Design of Artificial Intelligence Based Control System for Swarm Operated Unmanned Aerial Vehicles

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Abstract: This work involves the designing of control and intelligence system for a group of swam operated unmanned aerial vehicle. The project dealt with the development of a prototype quadrotor with an on-board control system having LPS (Local Positioning System) for position estimation. The quadrotor has been programmed using algorithms of Artificial Intelligence to perform mapping and demonstrate disaster management techniques that would be applicable in different scenarios. Concepts of swarm coordination, obstacle avoidance and RF communication has been implemented and demonstrated through simulation using VRep robotic simulator software. Control system design has been implemented and its efficiency has been verified using simulations. Software models of the system have been designed and verified using a low cost prototype sytem.

Keywords : Quadrotor, Swarm, Unmanned Aerial Vehicles, Artificial intelligence, control systems, mapping, shortest path algorithm, Local Positioning System, Kinetic Thrust Bench

1. INTRODUCTION

An unmanned aerial vehicle (UAV) is an aircraft capable of flying without a pilot on-board having its own on-board or base station operated control system. A Quadrotor, is a unique kind of UAV's that uses four-fixed rotors, with two rotors per axis (each orthogonally aligned with the other) powered by four motors to lift and propel the aircraft. Its special feature is its ability to perform Vertical Takeoff and Landing (VTOL) that makes it quite desirable as an UAV.

Aerodynamics concepts were used for the development of motor-propeller model. Propeller performance analysis was carried out using Blade Momentum Theory and an indigenous thrust bench was developed to experimentally obtain the performance characteristics and derive a relationship between Pulse Width Modulated (PWM) voltage and thrust produced. Mathematical modeling of kinematics and dynamics of Quadrotor was carried out. The flight behavior was analyzed and appropriate control strategy was developed. Control system design for Attitude and Altitude control involving PD (proportional and derivative) control was carried out and verified using MATLAB™ simulations. LPS algorithm was developed for position estimation which eliminates the use of GPS since it cannot be used for underground applications. Various artificial intelligence concepts of mapping and planning with obstacle avoidance was developed using Hybrid Automaton Strategy.

Search and rescue missions during fire, chemical hazards, remote surveillance and night vision guides during military operations, mapping of underground topology for mining and oil explorations, monitoring of overhead electrical distribution lines are some of the significant applications of this research work.

2. MATHEMATICAL MODELING OF QUADROTOR

Analysis of Quadrotor requires a number of reference frames because of the variability of state variable measurement. In order to map the measured quantities into a common frame, transformation matrices are required. A general transformation matrix after rotation in the XYZ plane is:

$$\begin{bmatrix} x(new) \\ y(new) \\ z(new) \end{bmatrix} = \begin{bmatrix} c\theta c\psi & c\psi c\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\theta \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - s\psi c\phi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \begin{bmatrix} x(old) \\ y(old) \\ z(old) \end{bmatrix} \quad (1)$$

where Φ denotes roll, θ pitch and Ψ yaw respectively.

Analysis of dynamics of a system requires application of pseudo forces in an non-inertial frame of reference. In a rotational frame, the system experiences Coriolis Effect which requires use of Coriolis force (Pseudo force) for the validation of Newton's Law in that frame. In an inertial frame:

$$m\frac{dv}{dt} = F \quad (2)$$

In order to incorporate the force balance in non-inertial frame, Coriolis force is used.

$$m\frac{dv}{dti} = m(\frac{dv}{dtb} + \omega \times v) = F \quad (3)$$

For the simplification of onboard computation, the effect of Coriolis forces has been neglected.

In order to model the Quadrotor 12 state variables are taken into account [x, y, z, u, v, w, Φ, θ, Ψ, p, q, r] indicating position, linear velocity, Euler angles and angular velocity in the three directions.

