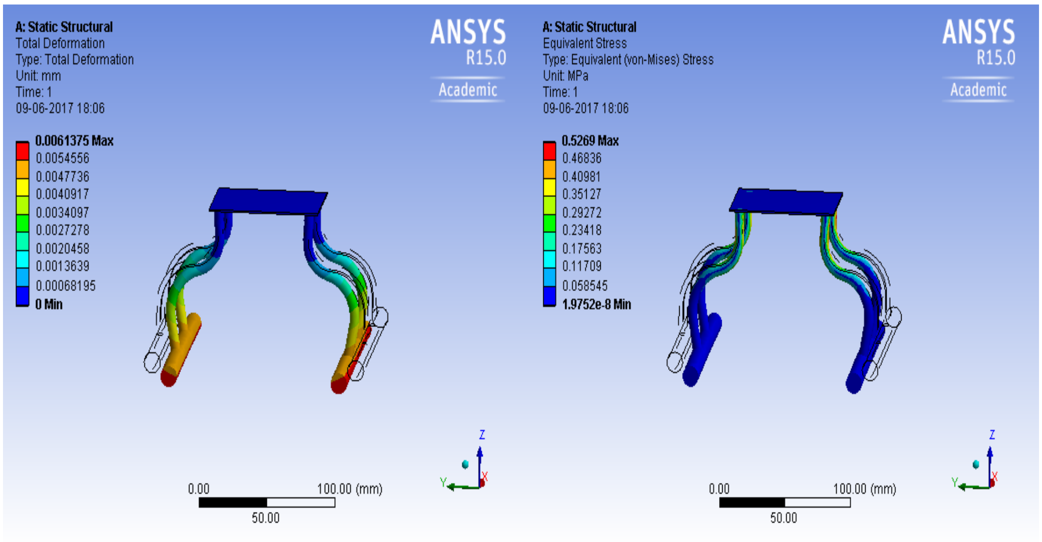


Figure 6.0.17 Total Deformation in Landing Gear

Figure 6.0.18 Equivalent Stress in Landing Gear

6.4.2.2. Embracing Plate:

Fixed arm

The fixed arm was already decided in the previous chapter to be made of unidimensional carbon fibre tube with a 10mm external diameter and 9mm of internal diameter, however it is also necessary to attach the motors to the tube and the tube to the main structure, and the best alternative to do so is using a simple embracing plate (figure 2.3(a)). Since this component is merely a junction enabler between the structure, the arm and the motor, a structural analysis is not important. This part consist merely on an hollow cylinder attached to a slim plate, the hollow cylinder is where the arm will enter and the plate is where the connections to motor or central plate will be performed, this connection is simply achieved by the cure process. The final dimensions of these parts are 12mm in height, and 20 /20mm for the structure connector, while for the motor connector 28 _ 20mm is required, due to the motor's diameter. As cast, a 10mmdiameter foam rod is needed to create the hollow cylinder and a rigid flat surface for the plain connecting area.

