ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

ADAPTIVE CONTROL OF A NOVEL TILT-ROLL ROTOR QUADROTOR UAV

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ADAPTİF DÖRT ROTORLU BİR İNSANSIZ HAVA ARACININ MODELLENMESİ VE KONTROLÜ

YÜKSEK LİSANS TEZİ

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OCAK 2015

Abdulkerim Fatih Şenkul, a **M.Sc.** student of ITU **Graduate School of Science and Technology** student ID **503111601**, successfully defended the **thesis** entitled "**ADAPTIVE CONTROL OF A NOVEL TILT-ROLL ROTOR QUADROTOR UAV**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 11 December 2014
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To my family,

FOREWORD

"Nothing cannot exist forever." by Stephen Hawking.
First of all I'd like to thank to my thesis advisor, Associate Professor Dr. Erdinc Altug for supporting me through out my studies and leading me to attend to the internatioanl conferences about my thesis.
Thanks to TUBITAK for supporting my project with the funds given under the project number 114M765.
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"When everything seems to be going against you, remember that the airplane takes off against the wind, not with it." by Henry Ford.

December 2014

Abdulkerim Fatih ŞENKUL
(Mechatronics Engineer)

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ABBREVIATIONS

VTOL **:** Vertical Take off and Landing
UAV **:** Unmanned Aerial Vehicle
İHA **:** İnsansız Hava Aracı
QTR **:** Quad Tilt Rotor
IMU **:** Inertial Measurement Unit
AHRS **:** Attitude and Heading Reference System

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MODELLING AND CONTROL OF A NOVEL TILT – ROLL ROTOR QUADROTOR UAV

SUMMARY

In the last years there is a drastic increase of demand on the unmanned aerial vehicles (UAVs). The UAVs are commonly used in military, scientific and civilian sectors where they are giving better results in surveillance & rescue missions and missions that take place in danger zones such as nuclear plants and battle fields. UAVs are often preffered due to their higher maneuverability, decreased radar signature, lower cost in long run, durability, as well as decreased risk for human life. That’s why vast researchers studying on UAVs are currently focusing to increase the abilities of these aircrafts.

Among the UAV world, vertical take off and landing (VTOL) units are also in a favorable position as there is almost no need for an extra landing field and airfield for take off and landing. As being one of the versions of VTOL units, quadrotor is a UAV platform in which there exists four rotors and propellers to create the necessary thrust force in order to enable the vehicle’s flight and determine the 3D position of its flight direction. However, as being an underactuated system, there is a limiting factor for the way quadrotor move. It is necessary to tilt the body frame along the desired direction of motion in order to change the 3D coordinates of the vehicle. Tilting the body frame can result with some undesired effects when the work area is limited and/or when there is a need to use of on-board cameras or sensors.

There are already some studies on tiltable rotor design for planes which are able to tilt their rotors only in one direction, enhancing an extra one degree of freedom for the rotor in question. This kind of a design improves the maneuverability such that the aircraft can switch from plane mode to helicopter mode by the transition of the tilting rotors. Moreover, there are advantages on the increase of the distribution of required force vectors by transfering and delivering the thrust force along the desired axes.

There are a few studies that have tiltable geometry for unmanned quadrotors and other VTOL units. However, their rotor tilting mechanisms are all limited along the one axis only. In these studies, rotors tilt either all at the same time at same direction with a pre-specified amount, or all tilt around one axis only.

Unlike the regular design, this study proposes an alternative propulsion system for quadrotors. The rotors of the quadrotor both have tilting and rolling capabilities around their axes adding 8 additional control inputs. Hence, upgrading the system being underactuated to overactuated.

In the first part of this study all the rotors are controlled such that they have the same tilt-roll angles depending on each other. After the tilt-roll capable system is designed and verified via Matlab simulations, further failure modes of the rotors, propellers

and outside environmental effects are added as a random noise signal. Then the system is controlled and balanced by driving each of the rotors' tilt-roll angles independently from each other. It is introduced in adaptive control of tilt-roll rotor quadrotor sections of this thesis.

The proposed design in this paper has more complex but more effective control system and algorithm with respect to the previous studies and regular quadrotors. What's more the possible failure modes of the system is analysed and some preventive-safe flight actions and further adaptive control systems in order to compensate for these failure modes are presented. This design eliminates the need of tilting the body frame, what's more it has relatively better performance in terms of lower reach, settling time and maximum overshoot values when travelling along 3D coordinates. The mathematical model of the tiltable-rotor type quadrotor and designed control algorithms are studied during the development stages of this work. The detailed explanation of the mathematical model, control system design and algorithm will be introduced in the following pages. In order to verify the results various simulations are developed on MATLAB and Simulink. Comparison of the proposed system performances are better than what a regular quadrotor suggests.

ADAPTİF DÖRT ROTORLU BİR MULTİKOPTERİN MODELLENMESİ VE KONTROLÜ

ÖZET

İnsansız hava araçlarının (İHA) askeri, bilimsel ve sivil alanda kullanımı özellikle son yıllarda oldukça artmıştır. Günümüzde birçok ticari, askeri ve deneysel İHA'lar mevcuttur. Bunlar çok farklı tipte ve boyutlarda olabilmektedir. Üniversiteler, araştırma merkezleri ve hobi olarak kumandalı sistemlerle ilgilenenler tarafında halen geliştirme aşamasında olan birçok İHA tipleri ve modelleri mevcuttur.

İHA'lar alternatifleri olan büyük boyuttaki klasik uçaklara oranla, yüksek manevra kabiliyetleri, düşük fiyatları, düşük radar görüntüleri, dayanıklılıkları, insan hayatının riske atılmaması gibi nedenlerle büyük fayda sağlamaktadırlar. Bu faydalar neticesinde günümüzde birçok alanda kullanımlarına rastlamaktayız.

Çok rotorlu insansız hava araçları havada asılı kalabilme ve manevra yetenekleri ile dikkat çekmektedirler. Çok rotorlu hava araçlarından, dört rotorlu Quadrotor hava aracı kontrolü ve tasarımı üzerine birçok çalışma bulunmaktadır. Bu hava aracı üzerine son yıllarda dikkat çekici çalışmalar olmuştur. Günümüzde quadrotor (quadcopter) hava platformu, birçok uygulama ve araştırma projesinde kullanılmaktadır. Bu hava platformunun uygulamaya daha fazla geçirilememesinde aracın hareket etme yöntemi etkin olmaktadır. Bu hava aracı, hareket etmesi istenen yöne doğru eğilerek hareket etmektedir. Gerçekleştirilen eğilme hareketi ile aracın gidilmek istenen yönde ivmelenmesi mümkün olabilmektedir. Öte yandan, bu eğilme hareketi araç üstünde genellikle bulunması beklenen kamera sistemlerinin görüntü alma kabiliyetini olumsuz etkileyebilmekte ve kameraların doğrultu açısının değişmesine sebep olmaktadır. Bu durum, özellikle gerçek zamanda görüntü tabanlı kontrol yapmakta olan hava araçlarının istenen şekilde çalışmasına olumsuz yönde etki edebilen bir problemdir. Bunun yanı sıra söz konusu durum yüksekten gözlem ve takip uygulamalarında büyük sıkıntı yaratmaktadır. Güncel sistemlerde kamera sistemini araçtan ayrı bir hareketli platforma koyarak, hava aracının hareketlerinden soyutlamak yoluna gidilmeye çalışılsa da, önerilen proje bu probleme daha faydalı bir çözüm getirmektedir.

Literatürde eğilebilen özellikte bazı döner-kanatlı hava araçları mevcut olmasına rağmen hiçbiri bu projede önerilen yapıda değildir. Standart quadrotor aracına alternatifi olarak geliştirilen eğilebilen özellikte döner kanatlı araçlar da mevcuttur. Bu yaklaşım ayrıca artan kaldırma kapasitesi de getirir. Bu tür hava araçlarının gerçek boyutta, insanlı versiyonları olan deneysel araçlar bile üretilmiştir.

Literatürde eğilebilen özellikte quadrotor hava araçları hakkında birkaç çalışma vardır. Söz konusu sistem dikine havalanabilen quadrotor ile uçak modları arasında değişebilen özellikte bir hava aracıdır. Bunu tüm rotorlarını aynı oranda ve tek bir eksen etrafında eğerek yapmaktadır.

Bugünkü çoklu-rotorlu hava araçlarının bazı limitleyici özellikleri bulunmaktadır. Sistemin istenilen koordinat düzlemine hareket edebilmesi için kendi ataletini kullanarak bir yöne belli bir açı değeri alarak ilerlemesi şarttır. Bunun başlıca sebebi toplamda 6 serbestlik dereceli hareketi toplamda 4 adet yerleşimsel olarak statik eksenli motorun oluşturduğu itki kuvvetiyle sağlamasıdır. Bu durum bazı uygulamaların kapasitesini olumsuz olarak etkileyebilmektedir. Bunlara örnek olarak görsel çekimler için kullanılan kameraların uçuş süresince istenilen yöne bakabilmesi için ekstra sistemleri şart koşmaktadır. Bu sistemler gimbal olarak da adlandırılan kamera yatağı düzenekleri ile de desteklenmektedir. Normal koşullarda yalnızca üst kalite çekim sistemlerinde böyle bir destek ürüne gerek duyulmasına rağmen, kamera yatağı kullanımı daha amatör düzeydeki sistemler için de uygulanması gereken bir hale gelmiştir. Ekstra masraf da bu sistemlerle beraber gelen bir yüktür.

Önceki çalışmaların aksine, yapmış olduğum yeni tasarım sayesinde motorlar kendi yunuslama ve yuvarlanma açıları yönünde eğilebilmektedir. Bu sayede kullanıcının yönlendirmesine göre quadrotor hava aracı istenen açıda havada sabit olarak konumlanabilmektedir. Bu gelişme yine aynı çalışma prensibi doğrultusunda quadrotor'un bir noktadan başka bir koordinat düzlemine yaptığı hareketi gövde açısını değiştirmeden, yalnızca motorlarının açılarını değiştirerek yapmasını sağlar. Bu seyahat boyunca önceki orijinal dizayna göre daha hızlı bir şekilde istenilen koordinat düzlemine aracın oturduğu ise Matlab üzerinde yapılan simülasyon ile gösterilmiştir. Bunun yanında geliştirme sürecinde de simulink ve Matlab programları da kullanılarak yeni algoritmalar ve kontrolcüler denenmiştir.

Bu tez çalışmasında özel bir tip quadrotor hava aracının tasarımı ve kontrolünün yapılmıştır. Literatürde görülen çalışmalarda quadrotor hava aracının çoğunlukla gövdeye sabit olarak monte edildiği, birkaç örnekte tüm rotorların hepsinin aynı oranda (tek eksen etrafında) yatabilen tipte olduğu görülebilir. Bu çalışmadaki amaç, sabit ve tek bir eksen etrafında yatabilen quadrotor hava aracının mevcut sıkıntılarının üstesinde gelinmesini sağlayacak, birçok farklı görevde kullanılabilir yeni bir hava aracı tasarımının yapılması, üretiminin gerçekleştirilmesidir. Önceki çalışmalardan farklı olarak bu hava aracındaki rotorların eğilebilmesi sağlanmaktadır. Bu tasarım hava aracının kendi gövdesini eğmesine ve kamera sisteminin görüş açısının engellenmesine gerek kalmadan aracın hareket edebilmesine imkân sağlamaktadır. Bu aracın her iki eksen etrafında yatabilen rotorları, kuvvetin istenen doğrultuda aktarılabilmesine olanak tanımıştır. Böyle bir yenilik hava aracına daha yüksek hareket kabiliyeti sağlamaktadır.

Rotorların eğilebilme imkânı her ne kadar kontrolü zorlaştırsa da, standart quadrotor hava aracının yapamayacağı bazı manevraların gerçekleştirilmesine, daha başarılı yönlendirme sağlanabilmesine imkân tanımaktadır. Bu yaklaşım standart quadrotor tasarımlarına göre büyük performans artırımı getirmiştir.

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Önerilen bu hava aracının x ve y eksenleri etrafında bağımsız olarak dönebilen rotorları sayesinde (her rotor için 2 adet olmak üzere) toplam 8 ek kontrol sinyali gerekmektedir. Her ne kadar mekanik olarak bu sistem daha karmaşık gözükse de birçok avantaj getirmektedir. Bu tasarım ile hava aracının eğilmesine gerek kalmadan hareket edebilmesi, gerektiğinde istenen şekilde ve miktarda kendi gövde açısını değiştirebilmesi sağlanabilmektedir. Hava aracının olası motor sistemi arızalara ve oluşabilecek dış bozuntulara karşı daha dayanıklı olabileceği öngörülmektedir. Mevcut quadrotor hava araçlarına göre daha iyi bir başarı getirmesi amaçlanan bu hava aracının avantajlarının ortaya çıkarılması da projenin diğer bir hedefi olup, yapılan simulasyonlar ile de desteklenmiş – gösterilmiştir.

Projenin ilk aşaması ön tasarım aşamasıdır. Gereklerin belirlenmesinin ve hava aracı parçalarının satın alınması bu aşamada yapılacaktır. Yapılan öntasarım çalışmaları sonunda, aracın özgün yazılmış algoritmalar ile simülasyon ortamında en az statik açılı motorları olan orijinal tasarım multikopterler kadar başarılı performansta uçması beklenmektedir.

Projenin ikinci aşamasında, Quadrotor hava aracının alınan parçalarla kurulması, otonom uçuş için programlanması, oluşturularak, çalışıyor olduğunun teyidi yapılacaktır.

Aracın dikey iniş kalkış ve seyir uçuşu esnasında kullanacağı itki sistemi dört alt bileşenden oluşmaktadır. İlk bileşen; göre dört adet, dişli kutusu olmayan pervaneyi 1:1 oranla çeviren; bu sayede aynı görevi yerine getiren muadillerine göre daha az gürültü çıkaran, daha verimli olan fırçasız motorlardır. Her biri azami olarak, kullanılacak pervane ile beraber maksimum devirde yaklaşık 1000-1200 gram itki sağlayabilecektir. Bu özelliği ile 4 motor gerektiği takdirde hava aracının ağırlığının 2 ila 2.5 katı arasında itki üretebilecekler; böylece aracın zor durumlardan kurtulma şansı veya bulunduğu ortamdan hızlıca yükselme olasılığı artacaktır. Bunun yanı sıra motorlar dikey eksene göre açı aldıklarında dahi aracı dengeli bir şekilde taşıyabileceklerdir. İkinci alt bileşen, dışarıdan hazır olarak alınacak olan pervanelerdir. Üçüncü alt sistem ise, fırçasız motorların sürülmesini ve kontrol edilmesini sağlayan elektronik hız kontrolcüleri olacaktır. Dördüncü ve son alt sistem ise motorları ile beraber bütün elektronik sistemi besleyen pillerdir. Günümüz pil teknolojisinin vardığı son nokta olan, yüksek akım çekilebilme kapasitesine sahip Lityum-Polimer (Li-Po) pil paketlerinin kullanılması tercih edilmiştir.

Projenin bir sonraki aşamasında simülasyon çalışması vardır. Hava aracının kontrolcüsünün Simulink ve Matlab programlarında geliştirilmesi yapılıp, statik motorlu orijinal (eğilemeyen rotorlu) hava aracına göre performansı değerlendirilecektir.

Simülasyonlarda uygun kontrolcülerin belirlenmesine müteakip, deneysel çalışmalara geçilecektir. Bu aşamada amaç, quadrotor aracının rotorlarının eğilebilir halde deneylerinin yapılması ve en dengeli kontrol yaklaşımını sağlayabilecek çeşitli kontrolcü ve sistemlerin geliştirilmesidir.

1. INTRODUCTION

In UAV control systems it is essential to build the control algorithm and the dynamics of the system such that the vehicle can have versatile and adaptive motion capabilities. Furthermore, it is always nice to have better stability features, withstand distrubances such as wind gusts, inbalances of actuators and possible failure modes in the plant.

Multicopters are one of the most advantageous tactical mission UAVs as they have vertical take off and landing feature and they have less complicated mechanical designs for instance with respect to jet engined aircrafts, typical helicopters, fuel driven planes, etc.

As being one of the types of multicopters, quadrotors have quite diversive fields of operations which makes it hard to estimate the working environments and working area of interest before. What's more due to the nonlinear behaviors of the environmental effects and actuators' transfer functions that may change in time due their life cycle behaviors, it is important to have the quadrotor's system dynamics to be adaptable to the changing conditions.

1.1 Purpose of Thesis

In order to have better overall stability, extended adaptability for changing environmental conditions and lesser overshoot and settling time performances with respect to the regular type quadrotors tilting and rolling features are added to the rotors of the proposed quadrotor. What's more the failure modes of this design is investigated and simulated so that more adaptive control of this tilt-roll rotor quadrotor can be developed for certain disturbances. In addition to that, the purpose of this thesis to establish some alternative dynamical system designs for quadrotors enabling the adaptation for the undesired conditions, compensate for possible failure modes, and work in limited environments.

1.2 Literature Review

In multirotor aircrafts there are some studies including the real life experiments with tiltable rotor geometry. Quad Tilt Rotor (QTR) is a one of the most famous types of quadrotor airframe. QTR enables the transition from helicopter mode to aircraft mode by tilting the rotors at the same time along an axis perpendicular to the front direction of the vehicle (pitch angle). It also has the benefit of extra lift [17, 18, 26]. There are two-well known experimental full-size aircraft prototypes produced: Curtiss-Wright X-19 Quad-tilt-rotor aircraft [19] and Bell X-22A [20]. X-19 was developed in 1963 which is shown in figure 1.1, and X-22A [20] was developed in 1966 which is in figure 1.2.

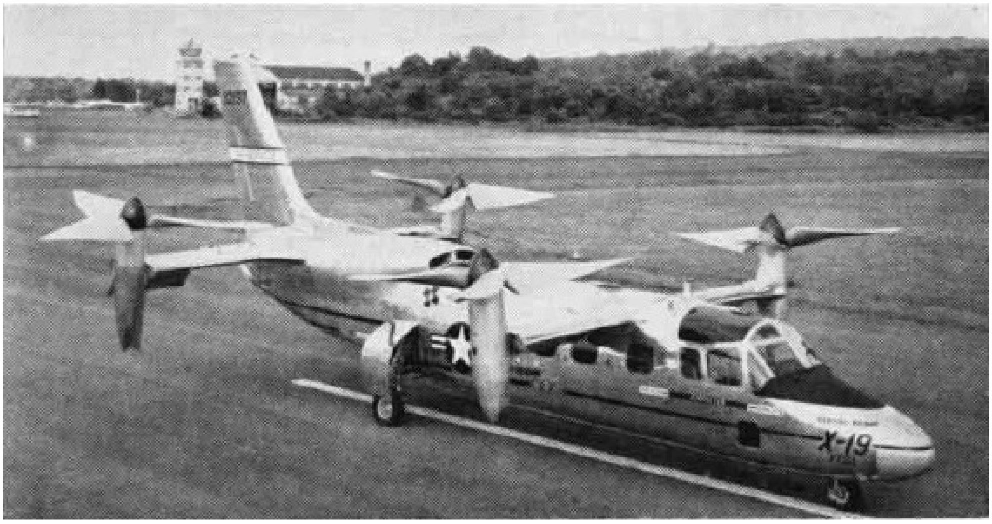


Figure 1.1: A photograph of Curtis-Wright X-19 Quad Tilt Rotor aircraft.

Figure 1.2: A photograph of Bell X-22A while flying.

Recently, Bell Helicopter and Boeing firms have announced that Bell Boeing Quad TiltRotor (V-44) is under development. V-44 will be a a four-rotor derivative of V-22 Osprey tiltrotor aircraft [21].

There are a few studies that have tiltable geometry for unmanned quadrotors. Cetinsoy et al. [22] proposed design and construction of a quad tilt-wing UAV named SUAVI in figures 1.3 & 1.4. The vehicle can switch between quadrotor to aircraft mode by tilting of all of the rotors at the same time. During the transition phase from multicopter mode to aircraft mode and vice versa, they needed to use an alternative control and stability algorithm. This algorithm is activated when the tilting angles are between 30 to 90 degrees. This control system is necessary due to winged type design and horizontal flight mode to be activated unlike in this study. The purpose of this transition state control algorithm is to keep the altitude of the vehicle at the desired value such that the aircraft can change itself into the desired form of either as a winged unit or a multicopter.

Figure 1.3: Cetinsoy's proposed design of UAV in plane mode.

When SUAVI is in horizontal position (plane mode), the horizontal control algorithm is activated. This control system uses the actuators as if they are driving the whole dynamic system as a plane. When the rotors are tilted to 90 degrees, after the transition state controller, the vertical type control algorithm is activated. In this control system, the electric motors are rotated such that they are driving the whole dynamic system as a quadrotor.

Figure 1.4: Cetinsoy's proposed design of UAV in multicopter mode.

There exists a study of Ryll et al. [23] proposed quadrotor UAV with tilting propellers. All of the 4 propellers can tilt independantly from each other about the axes connecting them to the quadrotor main body. This rotation can be actively updated during the flight conditions according to the their proposed control algorithm. Jeong et al. [24] proposed a tilting mechanism of the Omni-Flymobile that allows converting vehicle from flying mode to driving mode or vice versa by tilting rotors 90°. They have developed their system by filtering the angle values using Kalman Filter and using simple PID algorithm to control the proposed vehicle. Salazar-Cruz et al. [25] proposed stabilization and nonlinear control for a trirotor mini-aircraft, which has only one tiltable rotor. Although trirotors' stabilization, movement and control algorithms are slightly different from that of quadrotors, their idea of tilting the rotor to balance the vehicle in hover position gives inspration just as the rest of the latter works here to build my proposed thesis design.

In these studies, rotors tilt either all at the same time a pre-specified amount, or all tilt around one axis only. The main contribution of this paper is the introduction of the design and control of a novel quadrotor system. Unlike previous study that uses regular quadrotor, this study proposes an alternative propulsion system formed by tilting rotors. The rotors can be given pitch and roll angle with respect to airframe. Proposed quadrotor can enable tilting of each rotor independently along x and y axes, therefore adding 8 additional control inputs to the system. Although these additional control inputs make the system mechanically more complex, it brings various advantages. This design eliminates the need of tilting the airframe, and it suggests better performance with respect to regular quadrotor design.

2. MODELING

2.1 Frames of Coordinates

Quadrotors consist of four driver motors that are connected to four propellers in order to create the necessary thrust force to lift and move the air vehicle. In normal conditions, it is assumed that all the propellers axes of rotation are fixed to the body frame and parallel to each other. Thus, the only factor affecting to their thrust forces are created by the rotation speeds of the propellers that are driven by the rotors. In this chapter, I will introduce three types of models of quadrotors, which are regular type, tilt-roll rotor and adaptive tilt-roll rotor.

