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Mechatronic System Modeling and Analysis of Quad Rotor UAV

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Abstract

Quad rotor is a small Aerial Vehicle, which is lifted as well as propelled by four motors and control of vehicle is achieved by altering the pitch and rotation rate of one or more rotor discs. In comparison to a classical helicopter, Quad rotor is simple and easy to make, because of the absence of moving parts and the rotors axis being fixed. For achieving the control of such a highly unstable open-loop system, as the rotational speed of each rotor needs to be independently controlled, which makes it a challenging engineering problem.By virtue of advances made in the recent years, in MEMS (Micro-Electromechanical Systems), electrical energy accumulators, actuators and smaller integrated micro-controlled boards, number of studies and researches have grown in the field of UAVs and autonomous aerial robots. One such UAV is Quadrotor, over which research and development has been carried out, not only by universities and research institutions for civilian applications but also for military purposes. It is due to the inherent characteristics of UAV (Quad rotor),such as high manoeuvring ability at low translational speeds and in small volumes while being able to carry significant payload, thus making them especially adequate for aerial surveillance and monitoring tasks.

1. Introduction

A Quad rotor usually coming under the class of a Micro Aerial Vehicle (MAV), lifted and propelled by four motors, using Counter Rotating Symmetrically Pitched blades. Control of vehicle motion is achieved by altering the pitch and/or rotation rate of one or more rotor discs, thereby changing its torque load and thrust/lift characteristics. A quad-rotor is much simpler and easier to build in comparison to a classical helicopter, since the rotors' rotational axis is fixed and there are no moving parts, like aerodynamic control surfaces. Nevertheless, the rotational speed of each rotor needs to be independently controlled in order to achieve the control goals of such a highly unstable open-loop system, what makes it a challenging control engineering problem. In the recent years, especially due to advances in Micro-Electromechanical Systems (MEMS), electrical energy accumulators, actuators and smaller integrated micro-controlled boards, a growing number of studies in UAVs such as the quadrotor and related autonomous aerial robots has been carried out, not only by universities and research institutions for private civilian applications but also for military purposes.It is mainly due to the inherent characteristics of such aircraft, namely high manoeuvring at low translational speeds and in small volumes while being able to carry significant payload, thus making them especially adequate for aerial surveillance and monitoring tasks.

An Unmanned Aerial Vehicle (UAV), colloquially known as a drone, is an aircraft without a human pilot on board. Its flight is controlled either autonomously by computers in the vehicle or under the remote control of a pilot on the ground or in another vehicle. UAVs are often preferred for missions that are too "dull, dirty or dangerous" for manned aircraft.

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2. Unmanned Aerial Vehicles: A Classification

UAVs typically fall into one of six functional categories (although multi-role airframe platforms are becoming more prevalent):

- **Target and Decoy–** Providing ground and aerial gunnery a target that simulates an enemy aircraft or missile
- **Reconnaissance–** Providing battlefield intelligence
- **Combat–** Providing attack capability for high-risk missions
- **Logistics–** UAVs specifically designed for cargo and logistics operation
- **Research and Development–** Used to further develop UAV technologies
- **Civil and Commercial UAVs–** Specifically designed for Civil and Commercial Applications

3. Types of Unmanned Aerial Vehicles:

- **Fixed Wing Aircrafts:** A fixed wing aircraft is an aircraft capable of flight using wings that generate lift caused by vehicle's forward movement and the shape of the wings (Fig 1). The principle of operation is Bernoulli's principle

Fig: 1. IAI Heron in Flight: An Example of a Fixed Wing Aircraft

- **Rotary Wing Aircrafts:** A rotorcraft or rotary-wing aircraft (Fig 2) is a heavier-than-air flying machine that

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uses lift generated by wings, called rotor blades that revolve around a mast.

