PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

University of SAAD DAHLEB BLIDA 1

Institute Of Aeronautics And Space Studies

Aeronautical Construction Department

Final project to obtain the degree of

MASTER

Faculty : Aeronautics

Option : Avionics

Theme :

HAND GESTURE CONTROLLED QUADROTOR

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YEAR 2019/2020

DEDICATION

I dedicate this work :

In memory, to my father, who was and will be always the source of my hope, faith and strength until the end.

To a mother, who gave up on herself, her life, her success, to succeed her children. To a mother who fight to carry her sons from the bottom. I couldn't find any words to express you.

To my beloved sister and her husband and my little sweetheart niece for their encouragement.

To my brothers whose gave me many and many advices to make this work done.

I could not have done it without you . . . many thanks.

ACKNOWLEDGMENTS

As one journeys through life it is soon recognized that very little of what we accomplish as individuals is a solitary act. Cooperation and collaboration are what underlie our actions as human beings and it is through our inter-actions with others that we invariably create our art.

As such, my deepest gratitude goes first to God who has provided all that was needed to complete this project and the program for which it was undertaken for. There was never lack or want.

My sincere appreciation also goes to my promoters Dr.KOUIDER ELOUAHED Boulenouar and Dr. REDA YAGOUB whose contribution and constructive criticism has pushed me to expend the kind of efforts I have exerted to make this work as original as it can be. Thanks to them I have experienced true research and my knowledge on the subject matter has been broadened.

I am and will forever be grateful to my beloved family who has given me everything possible to make sure I achieve this feat. I can't find the words that express my gratitude. A big thank you goes also to all my friends and well-wishers who one way or another have been there and have continually prayed for my success. God bless you all.

ملخص

يركز هذا المشروع على بناء جهاز تحكم بإيماءات اليد. في السنوات الأخيرة ، أصبحت الطائرات بدون طيار ذات الطراز الرباعي أكثر شيوعًا نظرًا لأنها صغيرة ومريحة ومنخفضة التكلفة. تم اختراع العديد من التطبيقات المبتكرة في مجالات مختلفة ، بما في ذلك التصوير الفوتوغرافي والهندسة المعمارية والإنقاذ باستخدام تقنية الطائرات بدون طيار. ومع ذلك ، فإن جهاز التحكم التقليدي في الطائرات بدون طيار يتطلب كلتا يديه وهو ضخم ، وهو أمر غير مريح في معظم المواقف. ستكون وحدة التحكم اليدوية مفيدة لأولئك الطيارين الذين لديهم يد واحدة فقط للتحكم في طائرة بدون طيار. في الوقت نفسه ، يوفر نظام التحكم بالإيماءات طريقة أبسط لقيادة طائرة بدون طيار. سيعزز نظام التحكم هذا سلامة الطيارين وغيرهم. أيضًا ، ستصبح قيادة طائرة بدون طيار أكثر ودية للقادمين الجدد بسبب وحدة التحكم البديهية هذه.

يشتمل هذا المشروع على جزأين: وحدة تحكم بالإيماءات وبيئة اختبار. ستكون بيئة الاختبار لهذا المشروع عبارة عن محاكاة رباعية المحركات. بعد ذلك ، سيتم بناء جهاز التحكم بالإيماءات واختباره على هذا المحاكي. تشتمل وحدة التحكم بالإيماءات على 9 درجات من وحدة قياس بالقصور الذاتي للحرية و وحدة معالجة بالذكاء الاصطناعي. ستجمع وحدة قياس بالقصور الذاتي للحرية البيانات حول إيماءة يد المستخدم بعد ذلك ستتنبأ وحدة المعالجة بالذكاء الاصطناعي بحركة اليد و تخزن كل تلك البيانات كمدخلات ثم تنشأ الأمر الصحيح إلى المحرك الرباعي. أخيرا سيتم إرسال الأمر إلى الطائرة بدون طيار للتحكم فيها.

ABSTRACT

This project focuses on building a hand gesture controller. In the recent years, quadrotor style drones are becoming more and more popular since they are small, convenient, and low-cost. Many innovative applications in different realms, including photography, architecture, and rescue, are invented with drone technology. However, the traditional controller of drones requires both hands and is bulky, which is inconvenient in most situations. A hand controller will be helpful for those pilots who have only one hand available to control a drone. At the same time, the gesture control system offers a simpler way to drive a drone. This control system will enhance both the pilots' and others' safety. Also, driving a drone will become friendlier to newcomers because of this intuitive controller.

This project includes two parts: a gesture controller, and a test environment. The test environment for this project will be a quadrotor simulator. Then, the gesture controller will be built and tested on this simulator. The gesture controller includes a 9 Degrees of Freedom Inertial Measurement Unit (9 DOF IMU), and artificial intelligence processing unit. The 9 DOF will collect the user's hand gesture. Then, the AI processing unit will predict the hand movement and store all those data as input, and then generate correct command to the quadrotor. Finally, the command will sent to the drone and control it.

RESUME

Ce projet se concentre sur la construction d'un contrôleur de gestes de la main. Ces dernières années, les drones de type quadrirotor deviennent de plus en plus populaires car ils sont petits, pratiques et peu coûteux. De nombreuses applications innovantes dans différents domaines, y compris la photographie, l'architecture et le sauvetage, sont inventées avec la technologie des drones. Cependant, le contrôleur traditionnel des drones nécessite les deux mains et est encombrant, ce qui est gênant dans la plupart des situations. Un contrôleur manuel sera utile pour les pilotes qui n'ont qu'une seule main disponible pour contrôler un drone. Dans le même temps, le système de contrôle gestuel offre un moyen plus simple de conduire un drone. Ce système de contrôle améliorera la sécurité des pilotes et des autres. De plus, la conduite d'un drone deviendra plus conviviale pour les nouveaux arrivants grâce à ce contrôleur intuitif.

Ce projet comprend deux parties: un contrôleur de gestes et un environnement de test. L'environnement de test de ce projet sera un simulateur de quadrirotor. Ensuite, le contrôleur de gestes sera construit et testé sur ce simulateur. Le contrôleur de gestes comprend une unité de mesure inertielle à 9 degrés de liberté (9 DOF IMU) et une unité de traitement d'intelligence artificielle. Le 9 DOF collectera le geste de la main de l'utilisateur. Ensuite, l'unité de traitement AI prédira le mouvement de la main et stockera toutes ces données en entrée, puis générera une commande correcte au quadrirotor. Enfin, la commande sera envoyée au drone et le contrôlera.

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General Introduction

Over time, technological developments in aeronautics have a bigger impact in all aspects of human life and, surely, unmanned aerial vehicles (UAVs) play an important role in this process.

The main aim of this work is to design a smart hand with pre-specified gestures to control an UAV. A quadrotor configuration was taken into consideration for the development of hand gesture controller since this kind of platform is mechanically simple, versatile for performing aggressive maneuvers, and easily available for experimentation. In chapter 1 an introduction to UAVs along with a brief history is given. It is discussed why UAVs are important and what are their types and different domains of applications.

In chapter 2 we introduced an elementary basis for understanding and applying unit quaternions for describing dynamic models and designing controllers for UAVs. The quadrotor configuration is used as an example of this approach; however, this methodology can be extended for other types of aircraft. Comprehensive explanations of unit quaternions, their use for describing rotations, their main operations, and their relationships with vectors are provided. Then a general quaternion-based dynamic model, which can be applied to describe any rigid body, is developed, finally a quadrotor dynamic model is introduced. The first part of chapter 3 we provided an introduction to Human machine interaction (HMI) along with a definition of gesture controller system, then giving an overview about Artificial intelligence (AI) especially Neural Network (NN), finishing with a brief definition of hardware used. The second part presents an approach for instantaneous control of drones based on hand gestures. On the last part of this chapter, the experimental results were presented.

Chapter 1
Introduction to Unmanned Aerial Vehicles

I.1 Introduction

Everything started with a passion and a desire for flying like birds. Was looking to the world from above only a dream for humanity? Maybe that was the only thought of Hezarfen Ahmet Celebi when he jumped down from Galata Tower four centuries ago, for his first flight over Istanbul. Ahmet Celebi is a legendary character in Turkish history and we will probably never be sure of his flight's reality, but there is one thing that we are certain of; much has changed since that date. Flight technology has come to a point that he could not imagine, if he ever existed.

Today, aircraft are ideal vehicles of transportation, perfect weapons of warfare, and helpers of human beings, which makes life easier in many areas. Now, think that they are not very expensive or hard to produce and do not even need a pilot. UAVs, namely, Unmanned Aerial Vehicles, were developed for making this purpose real. Although they do not have a genius director, a human aboard, for controlling extraordinary situations without risking human life, UAVs are preferred to manned aircraft for their properties of being more economical, smaller, and lighter [**?**].

I.2 Unmanned Aerial Vehicles

I.2.1 A Brief History

Several names have already been used to describe unmanned aircraft. UAVs became UAS, the preferred term used by the Federal Aviation Administration (FAA). Other names included Remotely Piloted Vehicles (RPVs), a term that was used in the Vietnam War. Today the USAF has mainly substituted RPV for Remotely Piloted Aircraft or RPA [2].

The term UAV or unmanned aerial vehicle has been used for several years to describe unmanned aerial systems. Various definitions have been proposed for this term, like:

The definition of The Department of Defense Dictionary, which defines a UAV as: “A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload ” (According to Newcome) [3].

Figure I.1: Unmanned Aerial Vehicle (typhoon-4k quad-copter) [4].

Although UAVs is a recent concept which has become popular following uses especially in NATO operations during the Kosovo War and American operations like Operation Enduring Freedom, it has a history as old as manned planes from World War I. In fact, misunderstanding their role in military missions and not seeing their accomplishments clearly are key reasons why military planners did not think of them as a part of operations earnestly until themid-1980s [5], which brought about a reduced public interest in those vehicles up to that date [1].

Historically, the “Kettering Bug” built by Charles Kettering for the USA Navy in 1918 may be accepted as the first UAV. This prototype was successful enough to make the army order additional ones, but it has never flown operationally because of the termination of World War I. On the other hand, in the light of common opinion, it is possible to show the “Lightning Bug”, which was substantially used by the USA .during the Vietnam War between 1964 and 1972, as the ancestor of modern UAVs.

During that period, more than 3,400 combat UAVs were flown over North Vietnam, Laos, and China by Strategic Air Command 100th Strategic Reconnaissance Wing of the USAF [5].

I.2.2 Advantages

Unmanned Aerial Vehicle offer many advantages:

- For years, wars have been a potential death machine for humanity and, in that situation, having an assistant which can reduce your army’s loss of life becomes very important.
- The availability of using them during dangerous missions, when rapid information is needed.
- Another situation that suits a UAV is risky operations: for example, discovery flights in nuclear test areas, volcanic area. . . .etc.
- Operating a UAV can be better for economy, simply because it does not need a pilot.
- Being a moveable target for fighter aircraft weapons is a popular use for drone aircrafts.
- A combat pilot candidate can learn everything about fighting and flying in 6 weeks, a period nearly 17 times longer than the duration of the building process of a new Predator UAV.
- Being unmanned reduces the size of an aircraft and, when compared with large planes, a small plane has many more advantages.
- Being unmanned does not only mean not having a pilot; it also means not carrying many more devices necessary for the crew.

