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Assembly of an Experimental Quad-Rotor Type UAV for Testing a Novel Autonomous Flight Control Strategy

Shahida Khatoon[1], Dhiraj Gupta[2], Ahmad Saad Khan[3]

Abstract

In this research a prototype experimental Quad-rotor type UAV have been assembled using low cost components easily available in the Indian market. The quad-copter is used for testing a novel autonomous flight control strategy developed using embedded system. In order to enable a mini-UAV to perform target acquisition, localization and continuous surveillance in real world environment one must develop a technology which may be a combination of aircraft engineering, control systems, and wireless communication. The major limiting factors in developing the capabilities of small low cost UAVs are connectivity, computational processing power and lack of resource integration. To overcome these limitations in this research we have tried to assemble an experimental quad-rotor prototype UAV capable of being remotely controlled in the range of 20 meter, which is specifically designed as an economical, moderately functional, small airborne platform intended to meet the requirement for fast-response to time-critical events in many small private sectors or government agencies. The experimental prototype quad-copter has been successfully implemented and tested for 15 minutes smooth flight time.

Keywords

Unmanned Aerial Vehicle (UAV), Quad-rotor, ZigBee, Inertial measurement unit (IMU), Global positioning system (GPS), Pulse-width modulation (PWM), Radio controlled (R/C), Transmitter/Receiver (Tx / Rx), Electronic speed system (ESC), Brushless DC servo motor (BLDC)

Shahida Khatoon, Department of Electrical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia,Jamia Nagar, New Delhi-110025, India.

Dhiraj Gupta, Department of Electrical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia,Jamia Nagar, New Delhi-110025, India.

Ahmad Saad Khan, Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia,Jamia Nagar, New Delhi-110025, India.

1. Introduction

Unmanned Aerial Vehicle (UAV) also called autopilot system is planes with no human driver. Unmanned Aerial Vehicle (UAV) also called autopilot system is planes with no human driver required on-board and can aviate automatically under the control of some programs, or be remotely controlled by operators on the ground station. The UAVs can make long distance navigation with the help of automatic pilot, program control system, remote control and measurement system, navigation system, etc. Compared with their manned counterparts, the UAVs have the advantages of light weight and space-occupancy, low cost , good concealment, thus is ad hoc excellent in executing the dull, dirty or danger (Tri-D) tasks. An autonomous unmanned aerial vehicle (UAV) is used in hazardous situations where conditions are appalling for example natural disasters like floods, human fights etc. can create threats to human life there. They are also used for aerial survey and remote data collection applications that require cost effective better controlled UAV.

A UAV consists of the airframe, flight computer, payload, the base station, and payload controller and communication equipment. The UAV airframe is a simple flight weight, stable platform and aerodynamically efficient with a limited space for avionics. The flight computer collects the information through a set of sensors (accelerometers, GPS, gyroscopes, magnetometers etc.) The payload consist of cameras, infrared sensors etc, to gather information that can be partly processed on board or transmitted to the base station for further analysis. At base station, a computer system is designed to monitor the mission development and operate the UAV and its payload peripherals. The communication equipment is mixture of communication mechanism (radio modems, microwave links) to make sure the continuous connection between base station and UAV.

In many conditions, particular for large area, aerial photography is less expensive than ground surveying technique. In our model a wireless camera is attached to get large amount of image or video data and it could be used for various applications such as border patrol, maritime security, search and rescue etc. Surveillance applications include, livestock monitoring, wildfire mapping, pipeline security, home security, road patrol and anti-piracy. The trend for use of UAV technology in commercial aerial surveillance is expanding rapidly. This paper gives detailed outline of hardware implementation of generic UAV for many civil applications. The capabilities of these aircrafts open up new demands in the commercial sector as it offers aerial solution that may be expensive to acquire by manned platform.