As mentioned earlier, these quantities are measured in different frames of reference. Therefore mapping relationships are required for computational purposes:

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} c\theta c\psi & c\psi c\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\theta \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - s\psi c\phi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix}\begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (4)$$

$$\frac{d}{dt}\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} 1 & \tan\theta\sin\phi & \tan\theta\cos\phi \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \sec\theta\cos\phi \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (5)$$

$$\frac{d}{dt}\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} rv - qw \\ pw - ru \\ qu - pv \end{bmatrix} + \frac{1}{m}\begin{bmatrix} fx \\ fy \\ fz \end{bmatrix} \quad (6)$$

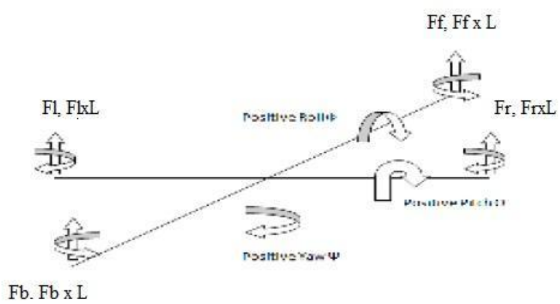

Fig. 1 Direction of forces on the Quadrotor

The above figure represents the forces and torque produced by each motor and propeller set.

$$Force_{total} = F_l + F_r + F_b + F_f \, (N) \quad (7)$$

$$Roll_{torque} = (F_b - F_f) * L(Nm) \quad (8)$$

$$Pitch_{torque} = (F_r - F_l) * L(Nm) \quad (9)$$

$$Yaw_{torque} = [(F_r + F_l) - (F_b + F_f)] * L(Nm) \quad (10)$$

$$Thrust \alpha (V_{tip})^2, V_{tip} \alpha \delta (duty) \quad (11)$$

$$Thrust = k_1 \delta \quad (12)$$

$$Torque = k_2 \delta \quad (13)$$

where k1, k2 are determined experimentally.

The following denotes the matrix form representation with duty cycles being fed to the motor controllers.

$$\begin{bmatrix} Thrust \\ Rt \\ Pt \\ Yt \end{bmatrix} = \begin{bmatrix} k1 & k1 & k1 & k1 \\ 0 & 0 & k1 & -k1 \\ -k1 & k1 & 0 & 0 \\ k2 & k2 & -k2 & -k2 \end{bmatrix}\begin{bmatrix} \delta l \\ \delta r \\ \delta f \\ \delta b \end{bmatrix} \quad (14)$$

3. CONTROL SYSTEM DESIGN

Design of the control system has been carried out to stabilize the motion of the Quadrotor as well as control its maneuvering.

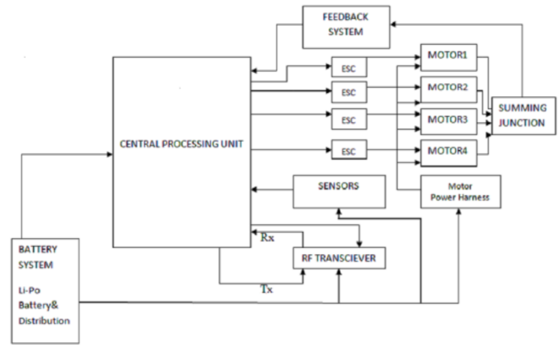

Fig. 2 Control Strategy of a single Quadrotor

As shown in Fig 2, a single Quadrotor would involve the actuation of four motors by electronic speed controllers (ESCs) that receive pulse width modulated (PWM) signals from the central processing unit. Sensors (opto-electronic, ultrasonic) provide the Quadrotor with the necessary vision that govern its decision making. RF trans-receiver allows communication with a remote station as well as another Quadrotor in the SWARM communication network. Lithium Polymer (Li-Po) battery provides the power to the entire system through an efficient power management system.