I.3 UAV types

According to the International Civil Aviation Organization (ICAO), unmanned aircraft is devided into two groups [6] [7].

I.3.1 Autonomous aircraft

Autonomous aircraft are controlled using on-board computers (following the online calculations or precoded control algorithms). It considered not to be suitable for regulation due to legal and liability issues.

Figure I.2: US military autonomous drone (MQ-9) [8].

I.3.1 Remotely piloted aircraft

Remotely piloted aircraft are controlled by a pilot on the ground. It subject to civil regulation under the ICAO and under the relevant national aviation authority.

Figure I.3: Remotely piloted aircraft [9].

I.4 Classification of UAV

I.4.1 Based on Aerodynamics

A variety of UAV system has been developed and in the advancement phase, some of them includes the Fixed-wing aircraft [9],multi-copter [10] , motor parachute and glider [11,12] , UAV with Vertical takeoff and landing [13,14] , congregating ready-made parts [15] and commercialized UAV[16,17]. All of them are specified for a mission and have their zeros and ones. Fixed wing drones are very simple but saturated in designing and manufacturing, because of successful generalization of larger fixed-wing planes with slight modifications and improvements [18].

- **Fixed wings:**
  Fixed wings are the main lift generating elements in response to forward accelerating speed. The velocity and steeper angle of air flowing over the fixed wings controls the lift produced. Fixed wing drones (figure I.4) require a higher initial speed to initiate a flight [19]. If fixed wing and Multirotor are compared for a same amount of payload, fixed-wing drones are more comfortable with less power requirement. Rudder, ailerons and elevators are used for yaw, roll and pitch angles to control the orientation of aircraft.

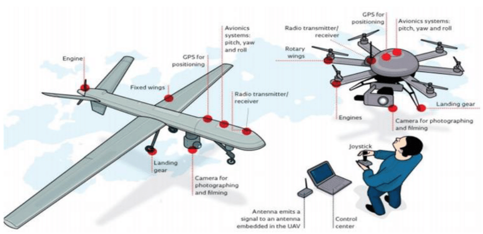


Figure I.4: Fixed wing and Multirotor aerial systems [18].

- **Multirotor:**
  Main rotor blade produces a forceful thrust, which is used for both lifting and propelling. Multirotor unmanned aerial vehicles are capable of vertical take-off and Landing (VTOL) and may hover at a place unlike fixed-wing aircraft [20,21] . Multirotor are designed by number and location of motors and propellers on the frame. Their hovering capability, ability to maintain the speed makes them ideal for surveillance purpose and monitoring. The only concern with Multirotor is that they need more power consumption and makes them endurance limited.

- **Multicopter:**
  Is divided into specific categories based on number and positioning of motors, each category belongs to a specific type of mission [22], and based on the mission requirement they are classified in various configurations such as Monocopter, Tricopter, quadcopter, hexacopter, Octacopter.

I.4.2 Based on Landing

Horizontal takeoff and landing (HTOL) and vertical takeoff and Landing (VTOL): HTOL may be considered as the extension of fixed-wing aircraft. They have high cruise speed and a smooth landing. VTOL drones are expert in flying, landing and hovering vertically [23], but they are limited by cruise speed because of the slowing down of retreating propellers [24].

I.5 Applications

Since Drones provide supremacy over conventional remote sensing technologies and their benefits lie in terms of less power consumption, less risk to human life, ease to data collection, hovering, and ultra-high spatial resolution forges them an excellent choice for surveying and mapping. Following pioneer, studies demonstrate the relevance and uniqueness of drones in the civil, logistics, agriculture and Defense sectors. Figure I.5 depicts the potential applications of UAV in civil, environment and defense sectors [18].

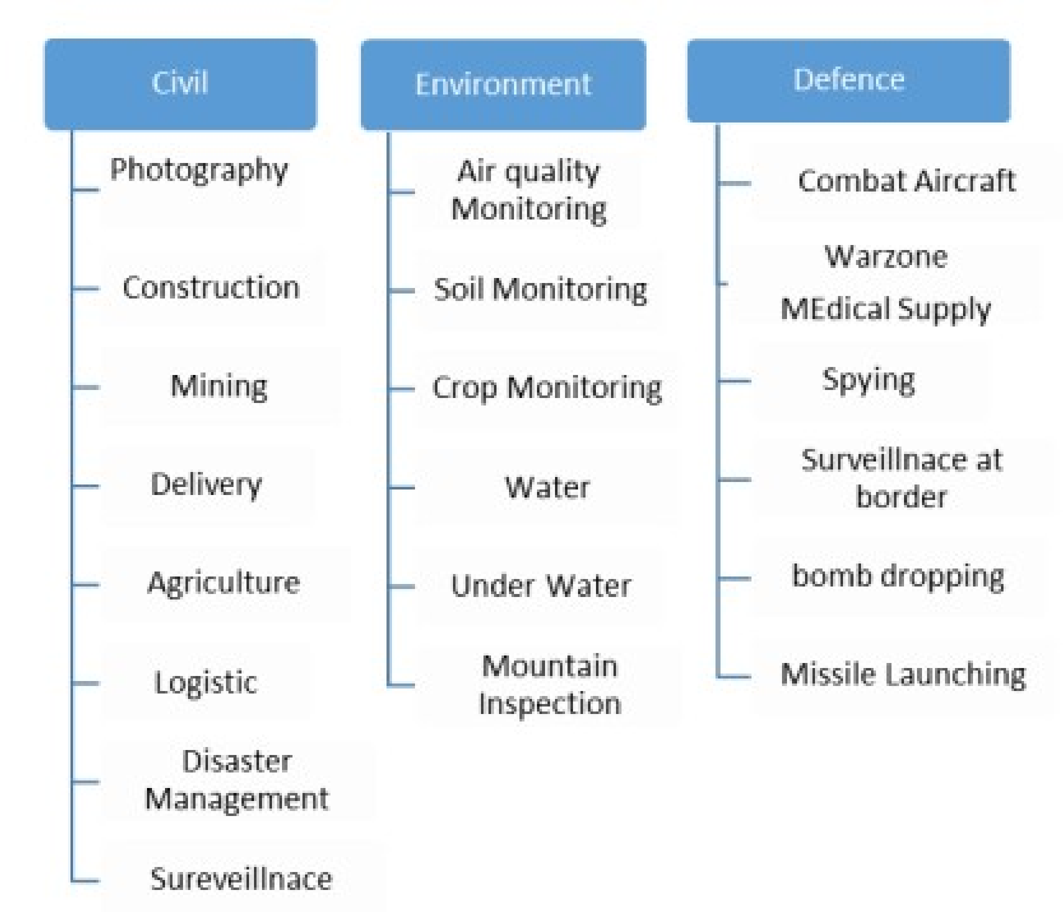


Figure I.5: Potential Applications of Drones [18].

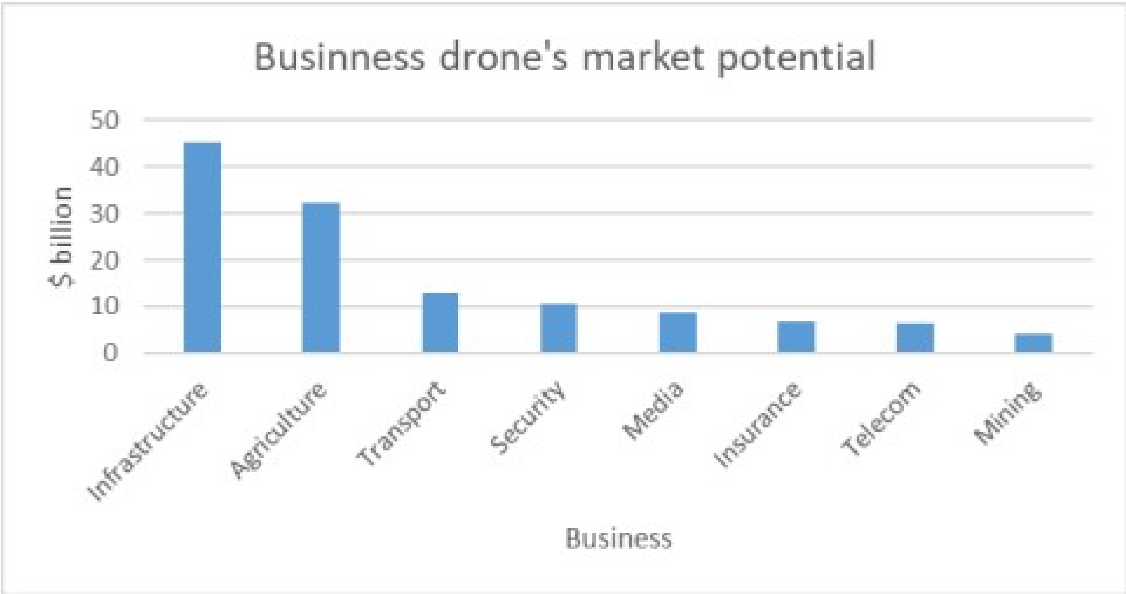


Figure I.6: Market Potential of Drones [18].

I.5.1 Drones in Agriculture

The sole aim of precision agriculture is to apply optimum amount of input at the right time and place to make better products. Common practices of precision farming are the data collection and variability mapping of agriculture lands, data analysis, making farming management decision based on results inferred from analysis and finally controlled application such as pesticide spraying and fertilisers.

I.5.2 Drones in Forestry, fisheries and wildlife protection

In this field drones can perform various tasks like:

- Targeted forest fire detection and monitoring using UAV onboard thermal and hyperspectral sensors [25].
- Survey forests and mapping canopy gaps.
- Animal poaching and adverse climate conditions: UAV equipped with thermal sensors along with satellite are being approached for tagging and counting of animals which help to curb the poaching of animals and conserve the wildlife [26].

I.5.3 Drones in Defense

The advent of UAV was started initially with the aim of transacting the war missions like intelligence, spying, reconnaissance vigilance and target detection; later they were introduced for civil and logistic applications [27] . USA, UK, Russia, India and Israel are the leading countries in the development and deployment of military drones. In 2017 the acceleration in the proliferation of military along with civilian drones was observed, and a maximum number of drone strikes by USA and UK were noted. Breakthrough research and remarkable advancements in the area of swarming drones, jet-powered and Microdrones. According to the Bureau of Investigative Journalism, the US launched more than two times more strikes in 2017 than the year 2016. Following the bar chart shows the data of US strikes on Somalia, Yemen and Afghanistan from the year 2014-2017 [28].