2. Literature Survey

Recently, there has been increased interest in the development of autonomous flying vehicles. In [1] Grzonka and Grisett presented a general navigation system that enables a small-sized quad rotor system to autonomously operate in indoor environments. To achieve this, they have systematically extended and adapted techniques that have been successfully applied on ground robots. In [2] Mikaelian and Rhodes introduced a logical model-based approach to identification of real option mechanisms and types, where the mechanism is the enabler of the option, while the type refers to the flexibility provided by the option. The expressivity of the logic combined with the structure of the dependency model allows the effective representation and identification of mechanisms and types of real options across multiple domains and lifecycle phases of a system. They demonstrated this approach through a series of unmanned air vehicle scenarios.

A method of combined ultra-high resolution satellite imaging, unmanned aerial vehicle (UAV) photography, and sub-surface geophysical investigation for anomaly detection is described by Lin and Navo in [3] which was employed in a non-invasive survey of three archaeological sites in Northern Mongolia. A method of geo-referencing the video data acquired by a small low-cost UAV is presented by Zhou in [4], which is specifically designed as an economical, moderately functional, small airborne platform intended to meet the requirement for fast-response to time-critical events in many small private sectors or government agencies for the small areas of interest. A new approach is presented by Lin and Lee in [5] with a fuzzifiedeigen system realization algorithm for identification of flight vehicle models in low-speed wind tunnel (LSWT) and high-speed wind tunnel (HSWT). The method based on the fuzzy logic inference structure is simple and effective. The results obtained are compared to those obtained by the conventional wind tunnel testing method. In [6] Špinka and Holub presented a case study of an open-source low-cost reconfigurable autopilot design for small unmanned aerial vehicles (the remotely operated Aerial Model Autopilot (RAMA) control system). A novel distributed hierarchical architecture, implementing graceful degradation and run-time system reconfiguration techniques, is introduced.

A novel technique for vision-based UAV (unmanned aerial vehicle) navigation is described in [7 and 8]. In this technique, the navigation (position estimation) problem is formulated as a tracking problem and solved by a particle filter. The state and observation models of the particle filter are established based on a stereo analysis of the image sequence generated by the UAV's video camera in connection with a DEM (digital elevation map) of the area of the flight, which helps to control estimation error accumulation. An important generalization is called flexible demand assignment (FDA) problem. In [9], a generalization of FDA is proposed that has many applications is shown to considerably reduces the size of the problem compared to some recent results. To test effectiveness of the proposed model, computational experiment with CPLEX for the UAV assignment problem is presented.

A new nonlinear controller for a quad rotor unmanned aerial vehicle (UAV) is proposed by Dierks and Jagannathan in [10] using neural networks (NNs) and output feedback. The assumption of the availability of UAV dynamics is not always practical, especially in an outdoor environment. Therefore, in this work, an NN is introduced to learn the complete dynamics of the UAV online, including uncertain nonlinear terms like aerodynamic friction and blade flapping. Although a quad rotor UAV is under actuated, a novel NN virtual control input scheme is proposed which allows all six degrees of freedom (DOF) of the UAV to be controlled using only four control inputs. Furthermore, an NN observer is introduced to estimate the translational and angular velocities of the UAV, and an output feedback control law is developed in which only the position and the attitude of the UAV are considered measurable. It is shown using Lyapunov theory that the position, orientation, and velocity tracking errors, the virtual control and observer estimation errors, and the NN weight estimation errors for each NN are all semi globally uniformly ultimately bounded (SGUUB) in the presence of bounded disturbances and NN functional reconstruction errors while simultaneously relaxing the separation principle. The effectiveness of proposed output feedback control scheme is then demonstrated in the presence of unknown nonlinear dynamics and disturbances, and simulation results are included to demonstrate the theoretical conjecture.