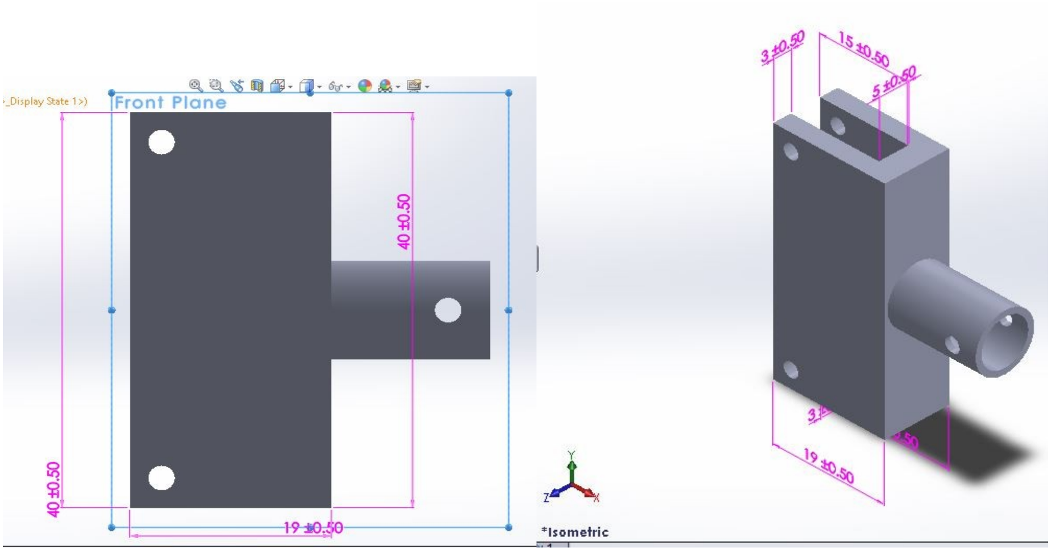


Figure 6.0.19 Dimension of Embracing Plate

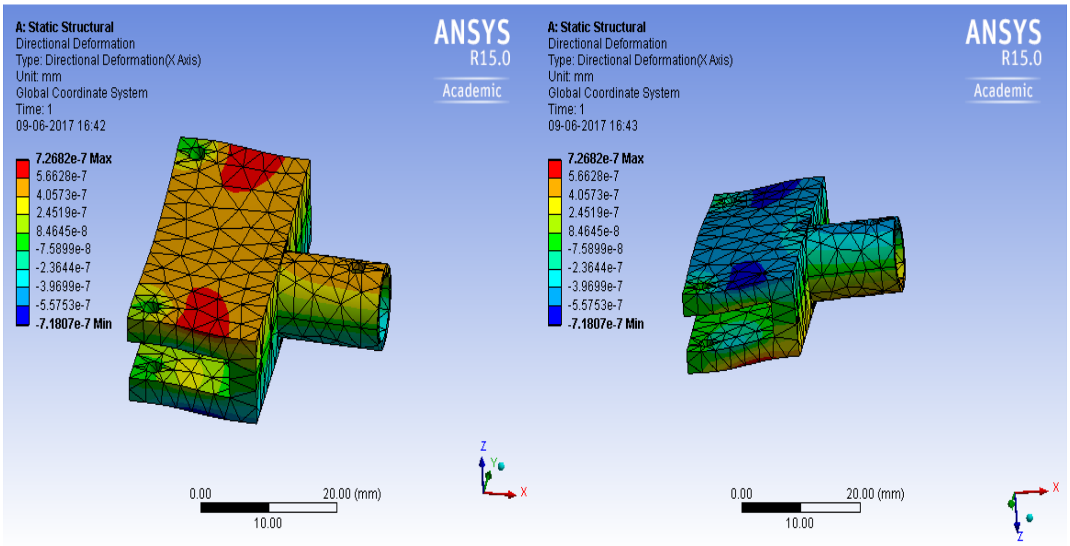


Figure 6.8 Directional Deformation of Embracing Plate

Figure 6.9 Directional Deformation of Embracing Plate

Deformation Criteria

According to AA ADM 1[12] the aluminium structure uses 2 deformation criteria according to their alloy composition L/360 and L/180.

L/360 is used for brittle edges and L/180 is used for ductile edges, here our material is ductile and there L/180 criterion is used.