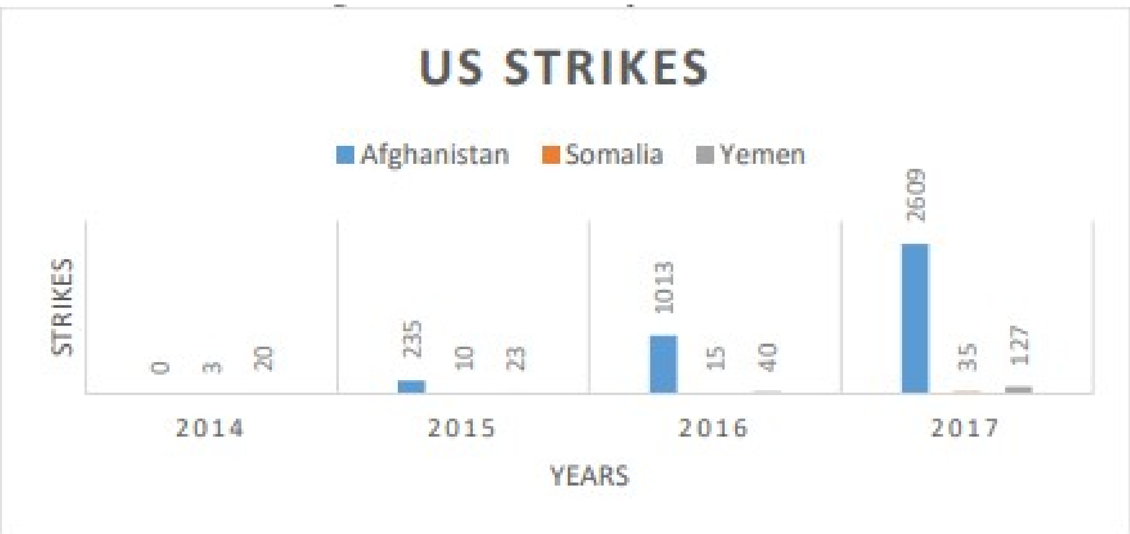


Figure I.7: Number of drone strikes carried out by the USA [18].

India recently has developed DRDO Lakshya, DRDO Aura, DRDO Rustom a Medium-Altitude Long-Endurance (MALE) system being used for target acquisition, releasing missiles, bomb dropping and combat missions [29].

I.5.34 Drones in civil application

Drones are being fascinated in all commercial stratums.

- Electrical companies are preferring drones for inspection of high tension lines with ease of risky task of climbs and power outages [30,31].
- Railway companies have employed drones for monitoring and inspecting the track faults in constrained access areas. The Indian government is planning 3d mapping of thousands of kilometers long railway corridors and national highways.
- Amazon inspired from margarita pizza delivery with drones.
- Drones are helpful in performing search and locate operations of missing people during calamities condition. A trial to locate people in Donegal mountain range, Ireland and rescue operation of 200 people in flood zone by Chennai police.
- Medical facility delivery using drones performed in many countries like the USA.

- Electricity generation through high elevation and high-speed drones is another exploratory area.

I.6 Conclusion

The future generation is dependent on drones; they will create a new market. Drones are being upgraded and adopted by almost all commercial markets including precision agriculture, logistics and infrastructures.

Future technology focused on increasing endurance, payload, improvement in the interaction between human and UAV and making clear rules and regulations for the safe and secure operation of UAV. Besides this, Integration of Artificial intelligence with drone technology will enable the drone to take decisions and independence to human controllers.

A day by day, in many areas, UAVs have taken the place of manned aircraft. Maybe one day, even passenger planes will be UAVs and there will no longer be a need for pilots. However, a crucial challenge awaiting us before we can use UAVs in all areas of human life.

Chapter 2
Quadrotor Modeling

II.1 Introduction

Unmanned aerial vehicles have been increasing in popularity over the last years, every day with more people interested on developing new applications for these robotic systems[32].
Most researchers have relied on the classical Euler angles (H. Goldstein 1962) to represent the dynamics of UAVs. This approach is intuitive and easy to implement, specially when simplifications are considered, e.g. maintaining small angles, slow movements, etc. However, when more arduous designs, tasks, or applications are involved, Euler angles representations encounter some problems, such as gimbal locks[33].A more stable and more simple mathematical tool for modeling these dynamics are quaternions.
Quaternions are a type of hyper-complex numbers that can be used to describe rotations in 3D space. Its computational stability comes from the fact that only unit quaternions are required to describe rotations, reducing numeric errors when they are normalized. They lack the gimball lock effect inherent to Euler's angles because of its relationship to the axis-angle representation. Their mathematical simpleness comes from the fact that no trigonometric functions are required directly when they are used to model a rigid body's dynamics, only arithmetic functions like quaternion products(which are computationally efficient)[34].

II.2 Priliminar notions

II.2.1 References

Before describing the mathematical model of a quadrotor, it is necessary to introduce the reference coordinates in which we describe the structure and the position. For the quadrotor, it is possible to use two reference systems. The first is fixed and the second is mobile. The fixed coordinate system, called also inertial, is a system where the first Newton's law is considered valid. The mobile reference system is united with the mass center of the quadrotor.

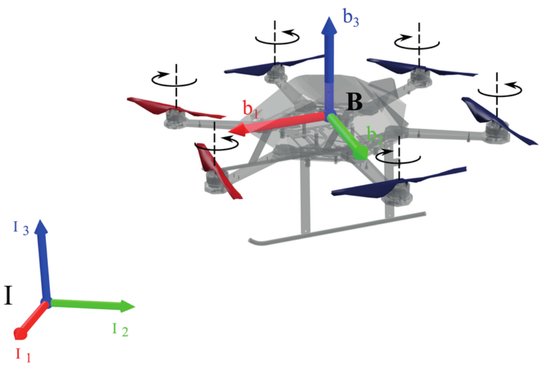


Figure II.1: Inertial and mobile reference frames [39].

II.2.2 Quadrotor motions

The attitude and position of the quadrotor can be controlled to desired values by changing the speeds of the four motors. The following forces and moments can be performed on the quadrotor: the thrust caused by rotors rotation, the pitching moment and rolling moment caused by the difference of four rotors thrust, the gravity, the gyroscopic effect, and the yawing moment. The gyroscopic effect only appears in the lightweight construction quadrotor. The yawing moment is caused by the unbalanced of the four rotors rotational speeds. The yawing moment can be cancelled out when two rotors rotate in the opposite direction. So, the propellers are divided in two groups. One group rotating counterclockwise and the other group rotating clockwise.(see figure II.2)

Figure II.2: Direction of propeller's rotations [40].

The space motion of the rigid body aircraft can be divided into two parts: the mass center movement and movement around the mass center. Six degrees of freedom are required in describing any time space motion. They are three mass center movements and three angular motions, namely, three translation and three rotation motions along three axes. The control for six degrees of freedom motions can be implemented by adjusting the rotational speeds of different motors. The motions include forward and backward movements, lateral movement, vertical motion, roll motion, and pitch and yaw motions. The yaw motion of the quadrotor can be realised by a reactive torque produced by the rotor. The size of the reactive torque is relative to the rotor speed. When the four rotor speeds are the same, the reactive torques will balance each other and quadrotor will not rotates,whereas if the four rotor speeds are not absolutely same, the reactive torques will not be balanced, and the quadrotor will start to rotate. When the four rotor speeds synchronously increase and decrease is also required in the vertical movement[35].

II.2.2.1 ***Vertical Lift:***

In order for a quadrotor to rise into the air, a force must be created, which equals or exceeds the force of gravity. This is the basic idea behind aircraft lift, which comes down to controlling the upward and downward force. Now, quadrotors use motor design and propeller direction for propulsion to basically control the force of gravity against the quadrotor. The spinning of the quadrotor propeller blades push air down. All forces come in pairs (Newtons Third Law), which means for every action force there is an equal (in size) and opposite (in direction) reaction force. Therefore, as the rotor pushes down on the air, the air pushes up on the rotor. The faster the rotors spin, the greater the lift and vice-versa (figure II.3(Elevation)).
Now, a drone can do three things in the vertical plane: hover, climb, or descend.

- **Hover Still :** To hover, the net thrust of the four rotors push the drone up and must be exactly equal to the gravitational force pulling it down.
- **Climb Ascend :** By increasing the thrust (speed) of the four quadcopter rotors so that the upward force is greater than the weight and pull of gravity.
- **Vertical Descend :** Dropping back down requires doing the exact opposite of the climb. Decrease the rotor thrust (speed) so the net force is downward.

II.2.2.2 ***Roll motion:***

Figure II.3(Roll) shows how we can obtain a roll motion. In that case, we should increase the speed of the rotors 1 and 3 (roll right) or the rotors 2 and 4 (roll left). This movement is coupled with a translational movement along the pitch axis.

II.2.2.3 ***Pitch motion:***

Figure II.3(Pitch)shows how we can obtain a pitch movement. In that case, we should increase the speed of the rotors 3 and 4 (pitch forward) or the rotors 1 and 2 (pitch backward). This movement is coupled with a translational movement along the roll axis.

II.2.2.4 ***Yaw motion:***

The yaw motion of the quadrotor can be realised by a reactive torque produced by the rotor. When the four rotor speeds are the same, the quadrotor won't rotates,whereas if the four rotor speeds are not absolutely the same, the quadrotor will start to rotate. (see figure II.3(Yaw))
The increase in lift force in one pair of rotors should be equal to the decrease in the other pairs to ensure that all of the thrust force remains the same.

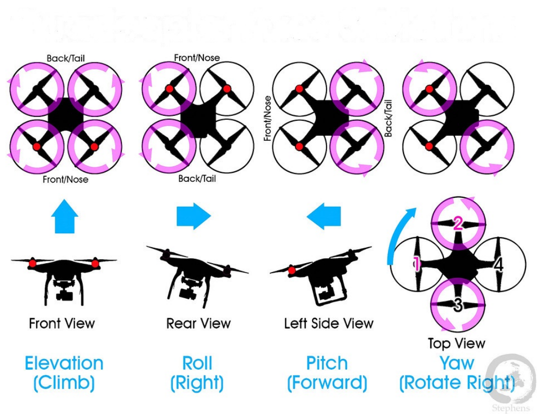


Figure II.3: Quadrotor motions [41].

II.2.2.5 ***Translational movement:***

As shown in figure II.4, to make a quadrotor do a translational movement, we should first tilt the quadrotor along the roll or pitch axis and then increase all the thrust produced to keep the importance of the component of z(yaw) axis of the thrust equal to the force of gravity.