A new variant of particle swarm optimization (PSO), named phase angle-encoded and quantum-behaved particle swarm optimization (θ-QPSO), is proposed by Ding , Zhou and Fu in [11]. Six versions of θ-QPSO using different mappings are presented and compared through their application to solve continuous function optimization problems. Several representative benchmark functions are selected as testing functions. The real-valued genetic algorithm (GA), differential evolution (DE), standard particle swarm optimization (PSO), phase angle-encoded particle swarm optimization (θ-PSO), quantum- behaved particle swarm optimization (QPSO), and θ-QPSO are tested and compared with each other on the selected unimodal and multimodal functions. In [12] Yang et. Al. firstly gave technical features of the catapult applied to the UAV of 200-kg class with an initial velocity of 30 m/s, and then makes a comparison between linear synchronous motors (LSMs) and linear induction motors (LIMs). The LIM is selected and the initial characteristics (thrust, input power, efficiency, current and mass) of the LIM working under different voltages and frequencies are calculated by a T model equivalent circuit method. The calculation suggests that the LIM exhibits better properties when it works under the higher voltage or higher frequency. When superconducting wires are applied to primary coils to construct a superconducting LIM (SLIM), the motor characteristics are also calculated and discussed. The SLIM gives a favorable opportunity to reduce the input power and current. A finite element method (FEM) is employed to simulate static field distribution of the SLIM and give electromagnetic properties to verify the equivalent circuit method. Nemra and Aouf presented a new INS/GPS sensor fusion scheme in [13], based on State-Dependent Riccati Equation (SDRE) nonlinear filtering, for Unmanned Aerial Vehicle (UAV) localization problem. SDRE navigation filter is proposed as an alternative to Extended Kalman Filter (EKF), which has been largely used in the literature. Based on optimal control theory, SDRE filter solves issues linked with EKF filter such as linearization errors, which severely decrease UAV localization performances. Stability proof of SDRE nonlinear filter is also presented and validated on a 3-D UAV flight scenario. Results obtained by SDRE navigation filter were compared to EKF navigation filter results. This comparison shows better UAV localization performance using SDRE filter. The suitability of the SDRE navigation filter over an unscented Kalman navigation filter for highly nonlinear UAV flights is also demonstrated. A novel approach to sea inspection with the assistance of robot is described in [14]. A software system for a simulation model of a UAV's automatic landing system is presented in [15] by Antsev and Sarychev. In [16] Ron Schneiderman, presented an exhaustive survey of applications of unmanned drones in the military and aerospace sectors. The simulation model allows us to determine the level of Influence of different distortions of the observed Image on the UAV's landing accuracy. [17] presents the flight plans generated for these VAV by new generation technologies (genetic algorithms) respecting the constraints of uses of the sensors (angles, distances of recording), the UAV performances (load factor in bend, height of cruise, speed of maximal stamina) as well as the environment of the theatre of operation (relief, meteorology, and restricted zones).

In [18] Ching and Chiu developed a vision-based flight control system that uses a skyline-detection algorithm for application to small unmanned aerial vehicles. The skyline-detection algorithm can detect straight or uneven skylines. The system integrates a remote controller, a remotely controlled airplane, a camera, a wireless transmitter/receiver, a ground control computer, and the proposed skyline-detection algorithm to achieve automatic control of flight stability. Static and dynamic tests are conducted to validate the system. In [19] Cho, Lee and Kim proposed a method that uses an aircraft with a single-antenna GPS receiver and Pitot tube to estimate wind speed and direction and to calibrate the airspeed. This sensor combination alone does not determine the true attitude of the aircraft, so the wind parameters cannot be obtained directly from the measurements.