Fig: 2. Quadrotor is a Rotary Wing Type

- **Blimps:** A blimp (Fig 3), or non-rigid airship, is a floating airship without an internal supporting framework, or a keel. A non-rigid airship differs from a semi-rigid airship and a rigid airship (e.g., a Zeppelin) in that it does not have any rigid structure, neither a complete framework nor a partial keel, to help the airbag maintain its shape. Rather, these aircraft rely on both a higher pressure of the lifting gas (usually helium, rather than hydrogen) inside the envelope and the strength of the envelope itself.

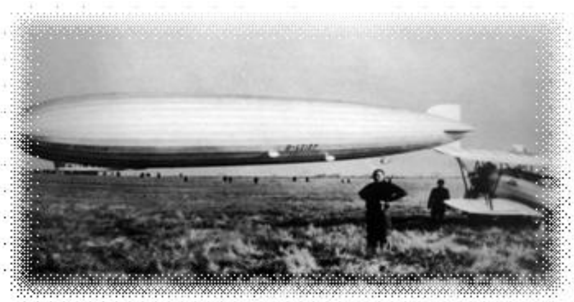

Fig: 3. Zepplin, Probably the Most Famous Blimp in History

4. Micro Air Vehicles

A micro air vehicle (MAV), or micro aerial vehicle, is a class of unmanned aerial vehicles (UAV) that has a size restriction and may be autonomous. Modern craft can be as small as 15 centimeters. The small craft allows remote observation of hazardous environments inaccessible to ground vehicles. A new trend in the MAV community is to take inspiration from flying insects or birds to achieve unprecedented flight capabilities.

5. Quadrotors

A Quadrotor usually falls under the category of a Micro Aerial Vehicle (MAV) and is characterized by the following properties:

- Lifted and Propelled by four motors
- Generally use Counter Rotating Symmetrically Pitched blades
- Control of vehicle motion is achieved by altering the pitch and/or rotation rate of one or more rotor discs, thereby changing its torque load and thrust/lift characteristics.

6. Advantages of the Quadrotor Concept

The advantages of Quadrotors, compared to the other configurations, are the following:

- Simplicity of Control System
- Reduced Gyroscopic Effect
- Improved Stability
- Higher Payload Capacity

7. Disadvantages of the Quadrotor Concept

These drawbacks, compared to the other configurations, could be summarized in the next list:

- Higher Weight, Lower Payload to Weight Ratio
- Greater power consumption
- Difficult to control and stabilize manually

8. Basic Dynamics of Quadrotors

Attitude Control: Attitude control refers to manipulating the roll, pitch and yaw angles and the roll, pitch and yaw rates in a controlled fashion so as to achieve overall stability of the airframe.

- **Pitch Control:** To pitch up thrust in the front rotor is increased (Fig 4) in a certain quantity while thrust in the rear rotor is decreased in the same quantity. By doing so a pitch moment is created while keeping global thrust and torque unchanged. Pitching down is analogous.

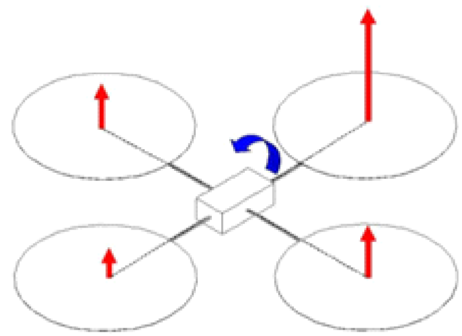

Fig: 4. Diagram Depicting Pitch Control

Roll Control: Roll control is performed in a similar manner, increasing thrust in one of the side rotors and decreasing in the other. As in the previous case, as soon as the roll starts the quadrotor will begin to descend.