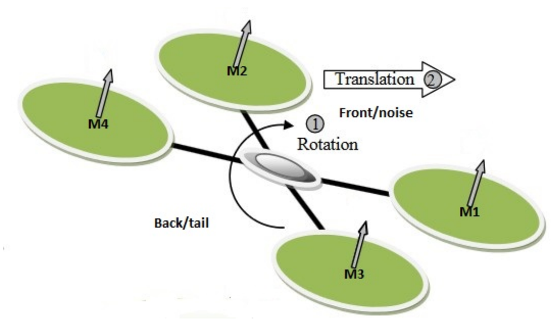


Figure II.4: Quadrotor translational movement [42].

II.2.3 Quaternion background

Quaternions were proposed by Hamilton in the nineteenth century as a three-dimensional version of complex numbers (represented as one real and one imaginary part). They are also known as "hypercomplex" numbers (the hypercomplex space is noted as $\mathbb{H}$) since they can be represented as one real plus three imaginary numbers as:

$$q \triangleq q_0 + q_1\hat{i} + q_2\hat{j} + q_3\hat{k}$$

Where:
$\hat{i}, \hat{j}, \hat{k} \in \mathbb{I}$, such that: $\hat{i}^2 = \hat{j}^2 = \hat{k}^2 = \hat{i}\hat{j}\hat{k} = -1$
And:
$q_0, ..., q_3 \in \mathbb{R}$

Another common representation of a quaternion is using one scalar number and a vector as:

$$q \triangleq q_0 + \overline{\mathrm{q}}$$

with: $\overline{\mathrm{q}} = [q_1 q_2 q_3]^T$

Since the space of three-dimensional vectors is included in the quaternion space, then vectors can be treated as quaternions with a scalar part equal to zero in all of the quaternion operations.
Considering the rotation illustrated in Figure II.5 as vector $\overline{\alpha} = [\alpha_x \alpha_y \alpha_z]^T$ with magnitude $\alpha = \|\overline{\alpha}\|$ in radians, acting on an axis represented as a unitary vector $\overline{\mathrm{u}} = \frac{\overline{\alpha}}{\|\overline{\alpha}\|}$, the **axis-angle representation** of this rotation is denoted as :

$$\overline{\alpha} = \alpha \overline{\mathrm{u}} \quad (1)$$

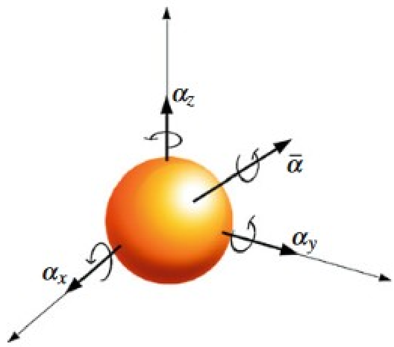


Figure II.5: Axis-angle representation of a rigid body rotation [32].

We know that a simple rotation, with magnitude ϕ in radians, over a plane can be represented using the **Euler formula** as $\mathrm{e}^{\hat{i}\phi} = \cos(\phi) + \hat{i}\sin(\phi)$. In the nineteenth century, a French banker named Olinde Rodrigues expanded the Euler formula to include three-dimensional rotations using quaternions. This expression, known as the Euler-Rodrigues formula is the exponential mapping of the axis-angle representation of a rotation, defined as:

$$q = \mathrm{e}^{\frac{1}{2}\alpha\overline{\mathrm{u}}} = \cos(\alpha/2) + \overline{\mathrm{u}}\sin(\alpha/2) \quad (2)$$

Notice that $\| q \| = 1$; and thus q can called a *unit quaternion*.
Inversely, the axis-angle representation of a rotation can be derived from a quaternion using the logarithmic mapping:

$$\overline{\alpha} = 2lnq \quad (3)$$

with:

$$lnq = \begin{cases} [000] & if\|\overline{q}\| = 0 \\ \frac{\overline{q}}{\|\overline{q}\|}\arccos(q_0) & if\|\overline{q}\| \neq 0 \end{cases} \quad (4)$$

II.2.4 Quaternion operations

Considering $q, r \in \mathbb{H}$, the quaternion operations are defined as:

- **product**

$$q \otimes r = (q_0 r_0 - \overline{\mathrm{q}} * \overline{\mathrm{r}}) + (q_0 \overline{r} + r_0 \overline{q} + \overline{q} \times \overline{r}) \tag{5}$$

Notice that quaternion product is not commutative.

- **Sum**
The sum of quaternion is simply the sum of each of its elements.

$$q + r = q_0 + r_0 + \overline{q} + \overline{r} \tag{6}$$

- **Conjugate**
The conjugate of a unit quaternion is defined as :

$$q^* = q_0 - \overline{q} \tag{7}$$

while the conjugate of a product of quaternion is:

$$(q \otimes r)^* = r^* \otimes q^* \tag{8}$$

- **Norm**
The norm of a quaternion is:

$$\|q\|^2 = q \otimes q^* = q_0^2 + q_1^2 + q_2^2 + q_3^2 \tag{9}$$

- **Inverse**
For any non-null quaternion, there exist an inverse quaternion such that:

$$q^{-1} = \frac{q^*}{\|q\|} \tag{10}$$

$$q \otimes q^{-1} = q^{-1} \otimes q = 1$$

- **Vector rotation**
Considering $\overline{p} \in \mathbb{R}^3$ as a 3D vector in a first reference frame(e.g, the earth coordinates) and $\overline{p}^{'}$ as the same vector but in a different reference frame (e.g, vehicle's moving coordinates),then $\overline{p}$ can be transformed into $\overline{p}^{'}$ by using the equation below :

$$\overline{p}^{'} = q^{-1} \otimes \overline{p} \otimes q = q^* \otimes \overline{p} \otimes q \tag{11}$$

where:
q represents the rotation of the second reference frame with respect to the first one.
Note this rotation does not affect the vector's magnitude.

- **Derivative**
The derivative of any unit quaternion can be obtained by differentiating (11) as:

$$\dot{\overline{p}}^{'} = \dot{q}^{-1} \otimes \overline{p} \otimes q + q^{-1} \otimes \overline{p} \otimes \dot{q} = \dot{q}^{-1} \otimes q \otimes \overline{p}^{'} + \overline{p}^{'} \otimes q^{-1} \otimes \dot{q} \tag{12}$$

We have: $q^{-1} \otimes q = 1$ (q is unit quaternion)
And: $\dot{q}^{-1} \otimes q + q^{-1} \otimes \dot{q} = 0$
So:

$$\dot{\overline{p}}^{'} = \overline{p}^{'} \otimes q^{-1} \otimes \dot{q} - q^{-1} \otimes \dot{q} \otimes \overline{p}^{'} = 2(q^{-1} \otimes \dot{q}) \times \overline{p}^{'} \tag{13}$$

Notice that $\dot{\overline{p}}^{'}$ is the translational velocity of the vector $\overline{p}^{'}$: $\dot{\overline{p}}^{'} = \omega \times \overline{p}^{'}$.
Where:
ω: is the rotational velocity of $\overline{p}^{'}$.
thus:

$$\omega \times \overline{p}^{'} = 2(q^{-1} \otimes \dot{q}) \times \overline{p}^{'} \tag{14}$$

which can be reduced to:

$$\omega = 2(q^{-1} \otimes \dot{q}) \Leftrightarrow \dot{q} = \frac{1}{2} q \otimes \omega \tag{15}$$

- **Axis-Angle representation and Angular velocity**
We can obtain an important property by differentiating the Euler-Rodrigues formula (equation (2)) in its exponential expression:

$$\dot{q} = \frac{d}{dt} \mathrm{e}^{\frac{1}{2}\overline{\alpha}} = \frac{1}{2} \mathrm{e}^{\frac{1}{2}\overline{\alpha}} \otimes \dot{\overline{\alpha}} = \frac{1}{2} q \otimes \dot{\overline{\alpha}} \tag{16}$$

From (15) and (16),we conclude that:

$$\dot{\overline{\alpha}} = \omega \tag{17}$$

- **Exponential**
The exponential of a quaternion is computed as :

$$\mathrm{e}^{q} = \mathrm{e}^{q_0} \left(\cos \parallel \overline{q} \parallel + \frac{\overline{q}}{\parallel \overline{q} \parallel} \sin \parallel \overline{q} \parallel \right) \tag{18}$$

II.3 Froce and moment in a rotor

According to blade element theory, the forces and moment developed on a uniform wing are determined by the lift and drag forces and a pitching torque (see figure II.6) [36]. For a given rotor i with angular velocity ω_i, the linear velocity at each point along the propeller is proportional to the radial distance from the rotor shaft [37]. Thus the following equations can be stated:

$$f_i = C_T \rho A_p r^2 \omega_i^2 \tag{19}$$

$$\tau_i = C_Q \rho A_p r^3 \omega_i^2 \tag{20}$$

where:
f_i: total thrust produced by rotor $i = 1, ..., 4$ acting perpendicularly to the rotor plane neglecting blade flapping effect.
τ_i: rotor torque.
r: rotor radius.
ρ: air density.
$A_p = \pi r^2$.
C_T, C_Q: non-dimensional thrust and rotor torque coefficients, wich can be computed using blade element theory [38].

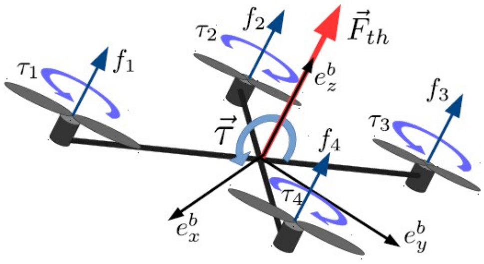


Figure II.6: Forces and torques acting on a quadrotor [33].

Usually, it is considered that the aerodynamic parameters from (19) and (20) are constants, $k_T \approxeq C_T \rho A_p r^2$, $k_Q \approxeq C_Q \rho A_p r^3$.
Taking into account a quadrotor symmetrical configuration, the total torque and thrust force produced on the vehicle by the propellers is computed as:

$$\overrightarrow{F}_{th} = \begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} k_T \omega_i^2 \end{bmatrix} \quad \overrightarrow{\tau} = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \quad = \begin{bmatrix} l(k_T\omega_1^2 + k_T\omega_2^2 - k_T\omega_3^2 - k_T\omega_4^2) \\ l(k_T\omega_1^2 - k_T\omega_2^2 - k_T\omega_3^2 + k_T\omega_4^2) \\ \sum_{i=1}^{4} k_Q \omega_i^2 (-1)^2 \end{bmatrix} \tag{21}$$

where:
τ_x, τ_y, τ_z: represent the total torque components produced in each axis of the body reference frame.
$\overrightarrow{F}_{th}$: represents the total thrust force, acting in the vertical axis of the quadrotor.
l: defines the perpendicular distance between any motor and axes,e_x^b or e_y^b.