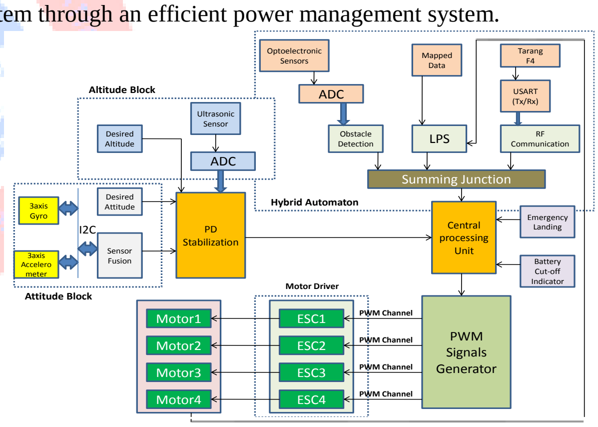

Fig. 3 Overall Control Block for a Single Quadrotor

As shown in Fig 3, the control system of the Quadrotor mainly comprises of: Central Processing Unit, Altitude control system, Attitude control system, motor drivers, Hybrid Automaton logic, safety indicators (battery cut-off and emergency landing).

The three inputs to the summing junction before the control block serve as a hybrid automaton that is decided by priority. The 3 elements of this automaton are Goal to Goal Strategy (Local Positioning System based on mapped data), Obstacle Detection and RF communication (emergency landing or counterpart Quadrotor). Depending on the situation (dynamic) or on a set priority (static), switching between different tasks is performed by the single Quadrotor in the network.

3.1 Altitude Control

Altitude stabilization is required during two main circumstances:

1) Hovering (remaining at a desired height)
2) Reaching a given Z-coordinate

During hovering, all the 4 motors are rotated with the same speed such that the thrust developed by them are equal and enough to balance the weight of the Quadrotor. However, during a change in altitude, all the motor speeds are either increased or decreased depending on the ascent or descent of the Quadrotor. Stabilization of the Quadrotor during altitude change or hovering is achieved through a PID controller.

Translational acceleration of the Quadrotor in z-axis can be obtained with using the following formula:

$$a = \frac{\sum_{1}^{4} F}{m} - g \qquad (15)$$

$$a = \frac{Fn}{m} \qquad (16)$$

where Fn denotes the net force in the upward direction. The following equation reveals position in z-axis (x1) and velocity (x2) in z-axis as 2 states (x1 and x2) and thus the state space model for altitude stabilization:

$$\dot{x} = Ax + By \qquad (17)$$

$$y = Cx + Dy \qquad (18)$$

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \qquad (19)$$

$$B = \begin{bmatrix} 1 \\ 1/m \end{bmatrix} \qquad (20)$$

$$u = Fn \qquad (21)$$

3.2 Attitude Control

Controlling the pitch, roll and yaw of the Quadrotor, in other words the attitude dynamics of the system helps to govern the orientation of the vehicle in space. Another set of equations are used to develop a state space model that would represent attitude dynamics. On linearizing the equations obtained in section 3 about the angles (0, 0, 0), we get the following set of equations describing the angular velocities in terms of the duty cycles.

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \frac{1}{J} \begin{bmatrix} k1 * L * (\partial 2 - \partial 4) \\ k1 * L * (\partial 1 - \partial 3) \\ k2 * L * (\partial 2 + \partial 4 - \partial 1 - \partial 3) \end{bmatrix} \qquad (22)$$

Combining the angular velocities with the Euler angles, we can represent the states as: $x = [\phi \;\; \theta \;\; \varphi \;\; p \;\; q \;\; r]^T$. Choosing the input vector to be a combination of the duty cycles, we obtain $u = [\partial 1 \;\; \partial 2 \;\; \partial 3 \;\; \partial 4]^T$. As it can be observed (from ? and ?), the attitude and altitude stabilization state space models are independent of each other. Hence, the two can be combined with the slight modification in the altitude state space matrix (inputs in terms of **δ**).

$$a_z = k1 * \partial 1 + \partial 2 + \partial 3 + \partial 4 \big/ m \qquad (23)$$