There exist mainly two types of quadrotor modes, which are named with respect to the frame type and the user's choice of interest. First one is called "+" (plus) and the other one is called "X" (cross). These names actually stand for expressing the front direction of the vehicle. In this study, we are concerned with "+" design. In plus design the front-back and sides of the vehicle coincides with plus sign. A regular "+" type quadrotor's typical free body diagram can be visualized in Figure 2.1 for better understanding of such a model.

In Figure 2.1, it can be seen that inertial frame of reference is taken to be North-East-Down (NED) frame. In this study, all the proposed quadrotors' are modeled according to NED frame. The purpose of using NED frame is that it is one of the most commonly used coordination frame model in current aircraft models. The idea is to stick with the universal frame system so that the proposed system in this thesis can be adapted to any other multi rotor system in rather easier way.

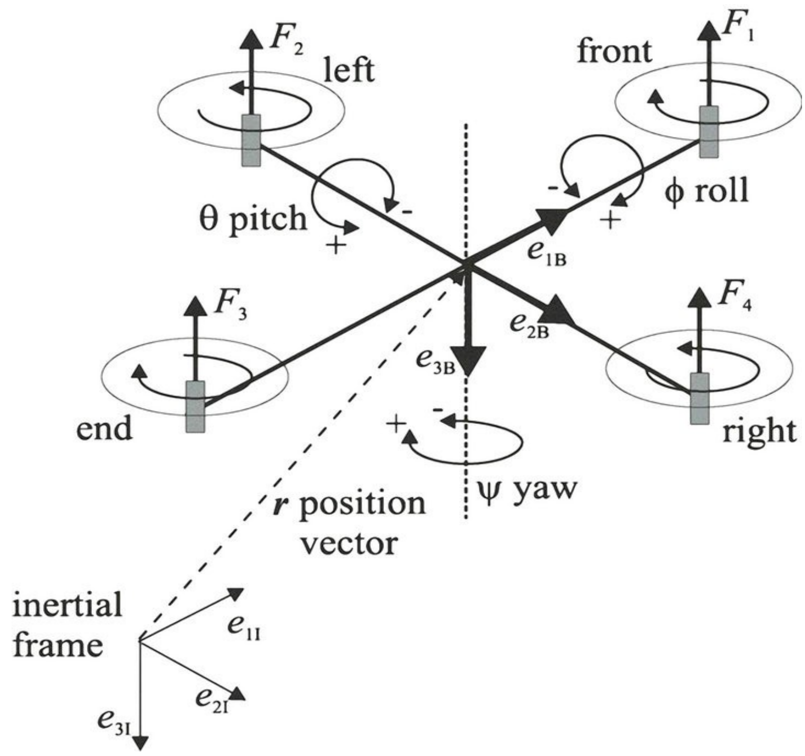


Figure 2.1: Free body diagram of a plus (+) type regular quadrotor UAV.

2.2 Modeling of a Regular Quadrotor:

Suppose that the quadrotor shown in Figure 2.1 is at hovering position without any yaw movement, this means in ideal conditions that all the rotation speeds (Ω) of the rotors are the same.

$$\Omega_1 = \Omega_2 = \Omega_3 = \Omega_4 \qquad \textbf{(2.1)}$$

In ideal conditions, we are assuming that the frame is a rigid body, propellers are rigid in plane and pitch is fixed, there is no air friction on quadrotor, free stream air velocity is zero and the design is symmetrical.

Body angular rates with respect to Euler time derivatives are introduced in the next chapter in the equations between 2.16-2.22. The calculations for the regular quadrotor model are done such that only the centre of mass of the vehicle is being concerned.

By using the momentum theory, aerodynamic thrust force of a propeller can be modeled as in the following [27]:

$$F_i = C_1 \frac{(1 - 2\pi LCS) + 2\pi(z_b - w_{z_b})}{P * \Omega_i} \quad \textbf{(2.2)}$$

Where L is the distance of center of propeller from origin, P is the pitch of propeller blade, F is the thrust force and C terms are as follows:

$$C_1 = k_t \rho A_p \Omega_i^2 R_p^2 \quad \textbf{(2.3)}$$

Where k_t is the aerodynamic thrust coefficient, ρ is a constant, A_p is the area of propeller, R_p is the radius of the propeller. According to equations, 2.2 and 2.3 C term denotes the turning direction of the rotors by taking either 1 or -1 value. Please check figure 2.1 to see the direction of rotation of the rotors.

In this study, it is assumed that the propellers are producing their thrust forces linearly. What's more, some coefficients due to the aerodynamic structure of the propellers are assumed that they are equal to one such that equation 2.3 becomes as follows:

$$C_1 = \Omega_i^2 \quad \textbf{(2.4)}$$

And similarly equation 2.3 as in equation 2.5

$$F_i = b{\Omega_i}^2 \quad \textbf{(2.5)}$$

Where, b is the drag force of the propellers. The disturbances on the propellers and wind disturbances are added as an extra function of time during simulations. Please check simulations chapter for details.

Linear momentum of the vehicle is as in the equations of 2.12-2.14.

Further model knowledge is introduced in the following sections of this chapter as they are commonly used other than the rotational motions of the rotors. In such equations, the tilt and roll angles of the rotors can be taken as 0 (zero) degrees.

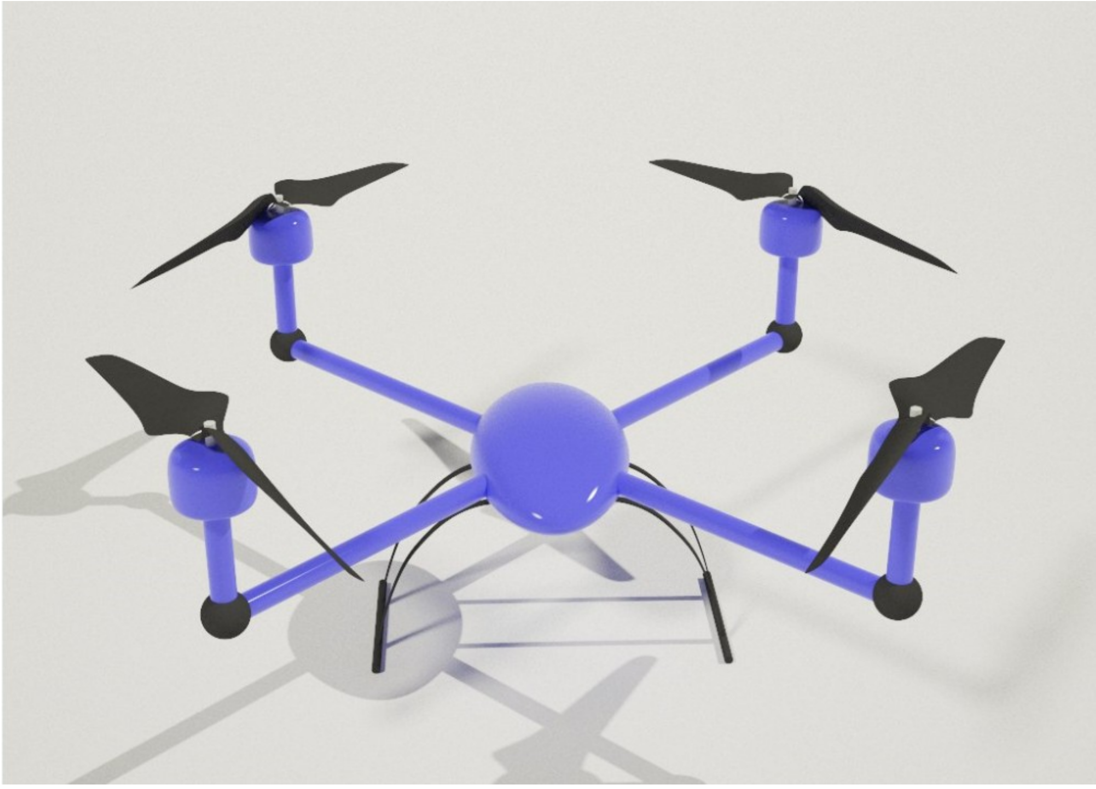


Figure 2.2: Illustration of a regular quadrotor with fixed rotors on body frame.

2.3 Modeling of Tilt-Roll Rotor Quadrotor

A regular quadrotor is an under actuated aircraft with four rotors that have fixed position with respect to the aircraft body frame. In this study, unlike in the regular definition, the rotors are able to rotate around pitch and roll angles. The required force is generated not by tilting body itself, but by tilting the required rotors. Table 2.1 presents the symbols and their definitions used in this section.

In figure 2.3 all the propellers can tilt independantly from each other about the axes connecting them to the quadrotor main body frame.

Free body representation of the tilt-roll quadrotor is given in figure 2.4 North-East-Down (NED) geographical coordinate system representation is used on this figure.

Body fixed frame is assumed to be at the center of gravity of the quadrotor where z axis is pointing downwards according to N, E, D (North, East, Down) geographical coordinate system. According to the Euler angle representation, angles of rotation about the aircraft's center of mass in x, y and z axes are defined respectively as roll (ϕ), pitch (θ) and yaw (φ). The earth's gravitational force mg is assumed to be constant and in downwards direction with respect to earth frame.

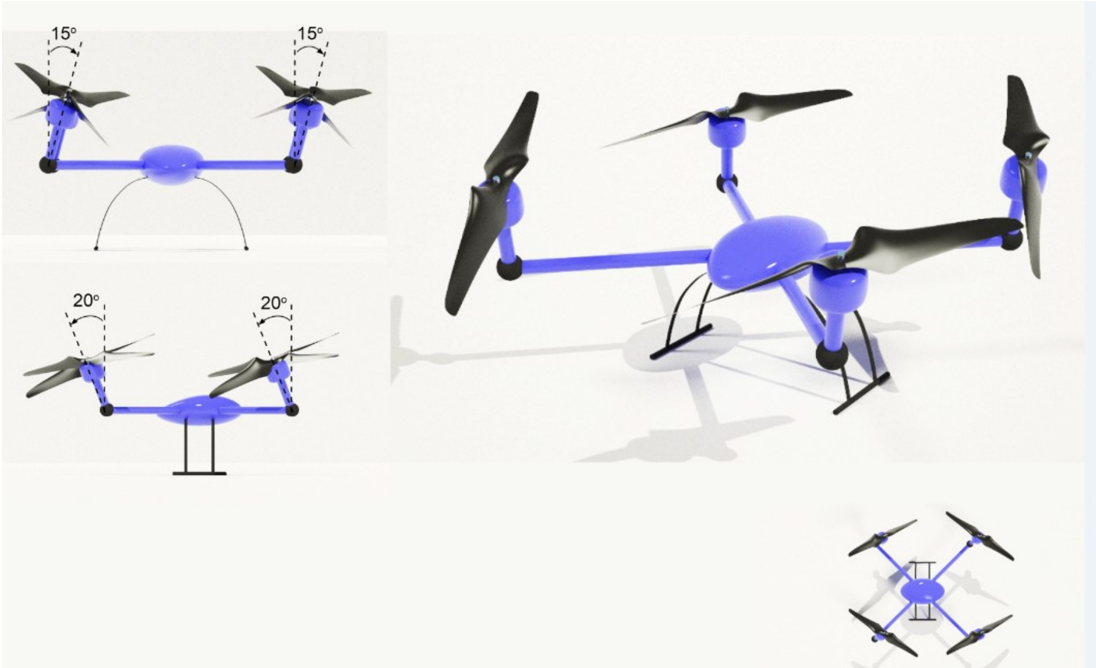


Figure 2.3: Illustration of a Tilt-Roll Rotor Quadrotor.

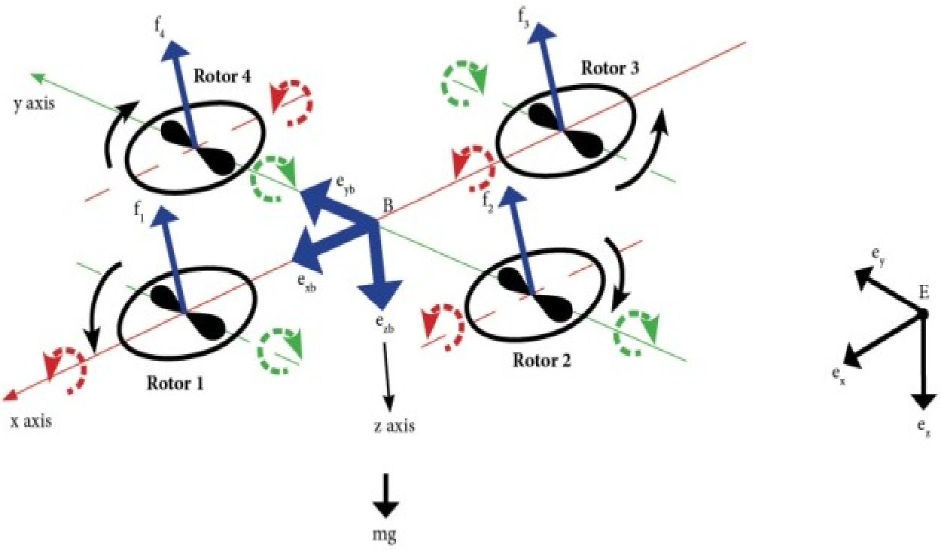


Figure 2.4: Free body diagram of a Tilt-Roll rotor quadrotor.

In figure 2.5 a close-up view of a single rotor is given. The rotation of the rotor distributes the total force of the rotor, F_i in x, y and z axes. Pitch (tilt) (θ_i), roll(ϕ_i) and angles of each of rotors are modeled and controlled where i corresponds to the rotor number $(i: 1,2,3,4)$. This rotation can be represented by a rotation matrix with Euler angles $(\varphi_i, \theta_i, \phi_i)$ as in equation (2.2) below:

$$YPR(\varphi_i, \theta_i, \phi_i) = R(z, \varphi_i).R(y, \theta_i).R(x, \phi_i) \quad \textbf{(2.6)}$$

Here yaw, pitch and roll angles $(\varphi_i, \theta_i, \phi_i)$ define the attitude of the vehicle's center of mass in the earth frame.

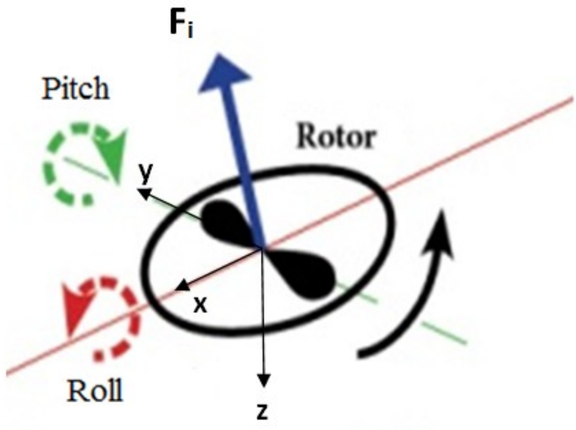


Figure 2.5: Rotor angles can be changed around x and y axes.

The force acting on the quadrotor body frame generated by this rotated Rotor 'i' is defined as F_i. Multiplication of the equation (2.2) with the thrust generated by the rotor leads to a rotated rotor thrust force vector as seen in equations 2.3 below:

$$\vec{F_i} = \begin{bmatrix} F_{ix} \\ F_{iy} \\ F_{iz} \end{bmatrix} = -F_i \begin{bmatrix} \mathrm{Sin}(\theta_i).Cos(\phi_i) \\ -Sin(\phi_i) \\ \mathrm{Cos}(\theta_i).Cos(\phi_i) \end{bmatrix} \quad \textbf{(2.7)}$$

where F_{ix}, F_{iy} and F_{iz} forces are the components of the thrust force along the x, y, and z axes respectively. Thus, the thrust of rotor *i* is equal as shown in equation 2.4 and 2.5 respectively.

$$F_i = \sqrt{F_{ix}^2 + F_{iy}^2 + F_{iz}^2} \quad \textbf{(2.8)}$$

$$F_i = b\Omega_i{}^2 \quad \textbf{(2.9)}$$

Where the rotation speeds of the motors are described by Ω_i and b is a constant namely the push factor.

For a set of required F_{ix}, F_{iy} and F_{iz} forces, corresponding tilt angles of the rotor can be calculated easily. The pitch and roll angles of the rotor and its rotation speed can be calculated as below equations:

Table 2.1: Symbols and Definitions.

Symbols	**Definitions**
e_θ	Error of pitch angle
θ_d	Desired pitch angle
θ_a	Actual pitch angle
e_ϕ	Error of roll angle
ϕ_d	Desired roll angle
ϕ_a	Actual roll angle
e_φ	Error of yaw angle
φ_d	Desired yaw angle
φ_a	Actual yaw angle
p	Angular velocity along X axis
q	Angular velocity along Y axis
r	Angular velocity along Z axis
e_X	Position error along X axis
e_Y	Position error along Y axis
e_Z	Position error along Z axis
X_d	Desired position along X axis
Y_d	Desired position along Y axis
Z_d	Desired position along Z axis
X_a	Actual position along X axis
Y_a	Actual position along Y axis
Z_a	Actual position along Z axis
U_T	Throttle Input
F_i	Force vector of propellers
y_θ	Control output for pitch angle
y_ϕ	Control output for roll angle
y_φ	Control output for yaw angle
τ_x	Total torque along x axis
τ_y	Total torque along y axis
τ_z	Total torque along z axis

$$\theta_i = atan\frac{F_{ix}}{F_{iz}} \tag{2.10}$$

$$\phi_i = asin\frac{F_{iy}}{\sqrt{F_{ix}^2+F_{iy}^2+F_{iz}^2}} \tag{2.11}$$

And using the equation 2.5 we have the rotation speeds of each of the rotor;

$$\Omega_i = \sqrt{\frac{\sqrt{F_{ix}^2+F_{iy}^2+F_{iz}^2}}{b}} \quad \textbf{(2.12)}$$

The idea behind this study is to fix the body of the aircraft to a user input reference point, so that the tilted motors will generate the required forces for stabilization. Thus, the axial forces must be calculated for the proposed aircraft to achieve necessary maneuvers. This is determined using a feedback control using the equations given in (4), where total thrust due to tilted four rotors are presented.

$$\sum_{i=1}^{i=4} F_{i_x} = F_x \quad \textbf{(2.13)}$$

$$\sum_{i=1}^{i=4} F_{i_y} = F_y \quad \textbf{(2.14)}$$

$$\sum_{i=1}^{i=4} F_{i_z} = F_z \quad \textbf{(2.15)}$$

Note that in order to maintain the hover position, $\mathrm{F_z} = \mathrm{mg}$ equivalence should be determined (in ideal conditions). Choosing the earth coordinate system where Z axis is pointing upwards, the actual accelerations of the aircraft can be determined:

$$\ddot{X}_a = \sum \frac{Fx}{m} \quad \textbf{(2.16)}$$

$$\ddot{Y}_a = \sum \frac{Fy}{m} \quad \textbf{(2.17)}$$

$$\ddot{Z}_a = \sum \frac{Fz}{m} - g \quad \textbf{(2.18)}$$

Vehicle's attitude and its time derivative in the world frame are defined as,

$$\alpha_w = [\varphi_i \quad \theta_i \quad \phi_i]^T \quad \textbf{(2.19)}$$

$$\Omega_w = \dot{\alpha_w} = [\dot{\varphi_\iota} \quad \dot{\theta_\iota} \quad \dot{\phi_\iota}]^T \quad \textbf{(2.20)}$$

Orientation of the body frame with respect to NED frame must be rotated with a transformation matrix called rotation matrix. Converting the body frame with respect to the world frame is given as in 2.21 below:

$$R_{B2W} = \begin{bmatrix} c(\varphi)*c(\theta)-s(\phi)*s(\varphi)*s(\theta) & c(\theta)*s(\varphi)+c(\varphi)*s(\phi)*s(\theta) & -c(\phi)*s(\theta) \\ -c(\phi)*s(\varphi) & c(\phi)*c(\varphi) & s(\phi) \\ c(\varphi)*s(\theta)+s(\phi)*s(\varphi)*c(\theta) & s(\varphi)*s(\theta)-c(\varphi)*c(\theta)*s(\phi) & c(\phi)*c(\theta) \end{bmatrix} \quad \textbf{(2.21)}$$

Similarly by using the rotation matrix in 2.21 we can convert the velocities of the vehicle as follows:

$$V_{quad} = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = R_{B2W}^T(\phi_i \quad \theta_i \quad \varphi_i).V_{world} \quad \textbf{(2.22)}$$

$$= R_{W2B}(\phi_i \quad \theta_i \quad \varphi_i).V_{world}$$

Angular velocities of the vehicle is represented by p, q and r (see Table 2.1). The formula for these values are given in equation 2.23.

$$\mathrm{T}(\alpha_\mathrm{w}).\Omega_\mathrm{w} = \begin{bmatrix} \mathrm{p} \\ \mathrm{q} \\ \mathrm{r} \end{bmatrix} \quad \textbf{(2.23)}$$

By using the equation 2.19 we have;

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = T(\alpha_w).[\dot{\varphi}_i \quad \dot{\theta}_i \quad \dot{\phi}_i]^T \quad \textbf{(2.24)}$$

Where $\mathrm{T}(\alpha_\mathrm{w})$ is the transformation matrix for velocity. That is in the form of the following matrix;

$$T(\alpha_w) = \begin{bmatrix} 1 & 0 & -\mathrm{Sin}(\theta_i) \\ 0 & Cos(\phi_i) & -Sin(\phi_i)*\mathrm{Cos}(\theta_i) \\ 0 & -Sin(\phi_i) & \mathrm{Cos}(\theta_i)*Cos(\phi_i) \end{bmatrix} \quad \textbf{(2.25)}$$

By taking the derivative of equation 2.24, we can have the angular acceleration of the vehicle which is calculated as in the following:

$$\begin{bmatrix} p(t) \\ q(t) \\ r(t) \end{bmatrix} dt = \begin{bmatrix} \frac{\tau_x(t)}{I_{xx}} \\ \frac{\tau_y(t)}{I_{yy}} \\ \frac{\tau_z(t)}{I_{zz}} \end{bmatrix} \tag{2.26}$$

Where τ terms stand for moments on arms due to the thrust forces generated by each of the arms, and I terms denote the mass moment of inertia which is assumed to be constants for each of the axes. In order to control the tilt-roll rotor quadrotor axial forces and torque (moment) values have to be equalized. That's why we need to balance the terms in the equations of 2.9-2.11, 2.20 and 2.22. In 2.22 we want constant angular acceleration value of 0 (zero) in ideal conditions. However, our proposed design with adaptive control would not need this requirement in some certain range.

