The Stability Analysis of Robust Quadcopter Control System

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Abstract— In this paper an exceptional design methodology of a low cost quadcopter device was presented. Modern control systems have given great opportunity to dominate the systems in order to reach stability very fast depending on PID controller parameters. The mathematical expressions and the simulation results emphasized that the proposed quadcopter device is under control and performs all the requirements effectively. The control aspect was applied on the entire axes of the motion by evaluating the $\mathrm{Pitch}, \mathrm{Roll}, \mathrm{Twist}$ over $\mathrm{x}, \mathrm{y}, \mathrm{z}$ axes respectively. Moreover, the altitude sensor in the quadcopter is considered the sensitive part that was well calibrated in order to lead the system to the controllability. Furthermore, the transmitted signal covers the module around 1 Km distance with respect to the RC receiver device. The paper applied different programs to complete the implementation and the programing satisfactions depending on Arduino microcontroller. Finally, the proposed quadcopter's work was analyzed mathematically by using MALTAB.

Index Terms— Quadcopter Design, Stability Analysis, Control System Design, PID controller, Quadcopter System Automation.

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1. INTRODUCTION

The mechatronic engineering and the robotics systems are developed considerably in the last decades allowing the engineers and system designers to invent units classified as high complexity [1, 2]. This field of study requires expertise in the modern control systems and even in the programming languages. The assumption states that learning the working principle of each component in a module separately is sufficient to build a system is not hundred percent true. The complexity of the modules can be different when they are operated as plant such as called in control system engineering. The stability of any system is considered the main challenge that a control system contests to reach it typically. Modern control systems and robotics systems are the fields that are discussed in this paper to present the effect of unique control system designs on the stability analysis of any critically damped system. The example system is chosen to be a quadcopter module. The quadcopter is a flying device constructed from a frame with four edges sorted by ninety degree, each terminal in the frame is equipped by a motor and propeller [3, 4, 5]. The quadcopter module allows six degrees liberty and minimally four actuators needed to be controlled linearly with respect to the altitude sensor. The orthogonal axes theorem is applied on quadcopter orientation procedure such that the three axes x, y, z orthogonally are mapped to its corresponding $pitch, roll, twist$ respectively. The four motors are allocated opposite to each other making the direction of the spin clockwise and anticlockwise in each dual motor side.

The paper studies the modern control that allows a new kind of supervision in order to reach the stability very fast based on the steady state error. It has to be mentioned that the stability is a complex task particularly in such sensitive projects. While, the modern control aspect applied control methodology on the motors independently depending on the Electronic Speed Control ESC module. Furthermore, the system designed PID controller to satisfy the stability

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depending on the gains $K_p, K_i, and\ K_D$. The calibration procedure of the proposed gain responses is too important to damp the peak over shoot and to lead the system to zero steady state error rapidly. In addition, the gains play another role to calibrate the altitude sensor depending on a mathematical algorithm that was performed in MATLAB, which computes the angular activities of the Gyroscope and Accelerometer sections by integrating the readings. It is worth mentioning that microcontroller selection is very great challenge due to the complexity and the sensitivity of these modules. There exist a lot of sensitive microcontrollers such as raspberry pi, FPGA, Arduino, and the other microprocessors [6, 7]. However, in this work the Arduino microcontroller was chosen due to its simplicity and the flexibility that lead the system to perform all the specifications effectively. Finally, the paper presents a design of a quadcopter device in a low cost and shows a unique kind of control method to dominate the system.

2. QUADCOPTER SYSTEM ELEMENTS

The proposed system is constructed from several components identified as follows:

1. Quadcopter Frame.
2. Quadcopter Motors.
3. Electronic Speed Controller (ESC).
4. Power Station.
5. Equilibrium Unit.
6. Arduino UNO Microcontroller.
7. Radio Receiver Controller.

2.1. QUADCOPTER FRAME

Quadcopter frame is the most important part that should be chosen wisely in order to design the physical structure of a plane. The frame carries the motors and joins the other components of the aircraft. The structure should be bulky such that the motors can spin without making collisions between each other. However, the weight of the frame must be taken into considerations therefore the motors can carry the frame competently. For more clarity, in this work the frame was chosen and demonstrated in Fig.1.