The new states becomes $x = [z \;\; v \;\; \phi \;\; \theta \;\; \varphi \;\; p \;\; q \;\; r]^T$. With these states and the appended values of A, B, C and D a combined state space is obtained with

$$A = \begin{bmatrix} 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \end{bmatrix} \qquad (24)$$

$$B = \frac{L}{J} \begin{bmatrix} 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&k1&0&-k1 \\ k1&0&-k1&0 \\ -k2&k2&-k2&k2 \\ 0&0&0&0 \\ \frac{k1}{m}&\frac{k1}{m}&\frac{k1}{m}&\frac{k1}{m} \end{bmatrix} \qquad (25)$$

$$C = \begin{bmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0 \end{bmatrix} \qquad (26)$$

$$D = \begin{bmatrix} 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \end{bmatrix} \qquad (27)$$

3.3 Sensors and Actuators

The Quadrotor is equipped with 8 optoelectronic sensors and one ultrasonic sensor below the Quadrotor to calculate the height of the Quadrotor above the ground.

1) Opto-electronic Sensors
2) Ultrasonic Sensor
3) Brushless DC Motors
4) Electronic Speed Controllers (ESC)
5) Inertial Measurement Unit (IMU): An inertial measurement unit consists of an Accelerometer and a Gyroscope.

3.4 Wireless Communication

One of the integral parts of this project is the idea of creating a SWARM network. SWARM indicates the formation of a systematic communication channel between the different Quadrotors in operation. Some of the main benefits of having a wireless network among the various robots are:

1) Optimizing the efficiency during search and rescue missions by dividing duties
2) Reducing the payloads to be carried by a single Quadrotor
3) Monitoring the status of different Quadrotors during operation

4. ARTIFICIAL INTELLIGENCE

In order to simulate the use of artificial intelligence in disaster management scenarios, simulations has been carried out keeping a room as the site for disaster management. The disaster considered in the simulations is that of a fire in the room.

4.1 Mapping

In order to provide artificial intelligence to the Quadrotor, it is essential that the site of disaster management needs to be mapped first. Once the mapping process is completed, the Quadrotor has an intuition of where the static obstacles are present. The Quadrotors will travel the entire place trying to find the obstacles. The map of the entire place is saved in the form of a 3 dimensional array

4.1.1Algorithm

Begin:
Initialize Quadrotor
Quadrotor lifts off and reaches a particular height 'h'
Map: Quadrotor starts mapping along the x-y plane.
If obstacle detected
then store obstacle coordinates
Continue Mapping
Decrement height to a new height "h"
If h not possible (floor reached)
then STOP
Else
Go to Map
End:

4.2 Disaster Management

After mapping, Quadrotors then can be used for the actual disaster management scenario. Multiple Quadrotors are assigned the job and they are in continuous communication with each other. As soon as a Quadrotor finds the point it will relay its co-ordinates to the fellow quads. The other quads using path planning algorithms will plan the shortest path to the point of action. The flow of this algorithm occurs as following:

1) Quadrotors are launched from different locations.
2) Quadrotor relays hazard information to others.
3) Other Quadrotors calculate shortest distance to hazard.
4) Quadrotors with shorter distances come to rescue.

4.3. Local Positioning System (LPS)

One of the main aims of developing the Quadrotor in our project is to carry out search and rescue missions in disaster situations which might include mines, man-holes and various other environments that would be out of GPS range. This inability of GPS to locate underground position led to the development of LPS algorithm that works based on triangulation method and depends on inputs from motors and sensors.

The first algorithm deals with the positioning of the Quadrotor at every turn.