II.4 Quaternion dynamic modeling

The translational and rotational state of any given rigid body can be expressed as $x = \left[\overrightarrow{p}\dot{\overrightarrow{p}}q\omega\right]^T$ where $\overrightarrow{p} \in \mathbb{R}^3$ represents the body's position in the inertial frame,$\dot{\overrightarrow{p}}$ its velocity; $q = q_0 + [q_1 q_2 q_3]^T$ defines the vehicle orientation with respect to the inertial frame, represented as a unit quaternion; and $\omega = [\omega_x \omega_y \omega_z]^T$ represents the rotational velocity in the body's frame located on its center of mass.Therefore, following Newton's equations of motion, the dynamic model of any rigid body expressed with unit quaternions is :

$$\dot{x} = \frac{d}{dt}\begin{bmatrix} \overrightarrow{p} \\ \dot{\overrightarrow{p}} \\ q \\ \omega \end{bmatrix} = \begin{bmatrix} \dot{\overrightarrow{p}} \\ m^{-1}F_I \\ \frac{1}{2}q \otimes \omega \\ J^{-1}(\tau - \omega \times J\omega) \end{bmatrix} \tag{22}$$

where:
J: is the inertia matrix with respect to the body's reference frame.
τ: represent the total torque with respect to the body's reference frame.
F_I: defines the total force applied to the body in the inertial coordinate system.

Equation (22) can be used to describe any mechanical system including aerial vehicles.

II.5 Quadrotor quaternion dynamical model

The quadrotor is a geometrically simple aerial vehicle. It consists on four parallel rotors with blades attached to a frame in cross configuration. The direction of the rotation of each blade is selected such that all torques on the rotors cancel out in stationary flight.
If the mechanical configuration is considered to be symmetric, and some effects as blade flapping and the misalignment on the motors' axes could be considered small enough, it can then be assumed that the forces and torques which act on the vehicle are only the ones illustrated on Figure II.7.

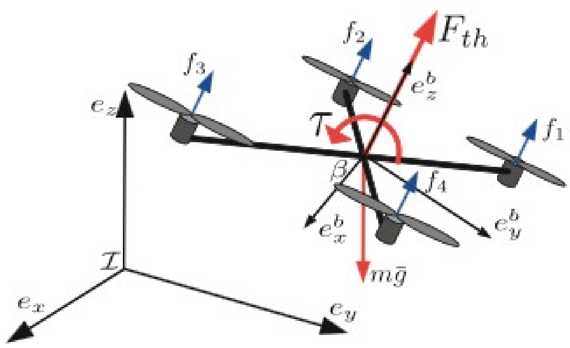


Figure II.7: Quadrotor free body diagram [32].

Here, two reference frames are considered.$I = [e_x e_y e_z]^T$ define the fixed inertial coordinates, and $\beta = \left[e_x^b e_y^b e_z^b\right]^T$ represents the moving frame located on the vehicle's center of mass, and $q = e^{\frac{1}{2}\overrightarrow{\alpha}}$ denotes a quaternion rotation from I to β.
F_{th} and τ symbolize the total thrust force and the total torque respectively, which are described in (21).
Note that both F_{th} and τ act on β, but applying a quaternion rotation from (11),it

is easy to change their reference frame to I.Thus, the quadrotor's dynamic model is expressed as:

$$\dot{x}_{quad} = \frac{d}{dt}\begin{bmatrix} \overrightarrow{p} \\ \dot{\overrightarrow{p}} \\ q \\ \omega \end{bmatrix} = \begin{bmatrix} \dot{\overrightarrow{p}} \\ q \otimes \frac{\overrightarrow{F}_{th}}{m} \otimes q^* + \overrightarrow{g} \\ \frac{1}{2} q \otimes \omega \\ J^{-1}(\tau - \omega \times J\omega) \end{bmatrix} \tag{23}$$

where:
$\overrightarrow{g} = [0 \quad 0 \quad g]^T$ corresponds to the gravity's vector.

Defining $F^I_{th} = q \otimes \overrightarrow{F}_{th} \otimes q^* + m\overrightarrow{g}$, the model can be represented using axis-angle notation:

$$\dot{x}'_{quad} = \frac{d}{dt}\begin{bmatrix} \overrightarrow{p} \\ \dot{\overrightarrow{p}} \\ \overrightarrow{\alpha} \\ \dot{\overrightarrow{\alpha}} \end{bmatrix} = \begin{bmatrix} \dot{\overrightarrow{p}} \\ m^{-1} F^I_{th} \\ \dot{\overrightarrow{\alpha}} \\ J^{-1}(\tau - \dot{\overrightarrow{\alpha}} \times J\dot{\overrightarrow{\alpha}}) \end{bmatrix} \tag{24}$$

Note from (23) and (24) that the quadrotor's rotational and translational dynamics are coupled, due to the orientation of F^I_{th} depending on the vehicle's attitude q. Nevertheless, using an appropriate approach and some properties of unit quaternions, the quadrotor can be easily stabilized despite its underactuated nature.

II.6 Decoupling the vehicle's dynamics

II.6.1 Quadrotor quaternion rotational model

From equation 23), the state vector of the rotational dynamics is :

$$\dot{x}_r = \frac{d}{dt}\begin{bmatrix} q \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{1}{2} q \otimes \omega \\ J^{-1}(\tau - \omega \times J\omega) \end{bmatrix} \tag{25}$$

or from (24):

$$\dot{x}'_r = \begin{bmatrix} \dot{\overrightarrow{\alpha}} \\ \ddot{\overrightarrow{\alpha}} \end{bmatrix} = \begin{bmatrix} \dot{\overrightarrow{\alpha}} \\ J^{-1}(\tau - \dot{\overrightarrow{\alpha}} \times J\dot{\overrightarrow{\alpha}}) \end{bmatrix} \tag{26}$$

If (25) is stabilized using using any appropriate controller τ_u , then the quaternion attitude will converge to $q_0 = 1 + [000]^T$ while the axis-angle orientation $\overrightarrow{\alpha}$ and its angular velocity ω will converge to zero.
Given a desired attitude trajectory defined by a reference quaternion q_d and its angular velocity ω,(25) and (26) can be defined in terms of the error quaternion $q_e \triangleq q^*_d \otimes q$ as:

$$\frac{d}{dt}\begin{bmatrix} q_e \\ \omega_e \end{bmatrix} = \begin{bmatrix} \frac{1}{2} q_e \otimes \omega_e \\ J^{-1}(\tau - \omega_e \times J\omega_e) \end{bmatrix} \tag{27}$$

if τ_u is correctly designed in terms of the attitude error. Then $q_e \rightarrow q_0$, implying $q \rightarrow q_d$.

II.6.2 Quadrotor quaternion translational model

From (23), the translational dynamics are given by:

$$\dot{x}_t = \frac{d}{dt}\begin{bmatrix}\overrightarrow{p} \\ \dot{\overrightarrow{p}}\end{bmatrix} = \begin{bmatrix}\dot{\overrightarrow{p}} \\ m^{-1}F_{th}^{I}\end{bmatrix} \tag{28}$$

Since (28) is a linear system, an appropriate desired force F_{th}^{I} can be designed such that x_t and $\dot{x}_t$ converge to zero. If a position error is defined as $\overrightarrow{p}_e = \overrightarrow{p} - \overrightarrow{p}_d$, where $\overrightarrow{p}_d$ represents a desired position for the UAV, then the translational error dynamics can be written as:

$$\frac{d}{dt}\begin{bmatrix}\overrightarrow{p_e} \\ \dot{\overrightarrow{p_e}}\end{bmatrix} = \begin{bmatrix}\dot{\overrightarrow{p_e}} \\ m^{-1}F_{th}^{I}\end{bmatrix} \tag{29}$$

Consequently, if an adequate controller is designed for F_{th}^{I}, the position error will converge to zero, which mean that the quadrotor can be stabilized in any desired position.

II.7 Coupled dynamics

Analyzing (29), it yields that the translational model can be seen as a fully actuated system, in which $\overrightarrow{F}_{th}^{I}$ can be designed to point at any direction. But considering the complete model of the quadrotor, the force that the propellers really exert depends on the attitude subsystem as seen in (23).

Supposing an appropriate F_{th}^{I} is designed to stabilize the translational subsystem (29), then an attitude trajectory can be computed such that the quadrotor's thrust vector F_{th} is pointed toward the desired control force. This trajectory is derived from the shortest rotation between both vectors and represented with a desired quaternion q_d.
Recalling the Euler-Rodrigues fomula from (2),q_d is defined as:

$$q_d = \mathrm{e}^{\frac{1}{2}\alpha_d \overrightarrow{u}_d} = \cos(\alpha_d/2) + \overrightarrow{u}_d \sin(\alpha_d/2) \tag{30}$$

where $\overrightarrow{u}_d$ and α_d denote, respectively, the axis and angle of the shortest rotation between F_{th} and F_{th}^{I}.
Defining $\hat{F}_{th}$ and $\hat{F}_{th}^{I}$ as the normalized vectors of $\hat{F}_{th}$ and $\hat{F}_{th}^{I}$,respectively (note $\hat{F}_{th} = [001]^T$ is constant), the cross product between these vectors is defined as:

$$\hat{F}_{th} \times \hat{F}_{th}^{I} = \overrightarrow{u}_d \sin(\alpha_d) \tag{31}$$

and the scalar product is given by:

$$\hat{F}_{th}\hat{F}_{th}^{I} = \cos(\alpha_d) \tag{32}$$

From the definition of the quaternion product, and treating $\hat{F}_{th}$ and $\hat{F}_{th}^{I}$ as quaternions with zero-value scalar parts,(31) and (32) can be obtained as:

$$\hat{F}_{th}^{I} \otimes \hat{F}_{th}^{*} = -\hat{F}_{th}^{I}\hat{F}_{th}^{*} + \hat{F}_{th}^{I} \times \hat{F}_{th}^{*} = \hat{F}_{th}\hat{F}_{th}^{I} + \hat{F}_{th} \times \hat{F}_{th}^{I} = \cos(\alpha_d) + \overrightarrow{u}_d \sin(\alpha_d) \tag{33}$$

Since equation (33) expresses twice the desired rotation needed in (30), some exponential and logarithmic properties are then applied, thus resulting in:

$$q_d = \mathrm{e}^{\frac{ln(\hat{F}^I_{th} \otimes \hat{F}^*_{th})}{2}} \tag{34}$$

Notice that since $\hat{F}_{th}$ acts only in the vertical axis of the quadrotor, then q_d will only compute the rotations around the xy plane of the inertial frame.
Considering Ψ_d as a desired rotation around the z axis of the vehicle's body frame, the desired quaternion can be enhanced as:

$$q_d = \mathrm{e}^{\frac{ln(\hat{F}^I_{th} \otimes \hat{F}^*_{th})}{2}} \otimes q_z = \mathrm{e}^{\frac{ln(\hat{F}^I_{th} \otimes \hat{F}^*_{th})}{2}} \otimes \mathrm{e}^{\frac{[00\Psi_d]^T}{2}} \tag{35}$$

Introducing (35) into the rotational error dynamic model from (27), and if τ is designed such that $q \to q_d$, then it implies that F^I_{th} point toward the desired control force such that the system (29) can be stabilized if the desired control force is correctly designed.