3. Quad Rotor Assembly

Quad rotors have been actively driven by its potential application such as surveillance, inspection and mapping etc. A quad rotor offers some advantages over fixed wing aircraft such as the ability of VTOL, and hovering. Quad-rotor UAVs have many benefits such as reliability, compactness, low maintenance, rotor mechanics simplification, payload augmentation, gyroscopic effects reduction, and, good maneuverability, etc. The main challenge of quad rotor is that they are inherently unstable and have fast dynamic behavior, requiring a fast sampling rate to maintain the system stability. A low cost fully autonomous prototype quad rotor UAV has been developed. The developed quad rotor is interfaced with radio controlled (R/C) Transmitter/Receiver (Tx / Rx) set for wireless operation which has successfully controlled the motor speed in all directions (yaw, pitch and roll) wirelessly. An autonomous control system is implemented on a microcontroller, the output of which controls the motor speeds providing control in roll, pitch, yaw and vertical displacement. This utilizes inertial measurement unit (IMU) together with a global positioning system (GPS) receiver and a camera as a primary sensor. Here the motors are controlled through pulse-width modulation (PWM), the axel of the motor is geared with a five to one reduction gear. The result of varying duty cycles of the motor drive stage results in varying angular velocities. The quad rotor system operates in two coordinate frames: inertial and body. The inertial frame (also referred to as the earth frame) is the coordinate axis where Newton's Laws apply. The countering forces to achieve hover are applied to the body frame which is fixed to the quad rotor itself and is allowed to rotate and translate. There are three pieces of electronics hardware used in our model, the vision system, a laptop running Simulink/microcontroller program and the electronics hardware on the quad rotor. The electronics hardware used on the quad rotor is having four sections, the motor drive stage, the motor controller, the power stage which provides 3.3v and 5v power to the board and the wireless receiver. The PCB was assembled using proto board since putting a breadboard on a flying object is not practically feasible. This board attaches directly to the motors and the battery. The only other electronics on the quad rotor are filtering capacitors on the motors. The power stage consists of a pair of linear voltage regulators. A 5 volt TLE7805 regulator is used for the microcontroller and a LM317 for the Xbee transmitter running at 3.3 volts. These parts were chosen due to having them on hand when we went to assemble the PCB. In order to control the thrust of the rotors, the speed of the motors are controlled through pulse width modulation circuit designed to take a 0- 5V pulsed signal and boost this to a 0-11V signal to use to switch a MOSFET on and off as a DC chopper configuration. To control the motor, we decided on the Atmel ATMega328p microcontroller. This microcontroller was chosen due to having the PWM outputs we needed, the serial link to the ZigBee we need, and already having familiarity with the microcontroller and owning the programmer. The motor controller is currently running off an external crystal at 20MHz to achieve a reasonable PWM speed.

4. System Design

The overall quad rotor system is divided into following main subsystems

i) Body of the Quad-Rotor (Chassis)
ii) Motor Propeller set and motor mounts of the quad rotor
iii) Electronic Speed Control system along with its power supply unit
iv) Inertial measurement unit (IMU)_ comprises of accelerometer, gyro pressure meter and altimeter.
v) Wireless transmitter receiver set
vi) GPS module_ to get the current location of the quad-rotor
vii) Wireless camera for surveillance application.

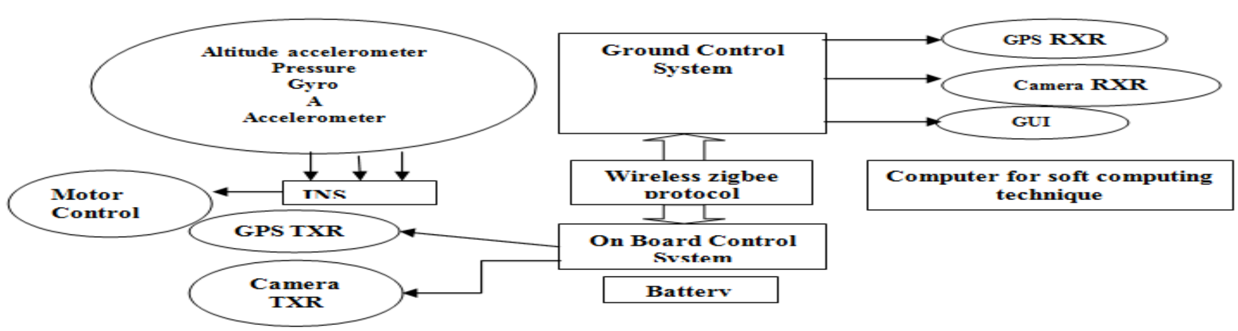

Fig 1: Block diagram of quad rotor model

5. Function of Subsystem

5.1 Chassis

The fixing of all parts of the quad rotor on a single frame and keeping all parts intact while on flight was a real challenge. The frame kept breaking; motors kept running out due to extremely high speed of the quad rotor. The ordinary motor mounts provided along with the motor were not strong enough to keep the motors in place during flight. Special motor mounts were molded using plastic and acrylic mixtures.