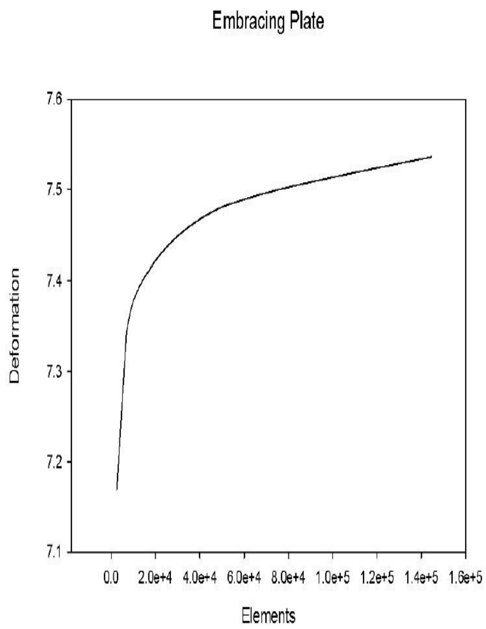


Fig 6.0.20 **Elements vs Displacement**

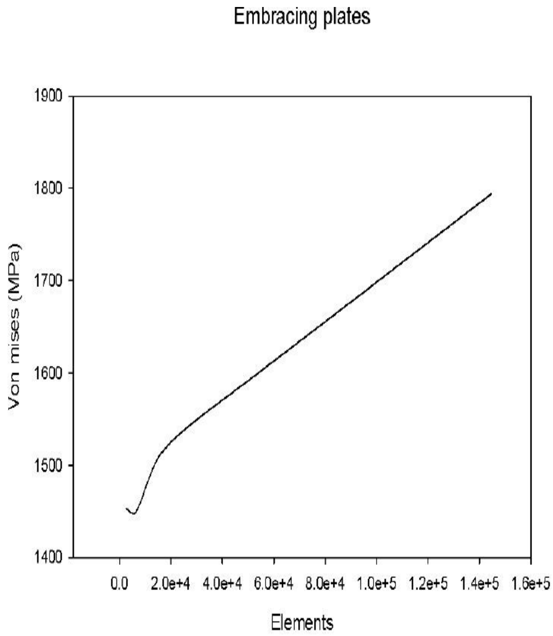


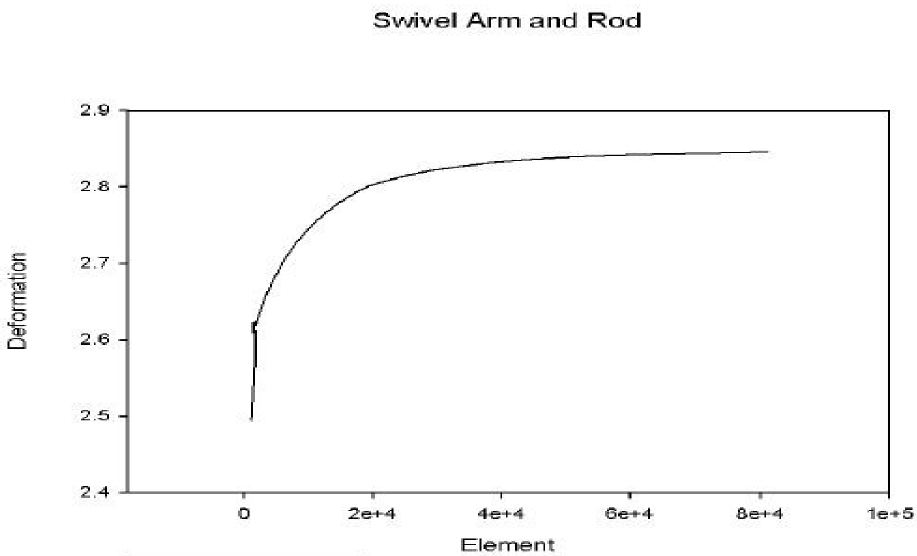
Fig 6.0.21 **Elements vs Von Mises Stress**

6.4.2.3. Swivel Arm:

Both swivel arm concepts follow the first-servo and second-servo configuration and both alternatives start with a carbon tube connected to the first-servo, stabilized by a bearing at the end of the central area, to take all the transversal loads from the servos. These components are considered to be part of the central area. Both alternatives will use the embracing plate alternative to fix the motor, since the motor in box proved very hard to construct properly, due to poor control in the construction tolerances.