- **Yaw Control:** Yaw control (Fig 5) is achieved by breaking the balance of torques that has been mentioned before. For instance, to yaw to the right thrust and therefore torque are reduced in the rotors rotating clockwise and increased in those rotating counter clockwise. This is done in such a way that the global thrust remains unchanged

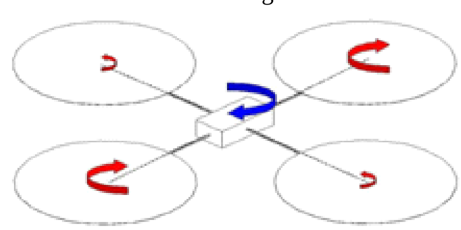

Fig: 5: Diagram Depicting Yaw Movement

9. Constructional Features of Quadrotors

Frame of the quadrotor is defined as the structure over which all other components are mounted. There are two major design considerations:

1. Maximization of structural rigidity
2. Maximization of absorption of vibration resulting from movement of motors.

Thus it must be ensured that the material used is rigid enough to sustain the forces acting on the frame but also flexible enough to absorb the resultant vibrations for accurate feedback from the microcontrollers mounted on the frame.

10. Materials Used

The three major materials that are used to manufacture frames are (Table 1):

1. **Carbon Fibre Reinforced Polymer:** It's a composite material with a polymer matrix and carbon fibre reinforcements. It has high strength to weight ratios and rigidity. Easier to mould and can be moulded into desired complex shapes. The costs involved in manufacturing are higher than its other counterparts.

It is a material consisting of fibres about 5–10 μm in diameter and composed of carbon atoms. To produce carbon fibre, the carbon atoms are bonded together in crystals that are more or less aligned parallel to the long axis of the fibre as the crystal alignment gives the fibre high strength-to-volume ratio (making it strong for its size). Several thousand carbon fibres are bundled together to form a tow, which may be used by itself or woven into a fabric.

Each carbon filament thread is a bundle of many thousand carbon filaments. A single such filament is a thin tube with a diameter of 5–8 micrometres and consists almost exclusively of carbon.Depending upon the precursor to make the fibre, carbon fibre may be turbostratic or graphitic, or have a hybrid structure with both graphitic and turbostratic parts present. In turbostratic carbon fibre the sheets of carbon atoms are haphazardly folded, or crumpled, together. Carbon fibres derived from Poly-acrylonitrile (PAN) are turbostratic, whereas carbon fibres derived from mesophase pitch are graphitic after heat treatment at temperatures exceeding 2200 °C. Turbostratic carbon fibres tend to have high tensile strength, whereas heat-treated mesophase-pitch-derived carbon fibres have high Young's modulus.

Carbon fibre reinforced plastics are a popular choice of material for the quadrotor frame designs because of its high strength-to-weight ratio and very good rigidity. Moreover their ability to be cast into complex shapes also adds to the appeal as it allow experimentation with frame design to account for de-stability caused by wind drift.CFRP are more enthusiastically/ widely used to manufacture propeller blades due to their high strength to weight ratio. Carbon Fibre Reinforced Plastics reduce the weight of the quadrotor significantly and the high stiffness allows the blades overcome the problem of collision between blades under strong wind conditions.

2. **Glass Fibre Reinforced Polymer:** It's a lightweight, robust and extremely strong composite material; however the strength and stiffness are lower as compared to CFRP. But the cost of manufacture is significantly lower.

Glass fibre is formed when thin strands of silica-based or other formulation glass are extruded into many fibres with small diameters suitable for textile processing.The types of glass fibre most commonly used are mainly E-glass (alumino-borosilicate glass with less than 1% w/w alkali oxides, mainly used for glass-reinforced plastics). Glass can undergo more elongation before it breaks, thus it is ideal for use as protective rings around the propellers as to provide secure rings for quadrotors operating in obstructing surroundings.

Fiberglass is an immensely versatile material which combines its light weight with an inherent strength to provide a weather resistant finish, which advocates its use for quadrotors used for outdoor quadrotor applications.

3. **Aluminum and its Alloys:** Aluminum alloys such a Duralumin are strong, lightweight and rigid but a disadvantage being their inability to absorb the vibrations being generated by the motors which will result in erratic signals and will hamper the control of the rotorcraft. To counter this disadvantage fibreboard is used to sheet the aluminum frame. This arrangement is cheaper but adds to weight and bulk of the frame thus taxing the batteries and the rotors.