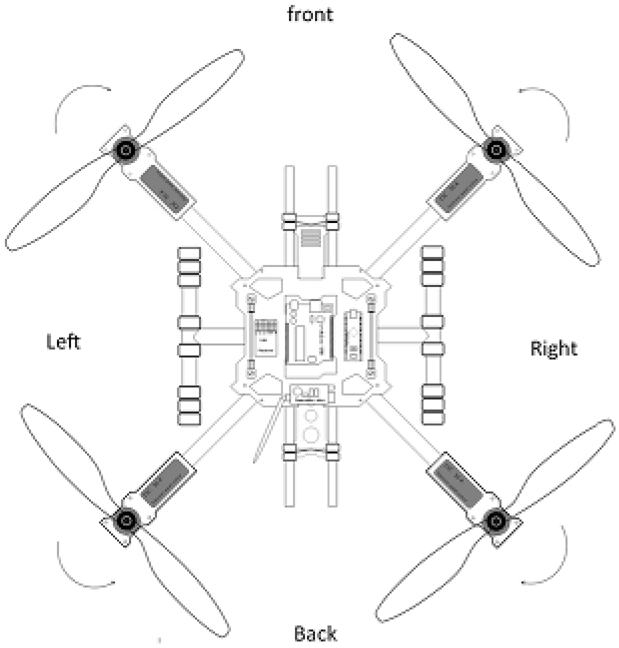

Fig.1. Quadcopter Frame

2.2. QUADCOPTER MOTORS

The motors start rotating the wings that equipped on each motor terminal leading the quadcopter to be moving drifty. The designers of the quadcopter structure need to put into their considerations the weight of the motor they use. It is worth mentioning that the most suitable motors to carry the copters are the brushless motors shown in Fig.2 that allow less weight and drift motion better than the other types. The proposed motor shown in Fig.2 is allowed to spin fast for a given voltage of 1 V in order to reach around 11000 KV. In addition, the motor gives a maximum current around 26 A that spins the motors safely and maximum power around 289 W at 12 V, 385 W at 15 V. Moreover, the weight of the motor is specified by 68g which classify the copter as very light and swift module. While, the control range of electronic speed control ESC is specified by 25 − 30 A. The wings of the motors are classified into various forms and shapes with respect to their size and weight. The diameter of the wings is the most important parameter that must be chosen wisely.

Wings diameters represent the pitch that reads the number of rotations at a time. This work presents a quad with a weight of 870 g that results magnificent fly aspect.

Fig.2. 1100 KV Quadcopter Motor

2.3. ELECTRONIC SPEED CONTROLLER (ESC)

Generally, a motor needs to be controlled in order to stabilize the motion approach of the entire system. This stabilization can be satisfied by ESC (Electronic Speed Controller). The ESC in Fig.3 acts effectively under the domination of PWM signals that controls the motors in the form of pulses. Each motor is provided by an average current sufficient to protect the motors against warm. The proposed ESC in this project provides the motors approximately by 20 A which has guaranteed a marvel performance for the quadcopter.

Fig.3. Electronic Speed Controller ESC Module

2.4. POWER STATION

This station is represented by a battery that provides the entire copter by the required power. The proposed station is lithium – ion battery specified by 11.1 V, 3300 mAh, and 35C capacity. The term Ampere hour (Ah) is the amount of energy charge in a battery that allow one ampere of current to flow in one hour. Furthermore, C describes the time taken for a battery to be discharged without harm. For more clarity, it is intended to show the battery station in Fig.4.

Fig.4. Power Station (lithium – ion battery)

2.5. EQUILIBRIUM UNIT

The selected module is named (SparkFun 9D) which subdivided into three components in one a package. Actually, the combination process of three components in a single piece helps to shrink the required ports to be wiring. The module shown in Fig.5 is constructed uniformly from Accelerometer, Magnetometer, and Gyroscope. The overall acceleration of the entire quadcopter is measured by using Accelerometer section with respect to the static acceleration from the gravity. The magnetic field available on the earth and surrounds the copter is measured by Magnetometer section to get a compass heading. Finally, the instant angular momentum all around the axis is measured by Gyroscope section. It is worth mentioning that there exists compatibility between the momentum and the other angles. Furthermore, the signal quality in the Gyroscope is too high due to the absence of the noise while it generates errors due to the uncertainty of the angular positions.