U-arm construction

The U-arm configuration consists of six different components, three of them off-the-shelf, a servo, a motor and a 258mm carbon tube, and three created components, two tube sockets connectors, the arm itself and an embracing plate. The tube sockets were initially envisioned as an acrylic 11mm diameter and height cylinder with an extrude cut of 10mm of both diameter and depth, and an M3 screw opening in the centre of the remaining 1mm thickness face. Then the sockets are glued to the tube and connected to the servo and the arm with the M3 screws and respective nuts. However the CNC available for the manufacturing of such intricate and narrow walls proved inefficient, and a carbon alternative was used instead, but only in the non-servo junction (figure 5.3 (a)). For the servo connections an aluminium hollow tube alternative with a skirt connecting to the servo was also created. Enabling a quick assembly and disassembly, this connection uses a 11mm diameter and height tube and two skirts, 180º apart, L-shaped 10mm height and 1mm thickness made from a 25mm aluminium strip bended in 90o angle and connected to each other through the tube by a M3 screw and bolt. The final weight of each socket is 5g and the servo is connected to the arm by four M3 screws and nuts.



The aluminium skirt socket is connected to the servo with two small (1:5mm in diameter) screws, whose weight was considered to be part of the servo itself.

Since the selected servo has 20mm of thickness in the head side, the width of the arm must be 30mm. The cast for the arm consists of a 279 /162/100mm parallelepiped with an external quarter 62 of a 100mm radius circle shape cut in two of the 100mm edges farther apart (5.4). In the middle of the cast, in its upper face, two 10mm in diameter foam rods are inserted, 30mm apart to make a cylinder in the finished piece, to insert the rod from the first-servo. The cast width is 100mm to allow the creation of both arms at the same time and also provide some margin for the cutting of the part. For the layup it is used a [0=90=45=-45=90=0]i configuration with i as the thickness in millimetres needed for the arm to respect the structurally sound tolerances required (SF = 2 and wmax = 5mm).

The FEM analysis is made with a 10N force and the maximum torque the servo was estimated to produce, 0:3621N:m (3:69kg:cm), and for the various thicknesses, table 5.4 shows that the best option is t = 3mm. So the exterior dimensions are 285/168/30mm with a curvature of 100mm and a connector for the first-servo tube of 50mm centred in the middle of the arm. The boundary conditions were set in the rod of the first-servo insertion, where all degrees of freedom were restricted. The force and moment of the motor-rotor couple, were applied in its exact position using MPC184 elements.

The critical section of the arm is located in the connection with the first-servo (figure 6.5 (b)) as expected, because it is the place where the stress concentrations will be greater. The maximum displacement is located in the arm's non-servo side limit (figure 6.5 (a)). Finally the embracing plate, where the motor will be placed, is glued and connected with a M3 screw to the tube coming from the second-servo with its centre (where the screw is) located in the intersection of both servo heads' direction. The motor is then fixed with two M3 screws and nuts. Finally the connection with the first-servo rod is also made by an M3 screw for easy replacement and arm switch between U-arm and slim-arm. The total weight of the U-arm is 120g.

Slim-arm construction

The slim-arm configuration is simpler than its alternative U-arm configuration and it is constituted by the same motor, rotor, embracing plate and tube socket connectors, however now the motor tube is much smaller (50mm) and two new parts are needed, as well as three carbon tubes with 100mm, 140mm and 140mm starting the identification from the motor. The new parts needed are three elbows and a servo support. The elbows are simply a 50/50mm, 90^{o} L-shaped carbon woven junction for the carbon tubes, made with the same cast as the embracing plate, a foam rod with 10mm in diameter, this time cut in a 45o angle and then glued to both cut sections. Both sections must be larger than 50mm and a single strip of carbon fibre woven is hand adjusted around the cast, resulting in a final weight of 2g for each elbow. For the servo support an analysis similar to the U-arm's arm was conducted, in the motor's position a force of 10N and a torque of 0:3621N:m was applied to various thicknesses with a [0/90/45/-45/90/0]i layup (table 5.5) and a 1mm thickness proved the best option because it respected all the required tolerances.