II.8 Conclusion

Quaternions, as a mathematical concept, have been known for more than a century.Nevertheless, their application in modeling of robotic systems, more specifically unmanned aerial vehicles, is relatively recent. Until the last few years,most researchers have chosen more conservative approaches as the Euler-Lagrange or Newton-Euler methodologies to describe dynamic models .However, intuitive representation has been surpassed by its many limitations, like the presence of important nonlinearities, undesired effects such as the Gimball-Lock, and an inherent complexity when multiple rotations and translations are present.

The goal of this chapter is to provide a clear introduction to dynamic modeling of quadrotors using unit quaternions. The objectives are to present the main concepts which are needed to apply this methodology to any aerial system and to present the particular application on quadrotors as an example. Although this approach can appear to be less intuitive and difficult to conceptualize, we believe that once the basic concepts are understood,the application of quaternions can really simplify dynamic models of any aerial system.

Chapter 3
Hand Gesture Controlled Quadrotor

III.1 Introduction

Human Machine Interaction, or more commonly Human Computer Interaction, is the study of interaction between people and computers. Whether its waking up in the morning to our digital radio alarm clocks, traveling to work in a car or train, using a laptop or desktop computer in our work place, or communicating to friends and family through mobile phones, it is safe to say that computer systems are everywhere in today society and human interact it with it [43].

The chapter is organized as follows: in Section III.2 we introduce gesture controlled system. In section III.3 we give some basic aspects about artificial intelligence and neural network, and the section III.4 present a brief definition about the hardware used. we discuss the system architecture and data collection in details in section III.5. We present the experimental results in Section III.6 . Finally, we provide a conclusion in Section III.7 .

III.2 Gesture controlled system

Humans naturally use gesture to communicate. It has been demonstrated that young children can readily learn to communicate with gesture before they learn to talk. A gesture is non-verbal communication made with a part of the body. We use gesture instead of or in combination with verbal communication. Using this process, human can interface with the machine. So our natural or intuitive body movements or gestures can be used as command or interface to operate machines, communicate with intelligent environments to control home appliances, smart home, drones, etc [44].

Gestural interfaces have a number of potential advantages:

- A single gesture can be equivalent to many keystroke s and mouse actions;
- The package can be held in one hand and operated with the other, permitting its use in shops, warehouses and manufacturing facilities, or where the other hand must be free to use a telephone, calculator, etc;
- The interface is silent, facilitating its use in group meetings;

And a couple of potential disadvantages:

- Handwriting is 2-5 times slower than keyboard entry for text;
- Gestural interfaces will be more expensive than keyboard/mouse interfaces for example;

Figure III.1: Gesture controlled quadrotor.

III.2.1 Types of gestures

Most of the researches are based on hand gestures. Direct control via hand posture is immediate, but limited in the number of Choices [45] .There are researches about body gesture, finger point movement. In the early stage, researchers used gloves with microcontroller and connected with the device through a wire. Head gesture is also in the research, but hand gesture was the most dominant part of gesture control system.

The ways of recognizing the gesture can be considered as a significant progress of the technology. Progress of image processing technology has played an important role here. Gestures have been captured by using infrared beams, data glove, still camera, wired and many inter connected technologies like gloves. Recent vision technique, video and web cam based gesture recognition has made it possible to capture any intuitive gesture for any ubiquitous devices from the natural environment with 3D visualization [44].

III.3 Artificial intelligence

The precise definition and meaning of the word intelligence, and even more so of Artificial Intelligence, is the subject of much discussion and has caused a lot of confusion. One dictionary alone, for example, gives four definitions of Artificial Intelligence [46]:

- An area of study in the field of computer science. Artificial intelligence is concerned with the development of computers able to engage in human-like thought processes such as learning, reasoning, and self-correction.

- The concept that machines can be improved to assume some capabilities normally thought to be like human intelligence such as learning, adapting, self-correction, etc.
- The extension of human intelligence through the use of computers, as in times past physical power was extended through the use of mechanical tools.
- In a restricted sense, the study of techniques to use computers more effectively by improved programming technique.

III.3.1 Artificial neural network

Inspired by the sophisticated functionality of human brains where hundreds of billions of interconnected neurons process information in parallel, researchers have successfully tried demonstrating certain levels of intelligence on silicon. Examples include language translation and pattern recognition software [47].

III.3.1.1 Definition

An artificial neural network (ANN) is the piece of a computing system designed to simulate the way the human brain analyzes and processes information. It is the foundation of artificial intelligence (AI) and solves problems that would prove impossible or difficult by human or statistical standards. ANNs have self-learning capabilities that enable them to produce better results as more data becomes available [48].

An artificial neural network consists of an input layer of neurons (or nodes, units), one or many hidden layers of neurons, and a final layer of output neurons. Figure III.2 shows a typical architecture, where lines connecting neurons are also shown. Each connection is associated with a numeric number called weight. The output, hi, of neuron i in the hidden layer is[47]:

$$h_i = \sigma(\sum_{j=1}^{N} V_{ij}x_j + T_i^{hid})$$

where:
σ : is called activation (or transfer) function
N : the number of input neurons
V_{ij} : the weights
x_j : inputs to the input neurons
T_i^{hid} : the threshold terms of the hidden neurons

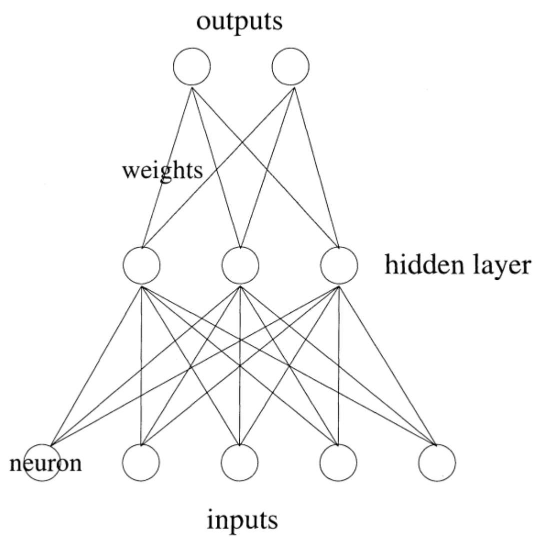


Figure III.2: Architecture of a neural network [47].

III.3.1.2 Multilayer perceptron

A perceptron is a simple binary classification algorithm, proposed by Cornell scientist Frank Rosenblatt. It helps to divide a set of input signals into two parts—"yes" and "no"[49].

The multilayer perceptron consists of a system of simple interconnected neurons, or nodes, as illustrated in figure III.3, which is a model representing a nonlinear mapping between an input vector and an output vector. The nodes are connected by weights and output signals which are a function of the sum of the inputs to the node modified by a simple nonlinear transfer, or activation function. It is the superposition of many simple nonlinear transfer functions that enables the multilayer perceptron to approximate extremely non-linear functions [50].

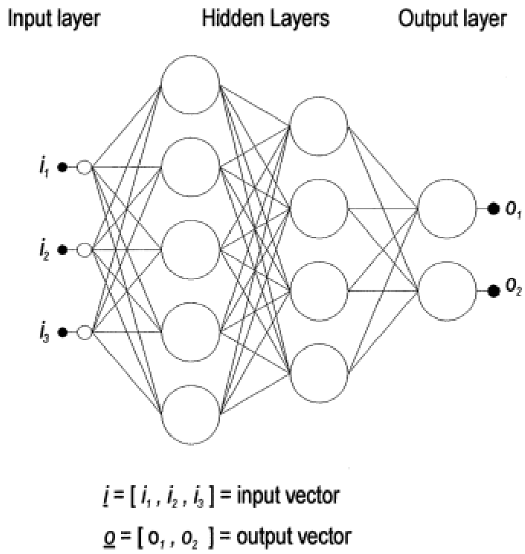


Figure III.3: A multilayer perceptron with two hidden layers [50].

III.3.1.3 Activation function

An activation function is a simple mapping of summed weighted input to the output of the neuron. It is called an activation function because it governs the threshold at which the neuron is activated and strength of the output signal.
Historically simple step activation functions were used where if the summed input was above a threshold, for example 0.5, then the neuron would output a value of 1.0, otherwise it would output a 0.0.
Traditionally non-linear activation functions are used. This allows the network to combine the inputs in more complex ways and in turn provide a richer capability in the functions they can model. Non-linear functions like the logistic also called the sigmoid function were used that output a value between 0 and 1 with an s-shaped distribution [51].

$$\sigma(u) = \frac{1}{1 + e^{-u}}$$

Other possible activation functions are the hyperbolic tangent function also called tanh that outputs the same distribution over the range -1 to +1 .

III.3.1.4 Training an artificial neural network

Once a network has been structured for a particular application, that network is ready to be trained. To start this process the initial weights are chosen randomly. Then, the training, or learning, begins. There are two approaches to training - supervised and unsupervised [52], in our case we have used the supervised training.

In supervised training, both the inputs and the outputs are provided. The network then processes the inputs and compares its resulting outputs against the desired outputs. Errors are then propagated back through the system, causing the system to adjust the weights which control the network. This process occurs over and over as the weights are continually tweaked. The set of data which enables the training is called the "training set." During the training of a network the same set of data is processed many times as the connection weights are ever refined.

III.4 Microelectromechanical systems

Microelectromechanical systems (MEMS) combine mechanical and electrical components into small structures in the micrometer scale. They are formed by a combination of semiconductor and microfabrication technologies using micro machine processing to integrate all the electronics, sensors, and mechanical elements onto a common silicon substrate. The major components in any MEMS system are the mechanical elements, sensing mechanism, and the microcontroller [53].

The micro-electromechanical system consisting of accelerometers and gyroscopes is one of the most important types of silicon-based sensors. The large volume demand for accelerometers is due to their automotive applications, where they are used to [54]:

- Activate safety systems, including air bags
- Implement vehicle stability systems
- Electronic suspension.

Figure III.4: MPU-9250 (MEMS).

Accelerometers are electromechanical devices that measure acceleration, the rate of change in velocity of an object. In other words, it's a device used to respond to any vibrations associated with movement [55]. However, the applications of accelerometers cover a much broader spectrum where their small size and low cost

have even a larger impact.
Gyro sensor, also known as angular rate sensor or angular velocity sensor is device that sense angular velocity.

III.5 Realization

III.5.1 Prototype architecture

The system consists of three units, a wearable unit, the AI processing unit, and a quadrotor as shown in figure III.5.

Wearable unit includes one MPU-9250 of 9 degrees of freedom (3 axis accelerometer, 3 axis gyroscope and 3 axis magnetometer) fixed on a bread board for capturing the hand gesture. Gesture board takes the measurements using the accelerometer and the gyroscope, and then the data is sent to the AI processing unit.