Even though aluminum is cheap, light weight, easily available and easy to cast and form, it's not as widely used to manufacture the frame of a quadrotors as aluminum is too weak and ductile. However alloying with suitable elements like copper (4 % by weight) gives us duralumin which has high strength to weight ratios. But duralumin is susceptible to corrosion, thus an extra layer of pure aluminum is punch pressed over the surface of the duralumin sheet to provide corrosion resistance.

However, the major drawback of using aluminum is its inability to absorb vibrations coming from the rotors and the electric mounted on the frame. The resulting vibrations will interfere with the signal being transmitted by the ultrasonic sensors as well as the reading of the IMU.

4. **Miscellaneous Materials Used:** Some uncommonly used material purely for research purposes are plywood, medium density fibreboards (MDF), printed circuit boards (PCB) etc. Medium-density fibreboard (MDF) is an engineered wood product formed by breaking down hardwood or softwood residuals into wood fibres and combining them with wax and a resin binder, and forming panels by applying high temperature and pressure. MDF and fibre boards are moderately strong. They are able to absorb the vibrations being produced by the rotation blades and the dc motors, but they are susceptible to facture during aggressive maneuvering and hence are used for limited testing purposes only. Printed Circuit Boards (PCBs) are also used to manufacture the entire frame of the quadrotor, rather than just the mounting assembly for the electronic components. The strength characteristics of PCBs are similar to those of MDF but they provide and added advantage of ease of access to mount additional electronic components.

Table: 1. A Comparison of Materials Used

MDF (Medium Density Fibreboard)	Glass Fibre Reinforced Plastic	Carbon Fibre Reinforced Plastic

Formed by combining wood fibres with wax and resin binder at high temperature and pressure.	Fibre Reinforced Polymer formed by a plastic polymer reinforced by fine glass fibres.	Fibre reinforced polymer formed by an aramid or thermosetting plastic matrix reinforced by carbon fibres with varying properties depending on the binding material being added to the matrix.
Density 500-800kg/m^3.	Density 1280-1950kg/m^3	Density 1900kg/m^3
Easy to shape and finish	Requires complicated moulding practices	Requires complicated moulding practices
Cheap	Costlier than MDF	Costliest
Stable Dimensions	Resistant to changes in temperature and humidity.	Can take complex shapes and has stable dimensions that don't change with temperature and humidity.
Low Stength	High strength and stiffness.	Highest strength and toughness. Extremely light weight and strong.

11. Manufacturing Techniques

1. Laser Cutting: It works by directing the output of a high-power laser, by computer, at the material to be cut. The material then either melts, burns, vaporizes or is blown away by a jet of gas, leaving an edge with a high-quality surface finish.
2. 3D Printing: is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes.3D printing is alsoconsidered distinct from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting or drilling.

Hand Construction: Cheap but not reliable.

12. Propellers

Propellers convert rotary motion from electric motors to provide propulsive force. They may be fixed or variable pitch. Propellers are similar in aerofoil section to a low-drag wing and as such are poor in operation when at other than their optimum angle of attack. Therefore some propellers use a variable pitchmechanism to alter the blades' pitch angle as engine speed and aircraft velocity are changed.

A well-designed propeller typically has an efficiency of around 80% when operating in the best regime. The efficiency of the propeller is influenced by the angle of attack (α) (Fig 5). This is defined as $\alpha = \Phi - \theta$, where θ is the helix angle (the angle between the resultant relative velocity and the blade rotation direction) and Φ is the blade pitch angle. Very small pitch and helix angles give a good performance against resistance but provide little thrust, while larger angles have the opposite effect. The best helix angle is when the blade is acting as a wing producing much more lift than drag.