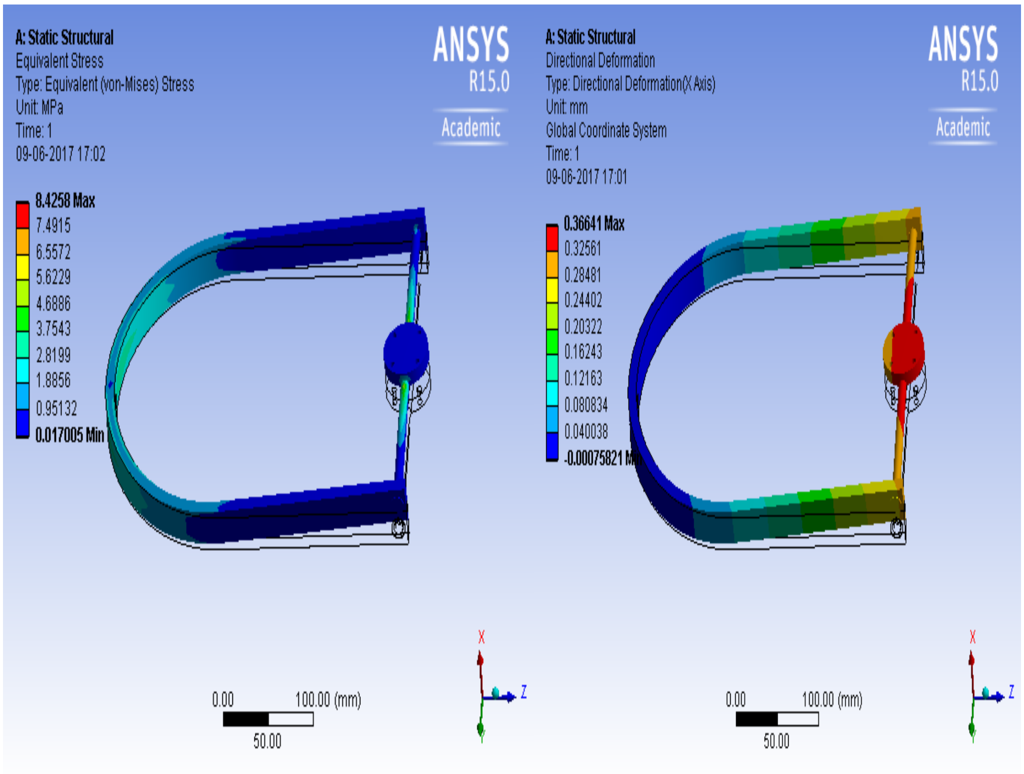


Figure 6.10 Directional Deformation of Swivel arm and Plate

Figure 6.11 Equivalent Stress of Swivel Arm and Rod

6.4.2.3. Central Area

The central area is the core of the QTR1, where all the mechanical and electronic components are located or are fixed to. The most important components of the central area, are the electronic ones, also known as avionics, necessary for the QTR1's control. As an example, depicted in figure 2.7 are the Arducopter's [15] avionics, where both essential and non-essential components are shown. The essential components are:

- A battery, the energy storage system;
- Four Electronic Speed Control (ESC) to control each of the motor's angular velocity;
- A decision platform, usually a micro-controller where the control software would be, in this case an Ardupilot Mega;
- A set of sensors (magnetometer, accelerometers ans gyroscopes), to aid the decision platform;
- Communication hardware, shown as a wireless connection to a computer (XBee) that could be replaced by a radio controller receiver;
- A Power Distribution Board (PDB) that is connected to the battery and redistributes its power to all the other electronic components.

A video camera can also be considered a part of the avionics, but since it is not a binding component, it will be considered as payload. As an addition a GPS receiver is presented, that can be used to turn a radio controlled quadrotor in a UAV quadrotor. Since the arm models selected for further study respect

17 the first and second-servo configuration, two servos plus all the avionics must be accommodated in this central area. All these electronic or mechanical components' selection will be addressed in chapter 4.