The four arms to connect motor base and central mounting station are hollow rods made up special alloy of copper and titanic that crew together. Each arm is connected at each end to the motor mounts and central frame. Angle brackets connect the arm to each section. Motors and batteries are mounted as far from the central axis as possible. Each motor screws down onto its bracket with shaft facing upwards on which the propellers are mounted.

5.2 The brushless Motor

The motor-speed servo system selected were four Turnigy D2836/11 750KV Brushless out runner motors to form the rotor of the quad-copter. A particular advantage of this motor is its high speed (24000-36000 rpm) that produce ample thrust to give sufficient lift to our model. The motors can safely provide 210 W at a maximum current of 14 Amps. Each rotor produces both a thrust and torque about its centre of rotation, as well as a drag force opposite to the vehicle's direction of flight. If all rotors are spinning at the same angular velocity, with rotors one and three rotating clockwise and rotors two and four counter clockwise, the net aerodynamic torque, and hence the angular acceleration about the yaw axis is exactly zero, which implies that the yaw stabilizing rotor of conventional helicopters is not needed. Yaw is induced by mismatching the balance in aerodynamic torques (i.e., by offsetting the cumulative thrust commands between the counter-rotating blade pairs).

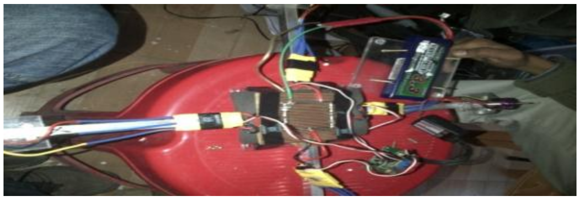

Fig 2: Motor and ESC assembly

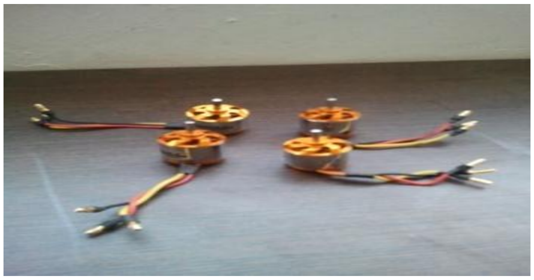

Fig 3: Four brushless motors

Angular accelerations about the pitch and roll axes can be caused separately without impacting the yaw axis. Each pair of blades rotating in the same direction controls one axis, either roll or pitch, and increasing thrust for one rotor while decreasing thrust for the other will maintain the torque balance needed for yaw stability and induce a net torque about the roll or pitch axes. This way, fixed rotor blades can be made to manoeuvre the quad rotor vehicle in all dimensions. Translational acceleration is achieved by maintaining a non-zero pitch or roll angle. The starting point of the design process is to determine the target size and total weight of the payload the quad rotor had to carry. This gives the idea about the size of the propeller used. Lesser the pitch of the propeller, higher will be the thrust. In our model we have used 10"X6" counter rotating propellers (pair):

Diameter: 10inch and Pitch: 6inch

Fig 4: Propeller unit and nuts and bolts

Fig 5: Propeller nuts and bolts

Table 1: Brushless motor specification

Battery	**2~3 Cell /7.4~11.1V**
RPM	**750kv~ 24,000 to 36,000 rpm**
Max current	**14A**
No load current	**0.8A**
Max power	**210W**
Internal resistance	**0.160 ohm**
Weight	**71g (including connectors)**
Diameter of shaft	**: 4mm**
Dimensions	**28x36m**
Prop size	**7.4V/12x6 11.1V/9x6**
Max thrust	**800g**
Battery	**2~3 Cell /7.4~11.1V**
RPM	**750kv~ 24,000 to 36,000 rpm**
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Max thrust	**800g**

5.3 Electronic Speed Controller (ESC)

The speed of the servo motors are controlled by this sub system ECS. The electronic speed controller is connected to the four brushless motors from one side and to throttle receiver on the other side. It has four wires for the four motors.