Total moment, M_t is calculated using the following equation:

$$M_t = M_d + M_{gyro} + M_{th} \tag{2.27}$$

Where M_d denotes the external disturbances, M_{gyro} is the gyroscopic effects of the propellers and M_{th} denotes the moment created by the rotation of the rotors. In this study we are interested with M_{th} along x, y and z axes and take M_{gyro} and M_d as random total disturbances changing in time. Therefore we can assume that

$$M_{random} = M_d + M_{gyro} \tag{2.28}$$

Then equation 2.23 becomes as follows:

$$M_t = M_{random} + M_{th} \tag{2.29}$$

2.4 Modeling of an Adaptive Tilt-Roll Rotor Quadrotor

In this study, it is assumed that M_{random} value is changing in time along one axis of an actuator. Suppose that this issue occurs with quadrotor`s one of the axes due to external (i.e. wind gusts) or internal (i.e. rotor, frame structure, propeller gains) disturbances. For ease of formulation x vector is chosen as the effected axis (any of axes x, y or z can be chosen). Let's say the total disturbances effecting on x axis of motor 1 is called the force penalty factor, f_{pe}, where f_{pe} is assumed to be randomly changing between 0.1 to 1.9. In this example we let this gain factor to be changing randomly to represent any disturbance function that is changing in time. In fact this function can be any polynomial that has the following relation in any given time t:

$$1.9 > f_{pe}(t) > 0.1 \quad \textbf{(2.30)}$$

This penalty factor represents the total random disturbances acting on one of the actuators including gyroscopic effects of the rotors, external disturbances and electro-mechanical inefficiencies of the electrical motor in time. Therefore, it can have direct effect to change the force gains of F_{x_i} and F_{z_i}.

For example, once the control algorithm determines required output speeds and angle values for the rotors which in normal conditions will produce a total desired thrust force of F_t. In this instance f_{pe} is introduced to the system as a gain factor on F_t. Suppose that $f_{pe} = 0.75$ and is effective only on x axis. In this case force vector on x axis will be $0.75\,F_x$ instead of F_x. It is not possible to control and stabilize the quadrotor with inequalities that exist in total torque and force vectors on axes. The modeling of the system is designed so that the same magnitude of F force will be produced at the defected axis without losing altitude and yaw control. Therefore, the resultant force F_{t_i} must be updated iteratively with adapted force vector of $F_{t_{new_i}}$. This can be achieved by changing the angle of the rotor while changing the speed of the rotor (i.e. changing the thrust force) so that the total force will be the same. In figure 4, the free body diagram of such system is given where β is the desired angle in ideal conditions that stands for the resultant force F_t and α is the updated angle for the updated force vector $F_{t_{new}}$ Finally the desired values of F_x and F_z must be close enough (in tolerance limits of 1 %) so that the equilibrium of the forces is maintained as of before. We can say that (β-α) and change in the speeds of the rotors, Ω_i are proportional to each other. i.e. if (β-α) gets smaller then Ω_i is expected to change in smaller amounts and vice versa for the case in which (β-α) gets bigger. If (β-α)=0 this indicates that the rotor speed, Ω_i will not change. Figure 2.6 represents one of the motor's force relation in 2D space including $F_x, F_z, F_t, F_{t_{new}}$. while adaptively controlling the halted direction.

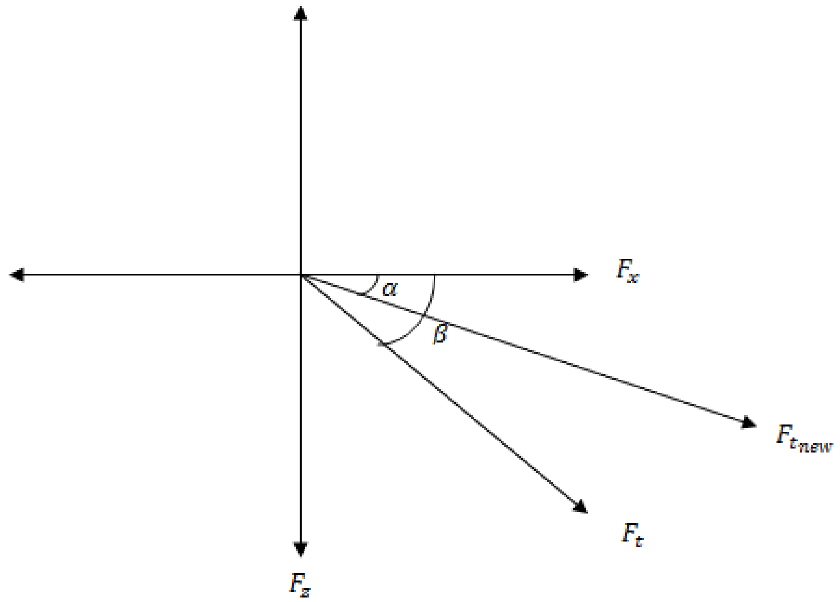


Figure 2.6: Free body diagram of adaptively corrected angle and force values.

3. CONTROL

In this thesis, there are mainly three design types of quadrotors' control system has been studied. Firstly, a regular quadrotor with fixed rotor angles with 0 (zero) degree has been worked on. By the means of zero degree, I take the propellers' thrust forces perpendicular to the body frame when the rotor angles are equal to zero. It is the same position as in figure 2.1 as introduced before.

In order to get rid of the complexity of nonlinear controllers, and differences of controller characteristics, during this study I decided to apply a universal control system, which I can use in every steps of the development of the new designs. Thereby, I choose to use PID controller for control and simulation steps of this study. Furthermore, when different models and approaches will be compared with each other; PID controller can easily be modified such that there will be rather few differences in the control parameters and variables. This is beneficial to compare two different models' performance characteristics and it is rather faster to establish and apply the same controller to both systems.

I first choose to apply a single layer PID controller where angle values of yaw (φ), pitch (θ), roll angles (ϕ) and throttle (U_T) are given as inputs by the user during active flight. The IMU (Inertial Measurement Unit) is at the same time measuring the actual angle values of the body frame and control the four of the rotors speed as output. However, this kind of a control is hard to compare as the user should be actively have to give some input and also the single layer PID controller is known to have rather worse performance characteristics with respect to a cascaded control system. That's why I upgraded the single layer PID controller system into more sophisticated, 4 layer cascaded PID controller where the user can just input the desired destination coordinates, and then the quadrotor can track that destination by arranging the rpm distributions of the rotors while holding quadrotor's stabilization and leading the vehicle to the desired location.

3.1 Control of a Regular Quadrotor

During this thesis, all of the quadrotors mentioned including regular quadrotors, the control system used is a cascaded type PID. For starters, the user has the option to define the following inputs and enter them to the control system respectively: desired coordinates of; X_d, Y_d, Z_d and starting angles of yaw (φ_{init}), pitch (θ_{init}) and roll (ϕ_{init}) (start point angles are assigned as inputs for simulation purposes only. In real life, AHRS (Attitude and Heading Reference System) will assign these angle values automatically). Before starting the flight, user is also able to assign the maximum velocity (v) and maximum angle (γ) values as constraints. Simple notation can be seen in eq. (3.1). (Please see table 2.1 for symbols and definitions).

$$\mathrm{Input}(X_d, Y_d, Z_d, \varphi_{init}, \theta_{init}, \phi_{init}) \underset{\max v,\gamma}{\Longrightarrow} \mathrm{Output}(\Omega_i, X_a, Y_a, Z_a, \varphi, \theta, \phi) \quad \textbf{(3.1)}$$

Once the inputs are assigned including the max velocity and angle values (by trial and error I have set max velocity to be 7 coordinates/second and max angle to be 20 degrees. Here we can assume that 1 coordinate distance is equal to 1 meter. Then max velocity becomes 7 m/s). After that, the following equations take place for PID control of the regular quadrotor. For altitude hold;

$$e_Z = Z_d - Z_a \quad \textbf{(3.2)}$$

$$U_T(t) = U_T(t-1) + Kp * e_Z - Kd * \frac{(\dot{Z})_a}{dT} \quad \textbf{(3.3)}$$

In addition, for calculating the velocity, position, desired angles to reach the target are calculated as follows:

Location errors are found:

$$e_X = X_d - X_a \quad \textbf{(3.4)}$$

$$e_Y = Y_d - Y_a \quad \textbf{(3.5)}$$

Velocity equations are defined in 3.6 and 3.7:

$$\dot{X}_d = \frac{Kp * e_X}{dT} - Kd * \dot{X}_a \quad \textbf{(3.6)}$$

$$\dot{Y}_d = \frac{Kp * e_Y}{dT} - Kd * \dot{Y}_a \quad \textbf{(3.7)}$$

Once the desired velocities are estimated from 3.6 and 3.7 the following set of, equations are activated in the algorithm;

Velocity errors are calculated:

$$\dot{e_X} = \dot{X}_d - \dot{X}_a \quad \textbf{(3.8)}$$

$$\dot{e_Y} = \dot{Y}_d - \dot{Y}_a \quad \textbf{(3.9)}$$

Having known the desired velocities, their errors and the accelaration of vehicle's center of mass, we can estimate and set the desired angles from the following PID loop:

$$\theta_d = \frac{Kp * \dot{e_X}}{dT} - Kd * \ddot{X}_a \quad \textbf{(3.10)}$$

$$\phi_d = \frac{Kp * \dot{e_Y}}{dT} - Kd * \ddot{Y}_a \quad \textbf{(3.11)}$$

And finally as we have the desired pitch, roll and yaw angles, we can calculate the necessary thrust forces which then be obtained by the rotation speeds of the propelers as given in detail in chapter 2.

$$e_\theta = \theta_d - \theta_a \quad \textbf{(3.12)}$$

$$e_\phi = \phi_d - \phi_a \quad \textbf{(3.13)}$$

$$e_\varphi = \varphi_d - \varphi_a \quad \textbf{(3.14)}$$

Angular rates during the flight interval are calculated as follows;

$$\dot{\theta} = \frac{p}{dT} \quad \textbf{(3.15)}$$

$$\dot{\phi} = \frac{q}{dT} \quad \textbf{(3.16)}$$

$$\dot{\varphi} = \frac{r}{dT} \tag{3.17}$$

Then control outputs are obtained as in the following form:

$$y_\theta = Kp * e_\theta(t) - Kd * p + Ki * \int_{t=0}^{t=\infty} e_{\theta(\tau)}\, d\tau \tag{3.18}$$

$$y_\phi = Kp * e_\phi(t) - Kd * q + Ki * \int_{t=0}^{t=\infty} e_{\phi(\tau)}\, d\tau \tag{3.19}$$

$$y_\varphi = Kp * e_\varphi(t) - Kd * r + Ki * \int_{t=0}^{t=\infty} e_{\varphi(\tau)}\, d\tau \tag{3.20}$$

Then the force and rpm distribution of the rotors are obtained as in equations 3.21-3.24:

$$F_1 = \frac{U_T}{4} - \frac{y_\theta}{2} + \frac{y_\varphi}{4} \tag{3.21}$$

$$F_2 = \frac{U_T}{4} - \frac{y_\phi}{2} - \frac{y_\varphi}{4} \tag{3.22}$$

$$F_3 = \frac{U_T}{4} + \frac{y_\theta}{2} + \frac{y_\varphi}{4} \tag{3.23}$$

$$F_4 = \frac{U_T}{4} + \frac{y_\phi}{2} - \frac{y_\varphi}{4} \tag{3.24}$$

3.2 Control of a Tilt – Roll Rotor Quadrotor

The control of the tilt-roll rotor quadrotor differs from the regular quadrotor. In this section, proposed controllers are presented.

In this work, the control algorithm is designed so that all the motors tilt with same angle values depending on the control output. This approach simplified the control work significantly, at a cost of reducing the potential benefits of the vehicle.

Calculating the θ_i and ϕ_i value of a single motor would be sufficient in terms of controllability of the system. This concept of this study lets all of the four motors to rotate at the same speed so that they produce the same amount of resultant forces $F_1 = F_2 = F_3 = F_4$. This will be different, if the motors act separately from each other with different rotational speeds and rotational angles. This concept will be considered in the future work.

For performance and applicability purposes, cascaded PID control is chosen for control and simulation of the proposed aircraft. There exists total of 4 cascaded PID loops where each of motor angles are controlled with the inputs received from the vehicle's position, velocity, altitude and total force vectors. In order to control all of these inputs, the following equations should be satisfied:

$$F_{i_x} = \frac{y_\theta}{4} \quad \textbf{(3.25)}$$

$$F_{i_y} = \frac{y_\phi}{4} \quad \textbf{(3.26)}$$

$$F_{1_z} = F_{3_z} = \frac{U_T}{4} + \frac{y_\varphi}{4} \quad \textbf{(3.27)}$$

$$F_{2_z} = F_{4_z} = \frac{U_T}{4} - \frac{y_\varphi}{4} \quad \textbf{(3.28)}$$

where throttle, U_T, is applied as an input in order to increase/decrease motor speeds so that the aircraft can increase, decrease or maintain its altitude (hover position).

For control purposes the angle errors must be determined. The angle errors are calculated using the formula in equation 3.12-3.14. Normally these equations are for calculationg body angle, we are now concerned with motor angles.In non-adaptive version of tilt-roll rotor quadrotor these angle calculations still hold as all the rotor angles are equal to each other.

Then control output, y_θ, y_ϕ and y_φ are already determined using the PID loops in equations 3.18-3.20:

For velocity, position and angle control of the aircraft please see the equations 3.4-3.17 in the previous chapter. However, in this case we are both controlling the y_θ, y_ϕ and y_φ outputs of the body frame and the rotor angles of y_{θ_i} and y_{ϕ_i}.

For altitude hold control of the aircraft, equations in 3.2 and 3.3 are used.

By controlling current throttle parameter in 3.3, one can control the altitude of the vehicle. It is useful to control the throttle value by using a feedback loop for a robust design for altitude hold purposes.

Unlike in regular quadrotor, calculation of the torque parameters also differ. There are 16 torque values to be calculated and moment equilibrium is defined as in the following matrices, where L_i is the armlength of the quadrotor and force F values please check equations 3.29-30:

$$\begin{bmatrix} \tau_{1_x} \\ \tau_{1_y} \\ \tau_{1_z} \\ \tau_{2_x} \\ \tau_{2_y} \\ \tau_{2_z} \\ \tau_{3_x} \\ \tau_{3_y} \\ \tau_{3_z} \\ \tau_{4_x} \\ \tau_{4_y} \\ \tau_{4_z} \end{bmatrix}_{16x1} = \begin{bmatrix} F_{1_x} \\ F_{1_y} \\ F_{1_z} \\ F_{2_x} \\ F_{2_y} \\ F_{2_z} \\ F_{3_x} \\ F_{3_y} \\ F_{3_z} \\ F_{4_x} \\ F_{4_y} \\ F_{4_z} \end{bmatrix}_{16x1} * [L_1\ L_1\ L_1\ L_2\ L_2\ L_2\ L_3\ L_3\ L_3\ L_4 L_4\ L_4]_{1x16} \quad \textbf{(3.29)}$$

Using the torque and force relations in the matrix introduced in 3.29 we can calculate the angular accelaration of the vehicle as in the following:

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \tau_{3_x} + \tau_{4_x} - \tau_{1_x} - \tau_{2_x} \\ \tau_{3_y} + \tau_{4_y} - \tau_{1_y} - \tau_{2_y} \\ \tau_{3_z} + \tau_{4_z} - \tau_{1_z} - \tau_{2_z} \end{bmatrix} * \begin{bmatrix} \frac{1}{I_{xx}} & \frac{1}{I_{yy}} & \frac{1}{I_{zz}} \end{bmatrix} \quad \textbf{(3.30)}$$

Please check figure 3.1 to visualise the simplified form of the cascaded PID used in the control algorithm. For regular quadrotor, rotor angles can be assumed to be zero degrees, meaning that they are perpendicular to body frame.

Note that the control output values in PID loops are constrained in safe limits so that the aircraft would not make too aggressive maneuvers.

3.3 Control of an Adaptive Quad Tilt –Roll Rotor Quadrotor

In this part adaptive control and optimal control algorithm is introduced. The control of the tilt-roll rotor quadrotor differs from the regular quadrotor. The target is having a fully functional multi-rotor without moving the body frame but the motor axes. In this chapter, the control algorithm is designed so that all the motors can be able to tilt and/or roll independently from each other.

For performance and applicability purposes, cascaded PID control is chosen for control and simulation of the proposed aircraft as introduced in the previous chapters. There exists total of 4 cascaded PID loops where each of motor angles are controlled with the inputs received from the vehicle's position, velocity, altitude and total force vectors. Please see the block diagram in figure 3.1.

In this study the adaptive control of the aircraft is designed assuming that the aircraft will go towards to one direction at a time in 2D space. In the examples and formulation given in modeling and control chapters these axes are chosen to be X and Z. An adaptive control algorithm for tilt-roll rotor quadrotor is proposed. In order to stabilize the system in figure 2.6 in which free body diagram of an actuator on the tilt-roll rotor quadrotor in 2D space is illustrated, force values are adaptively corrected by changing the rotation speeds and tilt-roll angles of the rotor.

By having these facts the following expressions can be obtained:

$$F_z = F_t * \sin(\beta) \tag{3.31}$$

$$F_{x_{gained}} = F_t * \cos(\beta) * f_{pe} \tag{3.32}$$

Where $F_{x_{gained}}$ represents the final value of $F_x$if no adaptive stabilization is applied on this axis (ie less than desired x force, F_x if $f_{pe} < 1$ and more if vice versa). Thus, if $f_{pe} = 1$ then $F_{x_{gained}} = F_x$

Similarly;

$$F_x = F_t * \cos(\beta) \tag{3.33}$$

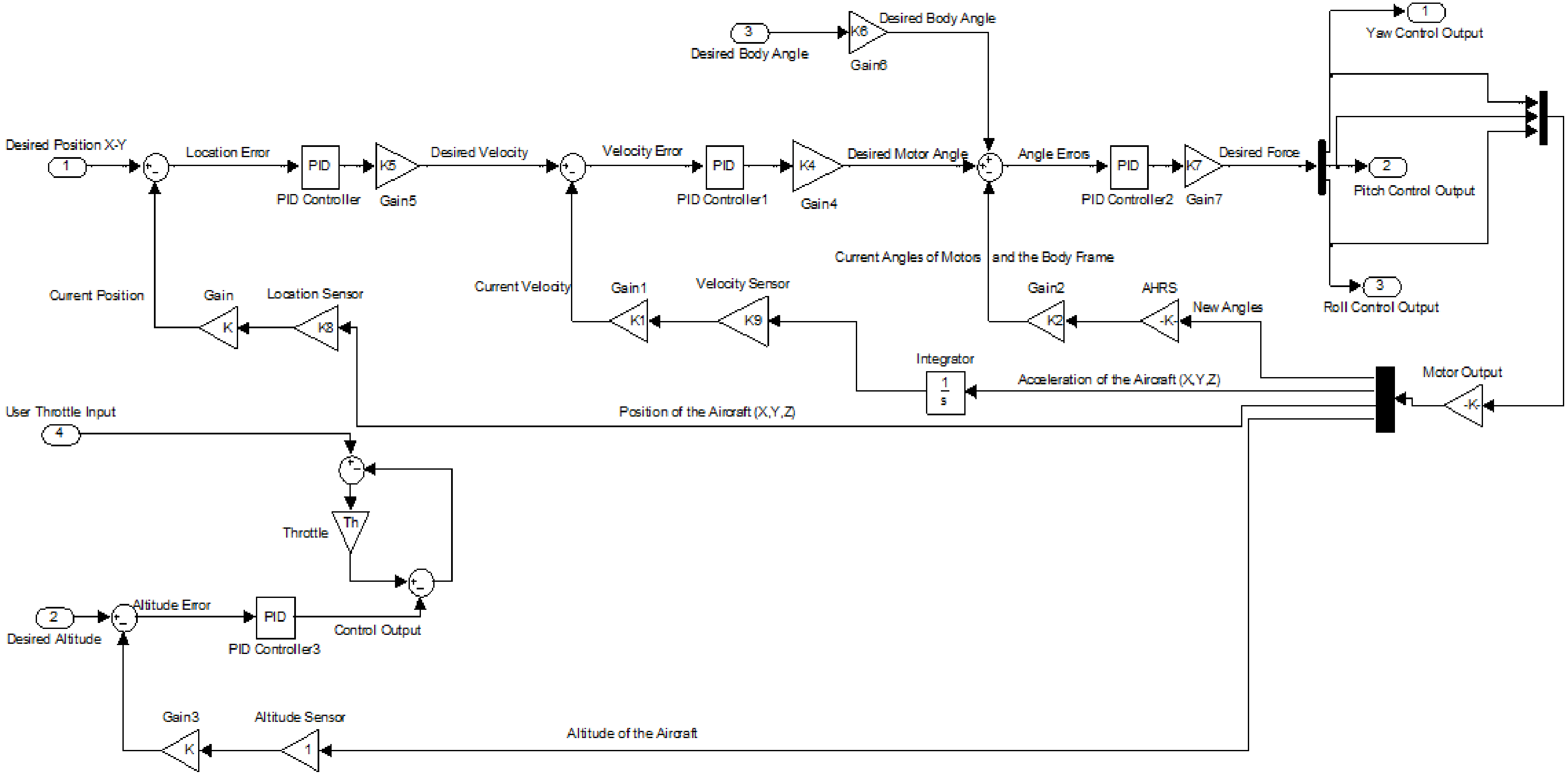


Figure 3.1: Block diagram of the PID control algorithm of proposed Quadrotor.

After adding the new angles and force vectors we get:

$$F_x = F_{t_{new}} * \cos(\alpha) * f_{pe} = F_t * \cos(\beta) \tag{3.34}$$

And

$$F_z = F_{t_{new}} * \sin(\alpha) = F_t * \sin(\beta) \tag{3.35}$$

By using the equations (7) and (8) new resultant force can be estimated as in the following:

$$F_{t_{new}} = F_t * \frac{\cos(\beta)}{\cos(\alpha) * f_{pe}} = F_t * \frac{\sin(\beta)}{\sin(\alpha)} \tag{3.36}$$

This is equal to the following equalities;

$$F_{t_{new}} * \cos(\alpha) * f_{pe} * \sin(\alpha) = F_t * \cos(\beta) * \sin(\alpha) = F_t * \sin(\beta) * \cos(\alpha) * f_{pe} \tag{3.37}$$

By using (10), the adapted angle, α is obtained as follows:

$$\alpha = \tan^{-1}\left(\frac{\sin(\beta) * f_{pe}}{\cos(\beta)}\right) \tag{3.38}$$

Once the adapted angle values are calculated as in 3.38, the rest of the control system is controlled just as in the part 3.2 of this thesis.