To accommodate all these components a strong yet light structure must be created. Its dimensions and number of levels will depend on the size and organization of the supra-cited components, and a spheroid aerodynamic cover shall also be taken into consideration, to decrease the drag from the QTR1 in forward flight but also in lateral flight or even in climbing movements. In Pedro's ALIV2 [18] the central cover had a maximum radius of 113mm but since the limit proposed for the QTR1's rotors distance was 600mm (300mm of radius) and the maximum length of the selected arm design was 140mm, considering a 50mm gap in both sides, the maximum radius for the central area cover will be 150mm, and all components plus the structure, should fit inside that radius. The fixed arm will need to have at least 600mm and must also be connected to this central area.

5.5 Complete Design of the Quadrotor

All parts are now fully designed and constructed, and the only difference between the models are their swivel arms, the remaining components is the same, and both models cannot exist at the same time, the swivel arms must be replaced to use each one of the alternative QTR1 configurations. In terms of weight the U-arm alternative theoretically weights 1788:33g, which is 11:77% above the initial weight estimation of 1600g, however the real model only weights 1749g, that reduces the error in relation to 9:31%. The source of this 2:25% difference between theory and reality comes from the laminate construction process, in which the quantity of epoxy resin used was in reality slightly inferior to the quantity studied. If the components were made in an autoclave, this could have been averted, although the possibility of this proportion misshapen was accounted for in the design process with a SF = 2 and so no component constitutes a risk for any of the QTR1 operations. The only effects of this small alteration in resin to fibre proportions result in a de facto larger rigidity and a minor Tsai-Wu failure criteria than the projected models, and of course lower weight.
For the slim-arm model the theoretical weight was 1690:34g with an error of 5:65% regarding the initially estimated weight of 1600g. The real model like for the U-arm model and for exactly the same reason presented a total weight of 1660g, 3:74% above the estimation

This increase in weight regarding the initial estimation is a result of both the quantity of screws, nuts and washers used, especially the M6 ones used for the central boards, as well as the amount of cabling needed to connect the motors to the ESCs, and the weight of the battery. All combined these components weight 658:2g, or 37:63% considering the U-arm alternative, and so in future versions of the project, aluminium screws, nuts and washers as well as lighter cabling or even a lighter battery, at the expense of endurance, shall be evaluated to reduce weight, nevertheless the current total weights of both version are within the design objectives. Representations of the designed U-arm and slim-arm QTR1 models and the really constructed U-arm alternative are shown in figure 5.17, and the detailed QTR1 weight is presented in appendix G.

The final U-arm model dimensions excluding the rotors, are 620 _ 642 _ 245mm, for the fixed arm, swivel arm, and total height respectively, or x,y and z-axis of the ABC frame. In the slim-arm model each swivel arm has less 2mm resulting in the final dimensions of 620_638_245mm. Nonetheless the distance between opposite rotors is 600mm and each one is 90o apart considering the centre of mass position. In terms of execution the designed parts proved very tough, and the requests of project were completed in the preliminary operational tests. Real operational tests shall only be conducted when a working control model for the QTR1 is completed in a future iteration of the project. The current QTR1 has undergone very limited testing, fixed to a table with duct tape, nevertheless in one test, mounted with rotors
5, and inferior motors to the ones selected, with all motors working at theoretically the same power, less than half the motor capacity, the duct tape peel off the table and the QTR1 pitched over the table to a 1:2m fall. Inferior rotors and motor were used because the optimum rotor could not have yet been really prototyped, and the selected motors are not yet available.