AI Processing unit based on the low-power embedded system Arduino Uno which contains the pre-trained neural network to predict the right motion of hand. After the data processing the AI Processing unit generates control commands and sends these commands to the quadrotor unit. The quadrotor receive the commands and upon the receiving commands it behaves.

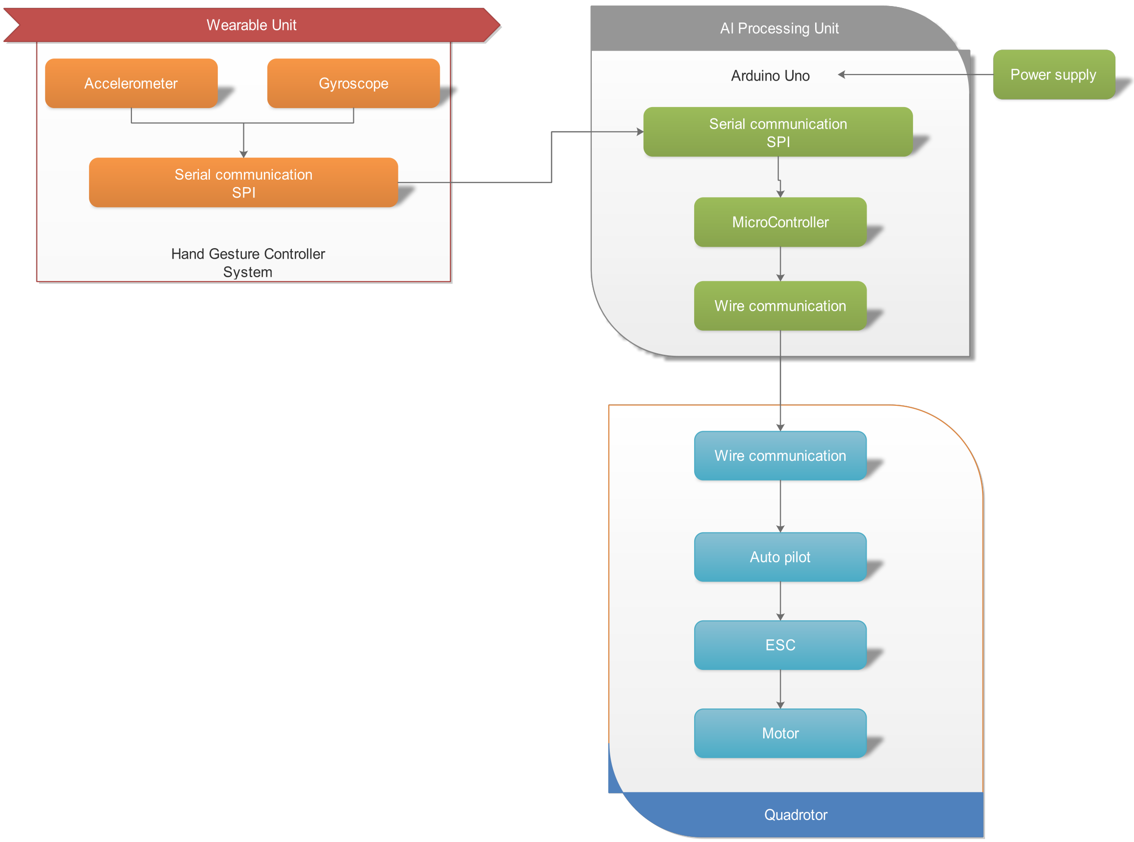
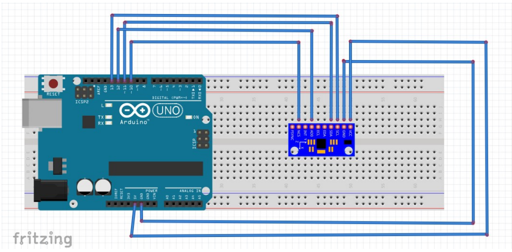
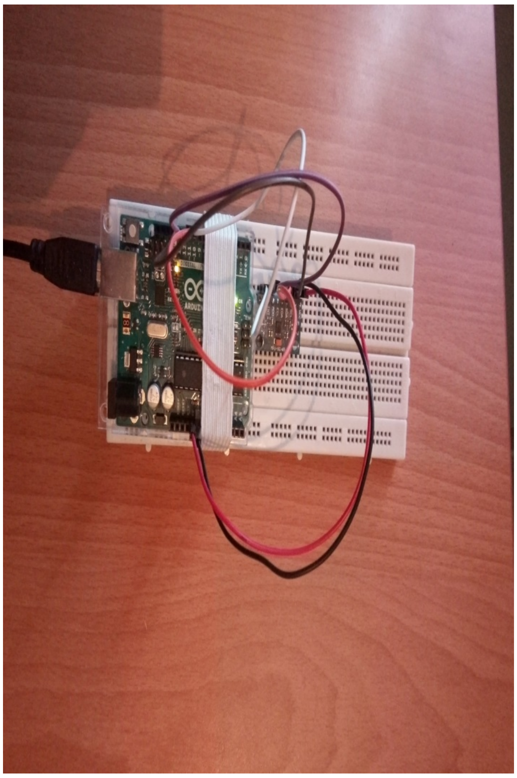


Figure III.5: System architecture .



(a)



(b)

Figure III.6: (a) circuit wiring. (b) real circuit wiring

III.5.2 Data collection

Our goal was to make the quadrotor moves according to one of pre-specified scenarios with each scenario being selected based on the corresponding gesture of the pilot. So the first phase was collecting data from the MPU-9250. For that we used arduino serial monitor as shown in figure III.7.

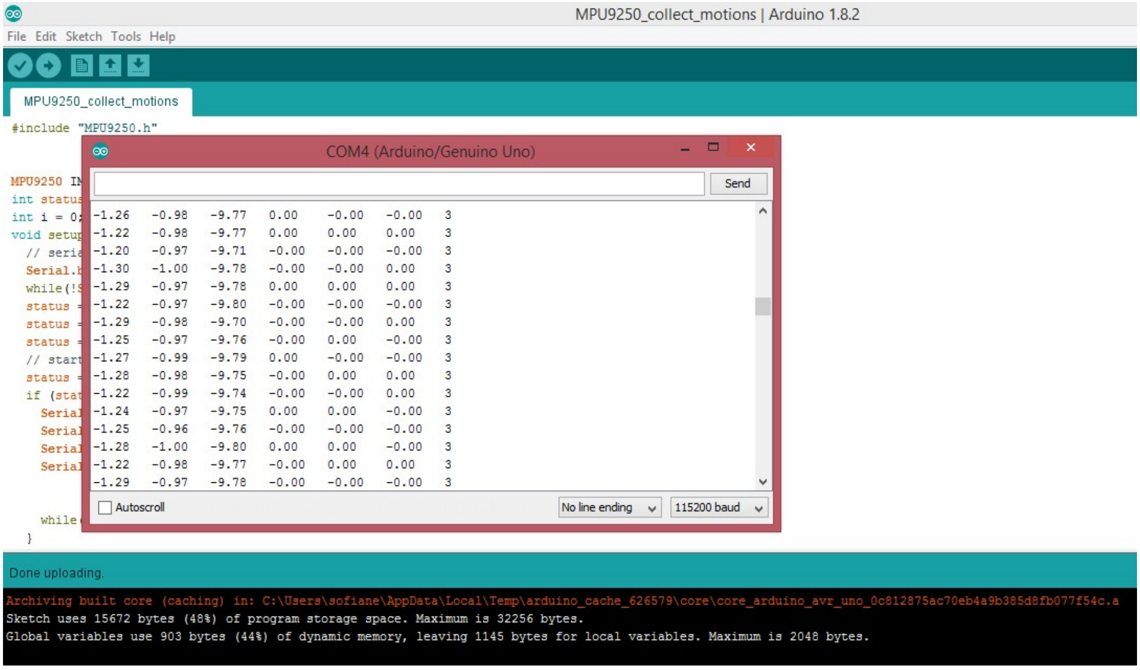


Figure III.7: MPU-9250 data collection.

In this phase we created the dataset with three methods:

- Linear acceleration and angular velocity
- Linear acceleration and angular velocity converted to quaternion values
- Linear acceleration and angular velocity converted to Euler angles values

Figure III.8 depicts the main steps of gesture-based quadrotor control, the left part shows the gesture; "label" and "action" depicts corresponding label and quadrotor movement.

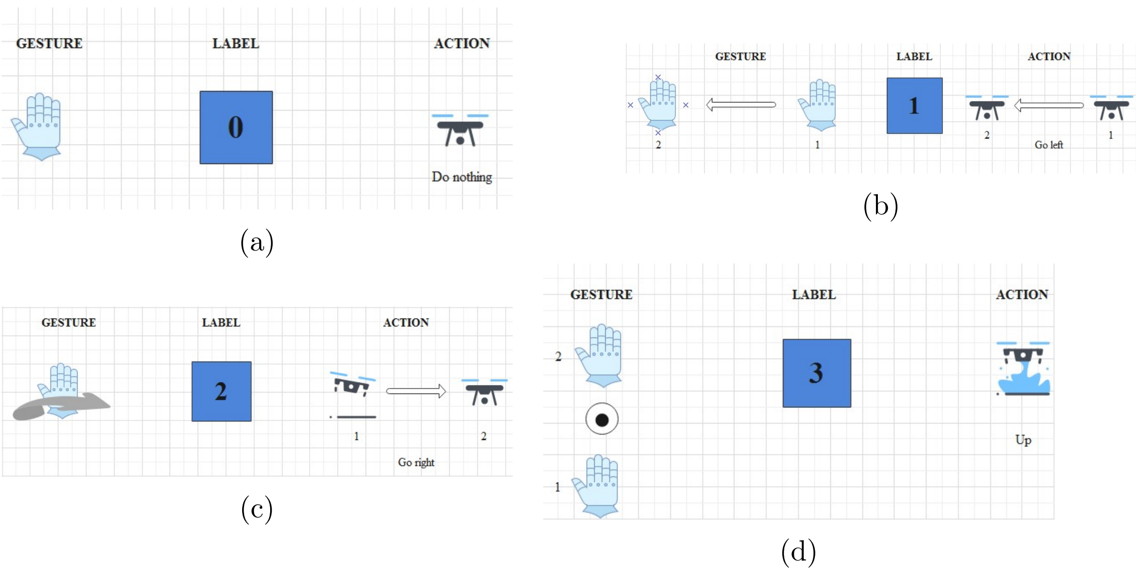


Figure III.8: Gesture-based quadrotor control.

III.6 Experimental results

III.6.1 Movements detection

In this phase we predict the trajectory of the hand and turn it into one of the pre-specified drone maneuvers. The main challenge is to obtain the system which is robust to the possible variations in gestures. Our idea was to use neural network which perform very well in this task giving a time prediction of some microseconds and accuracy of 97.65%.Neural Network was trained using google colab platform [56].