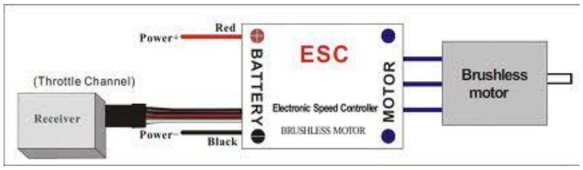

Fig 6: The connection diagram of the ESC

Table 2: ESC specifications

Max Amps	**25A**
Ubec	**5v / 3A Linear BEC**
Cells	**14 Volts DC / 2~3s Lipo**
Size	**48mm x 10mm 26mm**
Weight	**23g (Inc Wires)**

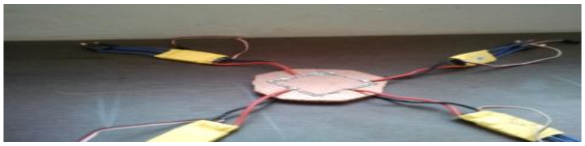

Fig 7: The connection diagram of the electronic speed controller board

5.4Inertial Navigation Board (INB)

The processing module of the quad rotor model is inertial navigation board (INB). Instead of installing a ready-to-use inertial navigation system (INS) easily available in the market we have designed our own inertial navigation board (INB) using Atmega 48 micro controller. This proto board has been interfaced with all the sensors, motors and electronic speed control system and the wireless transceiver. This not only reduces the overall development cost as well as provides better understanding of the control methodology of autonomous flying machine. The INB consists of four pieces of printed circuit boards, a main processing board, a serial communication board, an A/D data acquisition board and a DC-DC converter board.

The serial communication board is taken to extend communication between the main processing board and the peripheral devices, such as the servo controller ESC board, the sensors with the digital serial communication port and the A/D data acquisition board to collect the analog signals from the sensors with analog output. A full duplex transceiver is to provide communications between the ground computer system and the airborne computer system through wireless transceivers.

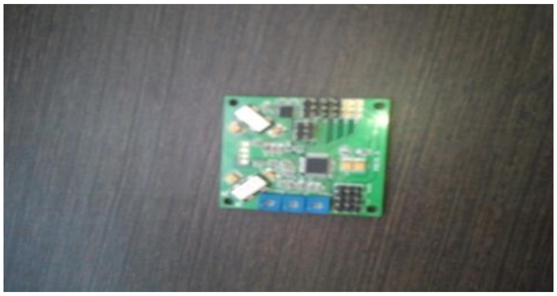

Fig 8: The prototype control board

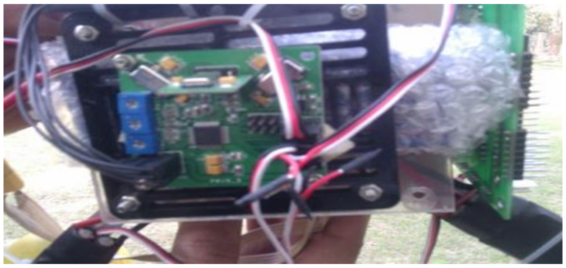

Fig 9: The proto-board fitted with all the peripherals

5.5 Wireless communication device

This unit is needed to establish communication between the airborne micro-controller band and the computer placed in the ground station. A full duplex radio transmitter receiver set provided by Turnigy power systems is being used in our model. The wireless transmitter is in the form of wireless remote control, which can be attached to the base control station.