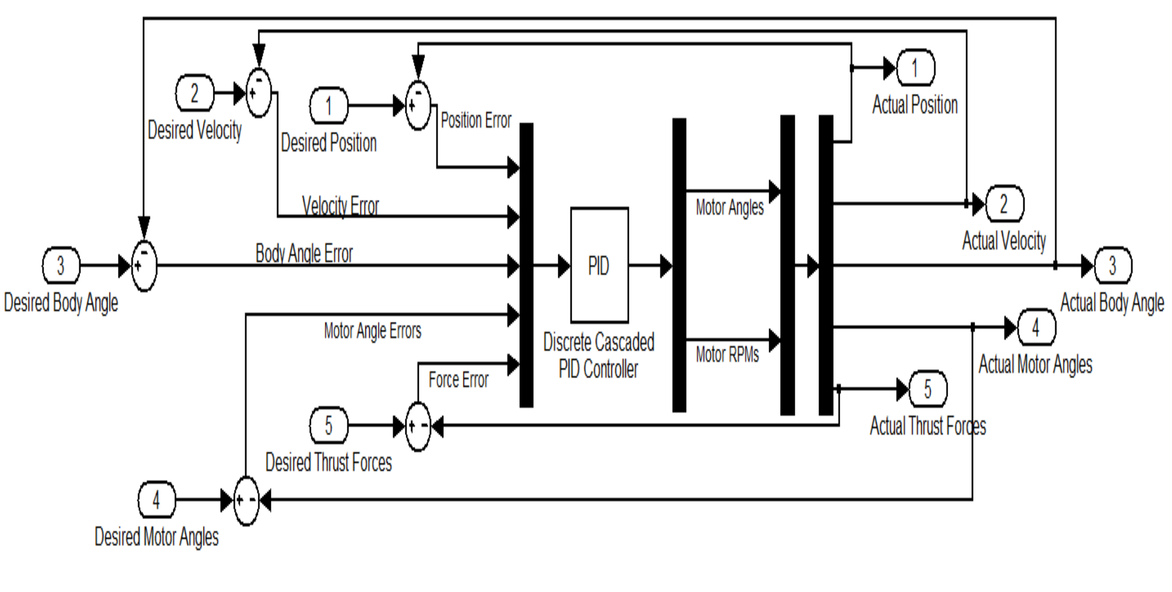


Figure 3.2: Simplified Cascaded Block Diagram of Tilt-Roll Rotor Quadrotor.

4. SIMULATION

Dynamic behaviors of proposed quadrotors are compared using simulations generated in Matlab and Simulink. A code in Matlab using cascaded PID algorithm which is already being explained in part 2 and 3 has been developed such that all types of quadrotors' simulation can be done in the same platform. In this section, the simulation results will be presented and the performance of the proposed vehicle will be compared to a typical regular fix rotor quadrotor.

In this study, the body frame angles of roll and pitch can be kept still at some user-defined value while the aerial vehicle is travelling along 3D coordinates. During the simulations given in the upcoming chapters θ, ϕ and φ angles are dynamically changed such that the quadrotors will come across with the worst case scenarios possible.

In the developed simulation platform, user can input the start and target coordinates for the quadrotors. Moreover, body frame angles, θ, ϕ and φ of the quadrotors can be set. In addition to these features the vehicle's throttle, θ, ϕ and φ angles can be changed during the flight simulation as if the user is using an RF remote controller for the vehicle.

In order to compare all the cases what's called as apples-to-apples the start and target coordinates are set the same for part 4.1. For part 4.2 due to the inability to control in 3D motions, the start coordinates are set the same but target destination has been changed. In this case, the starting coordinates are set as x=1, y=1, z=0 and desired position is set at x=18, y=18, z=8 on part 4.1. At the beginning the yaw angle, φ angle is set to -10 degrees according to the Earth's geographical coordinates.

4.1 Simulation Results of Regular Quadrotor vs. Tilt – Roll Rotor Quadrotor

When comparing the performance characteristics of a regular quadrotor versus proposed tilt-roll rotor quadrotor, At t=1, the vehicles' yaw angles, φ are changed from -10 to +10 degrees. When t=6, φ angles are set to 0 (zero) degrees. Moreover, θ, ϕ angles of the bodies are fixed to 0 (zero) degrees initially. In other words, remote controller input is set to zero degrees but the vehicles can autonomously change their body angles with respect to their controller outputs. In simulation 1, as shown in figure 4.1, yaw angle stabilization performance of tilt-roll rotor quadrotor is tested. During the simulation, in fact not only the yaw angle is assessed but also the tilt (θ_i) and roll (ϕ_i) angles (of rotors) are dynamically changing in time depending on the required control output fedback from cascaded PID algorithm.

In figures 4.2, 4.3 and 4.4, two types of quadrotors, the regular fixed rotor and the tilt-roll rotor, are plotted. During these simulations, both of the quadrotors track the same path to some pre-assigned coordinates. Their comparison in terms of settling time, maximum overshoot and reaching the target points are analysed.

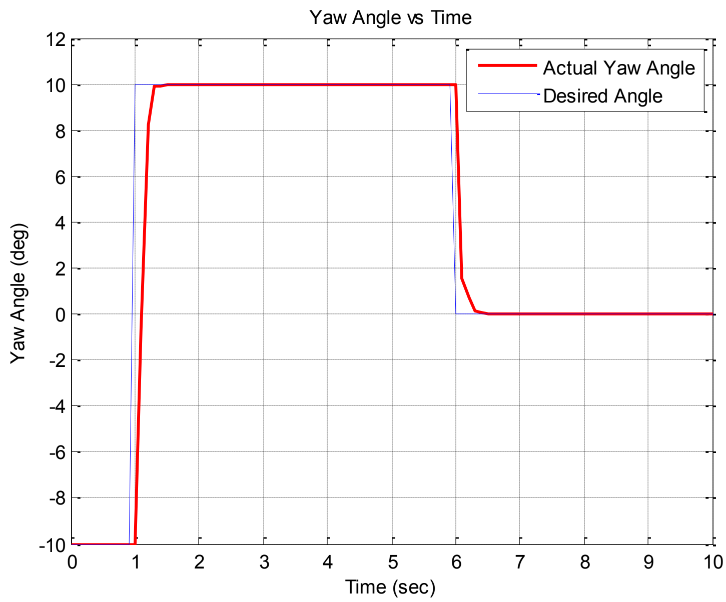


Figure 4.1: Tilt-roll rotor quadrotor yaw angle (φ) vs time simulation.

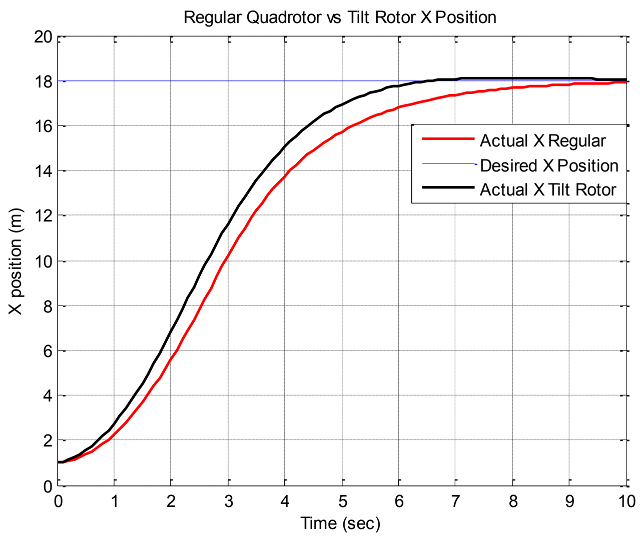


Figure 4.2: Regular vs. Tilt-roll quadrotor settling to desired position (x).

By looking at the resulting plots in the figures 4.2, 4.3 and 4.4; the new approach tilt-roll rotor quadrotor has better performance in terms of having lesser settling time in x, y and z coordinates. What's more, in figure 4.4 it is observed that the regular quadrotor has more overshoot value between 5th to 6th seconds of the graph.

"By examining the plots, it can be noted that in overall performance the tilt-roll rotor quadrotor has better results in terms of smaller overshoot and smaller settling time as compared to the regular fixed rotor quadrotor. However, both of the systems are controlled with relatively complex cascaded PID parameters which include at least 13 different PID coefficients. That's why additional tuning can be done by changing these coefficients so that both of the systems' performances will get better [26]."

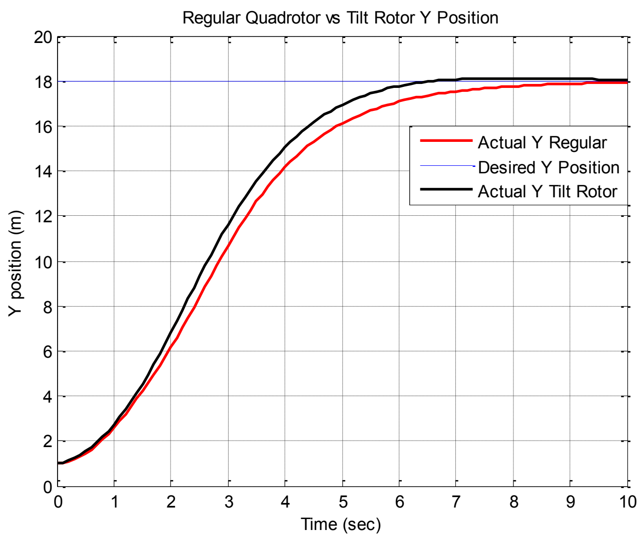


Figure 4.3: Regular vs. Tilt-roll quadrotor settling to desired position (y).

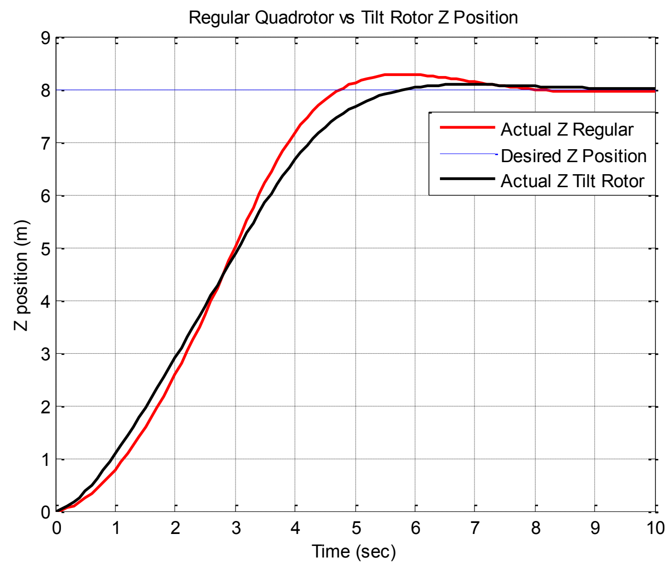


Figure 4.4: Regular vs. Tilt-roll quadrotor settling to desired position (z).

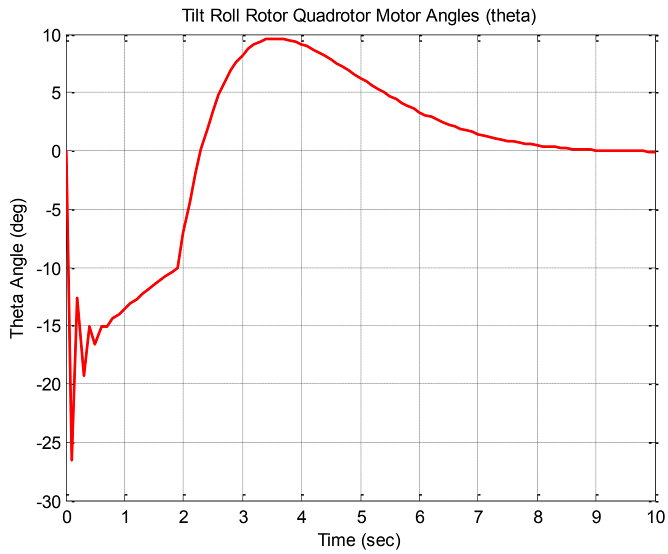


Figure 4.5: Tilt-Roll Rotor quadrotor's theta angle while cruising.

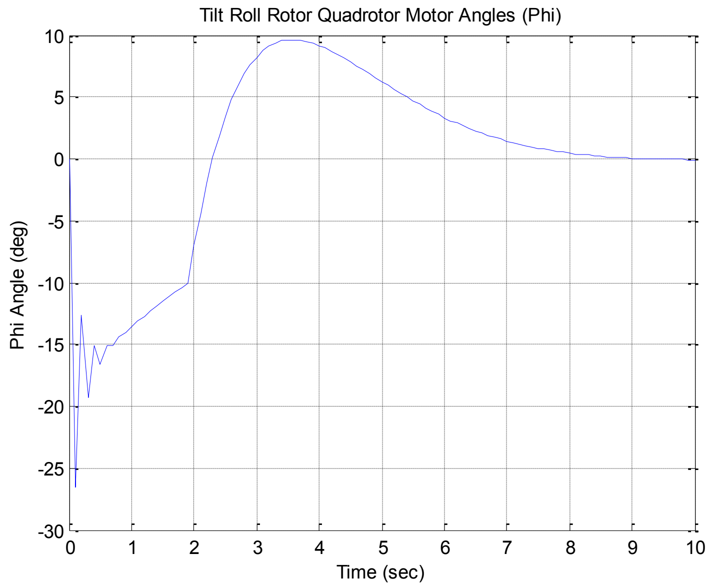


Figure 4.6: Tilt-Roll Rotor quadrotor's phi angle while cruising.

The most adventegeous feature of the tilt-roll rotor quadrotor is the way it moves. It is able to move by tilting the rotors, not the body frame unlike the typical design. The ability of tilting rotors promises a more stable flight of the airframe. the tilt (θ_i) and roll (ϕ_i) angles during the simulation are visualized in figures 4.5 and 4.6. The motor angles in these simulations are referenced with respect to the earth frame. All the rotor angles in non-adaptive tilt-roll quadrotor take the same value once the required angle values are calculated with control system. Due to the fact that the simulation inputs (from x=1, y=1 to x=18, y=18) and starting points of θ and ϕ are the same, the two graphs of θ and ϕ exactly match each other in this simulation.

As seen on the same graphs, at t=9 both of the motor angles get to zero degrees because the desired positions of x and y are reached by the aircraft. At this point, there is only need for vertical force which can be achieved by having the motors to be in upward position with respect to the earth frame ($\theta = \phi = 0°$).

4.2 Failure Mode Compensation Results of Adaptive Mode

The first simulation is done to compare 3 quadrotors that have 3 different control designs. They are being introduced with the same trajectory to track on x and z axes. The first quadrotor, Quad1, is a regular quadrotor whose frame position changes during time to change position and angles. The rotors of Quad1 are fixed and assumed to have no tilting or rolling motion. The second quadrotor, Quad2, is the tilt-roll rotor quadrotor that is proposed in [26]. Quad2 does not support adaptive control algorithm against disturbances such as gyroscopic effects, actuator inequalities, outside environmental effects (i.e.wind gusts) etc. Quad2's body frame stays almost at the pre-defined initial body frame angle. In this case it is set as zero degrees during the trajectory tracking and it is able to change coordinates by tilting & rolling of its rotors. Quad2's all the rotor angles are able to change at the same time. Quad3 is almost the same as Quad2 but it is further developed with the proposed adaptive control algorithm which enables the Quad3 to change its rotor speeds and angle values of the rotors independently from each other. This mechanism and control system enhances the quadrotor to stabilize itself against halted components or outer penalty gains.

4.3 Simulation Results of Adaptive Tilt – Roll Rotor Quadrotor Compared to Regular and Non-Adaptive Version

In the first simulation each of the three quads are given the same trajectory starting from the same location with the same heading position. However, it should be noted that penalty gain, f_{pe} is chosen to be 1 (no effect) during the first flight simulation. The resulting plots are given in figure 5 and 6.

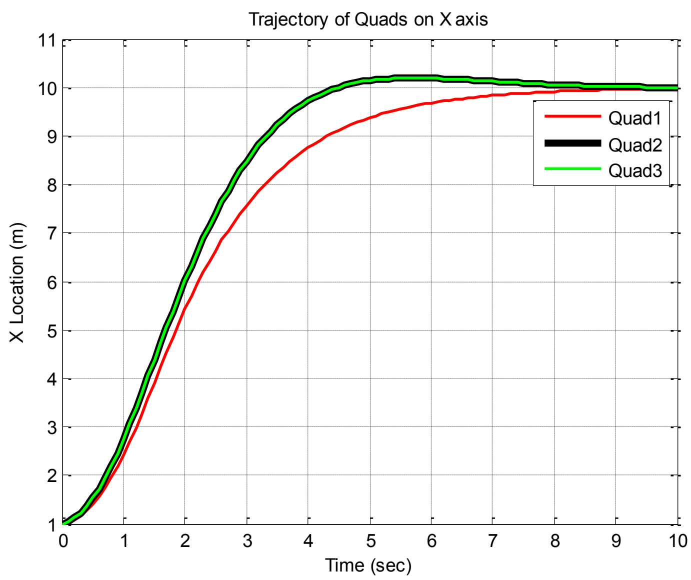


Figure 4.7: First simulation; penalty gain is set as 1 (nominal mode) on X axis.

Figure 4.8: First simulation; penalty gain is set as 1 (nominal mode) on Z axis.

As seen from above figures, tilt-roll rotor quads, Quad2 and Quad3 has relatively better performance in terms of settling time, maximum overshoot and oscillations. By comparing Quad2 and Quad3 from the figures 4.7 and 4.8 one can claim that their behaviors on reaching the target are almost the same. The resulting plots can be explained firstly by comparing the regular quad behavior with the tilt-roll rotor quads. It has already been known that tilt-roll quads have better results in terms of settling time and max overshoot value. However, Quad2 and Quad3 performed almost the same. This phenomenon can be explained by comparing their rotor angles during the flight. They are observed to be taking very close values with each other due to the fact that it is assumed that no disturbances are acting on the quads during this simulation.

The second simulation is done as we introduce a random penalty gain; f_{pe} that's changing from 0.1 to 1.9 as a function of time. Start and target points are chosen to be the same as before.

This simulation supposed to be done with 3 of the quads. However, Quad2 which does not have any compensation algorithm for large gain changes in penalty gain, go beyond the graph. That's why in figure 4.9 we only introduce Quad1 and Quad3. And further simulation is done for Quad2 (figure 4.10) by giving a relatively lower and fixed penalty gain of 0.95 for Quad2 while Quad3 has the same random penalty gain factor on x axis. By looking at the plot in figure 4.9, it can be seen that Quad1 just can barely compensate for the randomly changing penalty gain in the beginning of the simulation. But after the 5th second it begins to oscillate on z axis and is never be able to reach the target point. In the same graph Quad3 seems to cover almost the same path just as in the first simulation that's done in ideal conditions. Even though the penalty gain margin is large, the proposed adaptive control algorithm can estimate the error and compensate for the force changes on x axis which directly affects the stabilization of altitude control in z axis. In figure 8, even if the penalty gain is static and only 0.95 for Quad2, it can be clearly seen that Quad2 is unable to reach the desired location.

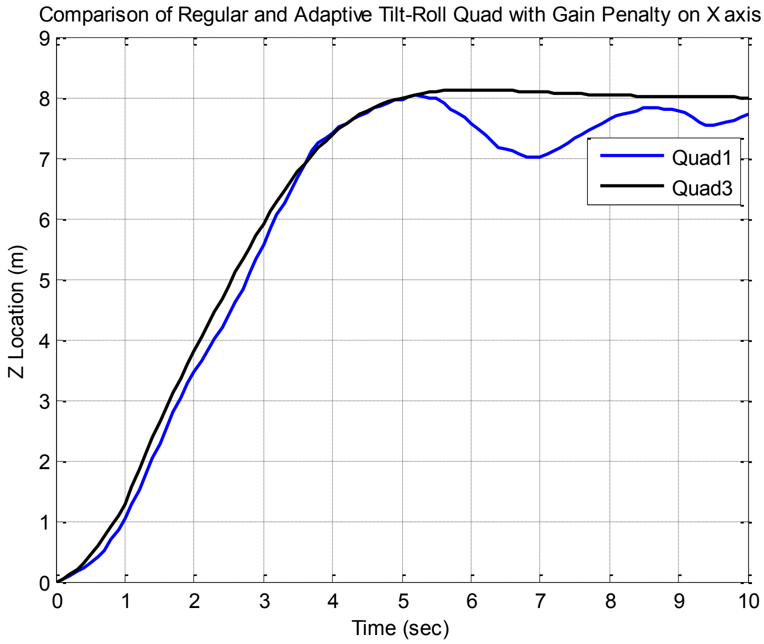


Figure 4.9: Penalty gain randomly changes between 0.1 to 1.9 on Z axis.

In figure 4.10 Penalty gain randomly changes between 0.1 and 1.9 for adaptively controlled quad.

In the next simulation with exactly the same settings as before, Quad3's performance characteristics are examined closely. In order to adapt itself to randomly changing penalty gains existing from inner and outer disturbances, Quad3 is able to change its' β, α angles and the force vectors F_t and $F_{t_{new}}$. In figure 4.11 there are 3 subplots representing the relation between desired angle, β, adapted angle, α, penalty gain, desired resultant force vector, F_t and finally the adapted resultant force vector, $F_{t_{new}}$.

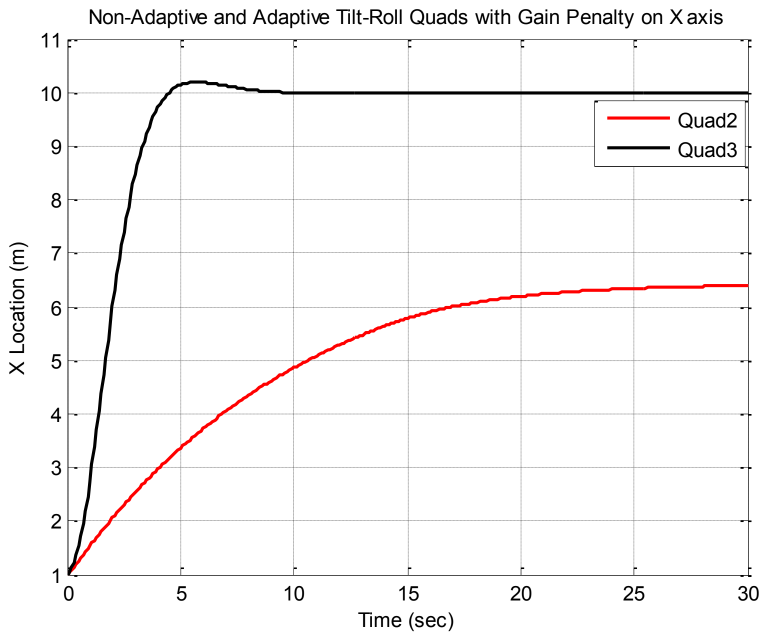


Figure 4.10: Penalty gain of non-adaptive tilt roll is fixed to 0.95.