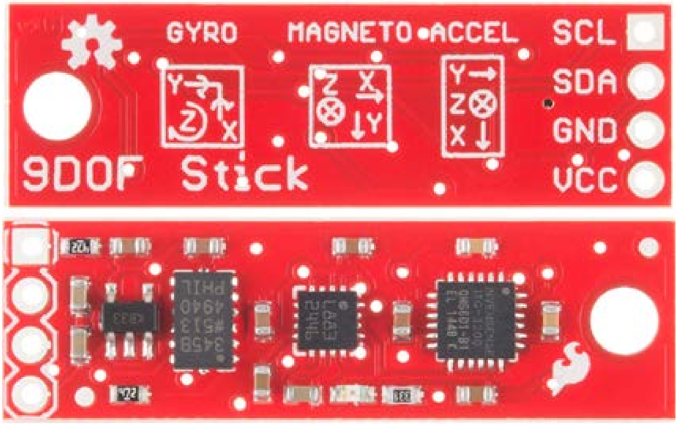

Fig.5. SparkFun 9D Altitude Sensor

2.6. ARDUINO UNO MICROCONTROLLER

Arduino microcontroller is an open source electronic board manufactured in different modalities such as Arduino mini, Uno, Mega, Nano ...etc. Arduino microcontroller is considered the most friendly board and easily compatible with the hardware and software [8]. This board deals with several sensors as inputs to manage data transfer efficiently. In addition, it acts well with motors, lights, specific kits, and some other actuators. The main component in Arduino UNO board is ATMEGA chip [9], which can be seen affixed on the top of the board. This chip holds the programing code that intentionally activates each part in the board. To be more specific, Arduino microcontroller with the specification of each port is shown in Fig.6.

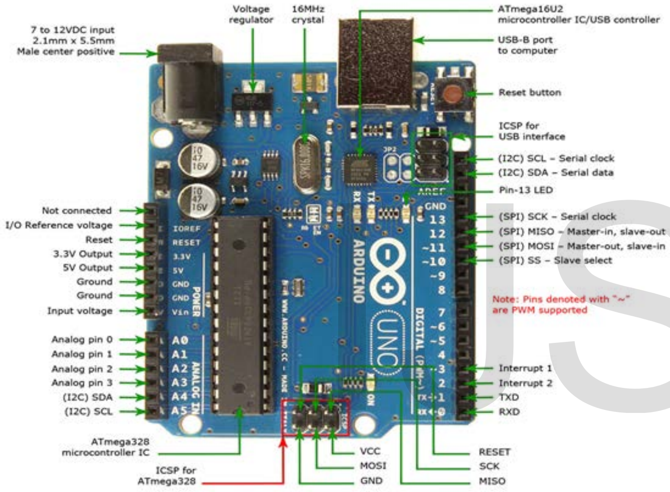

Fig.6. Arduino UNO Microcontroller

2.7. RADIO RECEIVER CONTROLLER

The RX radio receiver is connected to the Arduino microcontroller in order to receive the radio signals coming out from the transmitter antenna. The transmitted signal is converted to PWM control pulses that controls each channel individually. The proposed channels represent the four control actions identified by the pitch, roll, twist, and push. The proposed RC receiver works on a radio frequency of 2.4 GHz. Most of the recent invented RC modules have more than 4 channels while the employed 4 channels module was sufficient for this project. As shown in Fig.7, the RC module that was used in this work is *FRSKY* 4 channel – 2.4 GHz radio receiver.

Fig.7. FRSKY 4 channel – 2.4 GHz radio receiver

3. QUADCOPTER POSITIONING

In the first view, the copters are unsteady, unstable, and uncontrollable systems. The matter is considered difficult or impossible to start dominating the quadcopter module without altitude sensor for balancing procedures. Hereby, the altitude sensor is too important to control and sense the environmental changes around the module. The proposed idea states that a quadcopter must be integrated along with altitude sensor identified by Accelerometer, Magnetometer, and Gyroscope module, in order to control and stabilize the dynamical activities of the system. Further, the most appropriate controller to control the quadcopter is PID control system that provides great performance and endless sensitivity. The orientation procedure of the proposed quadcopter is shown in Fig.8.