This accident proves three important aspects of the QTR1 construction and operability. Firstly it has the power to easily lift itself, with a large margin for the rotor tilting, because if less than half the motor capacity was being used, with inferior components than the ones selected, means that the QTR1 can be lifted with just two motors. Secondly all parts that were designed to withstand only the weight of the QTR1, sustained a larger acceleration in collision than the acceleration of a soft regular landing, furthermore the landing was done in an upside-down position with the servo board hitting the floor, instead of the landing gear. Using equation 5.2 this fall G’s were equal to 3:30 and so the structure is even sounder than expected. Thirdly the battery, PDB and ESCs connection is working perfectly. It is important to note that the tests were performed with an RC connection, because there was no viable control platform available and no need to use the Ardupilot.

Chapter 7: Conclusion

The major achievement of the present work was the construction, for a future control system development, of a quadrotor platform with multiple degrees of freedom, the QTR1, theoretically capable of moving in all six degrees of freedom maintaining its central core perfectly levelled due to the rotation of two opposed rotors in two directions other than their rotation, and thus having the advantage of drag reduction in comparison with standard quadrotors, because in all translations the surface facing the airflow is independent of its velocity, and can be maximized to reduce forward drag, while for standard quadrotors, its velocity is proportional to a roll or pitch angle of all the quadrotor. This theoretical movement capacity was also fully determined with all translations and transient rebalancing operations fully described for a perfect future control software for the QTR1's flight operations. The aim of this project was to design and construct the inovative concept of a quadrotor with two tilting rotors, the QTR1, with the technical capacity available, and so all the necessary parts were built with an high tenacity carbon fibre laminated composite, with a safety factor of 2 in accordance with the Tsai-Wu failure criteria and a maximum deflection of 5mm for every part individually, and all final parts respected this criteria. A genetic algorithm with the blade element momentum theory was used to create an optimum rotor for the QTR1's hovering scenario. All the necessary variables for a rapid prototyping process of a real model were determined as well as the rotor's ideal aerofoil. In terms of the off-the-shelf components, several market alternatives for avionics, motors, servos and simple structural components were evaluated and selected according to existent quadrotors, need of the project and price. Two final models were developed, yet they only differed in the swivel arm's format, and so only one central area and landing gear were created, while two of each arm models were constructed, the U-arm and the slim-arm. The U-arm is the symmetrical U-shaped, stronger swivel arm alternative, while the slim-arm in the lighter and more simply constructed version constructed with three small carbon tubes and connecting elbows. However after construction and testing of both alternatives, the U-arm proved to be the best option for the QTR1. The final dimensions of the QTR1 in the U-arm configuration are 620 _ 642 _ 245mm with 600mm between opposed rotors and a final total weight of 1749g.

7.1 Future Work

In a future continuation of this project a revision of the total weight could be important but not mandatory, and so was proved by the small testing accident. Nevertheless the central stainless steel material could be replaced by aluminium to decrease 65:65% of weight in those components alone. In terms of the remaining components an optimization with reduction of material could also be studied, especially in the arm and landing gear. The skirt tube connectors could also be improved in case of necessity, adding two more strips, 90o from the existent ones. The cover studied in this work was not optimized for any other direction than forward flight, and provided good results, however for the other direction the results were penalized and the cover hypothesis is for that reason eliminated. It would be interesting, as an optimization process to design a cover that would increase the performances in all directions, not just forward flight. All these aspects are purely accessory, and would only improve the endurance of the QTR1, the crucial aspect of a continuation of this project is the QTR1's control implementation, because without it, an aircraft such as this cannot fly, and that is the the most important factor in all aircraft projects. Finally, and after a true control platform is fully functional, the transition of the QTR1 to a UAV would be the final iteration of this project.

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APPENDIX

List of Acronyms

Acronym	Meaning
QTR1	Quad Tilt Rotor 1
DOF	Degrees of Freedom
ESC	Electronic Speed Controller
VTOL	Vertical Take Off and Landing
DTU	Delhi Technological University
UAV	Unmanned Aerial Vehicle
RC	Radio Controlled
MAV	Micro Aerial Vehicle
Li-Po	Lithium Polymer
GUI	Graphical User Interface
IMU	Inertial Measurement Unit