4.3.1 Algorithm:

Begin:
Interrupt from RF communication
Go to motor control loop
Go to calculation loop (calculating displacement, deceleration) and return the values to motor control
Perform deceleration & achieve hovering
Start Quadrotor Stabilization
Use prerecorded navigation direction flags and distance to calculate the incremental changes in the x, y, z direction (delta value)
From the incremental values, calculate the new coordinates (x, y, z) in the position modification loop
Return and initiate new values of the direction flags
Go to motor control for executing the turn
Return to the main program

However, it is possible that the Quadrotor might not need to negotiate turn for a while in the case of which it would become difficult to track it if we rely only with positioning at every turn. Thus, LPS also takes into account the time since last turn and if this exceeds the sample time, its positioning is done again.

4.3.2 Algorithm:

Begin:
Interrupt received from the sampling counter
Go to calculation loop and calculate distance
Change the incremental values based on the values stored in the direction flags
Go to position modification loop and change the coordinates based on the incremental values
Return to main program

5. RESULTS

The results obtained have been categorized into three different sections:

5.1 Simulations

Simulations have been carried out to validate concepts implemented in this project. MATLAB™ SIMULINK has been used to simulate details of control systems design whereas VRep Robotic Simulator has been implemented to simulate various scenarios for artificial intelligence.

5.1.1 MATLAB Simulations

Control system was successfully designed for attitude (roll, pitch) and altitude control of the Quadrotor.

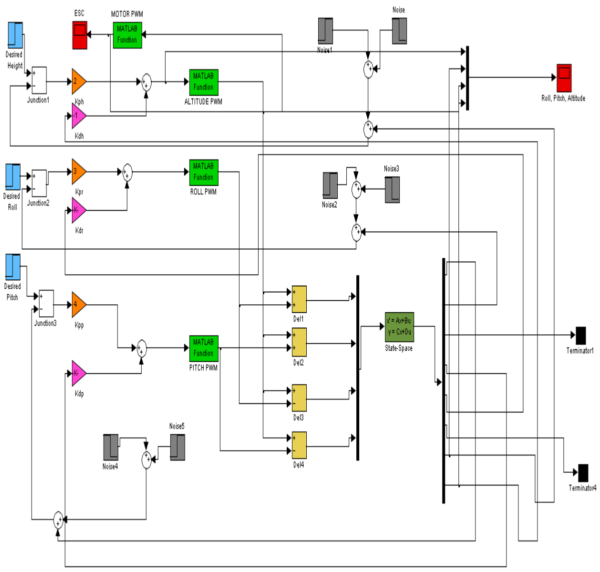

Fig. 4 SIMULINK Model of Quadrotor Control System

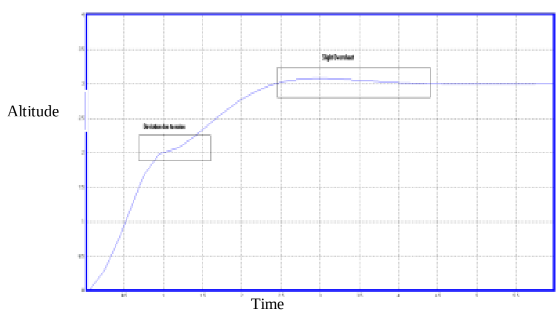

Fig. 5 Altitude Control

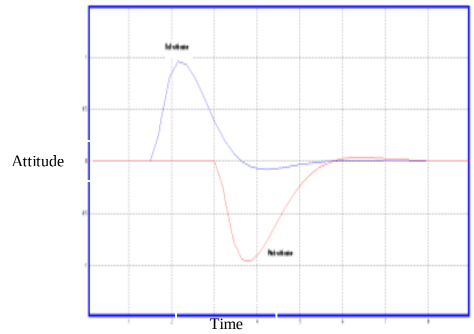

Fig. 6 Attitude Control

The altitude stabilization (Fig 4) demonstrates the Quadrotor reaching a desired height from stationary position at ground level. The attitude stabilization (Fig 5) demonstrates maintaining a zero roll and pitch during the change in altitude by Quadrotor.

5.1.2 V-Rep Robotic Simulator

The disaster management scenario and the mapping scenario implementing the concepts of Local Positioning System and SWARM have been successfully simulated using the VRep Simulation software.