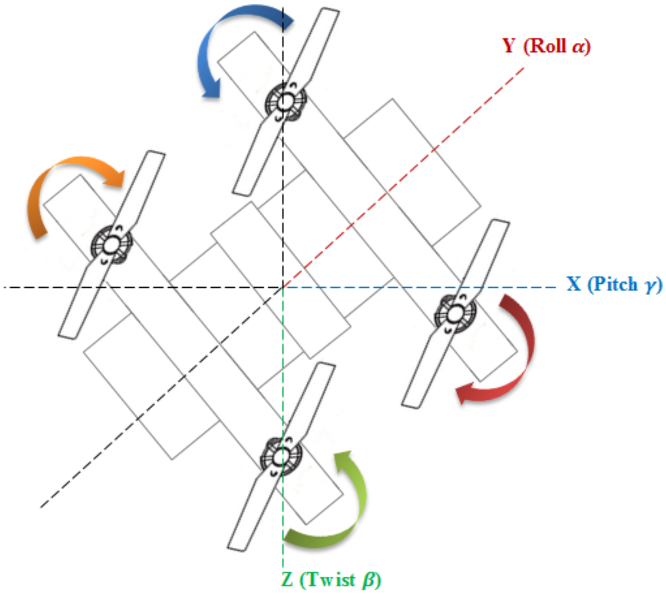

Fig.8. Quadcopter Axes Orientation

The quadcopter can have a stable flight mode by enhancing the controllability of the axes shown in Fig.8. The axes are represented by angular symbols denoted as $(\alpha, \gamma, \text{and } \beta)$ leading to typical controllability and observability for the parameters $(\text{Roll}, \text{Pitch}, \text{Twist})$ respectively. Firstly, the Roll and Pitch axes must be stabilized such that the altitude sensor determines the Roll and Pitchatitudes in order to control the height and the regular rotation of the quadcopter. There exists an assumption states that the well-controlled copters will not fall down regardless the power station crises. The proposed SparkFun 9D (altitude sensor) combines the Accelerometer, Magnetometer, and Gyroscope in a single module as mentioned before. The altitude sensor settles the quadcopter down by calibrating each sensor section in the altitude sensor separately depending on the programing code. For more confirmation, quadcopter orientation is controlled with respect to the Roll and Pitch depending on the following equations respectively:

$$\gamma = \arctan * \left(\frac{\omega_x}{\sqrt{\omega_x^2 + \omega_z^2}} \right) \dots \dots \dots \dots \dots \dots (1)$$

$$\alpha = \arctan * \left(\frac{\omega_y}{\sqrt{\omega_y^2 + \omega_z^2}} \right) \dots \dots \dots \dots \dots \dots (2)$$

While, the Twist side in the axes also needs to be controlled but the matter relatively is not difficult. It is worth mentioning that only Gyroscope and Accelerometer are in charged to sense the orientation of the Twist knowing that Gyroscope interacts partially more than the other sections.

4. CONTROL SYSTEM MODEL

The PID control system is considered the most suitable control systems to stabilize the quadcopter performance with respect to altitude sensor information. The PID controller is constructed from three parameters identified by proportional K_p, Integral K_i, and Derivative K_D. It is intended to use MATLAB simulation in order to create two different PID control systems and show the difference between the controllers depending on the employed gain responses in the system. The control system shown in Fig.9 demonstrates the PID block that without calibration, this means that the altitude sensor is neglected. Hereby, the assumption that states that it is impossible to control the quadcopter without altitude sensor module comes true and system suffers from great overshoot.