So, we trained NN with all the three datasets collected (section III.5.2), then we got the results shown in table 1.

Data form	Accuracy of classification	Time prediction
Quaternion	96.56%	6s
Euler angles	97.45%	6 to 10s
Linear acceleration and angular velocity	97.65%	Some microsecond

Table 1: Neural network time prediction of datasets collected.

From table 1, we can say that the best result is done with the linear acceleration and angular velocity dataset. The testing of gesture recognition was performed on the selected dataset consisting of 4000 sample. Each 1000 sample corresponds to one of the gestures (see Figure III.8) and thus is labeled with either do-nothing (0), go-left (1), go-right (2) and up (3).

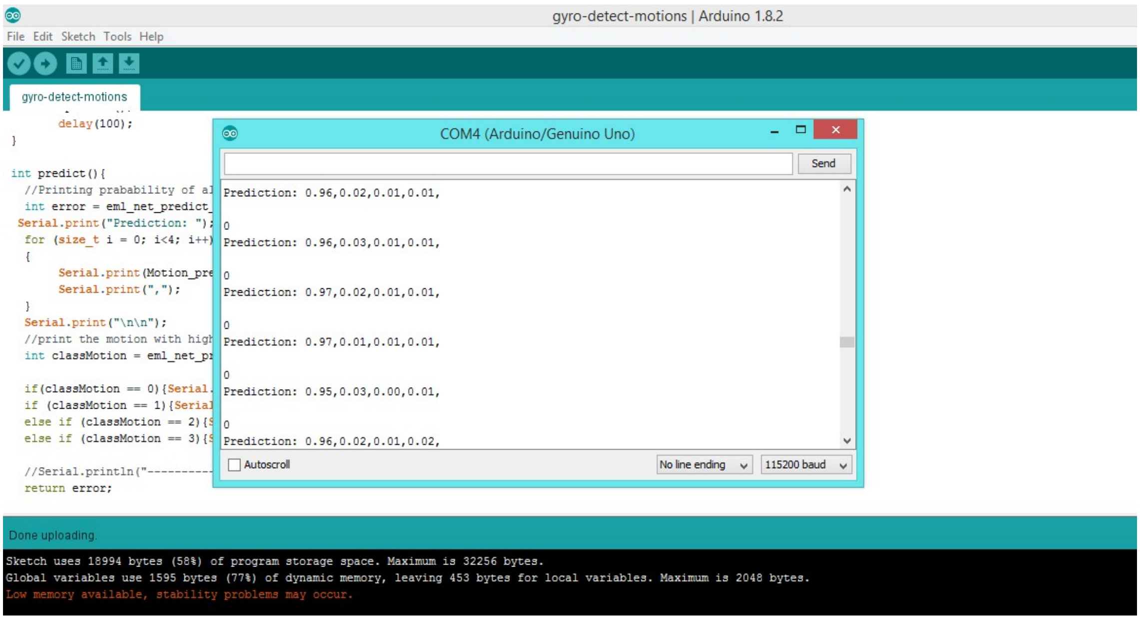


Figure III.9: Motions predict using neural network.

Table 2 show the performance of NN in classification of different hand motion.

	nothing	up	right	left
nothing	0.84	0.1	0.02	0.04
up	0.00	1.00	0.00	0.00
right	0.00	0.00	1.00	0.00
left	0.00	0.00	0.00	1.00

Table 2: NN motion detection performance.

III.6.2 Simulation

Control algorithms

To control the quadrotor behavior a quaternion-based control algorithms are used to globally stabilize the quadrotor. First an attitude control law is proposed to stabilize the vehicle's heading, then a position control law is proposed to stabilize the vehicle in all its states.
A. *Attitude algorithm:*

$$\dot{x}_{quad} = \frac{d}{dt}\begin{bmatrix} \overrightarrow{p} \\ \dot{\overrightarrow{p}} \\ q \\ \omega \end{bmatrix} = \begin{bmatrix} \dot{\overrightarrow{p}} \\ q \otimes \frac{\overrightarrow{F}_{th}}{m} \otimes q^* + \overrightarrow{g} \\ \frac{1}{2} q \otimes \omega \\ J^{-1}(\tau - \omega \times J\omega) \end{bmatrix} \tag{36}$$

$$\overline{\alpha} = 2lnq, \qquad \dot{\overline{\alpha}} = \omega \tag{37}$$

From the equations above (described in chapter II), , the attitude dynamic of the aerial vehicle could be expressed:

$$\frac{d}{dt}\begin{bmatrix} \overline{\alpha} \\ \omega \end{bmatrix} = \begin{bmatrix} \omega \\ J^{-1}(\tau - \omega \times J\omega) \end{bmatrix} \tag{38}$$

Observe that the terms J^{-1}, and $(\omega \times J\omega)$ can be compensated using an appropriate $\tau = Ju + \omega \times J\omega$ with u as the new control input. Thus, the previous model become:

$$\frac{d}{dt}\begin{bmatrix} \overline{\alpha} \\ \omega \end{bmatrix} = \begin{bmatrix} \omega \\ u \end{bmatrix} = \begin{bmatrix} \overline{0} & I_3 \\ \overline{0} & \overline{0} \end{bmatrix}\begin{bmatrix} \overline{\alpha} \\ \omega \end{bmatrix} + \begin{bmatrix} \overline{0} \\ I_3 \end{bmatrix} u = Ax_{att} + Bu \tag{39}$$

where x_{att} is the attitude of the quadrotor.Proposing

$$u = -K_{att}(x_{att} - x_{attd}) \tag{40}$$

where $K_{att} > 0$ denotes the gains and x_{attd} the desired attitude. Observe that this control law makes system (39) exponentially stable.

B. *Position strategy:*

From (36), it follows that:

$$\dot{x}_{pos} = \begin{bmatrix} \dot{p} \\ q \otimes \frac{F_{th}}{m} \otimes q^* + \overline{g} \end{bmatrix} \tag{41}$$

where: $x_{pos} = [p^T \quad \dot{p}^T]^T$
Notice that the quaternion norm is $||q|| = 1$ thus, the direction of the input vector $u_p = q \otimes \frac{F_{th}}{m} \otimes q^* + \overline{g}$ depends exclusively on the quadrotor's orientation, and remark that its magnitude depends entirely of the magnitude of the vector $\frac{F_{th}}{m}$.The algebraic relationship between $F_{th}, q \quad and \quad u_p$ is:

$$\begin{aligned} q' &= (bu_p + ||u_p||) + b \times u_p \\ q &= \frac{q'}{||q'||} \\ F_{th} &= b||u_p||m \end{aligned} \tag{42}$$

where b is a unitary vector denoting the axis in which the thrust acts in the body frame.

Let u_{pd} be a desired trajectory that stabilizes system (41) if $u_p \approxeq u_{pd}$. Substituting u_p for u_{pd} in equations (42) gives us the quaternion trajectory q_d and thrust vector trajectory F_{thd} that the quadcopter must follow in order for $u_p \approxeq u_{pd}$.As the thrust vector is a control input, it is defined as $F_{th} := F_{thd}$.

The angular velocity trajectory can be obtained from $\omega_d = \dfrac{d}{dt}(2lnq)$. Therefore, the desired attitude becomes
$x_{attd} = [(2lnq_d)^T \quad \omega_d^T]^T$

From the attitude control observe that K_{att} can be chosen such that $q \approxeq q_d$, which implies that $u_p \approxeq u_{pd}$ and then, the model (41) can be rewritten as:

$$\dot{x}_{pos} = \begin{bmatrix} \dot{p} \\ u_{pd} + \overline{g} \end{bmatrix} \tag{43}$$

Choosing u_{pd} such that it compensates the gravity vector $u_{pd} = u_{pos} - g$, this results in another linear representation for the position subsystem:

$$\dot{x_{pos}} = \begin{bmatrix} \overline{0} & I_3 \\ \overline{0} & \overline{0} \end{bmatrix} x_{pos} + \begin{bmatrix} \overline{0} \\ I_3 \end{bmatrix} u_{pos} = A_{pos}x_{pos} + B_{pos}u_{pos} \tag{44}$$

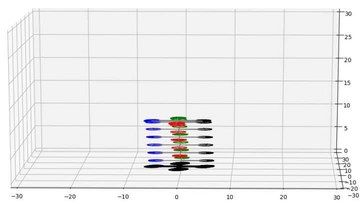
with u_{pos} denoting the new input. Proposing

$$u_{pos} = -K_{pos}(x_{pos} - xposd) \tag{45}$$

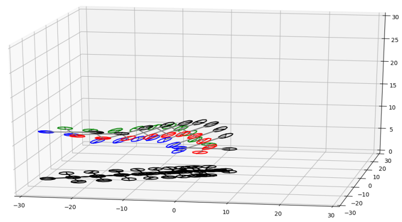
with x_{posd} as the desired position state, then this controller exponentially stabilizes subsystem (44).

Simulation results

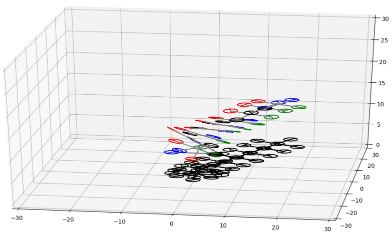
To simulate the quadrotor behavior when receiving the commands from our control system, we used a python script that reads the data coming from the control system using Pyserial library [57]. The figures below show the final experimental results of quadrotor behavior with different gestures.



(a)



(b)



(c)

Figure III.10: quadrotor movements. (a) up, (b)left, (c)right

III.7 Conclusion

In this work, we have demonstrated the system for drone intuitive control based on the AI ensuring gesture commands recognition. The system is realized on a low-power embedded system with AI capabilities. Google colab platform was used to train the neural network.

Our results demonstrate that a vast variety of real-time control algorithms, including the control by multiple gestures can be implemented on a battery powered embedded system without the use of a video camera. The proposed approach significantly extends human capabilities and can be scaled to implementing the control over multiple drones. Eventually it can bring the actual gesture machine interface into the real-world applications.

General Conclusion

Autonomous robotic systems have been developing in an accelerating pace in recent years, what started as an interesting concept, exclusive to only a few institutions, has become a global trend which is being constantly enhanced by researchers, companies and individuals all over the world.

Aerial drones can be used for a number of monitoring and control applications. Most of existing drones control platforms are quite primitive in terms of Human-Machine interface. They are usually a variation of a hand-held remote controller or ground control system. The proposed control method includes wearable sensors based on artificial intelligence presents one of many control methods that can be used to control drone's behavior.

For that we used an Inertial Measurement Unit (IMU) for capturing the hand movements. The control is implemented by the gesture recognition system based on Neural Network (NN). For implementing the embedded intelligence, we used a low-power embedded system able to run pre-trained neural network. As a result, the system can perform different gesture recognition tasks in real-time.

The proposed controller is validated in real-world experiments, displaying precise and robust performances.

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