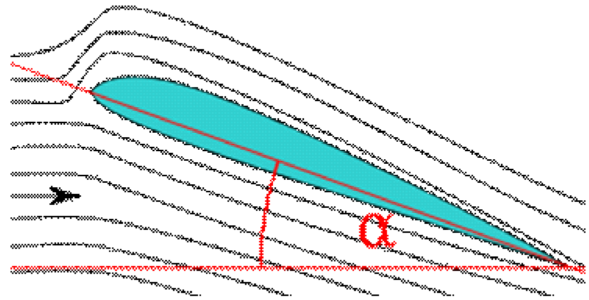

Fig: 5. Propeller Angle of Attack (alpha)

The aspect ratio of a wing is essentially the ratio of its length to its breadth (chord). Increasing the aspect ratio of the blades reduces drag but the amount of thrust produced depends on blade area, so using high-aspect blades can result in an excessive propeller diameter. A further balance is that using a smaller number of blades reduces interference effects between the blades, but to have sufficient blade area to transmit the available power within a set diameter means a compromise is needed. Increasing the number of blades also decreases the amount of work each blade is required to perform.

The purpose of varying pitch angle with a variable pitch propeller is to maintain an optimal angle of attack (maximum lift to drag ratio) on the propeller blades as aircraft speed varies. Automatic propellers had the advantage of being simple, lightweight, and requiring no external control.Even though with the added advantage of control that the variable pitch propeller blades provide, their design difficulties and the resulting calculation outweigh the advantages in case of micro - quadrotors.

In some cases the ground control can manually override the constant-speed mechanism to reverse the blade pitch angle, and thus the thrust of the motor (although the rotation of the motor itself does not reverse). This is called reverse pitch. It is used to help stabilise the quadrotor under windy conditions and allow the quadrotor to perform acrobatics and aggressive manoeuvring. The reverse pitch is also used to facilitate landing of the quadrotor.

Contra-rotating propellers use a second propeller rotating in the opposite direction immediately 'downstream' of the main propeller so as to recover energy lost in the swirling motion of the air in the propeller slipstream. Contra-rotation also increases power without increasing propeller diameter. But they are heavy and the current technology hasn't been able to reduce the size of the contra rotating propeller to be of any use in micro-quadrotors.

Propellers are manufactured with high precision tools like Computer Numerically Controlled (CNC) machines or through laser cutting. High degree of precision is required to achieve the best possible surface finish to minimise drag. The most commonly used material to manufacture the quadrotor propellers is carbon fibre or CFRP.

13. Forces Acting on a Propeller

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Five forces act on the blades of an aircraft propeller in motion, they are:

1. Thrust bending force: Thrust loads on the blades act to bend them forward.
2. Centrifugal twisting force: Acts to twist the blades to a low or fine pitch angle.
3. Aerodynamic twisting force: As the centre of pressure of a propeller blade is forward of its centreline the blade is twisted towards a coarse pitch position.
4. Centrifugal force: The force felt by the blades acting to pull them away from the hub when turning.
5. Torque bending force: Air resistance acting against the blades, combined with inertial effects cause propeller blades to bend away from the direction of rotation.

14. CADD Model of the Quadrotor

A computer aided design model (or a CADD model) is essential to make since it helps in visualizing what the final product looks like and also to iteratively make design changes during the development process. We used Solid Works as the platform to construct a model of the quadrotor. The design is still in its preliminary stage and we will continuously make changes to the design as and when limitations and inconsistencies are identified.

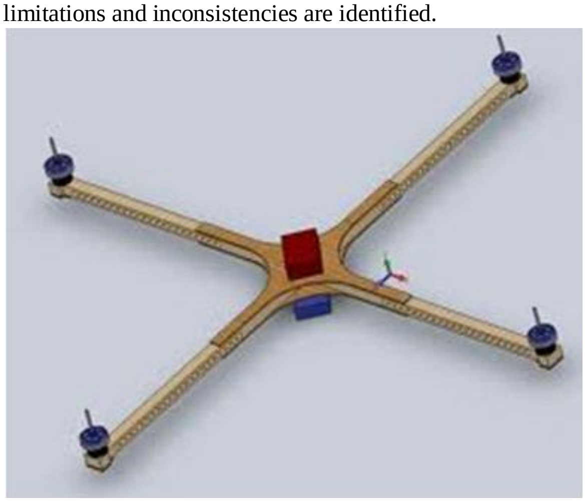

Fig: 6. A Preliminary CADD Model of the Quadrotor

15. Basic Electronics used in a Quadrotor

1. Lithium Polymer Batteries

A true LiPo battery uses a dry electrolyte polymer separator sheet that resembles a thin plastic film. This separator is sandwiched between the anode and cathode of the battery allowing for the lithium ion exchange – thus the name lithium polymer. This method allows for a very thin and wide range of shapes and sizes of cells.