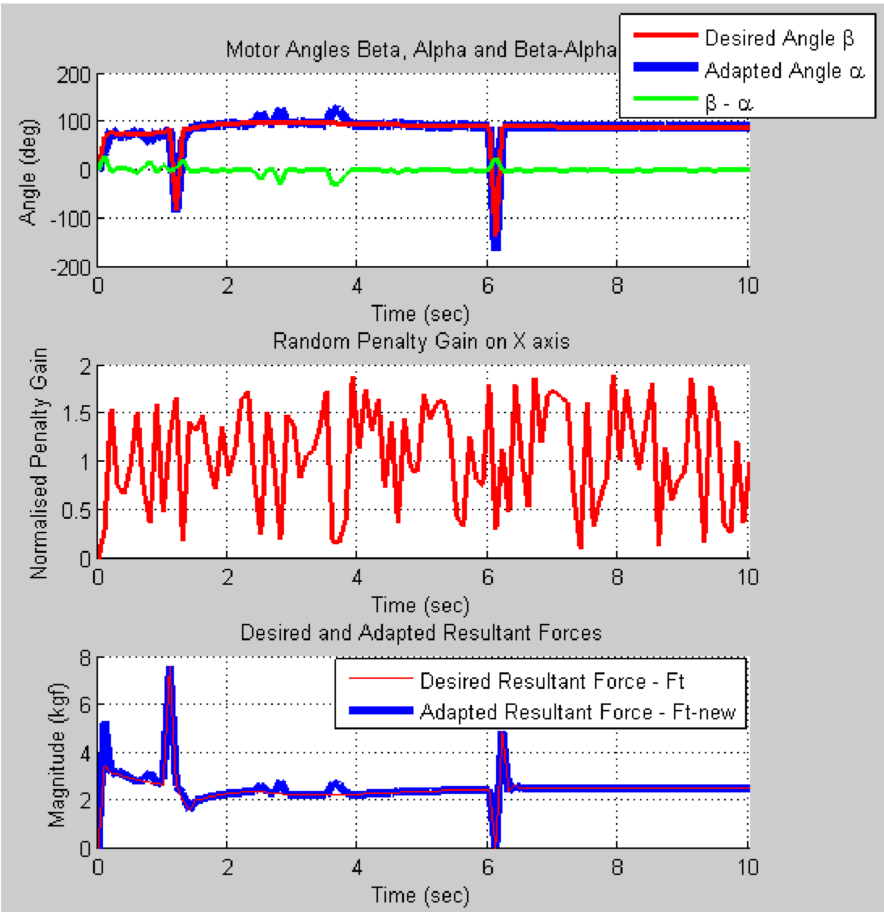


Figure 4.11: Third simulation.

In figure 4.11, Gain is randomly changing from 0.1 to 1.9 on Z axis.the first subplot shows how the desired angle, β is replaced by adapted angle, α. Although the penalty factor has a large variation, the changes in the angle values in order to compensate are relatively small. This result can be visualized by checking the first subplot's green line where the difference of desired angle and adapted angle $(\beta - \alpha)$ are introduced. It is almost zero degrees other than some local maxima situations in the seconds 1.6, 3.8 and 6.1. However, these local maxima points may be eliminated in real life applications by limiting the rapid change in angle values. What's more, it is very unlikely to have penalty gains more than 30% variation unless there is a fatal error, damage or crash.

By looking at the third subplot that includes the force vectors of the algorithm, it can be seen that both of the desired and adapted force vector values are almost the same with each other. The desired force, F_t, have a little better characteristics in terms of noisy output which is expected as the quadrotor's desired force vectors are obtained from a cascaded PID. As seen on the graph $F_{t_{new}}$'s noisy parts generally coincide with high sloped penalty gain changes (check for instance the behavior at 3.8 sec). But for these little differences in angle and force vectors, we know that Quad2 has failed to reach its target point. Then, it can be concluded that this new approach to adaptively stabilize the tilt-roll rotor quadrotors can be used on real time platforms as the changes in the angles and rotor speeds are low enough to apply to simple electric motor and servo systems.

Lastly, two more simulations have been run in order to compare the flight performance characteristics of the regular quad vs. Adaptive controlled tilt-roll rotor quad. Unlike in the previous simulations, this time penalty gain, F_{pe} is applied to all of the axes of quadrotors other than only one. In order to have apple-to-apple comparison with the previous simulations, at first arbitrary changing F_{pe} values are fixed between 0.3 to 1.7 as demonstrated in figures 4.12 and 4.13. In figure 4.12, 3D coordinates plot and 3 subplots are added. Subplots show the x, y and z axes outputs of the regular quad (Quad 1) and adaptive tilt-roll rotor quad (Quad 3). The snapshot is taken in the last second of the simulation at t=30.

As seen on 3D coordinates plot of figure 4.12, Quad 1, represented with blue heading line, seems unable to reach desired position of (10,1,8) coordinates unlike Quad 3 which is represented with red heading line. By deep-diving into sub-plots, it is clear that Quad 1 has a oscilatory response when settling to the X axis coordinates (Please see focused plot at X axis response of each of the quadrotors in figure 4.13). In figure 4.13 the Quad 1 has an oscilation around 9.8 to 10.3 points.

On Y axis response on the second subplot, although the trajectory is defined from (1, 1, 0) to (10,1,8) coordinates without any change in Y axis, Quad 1 is can be said to be negatively affected by the random penalty values resulting with unexpected sudden changes during its cruise. As seen on the second subplot there are some rough coordinate changes although it does not need to change its Y axis track from the beginning. Unlike Quad 1, Quad 3 holds its track solid and still on Y axis by keeping Y axis value of 1. In z axis response on the third subplot, it is noticable that Quad1 is unable to track its path smoothly and at the end of 30 seconds it reaches a value lower than the target z axis value of 8 on matlab coordinates frame. This result can also clearly be seen from the 3D coordinates plot on the west side of figure 4.12.In figure 4.12 F_{pe} is randomly changing from 0.3 to 1.7 for each of the axes, x, y and z.

However, Quad 3 proves that it has achieved to overcome each of the axes' penalty gains and settles to the desired coordinates of (10,1,8) at the end.

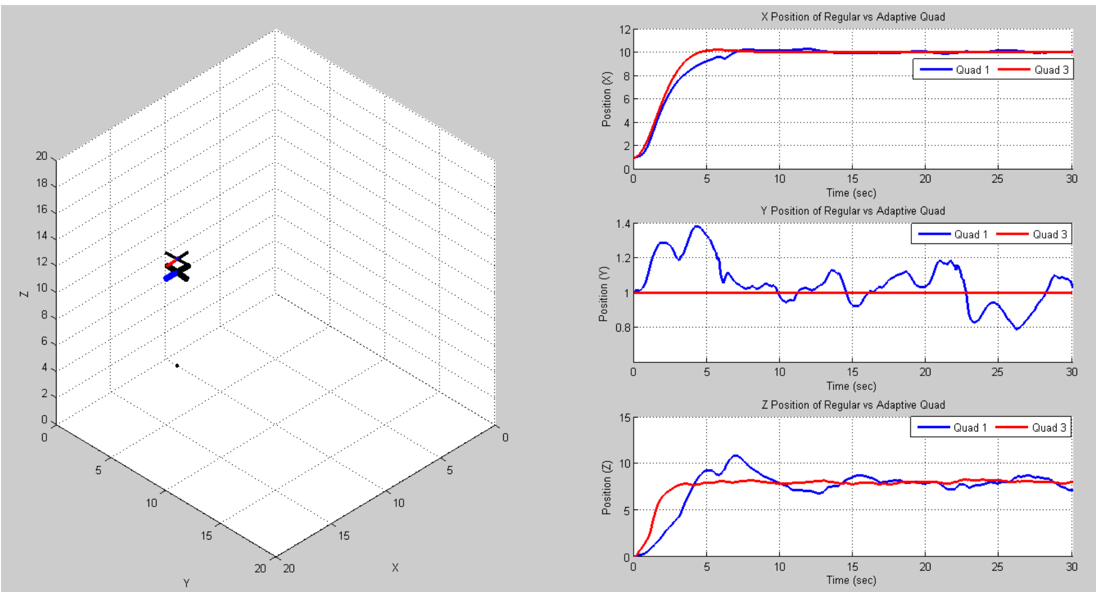


Figure 4.12: Penalty gain (F_{pe}) is applied to all of the axes of the quadrotors.

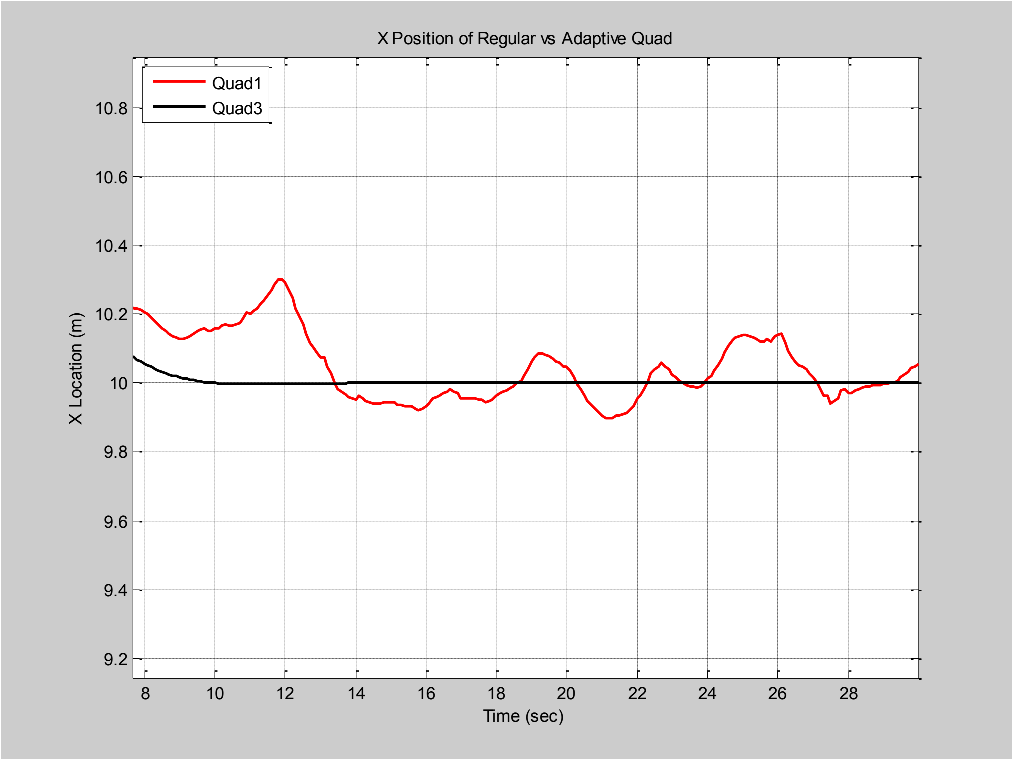


Figure 4.13: Zoomed version of figure 4.12, X axis subplot.

In the following simulation, penalty gain (F_{pe})'s variation is decreased such that it can take arbitrary values between 0.8 to 1.2. However, it is again applied to all of the axes of Quad 1 and Quad 3 as in the previous simulation. Please see the resulting plot in figure 4.14. In this simulation F_{pe} is randomly changing from 0.8 to 1.2 for each of the axes, x, y and z.

According to the graphs plotted in figure 4.14, it can be seen on 3D figure that the performance of the Quad 1 increased with the decreased variation of the penalty gain.That's why both of Quad 1 and Quad 3 seems to overlap each other on the graph. This also proves that the irregular behavior of the regular quadrotor is directly related with the variations of F_{pe}. On the other hand, Quad 3's cruise characteristics are more or less the same as it can keep up with diverse variation values. Only it can be noted that with the lesser variation of F_{pe}, Quad 3 has lesser oscilatory behavior. Please see figure 4.15 for more focused version of Z axis nearby the settling point of 8. However, this amount can be negligible as compared to the performance characteristics of regular quadrotor.

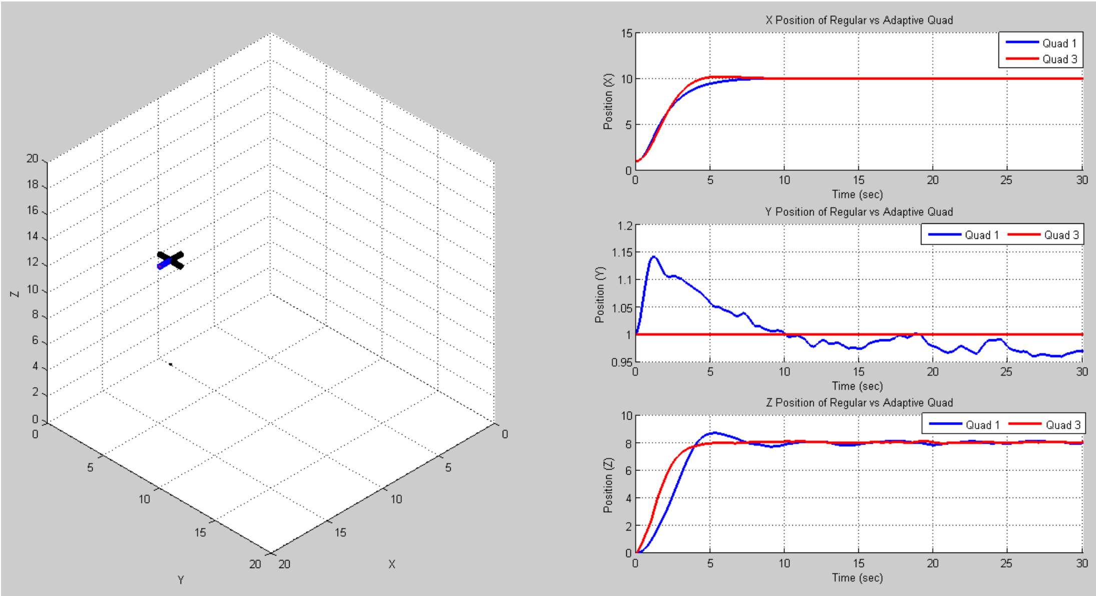


Figure 4.14: Penalty gain (F_{pe}) is applied to all of the axes of the quadrotors.

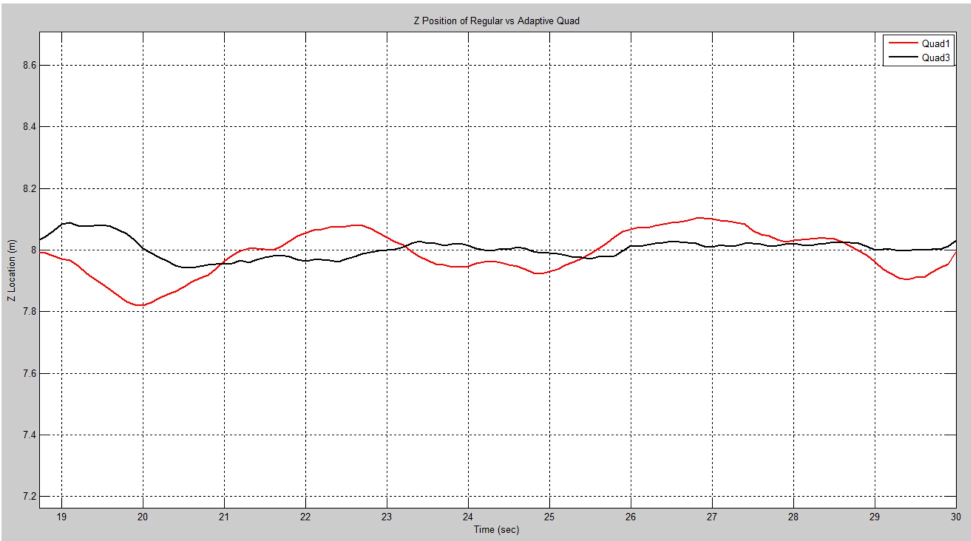


Figure 4.15: Zoomed version of figure 4.14, Z axis subplot.

5. SYSTEM DESIGN

In this section, mechanical and electrical design of the proposed quadrotor will be introduced. In the mechanical design sub-section, the following topics are covered: The designed and modelled frame specifications, dimensional features of the propellers and their characteristics, introduction to the tilting mechanism, actuators used in the mechanical system. In the electrical design sub-section, the following topics are covered: IMU system and the controllers, CPU, tilting mechanism's electrical configuration and the specifications of the actuators used.

5.1 Mechanical Design of the Tilt-roll Rotor Quadrotor

5.1.1 Frame of the quadrotor

There are mainly two frames considered in this paper. One of them is built in our ITU lab to simulate the results and connections of the sub-systems. The other frame is considered to be Wookong's flamewheel as I have already tested its' performance in another Quadrotor project. The specs of the frame, flamewheel is as in the following [28]:

- Frame Weight：478g
- Diagonal Wheelbase：550mm
- Takeoff Weight：1200g ~ 2400g
- Recommended Propeller：10 × 3.8in ; 8 × 4.5in
- Recommended Battery：3S~4S LiPo
- Recommended Motor：22 × 12mm (Stator size)
- Recommended ESC：30A OPTO

Recommendations specified above are taken into consideration when determining the take-off weight, sizes of propellers, capacities and voltage range of batteries, stator sizes of electrical brushles motors and ESCs.

5.1.2 Propeller specifications of the quadrotor

Propellers for the quadrotor is chosen such that the necessary thrust forces can be obtained even if the propellers are in tilted position due to the proposed control algorithm. Therefore, I first choose the adequate brushless motors which will be introduced in the actuators section, and their pairing propellers. For this reason, 900KV brushless electrical motors are paired with Ideafly's 10x4.5 inches carbon propellers as shown in the figure below.

Figure 5.1: 10x4.5 inches carbon propellers are used on tests.

5.1.3 Mechanical design of the tilting mechanism

In order for the proposed system to function properly, the tilting mechanism examples are examined from the similar system. The control system itself sets the limitations of ±15 degrees of tilt and roll motion for each of the rotors. Therefore, an off-the-shelf tilting mechanism that is able to provide these angle values both in pitch and roll directions with a robust control would be sufficient. After some research, within these specs in the bag, the relatively easier and robust way to turn a regular quadrotor into a tilt-roll rotor quadrotor is achieved by using automatic car wing mirror actuators. They are easier to be provided, what's more they can be run by using simple electronics tools within a proven robustness level. Not only these but also they already have both of tilt and roll control system when their operational plane lay-out is rotated 90 degrees. A simple lay out of the wing mirror is given in the following figure:

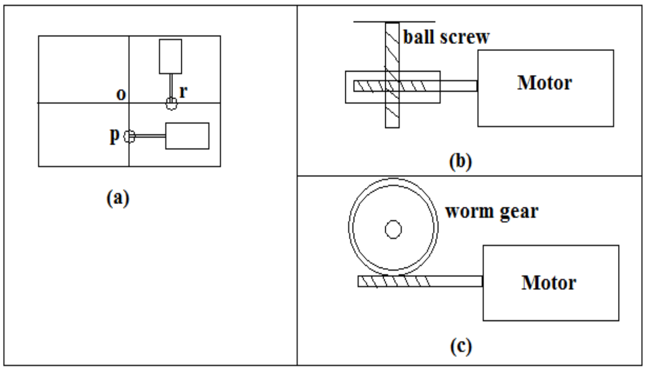


Figure 5.2: Proposed tilting mechanism.

The height of the ball screw mechanism and the distance between points O, R and P determine the pitch and roll limits of the mechanism. Please see figure 5.2 for the 2 DC motor driven schematic of wing mirror actuator design.

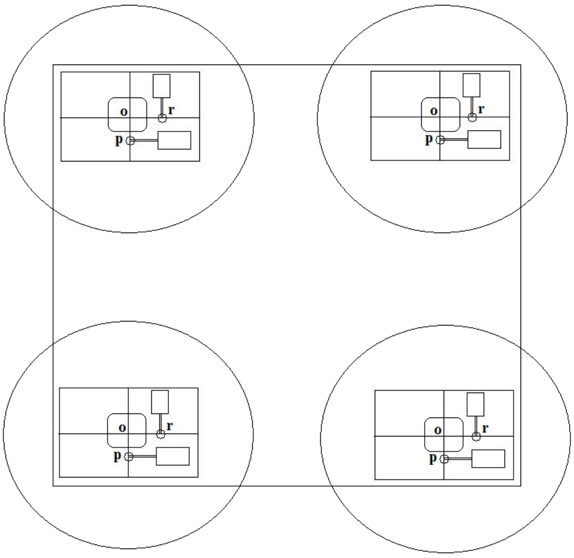


Figure 5.3: Initial design of proposed quadrotor.

Figure 5.3 shows the proposed quadrotor with tiltable rotors. Fabrication of the proposed tilt-roll rotor quadrotor is completed using MCI wing mirror actuators.

From a typical Ford commercial vehicle, I have provided the wing mirrors whose supplier is called MCI (Mirror Controls International). From the datasheet of the same supplier, I have the 2D drawings of the actuator system used to determine the angle change of the wing mirror as in the following figures.

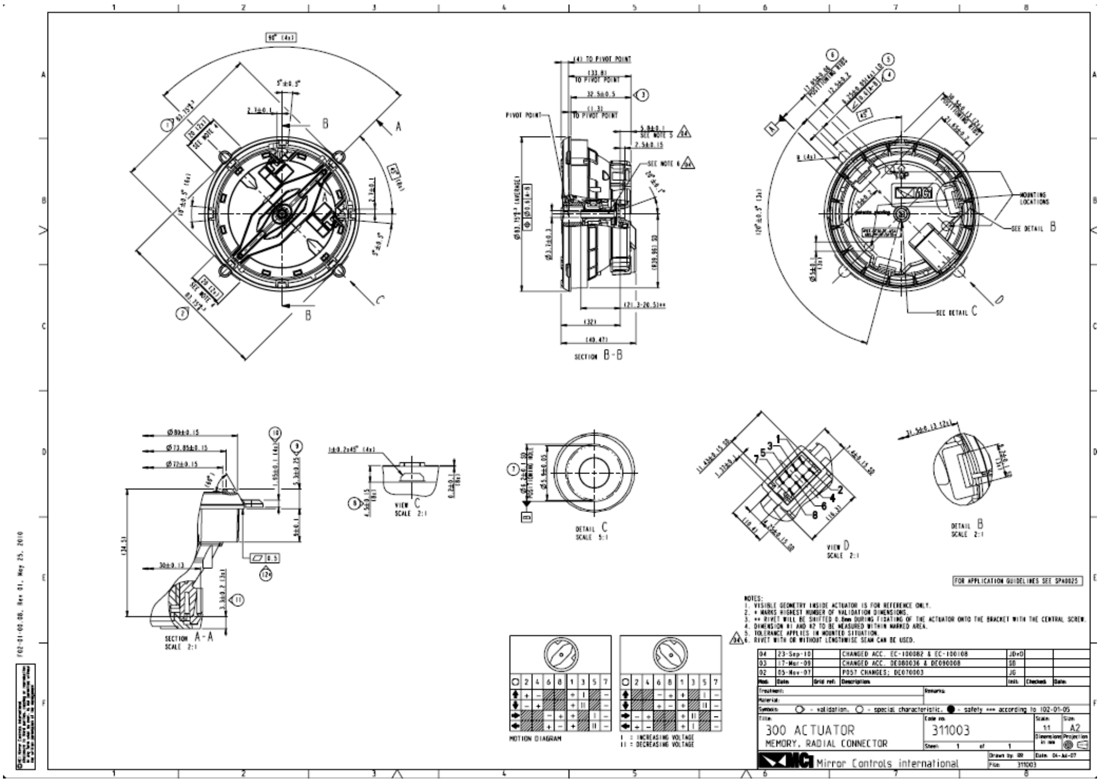


Figure 5.4: 2D drawing of an automatic wing mirror actuator in details.