Fig. 7a Disaster Management Stage1

The above figure (Fig 7a) shows the 2 Quadrotors in action, searching the disaster scene (in this case, source of fire). Both of them follow different routes that reduce workload and time.

Fig. 7b Disaster Management Stage2

In (Fig 7b), it can be seen that one of the Quadrotor has located the origin of fire and has transmitted its location to the other Quadrotor. On reception of its new destination coordinates, the second Quadrotor can be noticed approaching its counterpart.

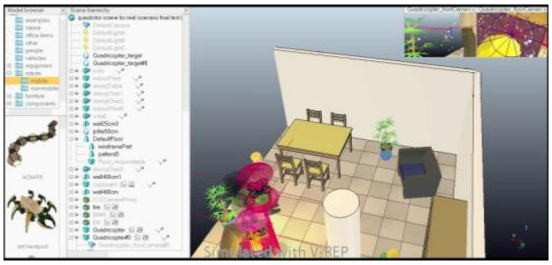

Fig. 7c Disaster Management Stage3

In the above figure (Fig 7c), the last stage has been shown where both the Quadrotors confluence at the origin of fire. The coordinate determination of the Quadrotors and calculation of the shortest path to reach the first Quadrotor has been carried out using Local Positioning System.

5.2 Experimental Test Benches

For modeling of motor-propeller pair, a experimental bench was designed

5.2.1 Kinetic Thrust Bench

It is very important to derive relation between PWM and the thrust generated for designing efficient control system. This experimental bench was used to arrive at the relation.

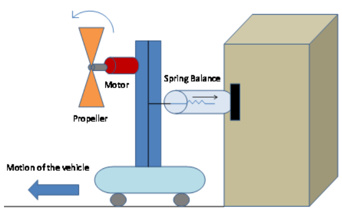

Fig. 8a Kinetic Thrust Bench

Fig. 8b Kinetic Thrust Bench Experiment

As shown above, the setup consists of a metal vertical column on which is fixed the motor-propeller pair. The vertical rests on the movable base. The metal column is also fixed to a stationary wall with spring balance which gives the reading of the thrust produces by the motor-propeller pair for the given value of duty cycle. Using the values of duty cycle obtained for the respective thrust generated by the motor-propeller set, a linearized graph can be obtained, from which the relations are obtained as follows:

$$\begin{aligned} F_1 &= 6.7\delta_1 - 0.007 \\ F_2 &= 6.75\delta_2 - 0.014 \qquad (28) \\ F_3 &= 6.8\delta_3 - 0.001 \\ F_4 &= 6.95\delta_4 - 0.055 \end{aligned}$$

$$F = 7 * \delta \qquad (29)$$

As we previously knew f = k1 * δ, the value of k1 can be assigned to 7.

5.3 Hardware Implementation

The prototype model developed is shown below:

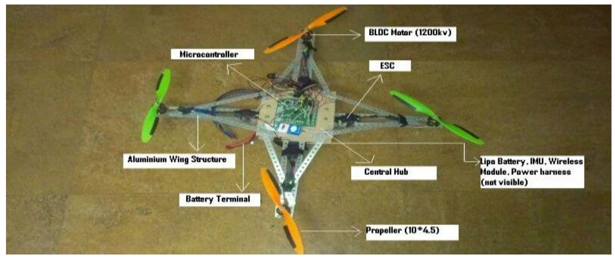

Fig. 9 Quadrotor Prototype

6. CONCLUSION

The disaster management scenario and mapping involving the implementation of Local Positioning System as well as SWARM communication have been successfully simulated using the V-rep Simulation software. Control system was successfully designed and verified using MATLAB™ simulations. A part of this system was implemented on the Quadrotor prototype which enabled it to perform successful flight with decent endurance. Future Work of this research would focus on

1) Hardware up gradation by using carbon fiber for good strength and lightweight.
2) Speed Feedback using contactless tachometer better modeling using real time speed feedback.

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