Fig 10: Wireless remote control unit

Table 3: Remote Control Specifications

Number of Channel	**8ch ppm/9ch pcm**
Display	**128*64LCD**
Support Type	**Heli/Acro/Glid**
Support user	**8**
Stick model	**4**
Encoder type	**ppm/pcm**
Subtrim	**Yes**
Simulator Interface	**Yes**
Buzzer	**Yes**
Mode	1
Low Voltage Show	**Yes**

Full duplex wireless receiver is placed on the air-borne inertial navigation board (INB). The transceiver is a dual band (full duplex) module so that the base station can send and receive data to and from quad-rotor model. The 2.4 GHz has nine channels out of which only four channels are used in our model. It has enough bandwidth to control five more peripheral devices. The remote control unit consists of 2 control sticks, trim levers and switches and dials on the face and top of the transmitter body, so as to be within easy fingertip reach. These switches and dials are usually set up for retractable landing gear and flaps. There is also a collapsible antenna on top of the transmitter and a battery level indicator.

5.6 Integrated Sensor Unit (ISU)

The Integrated sensor unit comprises of major sensors which provides data such as speed, velocity, angle, altitude, magnetic field direction and actual global position. Path planning can be done by this unit. The sensors give very useful information like relative height and heading pitch and roll angles along with the spinning speed of the main rotor. Although the sensors cannot measure the relative motion between the aircraft and the surrounding air, they can provide sufficient signals to control the movement of the helicopter effectively for airspeed up to 20 m/s. Because the aerodynamic effect from the fuselage of the helicopter is so small in the small airspeed, it can be safely ignored. Also, the relative movement between the helicopter and its surrounding air has less effect to the aerodynamic effect on the spinning rotor compared to the rapid spin of the main blades. The ISU consist of gyro and accelerometer.

5.6.1 Accelerometer

The Accelerometer Module features temperature compensation and g-Select which allows for the selection among 4 sensitivities. It requires no external devices and works on 2.6V to 5V power supply. It can be directly interfaced to ADC of a microcontroller without any external components. This module can be used to sense motion or tilt(in case of non-moving) in 3 axis. Simple 5 pin interface (VCC, GND, Xout, Yout, Zout). Selectable Sensitivity (1.5g/2g/4g/6g) and Sleep Mode Selectable through jumpers or microcontroller. Integral Signal Conditioning with Low Pass Filter. Robust Design, High Shocks Survivability.

Table 4: Accelerometer specifications

S.N.	Different Parameters	Specifications
1.	Small size	28mm X 23mm
2.	Sensitivity	1.5g/2g/4g/6g
3.	Low Current Consumption	500 µA
4.	Low Voltage Operation	3.6V to 5V
5.	High Sensitivity	800 mV/g @ 1.5g

5.6.2 Gyroscope

It is a dual-axis gyro. The Gyro measures angular velocity along with the pitch , roll and yaw axes with a full scale of ±300°/s. Two different analog outputs are provided for both x and z axes amplified. A regulated voltage 5VDC should be supplied to the power pins. It is fitted with the filtering circuits and can directly connect the output.

Table 5: Gyro Specifications

S. No	Different Parameters	Specifications
1	Complete rate gyroscope on a single chip Pinouts: GND, VCC, X(Pitch), Z(Yaw), Self Test, Power down	
2	powered shock survivability	2000 g
3	single-supply operation	5V
4	Operation	105°C
5	Filter	On-board
6	X (Pitch rate) and Z (yaw rate) response High vibration rejection over wide frequency	

This breakout board includes the gyro and all necessary filtering capacitors. The amplified outputs of both axes are connected to the 0.1" pitch headers, along with the power-down, self-test and power pins. Special features of the gyro include X (Pitch rate) and Z (yaw rate) response, high vibration rejection over wide frequency, radiometric to referenced supply. An Atmega128 micro controller is interfaced to motors for flight control. The signals for control are generated by the base station on the basis of accelerometer and gyro. The remote control receiver section is also the part of this control segment and is responsible for UAV's flight control signal reception.

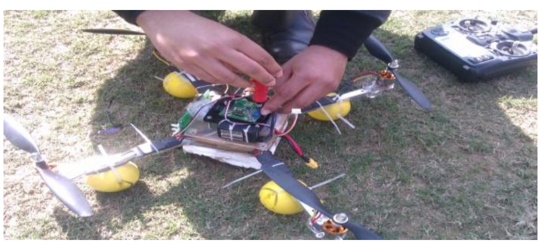

Fig 11: Tuning of gyro and accelero before takeoff.