The problem with true LiPo cell construction is the lithium ion exchange through the dry electrolyte polymer is slow and thus greatly reduces the discharge and charging rates. This problem can be somewhat overcome by heating up the battery to allow for a faster lithium ion exchange through the polymer between anode and cathode, but is not practical for most applications. If they could crack this problem, the safety risk of lithium batteries would be greatly reduced

LiPo batteries have become extremely popular in the RC Hobby world especially in the Micro Air Vehicle Category because of the three main advantages in offers:

- Light weight and can be made in almost any shape and size.
- Have large capacities, meaning they hold lots of power in a small package.
- Have High Discharge rates to power the most demanding electric motors.

2. Brushless DC Electric Motor

(BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors) are synchronous motors that are powered by a DC electric source via an integrated inverter switching power supply, which produces an AC electric signal to drive the motor. Additional sensors and electronics control the inverter output amplitude and waveform. A typical brushless motor has permanent magnets which rotate and a fixed armature, eliminating problems associated with connecting current to the moving armature. An electronic continually switches the phase to the windings to keep the motor turning. The controller performs similar timed power distribution by using a solid-state circuit rather than the brush/commutator system.

Brushless motors offer several advantages over brushed DC motors like More torque per weight, More torque per weight, More torque per watt (increased efficiency), Increased reliability, Reduced noise, Longer lifetime,Overall reduction of electromagnetic interference (EMI), No airflow inside motor for cooling ,Protected from dust and foreign matter, More efficient at converting electricity into mechanical power than brushed motors -this improvement is largely due to the brushless motor's velocity being determined by the frequency at which the electricity is switched, not the voltage

Inspite of all the advantages, there are a few disadvantages which the brushless motors have. High cost, Requires the use of complex Electronic Speed Controllers and Too much power results in development of heat which weakens the magnets and winding's insulation and thus results in poor performance

3. Electronic Speed Controller

Electronic Speed Controller (ESC) is an electronic circuit and performs the following functions: To vary an electric motor's speed, its direction and to act as a dynamic brake.

It provides an electronically-generated three phase electric power low voltage source of energy for the brushless motors. Brushless ESC systems basically drive tri-phase brushless motors by sending a sequence of signals for rotation.

4. Transmitter – Receiver Pair

Manual Control of most aerial vehicles is achieved by means of a Radio Controlled Transmitter – Receiver Pair

Transmitter

A radio transmitter is an electronic circuit which transforms electric power from a battery or electrical mains into a radio frequency alternating current, which reverses

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direction millions to billions of times per second. Some typical characteristics are:

- A typical RC Transmitter has about 4 to 6 channels with at least 4 of them being proportional, which means the controlled surfaces or devices will move proportionally to the movements of the control sticks.
- Additional channels may function only in "on-off" manner like a switch
- Most R/C systems today use frequency modulation (FM) as it better rejects interference than the earlier amplitude modulation (AM).
- Most R/C systems today use frequency modulation (FM) as it better rejects interference than the earlier amplitude modulation (AM).

Receiver

In radio communications, a radio receiver is an electronic device that receives radio waves and converts the information carried by them to a usable form. The antenna intercepts radio waves (electromagnetic waves) and converts them to tiny alternating currents which are applied to the receiver, and the receiver extracts the desired information. The receiver uses electronic filters to separate the desired radio frequency signal from all the other signals picked up by the antenna, an electronic amplifier to increase the power of the signal for further processing, and finally recovers the desired information through demodulation.