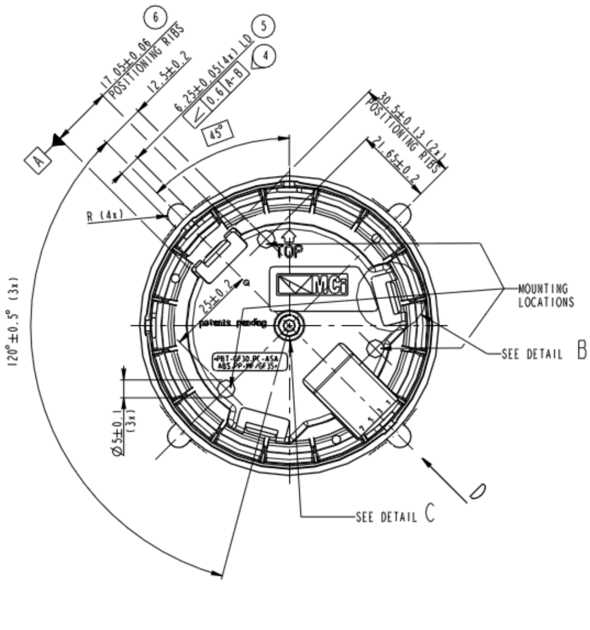


Figure 5.5: 2D drawing of an automatic wing mirror actuator (Top view).

As this actuator system will be driven to hold the quadrotor in desired positions according to the feedback control loop explained in the control section of this paper, the product specifications and limits should be understood well. System photo is taken as in figure 5.6:

Figure 5.6: Photo of the used MCI actuator (Top view).

The following tables of Table 5.1 and Table 5.2 are general product and functional measurement data of MCI actuators:

Table 5.1: General product specifications of MCI wing mirror actuators.

DESCRIPTION	**Specification**
Actuator dimensions	Top level drawing 3XXXXX {**SC**}
Actuator color	Black
Application mirrorglass weight up to*	0.365 [kg]
Working temperature range (Tb)	-40<Tb<85 [°C]
Working voltage range (Ub)	9<Ub<16 [VDC]
Supply voltage potentiometer (Um)	4.7<Um<5.3 [VDC]

Table 5.2: Functional measurement data of MCI wing mirror actuators.

DESCRIPTION	Specification
Actuator weight (m)	<0.135 [kg]
Travel angle (S)	26 ± 2 [°]
Freeplay (St)	<0.4 [°]
Traveling speed (ω)	3< ω <4.5 [°/s] {**SC**}

The actuator system can be driven between the voltage intervals from 9V to 16V as given in table 5.1. Therefore, I decided to use one 3S Lipo battery to drive both of the electronic board, tilting mechanism (i.e. MCI wing mirror actuators) and the electrical brushless motors.

As seen on table 5.2, one of the actuator's weight is135 grams. I have used 4 of them which makes a total of 540 grams of additional payload. This amount can be compensated by the use of high efficiency brushless motors and propellers. The weight of the whole quadrotor system including these actuators will be approximately 2.2kg. in total.

5.1.4 Mechanical design of the actuators

Choosing the appropriate brushless motors for the quadrotor system is very important as they are directly related with the thrust force generated and delivered to the system. What's more, by the use of the propellers, the total drag force is generated. This drag force is related with propellers' pitch angle and KV value of the brushless rotors. Therefore, as the drag force gets higher, the useage of battery power increases. In my system, the most important feature for the actuators to provide high thrust force. That's due to the fact that I have 2.2kg of quadrotor and the the propellers can tilt up to 15 degrees. This tilting motion requires the rotors to rotate faster in order to hold the quadrotor in altitude control as described in the control section of this paper.

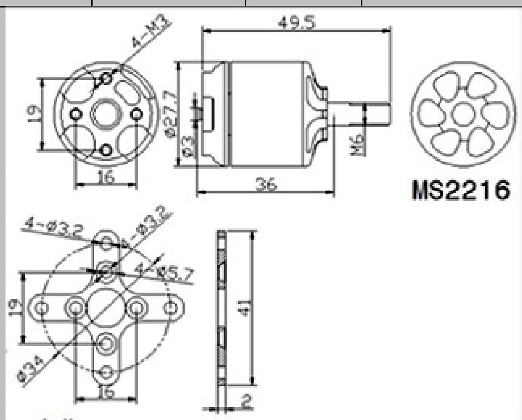
According to the facts given above, I have chosen High performance brushless T-motors as my main actuators. Please see figure 5.6 and 5.7 for sample picture and specifications of the motor respectively.

Figure 5.7: Sample photo of T-motor brushless motor for the multi copter.

Motor: MS2216-11 KV:900

Technical Datas	
KV	900
Configuration	12N14P
Stator Diameter	22mm
Stator Length	16mm
Shaft Diameter	3mm
Motor Dimension(Dia. * Len)	Φ27.7×33.5mm
Weight(g)	75
Idle current(10)@10v(A)	0.6
No.of Cells(Lipo)	2-3S
Max Continuous current(A)180S	18A
Max Continuous Power(W)180S	200
Max. efficiency current	(6-12A)>78%
internal resistance	58mΩ

Recommended Prop(inch)			
Standard	3S-1045/1047	Max thrust	3S-1155



Tested with T-motor 20A ESC

Prop	Volts (V)	Amps (A)	Watts (W)	Thrust (g)	Thrust (oz)	Efficiency (g/W)	Efficiency (oz/W)
1045	7.4	8.0	59.2	540	19.05	9.12	0.32
	8.5	10.2	86.7	720	25.40	8.30	0.29
	10	12.1	121	930	32.80	7.69	0.27
	11	13.4	147.4	1000	35.27	6.78	0.24
1155	7.4	9.3	68.82	630	22.22	9.15	0.32
	8.5	11.7	99.45	780	27.51	7.84	0.28
	10	13.5	135	1000	35.27	7.41	0.26
	11	15.0	165	1070	37.74	6.48	0.23

Figure 5.8: Technical data of T-motor brushless motor for the multi copter.

5.2 Electrical Design of the Tilt-roll Rotor Quadrotor

5.2.1 IMU and the controllers

There are mainly several options for IMU modules and their controllers. In the first trials, I will simulate and demonstrate the system by modifying a build-in quadrotor controllers (i.e. DJI Wookong and/or Arducopter). In these ready-to-fly boards, frame modification for the tilting rotors will be held according to the model explained previously on this paper. Once the system achieves the desired flight performances with a manual control of the tilting rotors, there will be modifications in the flight algorithms such that the quadrotor is able to autonomusly control its' tiltable rotors in order to keep up with the tracjectory defined as a task. Therefore, following IMU and controller systems are planned to be used in the futureworks of this project:

- DJI Wookong controller and built-in IMU [28],
- Arducopter controller and built-in IMU [33],
- Arducopter controller and external IMU that supports INS [31], [32], [33],
- Self designed electronic board with an external IMU that supports INS [31], [32].

In this list above, the external IMU that will be used with Arducopter and self designed electronic boards would be one of the two options as follows: Vectornav VN-200 or MTI-G700 GPS. Both of those IMUs can give position and velocity calculations, therefore, tilting ability can be used both for hovering (with a user defined body angle up to ±15 degrees) or GPS position hold.

5.2.2 Electrical design of the tilting mechanism

The proposed quadrotor requires four tilting mechanisms. The mechanisms should be low weight, are able to hold the resistance torques, and enable the pitch and roll motions independent of each other.

One possible solution to the design came from patent search of tilting mechanisms. Authors [29] proposed a similar mechanism for tilting car mirrors.

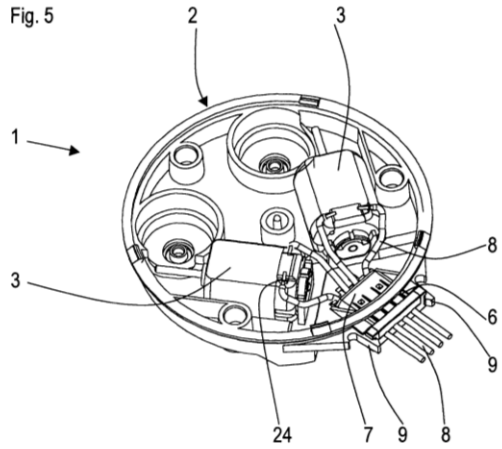


Figure 5.9: A car mirror tilting mechanism [29].

Figure 5.9 shows the proposed tilting mechanism. Each mechanism requires two micro DC motors for tilt and roll motions. Fig 5.2 shows the top view of the tilting platform. Lift generating motor and rotor sets will be placed on each platform. The points P and R, are where the platform is actuated to have pitch and roll motions, respectively. The mechanism will tilt with respect to the center point O.

Each motor shaft has a worm which attached to a worm gear as shown in the top view in Fig 5.2 c. This arrangement reduced rotational speed and allows higher torques to be transmitted to the tilting mechanism. The worm gear has a ball screw inside as shown in side view of Fig 5.2.b, which will rise and lower the platform as required.

Electrical circuit design of the tilting mechanism is introduced in figure 5.10. The raotation of the axes and horizontal-vertical control inputs are given according to this diagram. In the tilt-roll system on the quadrotor, X1 and X2 are used for tilt motion of the rotors and Y1 and Y2 are used for roll motion of the rotors. The ground connection is fixed the same with the main Li-Po batteries and control board of the quadrotor.

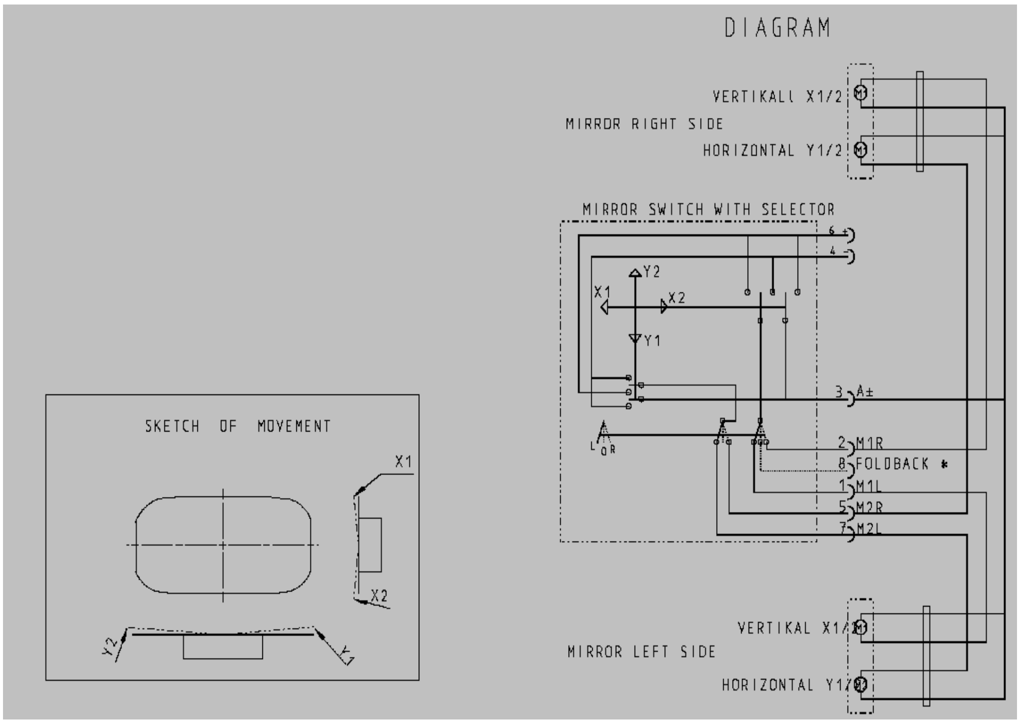


Figure 5.10: 2D circuit diagram for tilting mechanism.

5.3 Conceptual Design of Tilt – Roll Rotor Quadrotor

5.3.1 Built system with prototype parts

In our automation systems lab, I have built a representative conceptual design of tilt-roll rotor quadrotor with prototype level parts. Please see figure 5.11 for the initial photo of the quadrotor.

In this design, MCI's car side mirror tilting mechanism is successfully transferred to the quadorotor system as seen in the above figure. By using this tilting mechanism, it is possible to change four of the rotors surface planes along x and y axes with tilt and roll motions. In the figure it is already clear that the front motors (#1 and #4) are both tilted and rolled with respect to the quadrotor frame of reference.

In the futureworks of this project, once all of the design intend level parts are received as explained in sections 5.1 and 5.2, tilt-roll rotor quadrotor will be re-built such that the tilting arms can be controlled from a remote controller manually and automatically according to the control inputs obtained.

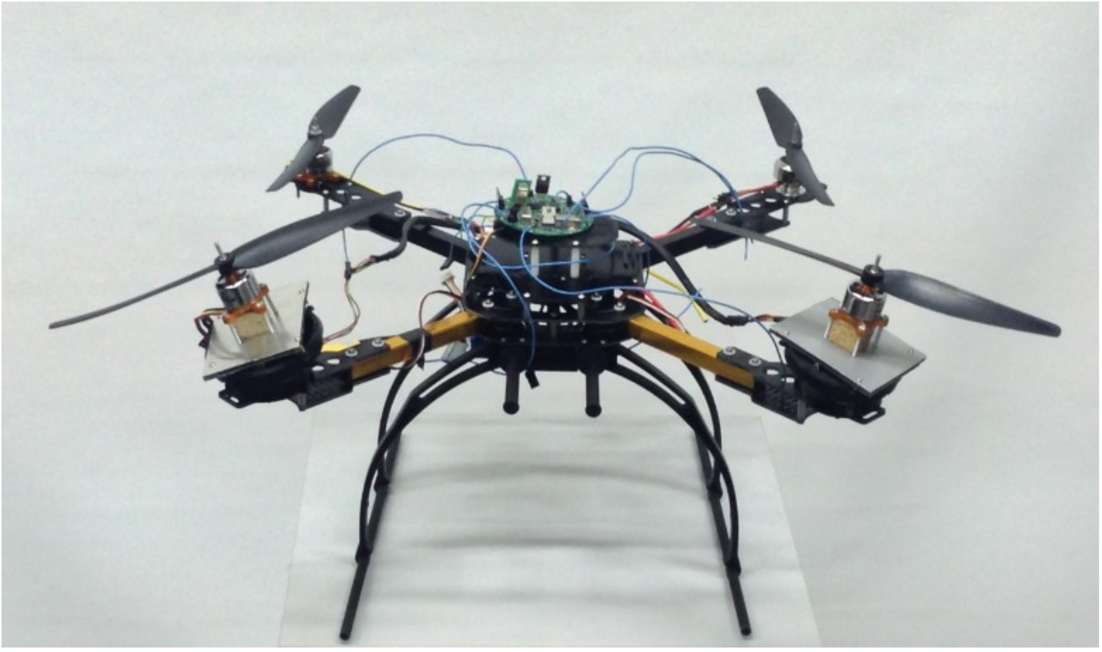


Figure 5.11: Conceptual design of tilt-roll rotor quadrotor with prototype parts.

6. EXPERIMENTS AND RESULTS

As the proposed design is brand new and haven't been tested before, comparing the simulation results with the real life data is important. Therefore, I have built two quadrotors, a regular quadrotor and tilt-roll rotor quadrotor, one by one on the same air frame using exactly the same components and sensors in order to compare the flight performances of each of the aircrafts.

6.1 Initial Built of the Test Vehicle

At the beginning, a standard quadrotor have to be built so that I can initially calibrate, test, balance and mount the basic common components such as controller modules, brushless motors, propellers, speed controllers, wirings and connectors.

What is more, even if it will be a regular type quadrotor, I know from the past experiences that the first flights of the multicopters can have some issues due to lack of speed controller calibration, poor locating of the imu, unbalanced propellers, poor soldering quality of the connectors and electronic parts, misarranging of the flight parameters and attitude gains. Fortunately, I can differentiate these problems and focus on the proper solutions from the characteristics and behavior of any troubleshoots that may happen. For example, if one or more components are not working or working with unexpected behaviors, this issue can be related with the components themselves or due to poor wiring or connector-soldering qualities. If the quadrotor's remote control is not working, this can be due to not linked transmitter or the TX may not have been calibrated or have been calibrated insufficiently. Finally, if there is a fault in the flight characteristics of the quadrotor, it is better to check the propeller balance (if there is vibration) or if there is wobbly or oscillatory behavior while flying, it is directly related with the flight gains.

Firstly, I built two frames; one is the main frame with longer arm lengths of 70cm each, one is the with shorter arm lengths of 60cm. Please see below in figure 6.1 for the pictures of air frames used in these experiments.

Figure 6.1: Conceptual design of tilt-roll rotor quadrotor with prototype parts.

The main frame (on the right hand side of the picture in figure 6.1) is used for the flight and experiments while the shorter one is kept as substitute of the main frame incase the flight performances of the longer armed frame has poor results or incase of fatal crash situations.

Once I have built the airframes, the wiring and their connectors need to be prepared and soldered including power cables, battery connectors, battery charger connectors, electronic speed controller wiring and connectors.

3S battery's connector (female) is soldered first (figure 6.2). The rest of the connectors are chosen with respect to this.

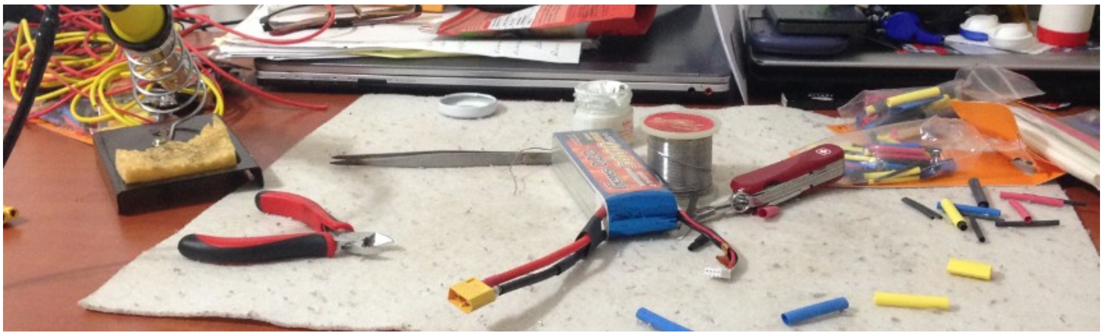


Figure 6.2: 3S battery’s connector (female) is soldered first.

Next step is to prepare electronic speed controllers (ESCs) such that their connectors (male) can fit to the battery (figure 6.3). The rest of the connectors are chosen with respect to this.Once the connectors are soldered, ESCs can be calibrated with intermediate-timing (figure 6.4).

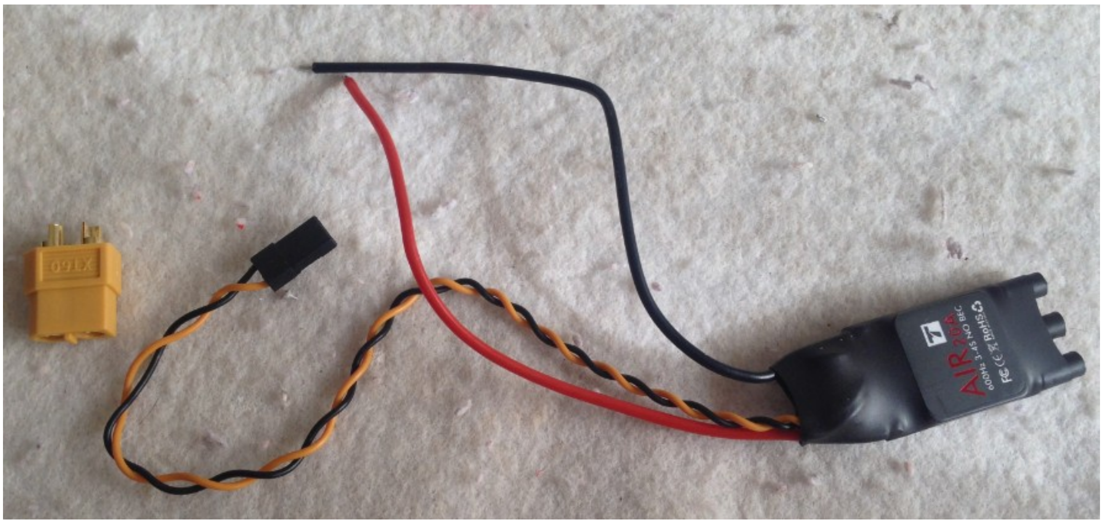


Figure 6.3: Male connectors are used for ESCs.

Figure 6.4: ESCs need to be calibrated with intermediate-timing.

Once all the calibration and soldering process of 5 of the ESCs (one of them is substitute) are completed, power cables and connectors are soldered. All the soldering process of the power cables and ESCs must be done carefully as the poorer quality soldering may result with fatal crashes of the aircraft. What's more short circuit is something to be avoided in all cases therefore, I take precautions such as using double layers of soldering shrinks as seen in figures 6.5-7. In figure 6.5 4 of the cables are prepared for the ESCs and one of them is input for the 3S Li-po battery. In figure 6.6 careful shrinking is done to prevent any risks of short circuits.