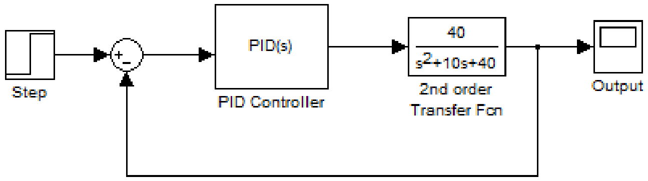

Fig.9. Traditional PID Feed Back Control System

The response of the system can be represented by the error signal that is needed to be controlled and sensible. For that reason, this error signal can be denoted as $e(t)$. The other parameters represent the PID controller such that p is the proportional gain $(K_p * e(t))$, i is the integral gain $(K_i * e(t))$, and D is the derivative gain $(K_D * e(t))$. As a result, the three parameters are summed to realize the PID control system.

Furthermore, the simulation result in Fig.10 shows that the response of the system takes much time in order to marginally reach the stability and suffers from larger overshoot that might lead the quadcopter to be tipped down immediately.

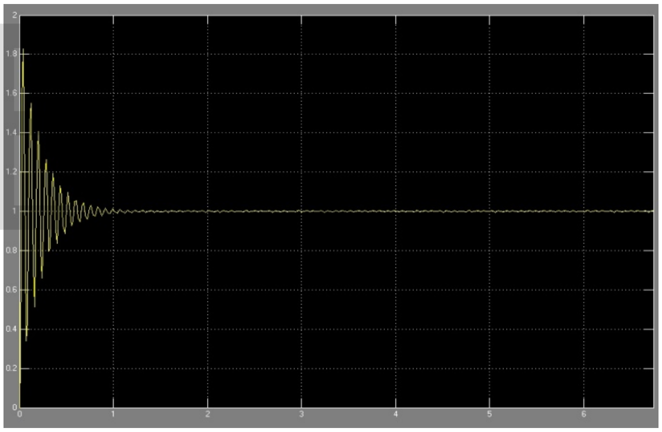

Fig.10. The Response of the Traditional Control System

In order to solve the problem, it is intended to enhance the feedback control system by representing the PID system as gains. This procedure can be performed by assigning values for each parameter identified by (300, 350, and 10) for all K_p, K_i, and K_D parameters respectively. As shown in Fig.11, the output signals of the gains K_i, and K_D are mapped to an integrator and derivative blocks respectively. Hereby, it can be stated that the gains are represented by the calibration method to enhance the read of altitude sensor.

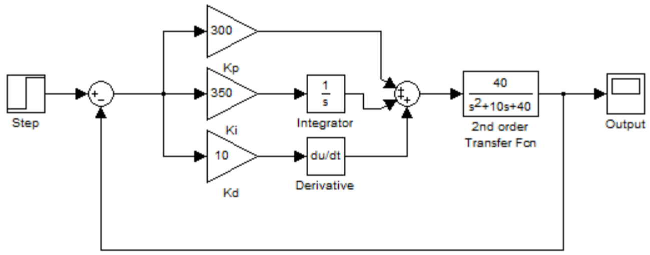

Fig.11. PID Control System

Moreover, the simulation result in Fig.12 shows that the peak overshoot has disappeared and the system reached the stability very fast with respect to the gains and the second order transfer function.

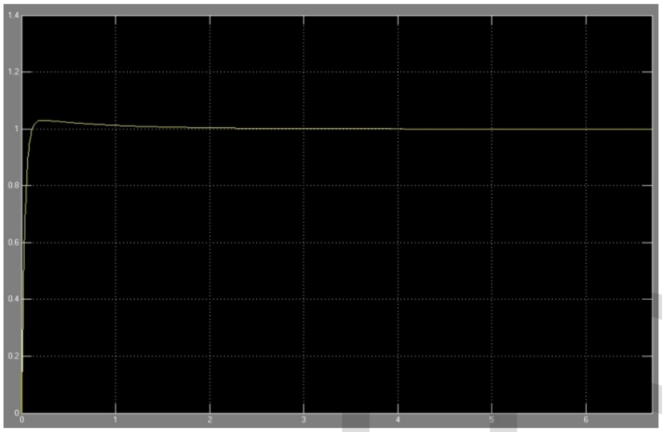

Fig.12. The Stable Response of the PID Control System

5. IMPLEMENTATION AND DISCUSSIONS

The operational mode of the quadcopter is too simple making the implementation needs to be flexible. The Arduino microcontroller is considered the heart of the quadcopter that control the entire system and manages signal direction back and forth. As shown in the *Fritzing* software schematic connection in Fig.13, the Arduino UNO comprises the connection of the entire system's modules hence the microcontroller can work as the supervisor of the system.