16. General Layout of Electronics in Quad Rotor

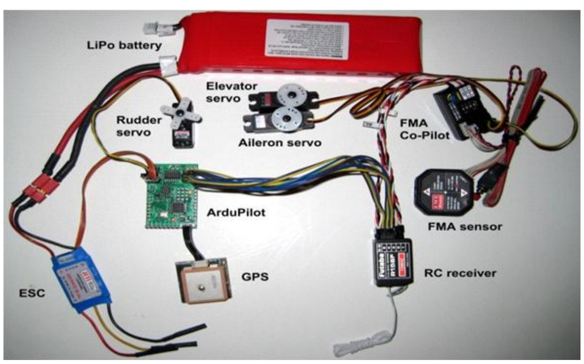

Fig: 7. General Schematic of the Electronics Components to be used

17. Autopilots and Flight Control

1. Autopilots

Automatic pilots, or autopilots, are devices for controlling spacecraft, aircraft, watercraft, missiles and vehicles without constant human intervention. Most people associate autopilots with aircraft, however the same principles apply to autopilots that control any kind of vessel. Autopilots can be used to replace or assist humans in high precision control operations.

2. Parts of an Autopilot System

The autopilot system is an amalgamation of several components. Each of these components play a major role in overall functioning of the autopilot. These components are:

- **Inertial Measurement Unit (IMU):** The Inertial Measurement Unit measures the roll, pitch and yaw angles as well as the roll rates, pitch rates and yaw rates about the three axes. This is done with the help of three gyroscopes, three accelerometers and three magnetometers which are present inside the unit.
- **Global Positioning System (GPS):** The GPS or Global Positioning System helps in 3 Dimensional localization of the aircraft using three or more satellites. This method is known as Triangulation (explained in the figure 8)

Fig: 8. Diagram Explaining Triangulation

- **Pressure Sensors:** A pressure sensor usually acts as a transducer; it generates an electrical signal as a function of the pressure imposed.In Unmanned Aerial Applications, Pressure sensors are used basically for Altitude estimation and Flow Estimation (with the help of a Pitot tube).
- **Microcontrollers:** A microcontroller (sometimes abbreviated µC, uC or MCU) is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. Program memory in the form of Flash Memory. The system control code (eg PID control) basically runs in the microcontroller. It receives input signals from the sensors like IMU, pressure sensor and GPS, executes the computations and sends the output in the form of PWM signals to the actuators like servos and motors (motors in this case)

Examples: CortexM4F Microcontrollers, ATMEGA Microcontrollers

18. Flight Control: The PID Algorithm

A Proportional-Integral-Derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used industrial control systems. It is considered to be one of the most robust algorithms in process control of dynamic systems. This algorithm is used for Stabilization and Hover Control of Quadrotors

19. Flowchart

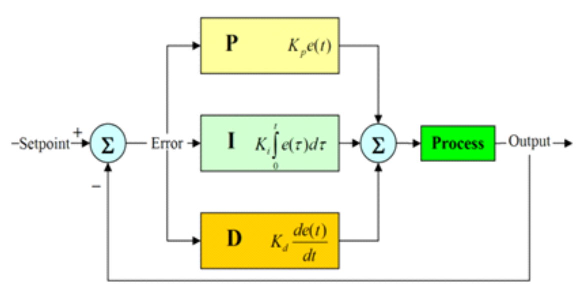

Fig: 10. Relevant STIMULINK Diagram to be applied for Quadrotor Control

20. Conclusion

Studying the Mechatronic system of Quad rotor type of UAV, in this work, great prospects and possibilities could be seen assessed, that has become possible due to advanced electrical actuation systems, new generation controllers and enhanced Intelligence incorporated with help of several modern electronic components, with help of which, resulting system can be made more and more autonomous. Step ahead a preliminary CADD models have been developed and have been tweaked around with the MATLAB code to study about the PID controller through it. Further we have plan to fabricate the quadrotor frame by using one of the best and the most feasible technique, procure the electronics and move on to the systems integration phase, and ultimately submitting a fully autonomous and a robust quad rotor.

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