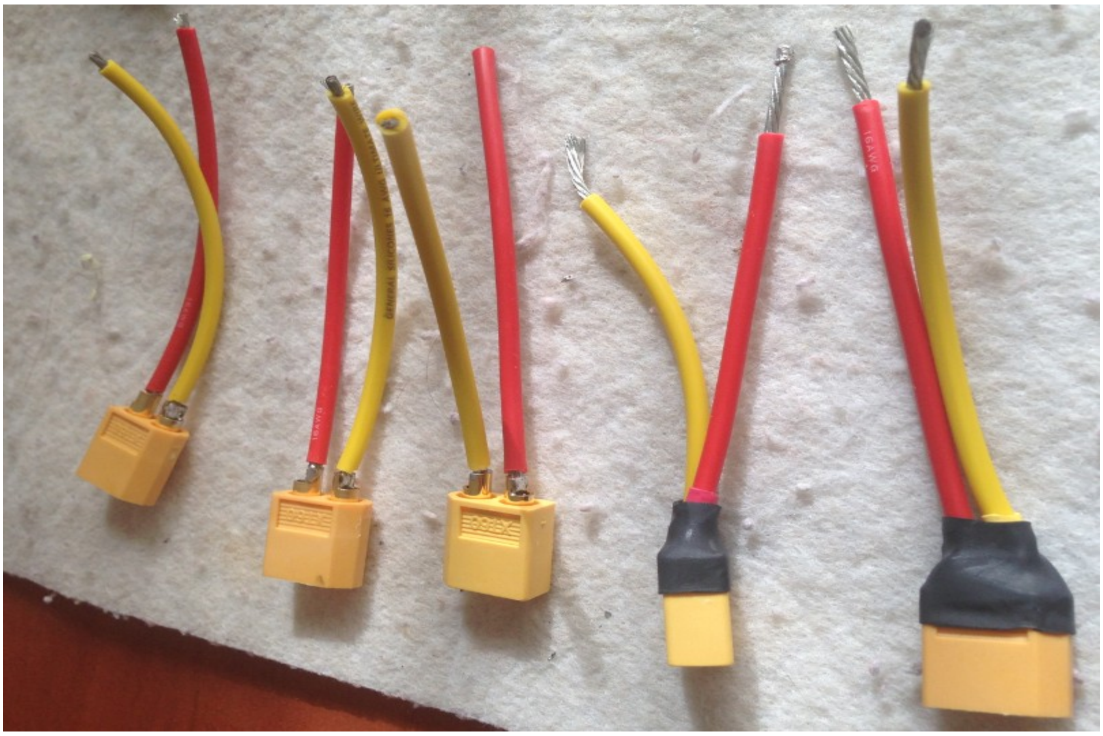


Figure 6.5: Preparation of power cables.

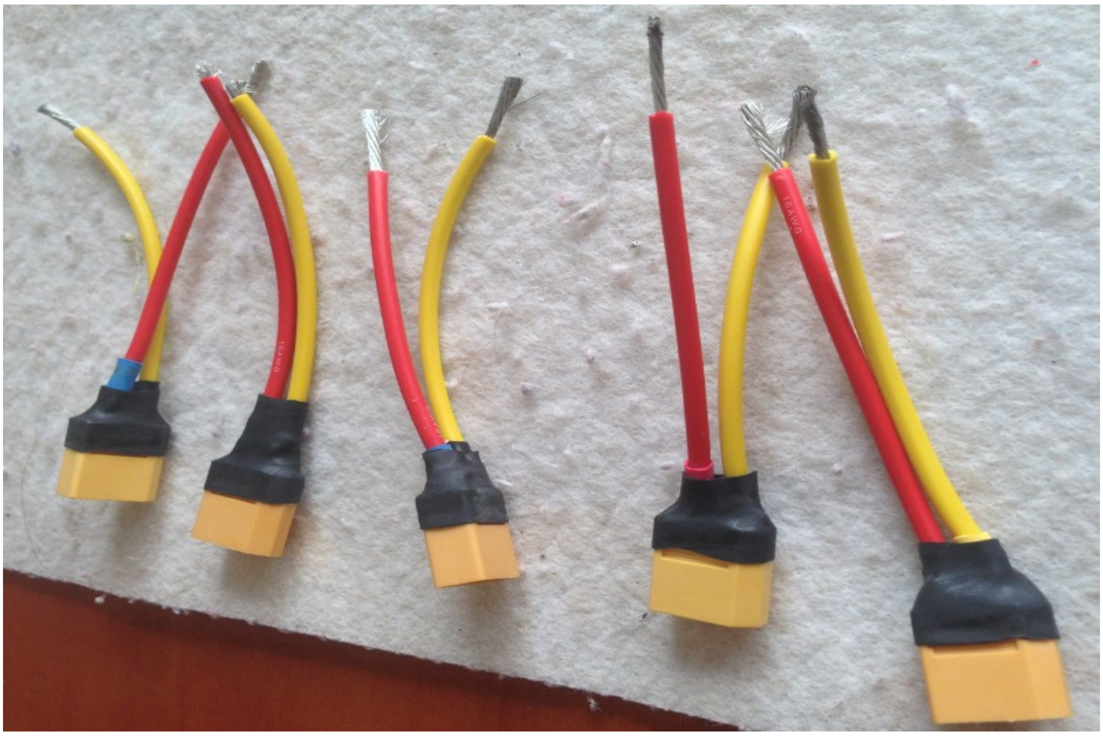


Figure 6.6: Double layers of soldering shrinks are used.

Figure 6.7: A bundle of power distribution cables are built to be used.

Once all the cabling is finished, quadrotor is built using Naza v2 flight control module. ESCs and cables are fixed using electrical tapes to the air frame and imu module is fixed in the middle of the frame. The front direction of the imu is set such that X type quadrotor frame is considered. When looking from behind of the quadrotor front right hand side arm is numbered as 1 and the one on the left handside is set as 2. Arm #3 is back left hand side and arm #4 is the one at back right hand side of the quadrotor. In figure 6.8 and 6.9 set up without fixing of the modules with tapes can be seen from back and top views. In figure 6.9 Arm#1 is front (top of the picture) red color arm, arm #2 is front white color arm, arm#3 is back red color and arm#4 is back white color arm.

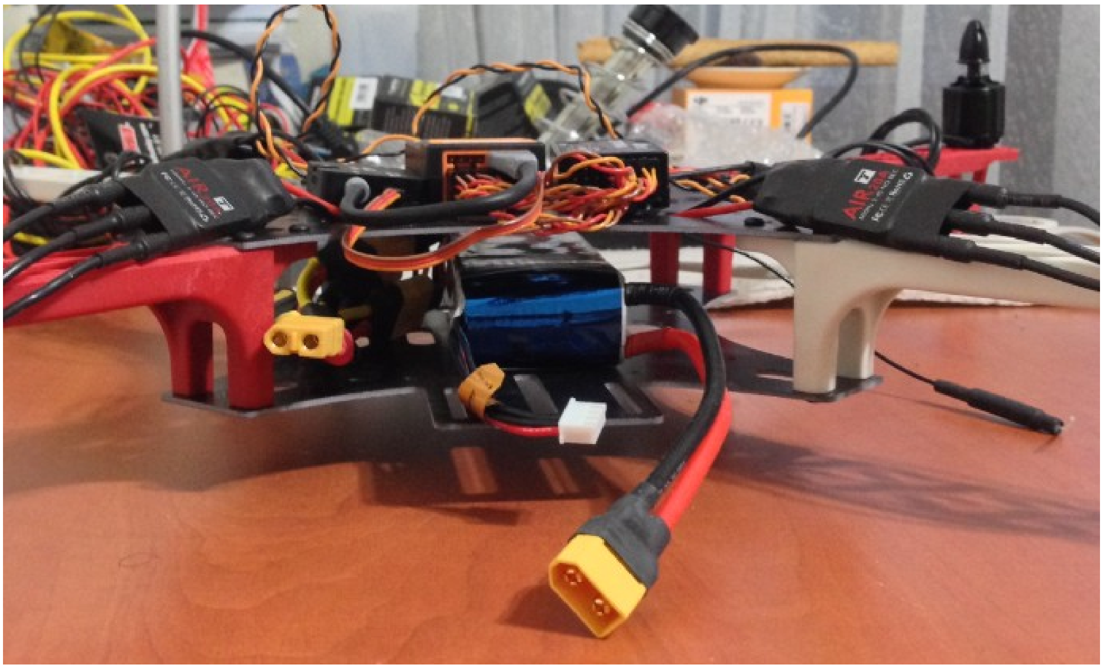


Figure 6.8: Initial built of the regular quadrotor - back view

Figure 6.9: Initial built of the regular quadrotor - top view.

6.2 Test Results and Corrections on the Original Quadrotor

Once all the components and propellers are fixed, the test flights are held in order to adapt the proper gain factors and solve issues if any. Arms 1 and 3 have counter clockwise propellers and arms 2 and 4 have clockwise rotating propellers installed.

In the first couple of flights nominal flight values are used, however, it seems that the attitude and altitude control has some poor behaviors. It does not change even if I change some gain parameters. In this case, there are three alternatives to think of brushless motors, ESCs and propellers. In order to understand the fault, I change one component at a time and re-fly the vehicle, trying adjust the basic gains. In the first try of changing the late starting motor, it did not have any improvements. Similarly by changing the calibration of the ESCs and ESCs as components, the result is more of less the same. In the mean time, I see that there is also some vibration in the 3rd arm. Therefore, I conclude that the problem should be due to unbalanced propellers. In the last flight with those unbalanced propellers, I even have a small crash resulted with a breakage of a propeller as seen in figure 6.10. Crash happened because of imbalanced propellers.

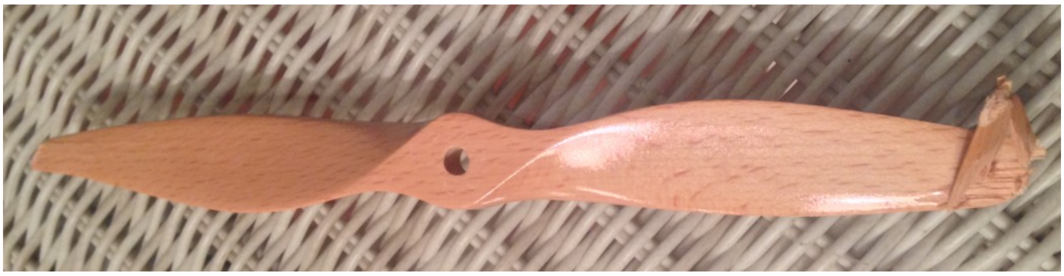


Figure 6.10: Broken propeller due to the crash.

In the first step I did not give much chance about the propeller imbalance as they are brand new, but the new set up in figure 6.11 proves that changing the propellers from wooden to carbon fiber totally make the difference. By slight adaptation of the basic parameter gains used in figure 6.12, I get my stable regular quadrotor flying (figure 6.13). In figure 6.13 Successful indoor flight with regular quadrotor at hovering position can be seen.

Figure 6.11: Ready-to-fly configuration of the regular quadrotor.

Naza v2 regular quadrotor stable flight parameters are optimized as below:

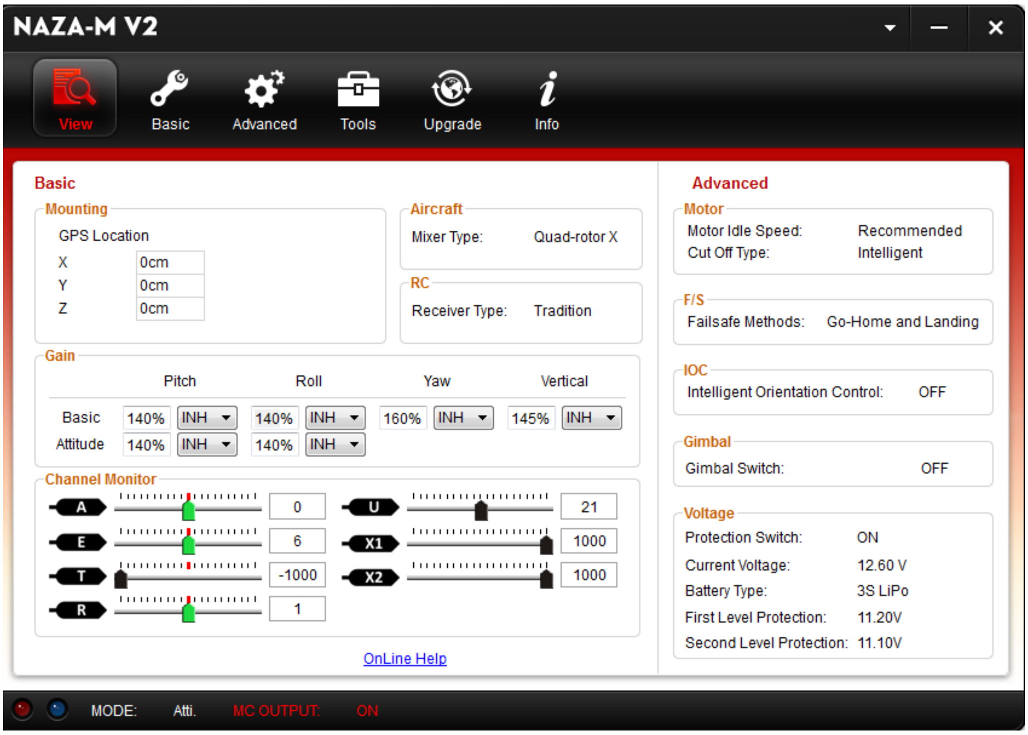


Figure 6.12: Regular quadrotor stable flight parameters.

Figure 6.13: Regular quadrotor at hover position.

6.3 Designing the Adaptor Mount Parts for Tilt-Roll Rotor Mechanism

In order to implement the dc motor controlled car wing mirror actuators to the quadrotor, 2 adaptor parts are necessary. Otherwise, it is not possible to match the electric motor's mounting holes, airframe's holes and the actuator's plastic case to each other. Therefore, by using Catia CAD software, I have designed 2 different mounting adaptor parts: One for mounting electrical motor to the mirror actuator and the other one is designed for fitting the actuator to the airframe. In figure 6.14 the part connecting electrical motor to the actuator is introduced.

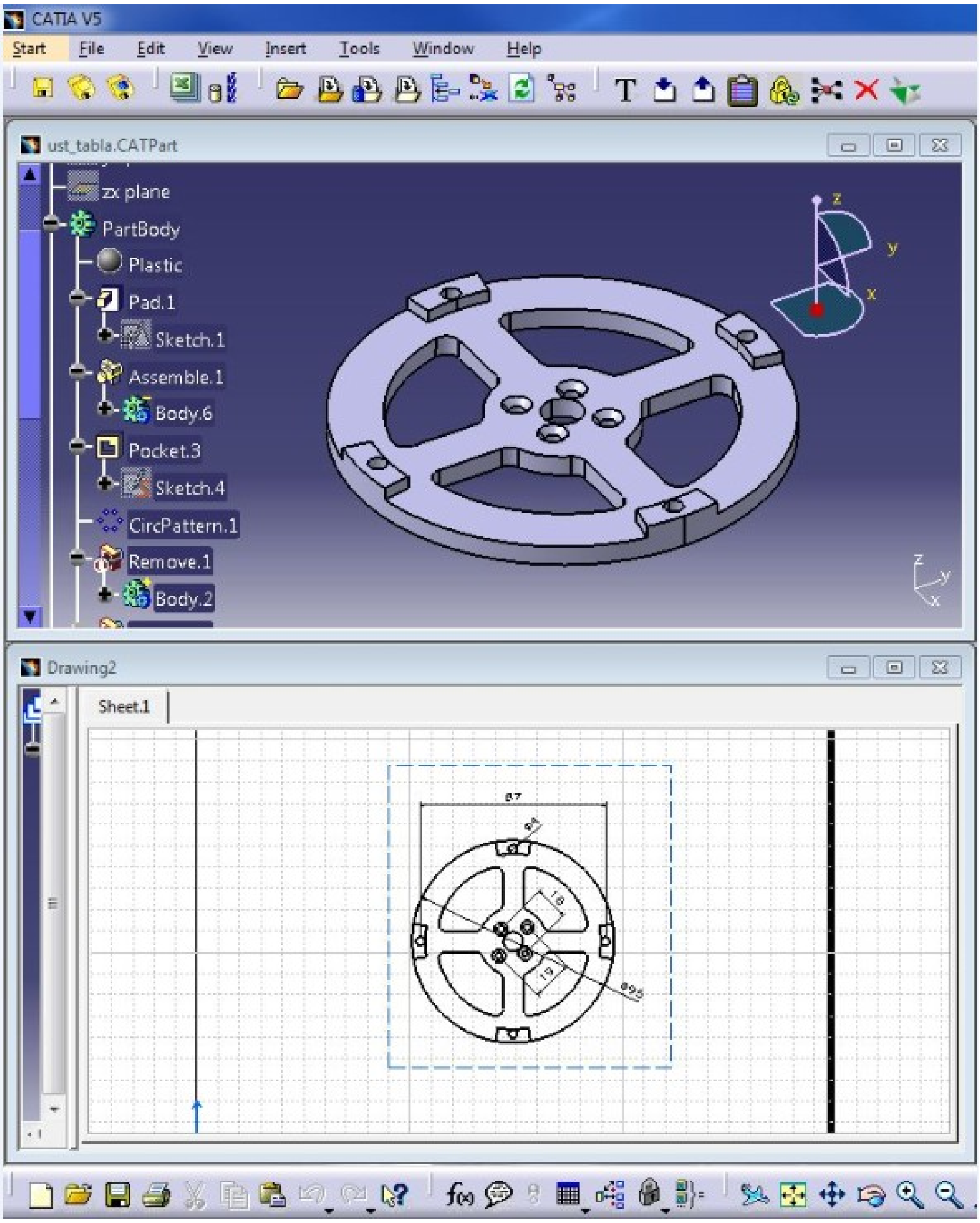


Figure 6.14: Part 1: Adaptor part to fit electrical motor to the actuator is designed.

Similarly in figure 6.15 the adaptor part to fit the actuator to the body frame is given. It should be noted that the four holes in the middle of both of part 1 and part 2 have to be drawn and produced accurately in order to fit the arms and the electrical motor. Part 2 must fit both of the body arm and the wing actuator's case correctly. Please see figures 6.16-17 for one of the body frame arm's top view picture and mirror actuator's bottom view. In figure 6.16, 4 holes in the middle must fit to the adaptor part 2 to carry the whole actuator design in stable position. In regular quadrotor these holes are for fitting the electrical brushless motors directly.

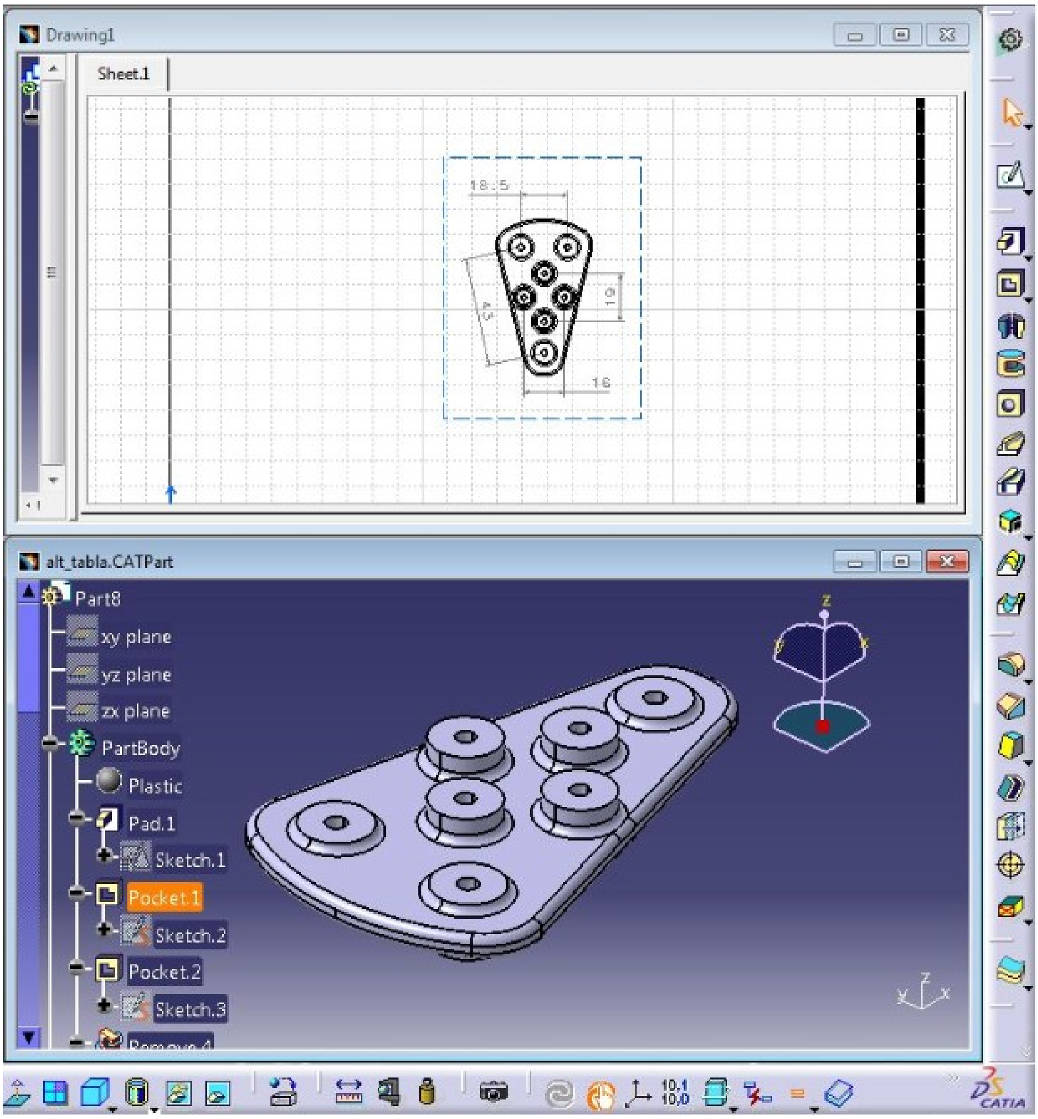


Figure 6.15: Part 2: Adaptor part to fit the actuator to the body frame is designed.

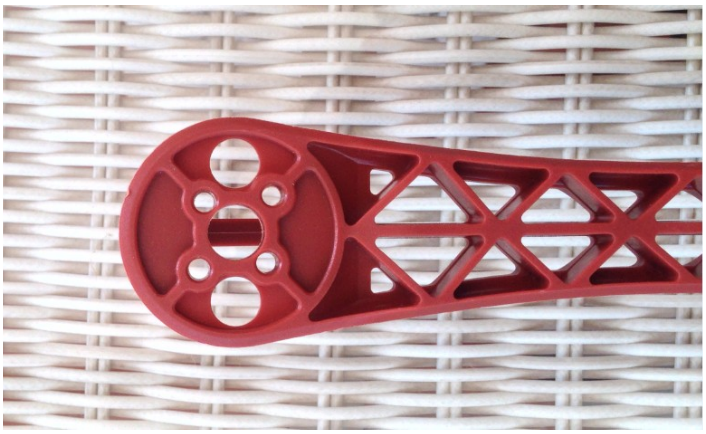


Figure 6.16: Close-up top view of one of the body frame arms.