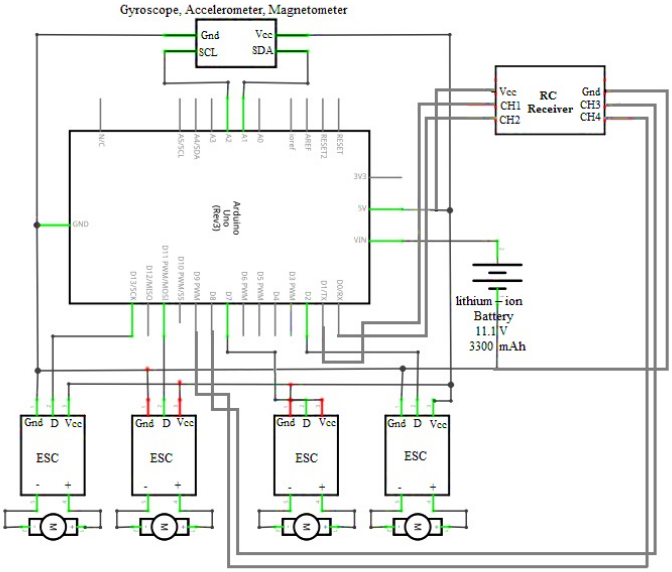

Fig.13. Overall Schematic System Connection

The motors are controlled by the electronic speed control ESC that manages the speed and the direction of the spin. Hereby, the motors must be operated in opposite directions such that each dual motor rotates clockwise and counterclockwise in a converse form. As mentioned before, the SparkFun 9D module joins the functions of the Accelerometer, Magnetometer, and Gyroscope in a single module depending on SCL and SDA terminals and the programing code, knowing that connection complexity was shrunk using I2C bus. Furthermore, the RC receiver side in the system receives the signals coming from the transmitter by converting those signals into readable PWM signals by the proposed microcontroller. The matter was solved in the programing code by assigning a void function to subdivide the duty cycle in milliseconds into sub milliseconds in order to read the height of the pulses partially and realize the corresponding information. It is worth mentioning that the transmitted signals represent the instructions to satisfy pitch, roll, twist, and push activities.

The Accelerometer section is the most regions that can be subjected to the hard noises due to the vibrations that are caused by the motors involuntarily. While, the Gyroscope section is considered less effectible by the noise which allow the rotational angles to be estimated accurately. The perfect estimation regarding the altitude sensor was reached by making a combination for the readings of the Gyroscope and Accelerometer as integration with respect to the programing code. By using MATLAB, the readings of the altitude can be computed with respect to the gain K such that the higher gain value represents concentrated Accelerometer read, low gain value represents colossal noise immunity by the Gyroscope. For more confirmation, the computation algorithm is given as follows:

Algorithm

$$\theta_{ACC} = \mathrm{atan2}(Y_{ACC}, X_{ACC}) \ldots\ldots\ldots\ldots (3)$$

$$\theta_{e(t)} = \emptyset_{Est} - \theta_{ACC} \ldots\ldots\ldots\ldots (4)$$

$$\emptyset_{Est} = \emptyset_{Est} + (Out_{Gyro} - \theta_{e(t)} * K)dt \ \ldots\ldots\ldots (5)$$

Where, θ_{ACC} is the angle of the accelerometer, Y_{ACC}, and X_{ACC} are the axes of the accelerometer depends on, $\theta_{e(t)}$ is the angle of the error, $\emptyset_{Est}$ is the estimated angle, Out_{Gyro} is the output of the Gyroscope and K represents the gain.

For simplicity, it is intended to demonstrate the overall connection aspect and the working principle of the proposed quadcopter as shown in the block diagrams in Fig.14.