5.7Battery Unit

The selection of battery type for the quad rotor model is a very important step as it should be light weight and at the same time should have enough power rating and long life. After studying the specifications of various types of batteries Lithium-Polymer battery is chosen which is very small in size and weight compared to Ni-Cd, Ni-MH and Lead Acid Batteries and has a long life with full capacity for up to 1000 charge cycles.

Table 6: Battery specifications

S.N.	Different Parameters	Specifications
1.	Capacity	2200mAh
2.	Full Charge	180 minutes
3.	3X Li-Po	4.2V 2200mAh cells
4.	Weight	123g (including wire, plug & shrink
5.	Volume	10cm*3.3cm*2cm
6.	Discharge Current	20*2200maH = 44Amp
7.	Max Charging Current	1A

6. Conclusion

In this paper we have outlined the details of design and assembly of an experimental prototype model of quad-rotor UVA platform. The key challenges faced during development of the quad rotor model were dynamic stability and economic viability. The thrust generated disintegration problem of the rotor assembly was solved by designing special material for motor mounts consisting of glass plastic and acrylic mixture. The hollow frame rods were made up of alloy of copper and titanic which enhanced the material strength and the assembled model demonstrated significantly stable flight. We have constructed our model using inexpensive components easily available in Indian market. The designed quad-rotor is economical, moderately functional, and is an excellent platform for academic research purpose. In contrast to military UAV users, which undertake highly specialized missions with highly accurate and reliable instruments, this paper presents a low-cost UAV system for civilian applications. A low-cost civilian UAV platform have been designed, which is specifically designed as an economical, moderately functional, small airborne platform intended to meet the requirement for fast-response to time-critical events in many small private sectors or government agencies. A novel in-flight autonomous control strategy has been implemented on the experimental UAV.

Fig 12: Complete Quad-rotor model

The experimental results demonstrate that the UAV design presented in this paper can be used for surveillance application. The assembly has been done using low cost components easily available in Indian market. The experimental prototype quad-copter has been successfully implemented and tested for 15 minutes smooth flight time. The flight control strategy is attempted in manual and autonomous modes both have been validated successfully.

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Prof. Shahida Khatoon is born in Delhi, India in 1968. She obtained her B. Tech (Electrical Engg.) in 1990, M. Tech (Controls and Instrumentation) from IIT Delhi in 1993, and PhD degree in (Electrical Engineering) in 2004. She started her career as Lecturer in the department of electrical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia, Jamia Nagar New Delhi, INDIA. She was promoted to Associate Professor in 2005, and then to professor in 2011 in the same department. Her field of specialization is controls and automation, she has three PhDs awarded under her guidance and supervising eight more research students. She has thirty six research publication in national and international conferences and twelve publications in international journals. She has completed one UGC sponsored major research project on unmanned aerial vehicles, and currently she is perusing another research project on wireless sensor networks sponsored by DST, Ministry of Science and Technology, Govt. of India. of regular papers.

Dheeraj Gupta is born in Allahabad, Uttar Pradesh, India . He got his B. Tech and M. Tech degrees in Electronics and Communication Engg.), from MNIT, Allahabad. He is currently pursuing his PhD degree in Dept. of Electrical Engineering from Jamia Millia Islamia under the guidance of Prof Shahida Khatoon in Control and Automation. His area of specialization is Control and Automation. He has four research publications credited to his name. Presently he is the Dean and Head Dept. of Electronics and Communication Engineering in GNIIT, Greater Noida, UP.

Ahmad Saad Khan is born in Delhi, India in 1991. He's currently pursuing his B.Tech degree from Jamia Millia Islamia in the field of Electronics and Communication. He has co-authored 2 research publications in the field of Wireless Communication and Robotics. His area of interest includes Wireless Communication and Telecommunication Systems. He has worked as a research assistant in 2 major projects sponsored by UGC and DST, Ministry of Science and Technology, Govt of India. He is currently a CSI and IEEE Student member.