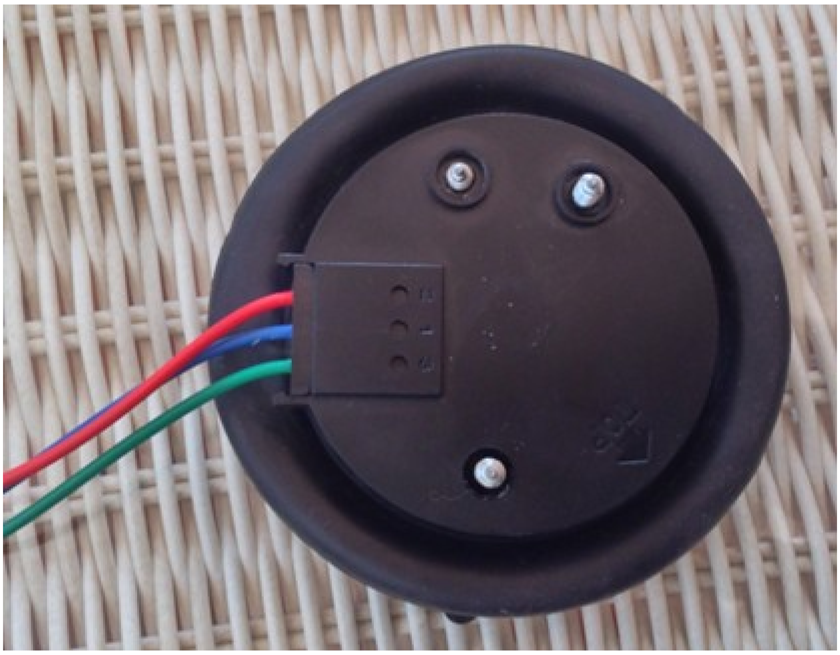


Figure 6.17: Bottom view of the wing actuator's case.

In figure 6.17, Routing #1 is GND, and #2 is for tilt control and #3 is for roll control.

All of these designed parts are 3D printed as prototypes in order to fit the real parts on the adaptors. Later on the rest of the corrected parts will be produced in our ITU lab.

The parts in figure 6.14 and 6.15 are 3D printed in Ford Otosan. Please see figures 6.18- below.

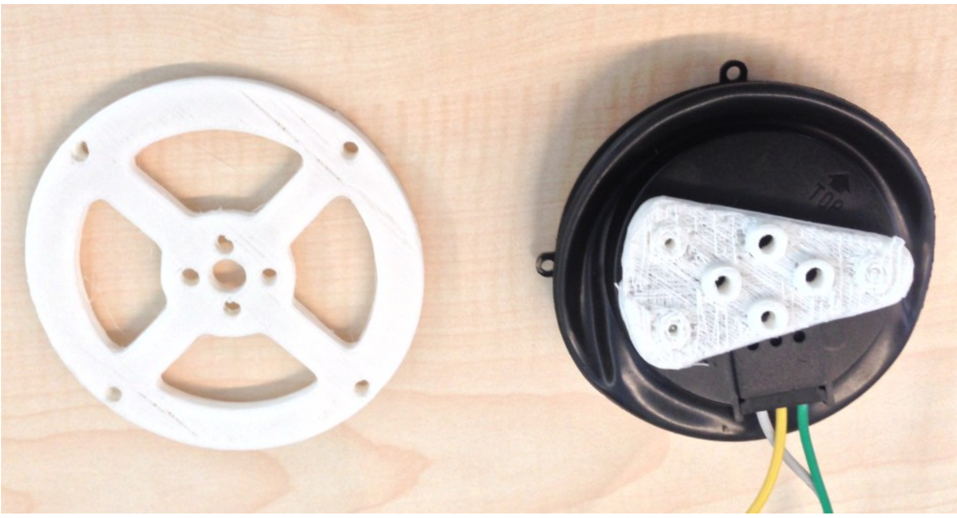


Figure 6.18: Designed adaptor parts are 3D printed as prototypes for corrections.

Detailed pictures about the fitting of the threads, 3D printed parts and on-arm assembly pictures are as in figures 6.19-6.23 as follows. In figure 6.19 'Top' sign arrow on the case denotes the pitch rotation of the actuator.

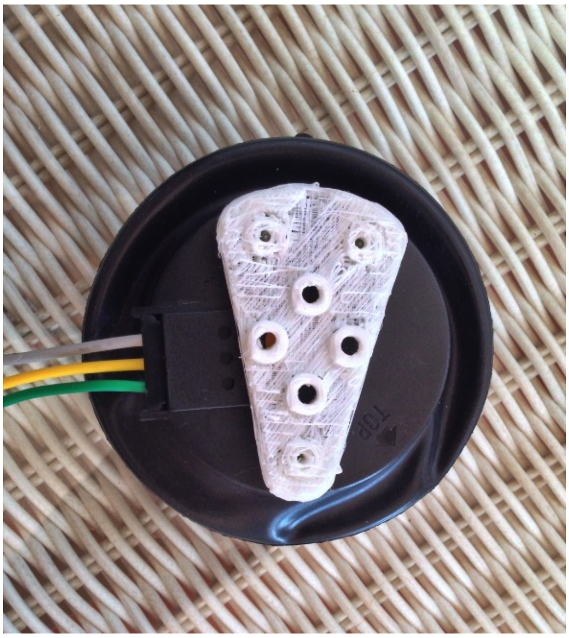


Figure 6.19: Part 2, close – up view from the bottom side of the actuator case.

Figure 6.20: Brushless motor is mounted on part 1 from the holes in the middle.

In the above picture, The outer holes of the designed adaptor will let the motor to be attached to the actuator.

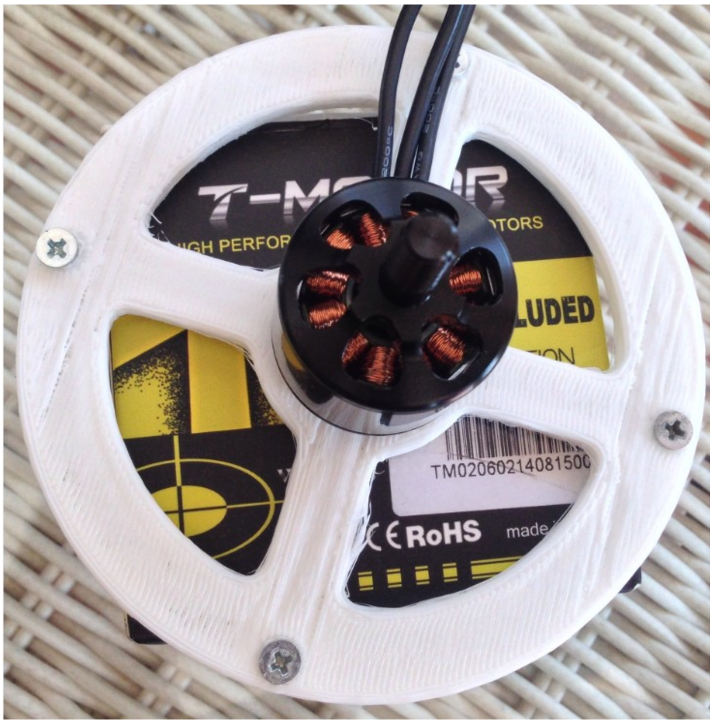


Figure 6.21: Top view of the part 1 assembled with electrical brushless motor.

As seen in figure 6.21 the outer threads are designed such that they can fit on the mirror actuator.

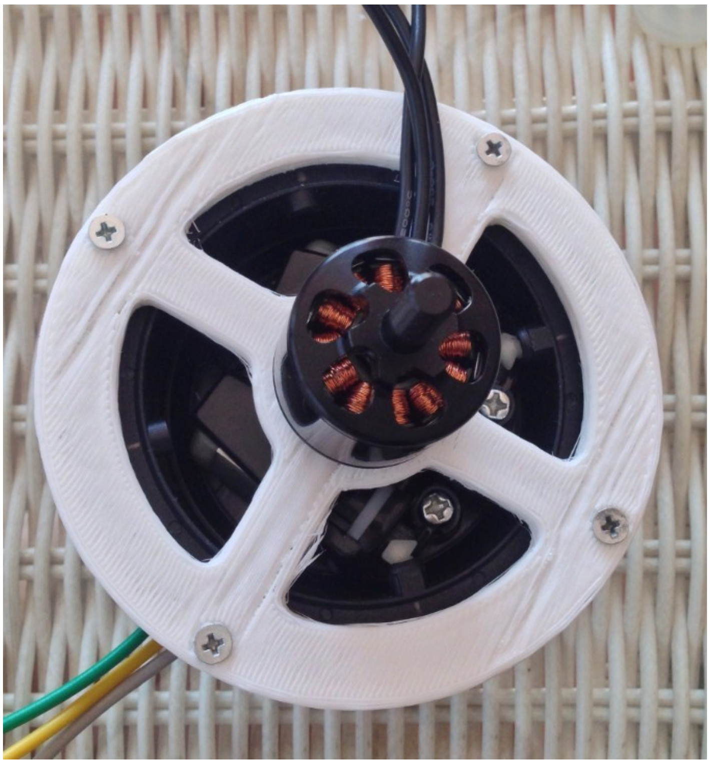


Figure 6.22: Electrical motor is mounted on the mirror actuator.

Figure 6.23: Tilt-roll rotor system for one motor is mounted on the body frame.

As seen on this picture, roll motion is given with DC motors driving the tilt-roll rotor system.

6.4 Controlling the Tilt-Roll Rotor Actuator

Tilt-roll rotor quadrotor is controlled from the car wing mirror actuators as stated from the previous chapters. In this sub-section, I will give details about the control of the 2 DC motor mechanism of each of the actuators.

By considering the simplicity of the coding, the modularity of the programmable cards and from my previous experiences, I decided to drive and control the system using Arduino UNO cards. They are easy to install and sufficient enough to control tilt-roll rotor actuators via RC.

After doing some web research, I ordered two motor shields for my two Arduino UNO boards. Each of those motor shields are able to run 2 motors and for the reliability of the code it is good enough to run the actuators only on either tilt or roll direction. The idea is to control both of tilt and roll motions of the actuators by using a total of 2 channels from the RC transmitter unit. Please see figure 6.24.

With the code I have developed with Arduino Uno board, all of the actuators can be controlled simultaneously with a RC. Arduino UNOs are connected to two of arduino motor shields that drive DC motors of the tilt-roll actuator.

For the time being, the code and the system to run the quadrotor with tilt-roll rotor actuators are ready for manual flight control from RC. For futureworks, whole control system will be designed such that Naza controller will be replaced with my own developed flight controller that can enable or disable tilt-roll rotor control algorithm.

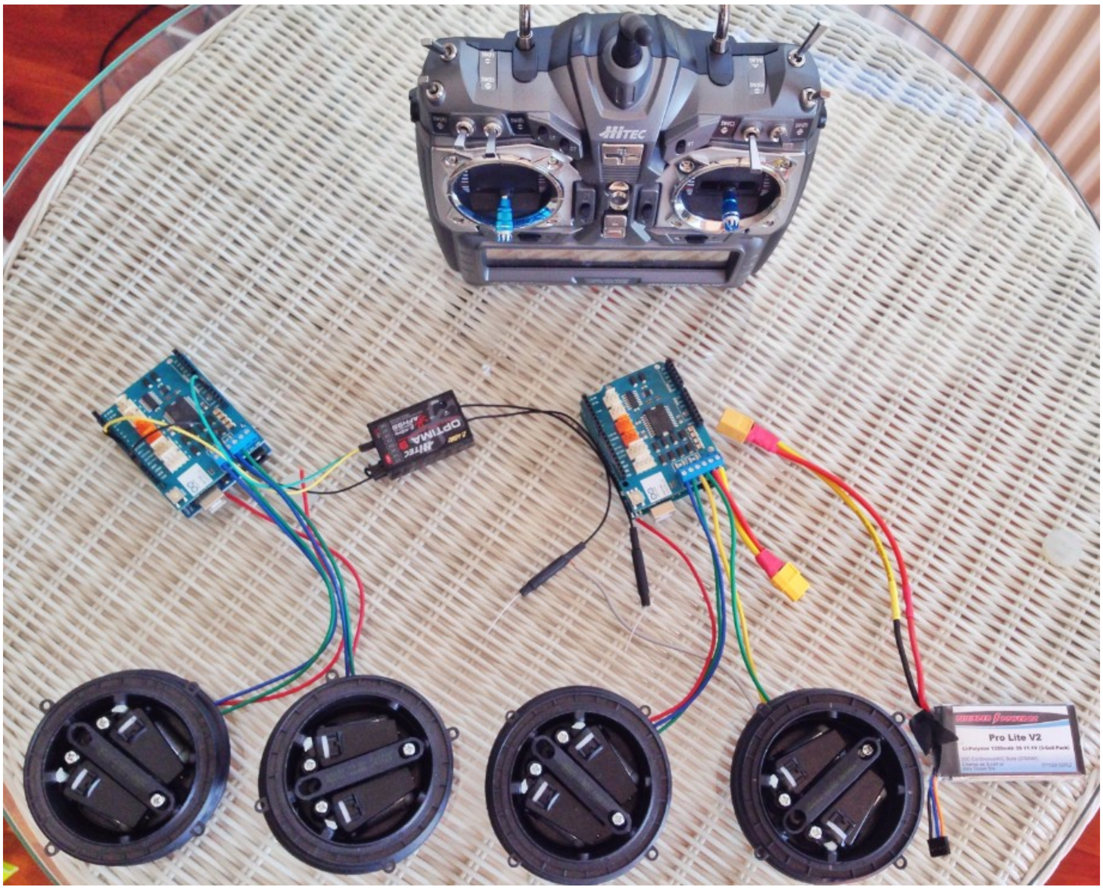


Figure 6.24: 4 of the actuators are controlled from RC.

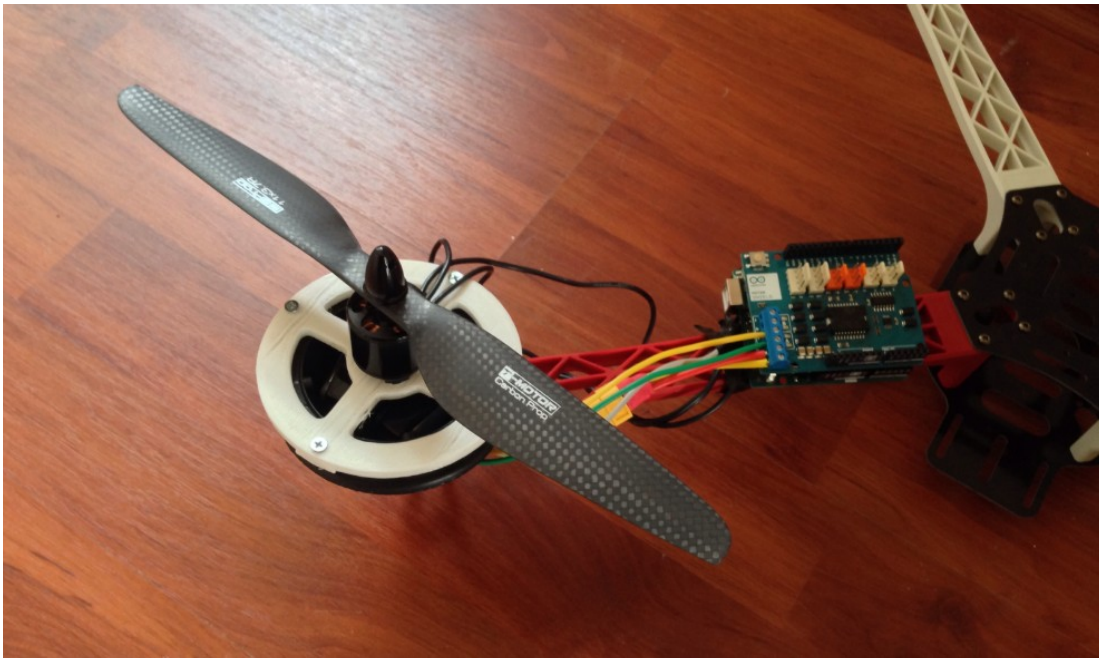


Figure 6.25: Tilt-roll rotor mechanism for one of the arms is implemented.

7. CONCLUSIONS AND RECOMMENDATIONS

One of the limiting factors that prevents further implementation of the quadrotor systems into various applications, is the way quadrotor moves. It needs to tilt along the desired direction of motion. This tilting enables motion of the quadrotor; on the other hand, it has an undesired effect of changing the direction of view of on board camera. This becomes an issue for surveillance and other vision based tasks. This study presented the design and control of a novel quadrotor system. Unlike previous study that uses regular quadrotor, this study proposes an alternative propulsion system formed by tilting rotors. This design eliminates the need of tilting the airframe, and it suggests superior performance with respect to regular quadrotor design. The mathematical model of the tilt-able rotor type quadrotor and designed control algorithms are explained. Various simulations are developed on Matlab program, in which the proposed quadrotor aerial vehicle has been successfully controlled. Comparison of the proposed system to regular quadrotor suggests better performance.

Determining optimum control response at different conditions is a challenge, which will be investigated in our future work. We are at the process of designing the proposed vehicle. As the fabrication is complete, experimental validation of the design and control algorithms will be possible.

It is required to tilt the quadrotor along the desired direction of motion. This tilting enables motion of the quadrotor; on the other hand, it has an undesired effect of not able to stabilize itself at any frame angles. This becomes an issue for surveillance and other vision based tasks. These handicapped characteristics of the quadrotors can be fixed by tilting-rolling the rotors around their axes. However, it is very likely to be introduced with fixed or changing erroneous forces along a specific axis due to imperfections on the inner structure of ESCs, electric motors, electronic components, propellers. What is more, in outside flights it is necessary to compensate for changing wind forces during time. This study presented the design and control of a novel quadrotor system with tilt-roll rotor control that can compensate for penalty gains through one axis. Various simulations are developed on Matlab, in which the proposed control algorithm proves better performances with respect to regular quadrotors as well as better stability features with respect to another tilt-roll rotor capable quadrotor that does not have the proposed adaptive compensation algorithm.

This study presents the design and control of a novel quadrotor system that can tilt its rotors independently so that it can adaptively update its rotor angles and speeds to compensate for not ideal conditions including wind and motor-propeller gains in a certain axis. However, it is currently applicable only for 2D space solutions. In real life applications, cross-functional trajectories will also be affected with some random distortions while the vehicle is moving along in 3D space. That is why the problem solution needs to be studied in a more complex rotation matrix. What's more, an optimal control for each of the rotors' angle, force vector will be studied in order to assign the best stabilization factor as the total energy consumption is kept at minimum. It is currently an ongoing study, which will be proposed in future works.

In order to advance in this compensation technique in real-life applications, the optimal control algorithm should be able to assign every rotor's rotation matrices that are updated according to the cost function. The cost function may include the properties of the lowest energy consumption and obtain the maximum thrust forces where necessary. Determining such an optimum control that can work at various environmental conditions is a challenge, which will be investigated in our future work. We are at the process of designing the proposed vehicle.

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Professional Experience and Rewards:

December 2012 – Ongoing: Product Development and Powertrain Program Integration Engineer, Ford Motor Company, Product Development Department. Gebze, Kocaeli/TURKEY.

Ford Cargo Trucks Development Project: Integrating different teams to produce a high quality product. Functional design issues are being tracked and reported out to related engineers, supervisors, managers and the director. CAD design interferences and clearance specifications are tracked and binned to related team members. Weekly meetings for program time planning, vehicle shopping list, design review, issue management, program steering are held with different titles from engineer to director level. Productions plants are weekly visited and investigated in the test build phase of 2016 modely year trucks. The issues are managed and solved during the build and test phases of different model year products.

January 2011 – November 2012: R&D Mechatronics and Control Engineer, Atlantis Unmanned Vehicle Solutions, Research and Development Department. Altunizade, Istanbul/TURKEY.

Unmanned Aerial Vehicles (UAV) Project: Control system design of an autonomous quadrotor, Aeroseeker. Quadrotor system integration and development, motor control and test flights. AHRS (Attitude and Heading Reference System) calibration and tests for different kinds of AHRSs for overall performance. Design of a 9 DOF AHRS from scratch: Sensor calibration, coding, pcb mounting and running-testing the whole system. Propeller balancing, brushless electric motor durability and performance testing. Component and vehicle level tests during the project.

Unmanned Underwater Vehicles (UVV) Project: Control system design of an autonomous unmanned underwater vehicle, Aquaseeker. System integration and development, motor control and system dynamics research. System mounting and stress tests for various parts.

Exhibition: Exhibited company's products at IDEF'11 (Istanbul, TURKEY) and SOFEX'12 (Amman, JORDAN) fairs.

June-Aug. 2009: Internship, VESTEL DEFENCE INDUSTRY, Research and Development Department. Sabiha Gökçen Airport, Istanbul/TURKEY.

Unmanned Aerial Vehicles (UAV) project: Autopilot and motor control, test flights and test analysis of the UAVs, Karayel and Efe .

List of Publications and Patents:

ICUAS'13 Conference: Part of Master's Thesis project namely "Modeling and Control of a Novel Tilt – Roll Rotor Quadrotor UAV" has been accepted and succesfully presented to the attendees of the conference established in Atlanta, GA – USA (May, 2013).

IEEE Publication: Article published as; Fatih Şenkul, Erdinç Altuğ, "Modeling and Control of a Novel Tilt – Roll Rotor Quadrotor UAV", International Conference on Unmanned Aircraft Systems (ICUAS'13).

ICUAS'14 Conference: Part of Master's Thesis project namely "Adaptive Control of a tilt-roll rotor Quadrotor UAV" has been accepted and succesfully presented to the attandees of the conference established in Orlando, FL –USA (May, 2014).

IEEE Publication: Article published as; Fatih Şenkul, Erdinç Altuğ, "Adaptive Control of a tilt-roll rotor Quadrotor UAV", International Conference on Unmanned Aircraft Systems (ICUAS'14).

PUBLICATIONS/PRESENTATIONS

ON THE THESIS

- **F. Şenkul and E. Altuğ** 2013: Modeling and Control of a Novel Tilt – Roll Rotor Quadrotor UAV. *Proc. of IEEE International Conference on Unmanned Aircraft Systems (ICUAS'13), pp. 1071- 1076,* May 28-31, 2013 Atlanta USA.
- **F. Şenkul, E. Altuğ** 2014: Adaptive Control of a Tilt – Roll Rotor Quadrotor UAV . *Proc. of IEEE International Conference on Unmanned Aircraft Systems (ICUAS'14), pp. 1132-1137,* 27-30 May 2014, Florida USA.