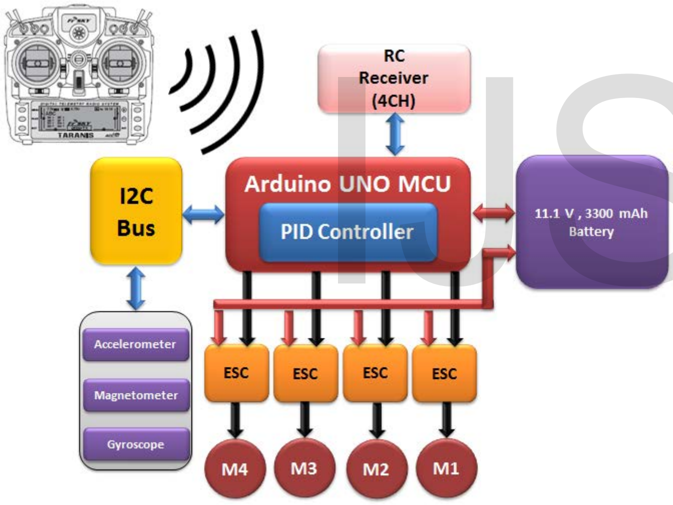

Fig.14. System Combination Block Diagram

For simplicity, it is intended to present the programing code as a flow chart shown in Fig.14 in order to allow the direct awareness and the tracking simplicity to recognize the equations and the programming steps in a tide way. The chart starts by waiting for a signal form the transmitter to activate the system. Once the signal is pulsed, the system will be activated and the motors start rotating counterclockwise depending on right hand rule in their full speeds. It is proposed that the Gyroscope and Accelerometer modules can sense the reading after a decimal reading of 5 as a threshold. Hence it is intended to make a comparison between x and y and the motors are operated in a full or half speed accordingly. The main task starts where the transmitted signal is allowed by the transmission antennal controller such that the forward F, backward B, left L, right R, pull up PU, pull down PD, and turn OFF buttons can operated the motors in different speed levels as shown in the flow chart in Fig.15.

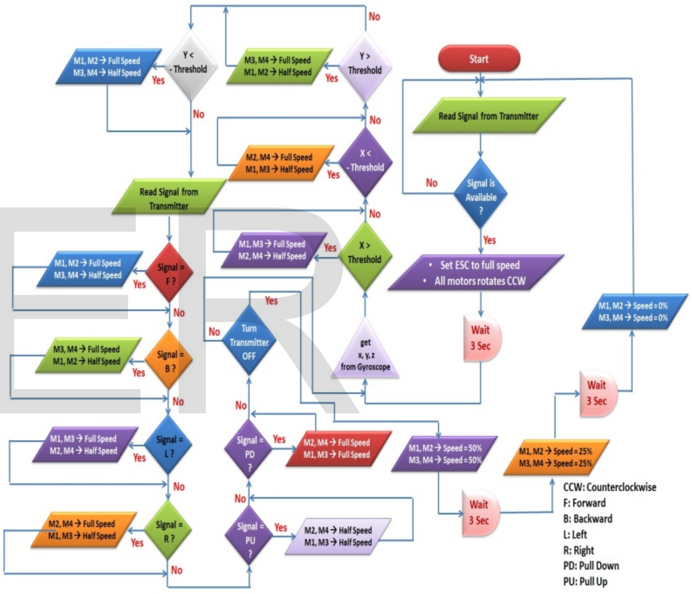

Fig.15. Programming Code Flow chart

6. CONCLUSIONS

The paper presents a unique quadcopter design and implementation technique economically. The challenge was fulfilled by implementing the modern control system to stabilize the system by supervising the direction and the speed of four motors based on ESC with respect to the PID controller over 1 Km distance. The PID controller allowed the entire module to eliminate the peak overshoot, the oscillation, and to reach stability in a rapid way. In addition, the calibration of the gains K_p, K_i, and $K_D$based PID controller provided the entire system by a new technique to integrate the read output of the Gyroscope and Accelerometer. Hereby, it can be stated that the quadcopter system are controlled partially depending on the calibration procedure that must be applied wisely on the parameters of the PID system. Furthermore, the integration process produced a great reduction in the noise generated by motors hesitation or vibration due to the value of gain K that presented in the mathematical algorithm in MALTAB. Finally, as a future extension the proposed quadcopter can be equipped by a GPS system in order to prevent the module to depart the covered area.

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