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# Non-Linear Robust Attitude and Altitude Control of a Quadrotor with Object Detection

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***Abstract*—Quadcoptershavebeen increasinglyemployedindiverseresearchprojectsin both militaryandcivilianapplications. Thisisbecauseoftheirhighmaneuverabilityandaccurate mobility and hence suitable for both indoor and outdoor applications. Autonomous Quadcopters should becapable oftaking-off, landing and following apre-settrajectory without anyexternal control. However due to inherent non linearity and under actuated properties it is not an easy affair to control the quadrotor. A control structure with at least two loops is necessary to enable the tracking. This brief however deals only with the attitude and altitude control of the quadrotor. A nonlinear controller named RobustIntegralofSignofError (RISE)controller is adopted for the inner attitude control loop.RISE controller has superior tracking capability and robustness in presence of bounded external disturbances and model uncertainties. A traditional PID controller is used to control the attitude. Quadrotor helicopteris assumed to be a rigid body and the dynamics were modelled using Newton- Euler equations to describe the six degrees of motion of the Quadcopter. The translational and rotational dynamics are decoupled to facilitate the two loop control structure. MATLAB implementation of the above control structure along with an introduction to feature detection methodologies are discussed in this brief.**

***Index Terms*—Quadrotor, RISE, robustness, PID, feature detection**

## I. Introduction

Quadrotor controlhavealwaysbeenaninterestingareafor controlengineers in the recent past owing tothe highly nonlinear natureof thesystem , it's under actuated dynamicsandthe various challengesfaced byitinthe real time applications. Many of the system parameters like aerodynamic coefficients are difficult to be calculated beforehand which leads to model uncertainties. The Quadrotor can also be affected by wind gusts andother environmental factors. Since it is an aerial vehicle, it has little or no friction and hence it has no inherent damping properties. Many control techniques have been developed over time to cater these needs. Since thedynamicmodelof aQuadrotorcanbelinearized at many operating points,many traditional linear control methods[3],[4]have been usedtostabilize theQuadrotorinasmallrange around theequilibrium point around which they are linearised.But the performance of such controllers may not be satisfactory if we consider the nonlinearities and a wider operating range. Thereforeinrecentpast, researchers tend to look formoreand morenonlinear and robustcontrolmethodologies and as a result lot of control techniques have been explored. To compensate for theunder actuatedproperty,variouscontroltechniqueshave beendevelopedfor theQuadrotor and otherunderactuated mechatronicsystems, suchas awheeledmobilerobot,anunderwater vehicle,andoverheadcranes[5].In[7],anovelrobustback stepping-based controllerthatisbasedonanintegralsliding-modeapproachisproposedfor anunder actuatedQuadrotor.Althoughthedesignprocedureoftheback-stepping schemeisvery clearandtheproofofthestabilityisstandardized,thecontrolgainsarenoteasily tuned and chattering like behavior is observed.

In[8],thedynamic systemoftheQuadrotorisdividedintotheinnerloopandtheouter-loopsubsystem.Suchschemeisnotdifficultforimplementation,butthestabilityofthe closed-loopsystemcannotbeeasilyguaranteed.Toovercomethisdrawback,aninner-and outer-loop-basedflightcontrollerisproposedin [9],andtheAsymptoticStability(AS)of theclosed-loopsystemisprovedviaatheoremofcascadedsystems.Tocompensateforthe parametricuncertainties in the system

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an adaptivenonlinearcontrolmethodwill be a suitablechoiceandhas beenwidelyutilized[10].But the problem lies in the fact that, the classic adaptive control methodalwaysrequires a LinearParameterization(LP)condition,andsometimes, thecontroller's singularitieswill comeintoaction [11].Recently,anewadaptivecontroldesignusingtheimmersionand invariance(I&I)methodologyisfirstproposedin[12]andthenwas further studied and worked on bymany researchers[13]– [16]. Thisapproach,is quite different from the classicadaptivemethod, anddoesnot requiretheLPcondition,nordoesitrequirecertaintyequivalence.Italsosimplifies the stabilityanalysisusingtheLyapunovmethod by showing up byprovidingcrossterms in the Lyapunov function [8].In[14],anI&Imethodisusedtoestimatetheunknownmassofa Vertical Take Off and Landing vehicle,and itguaranteesthat theestimationconvergestoitstrue value.In[15],tocontrola miniQuadrotor UAVand overcometheuncertaintiesrelatedwiththethrustanddrag coefficients,Fujimoto*etal.* simplifiedthedynamicmodelanddevelopedanadaptive controllerviatheI&I methodology.

Due to the presence of external disturbances, devotedtothedesignofarobustcontrollerforaquadrotor.In[13],ageneralsliding-mode control(SMC)isdevelopedforaclassofuncertainunderactuatedsystemsandthenutilized tostabilizeaquadrotor.However,one of the maindrawbacksoftheSMCisthechatteringissue, which might deteriorate the control performanceduring practical implementation. To achieve a continuouscontrolstrategy,arobustintegralofthesignumof theerror(RISE)-based controllerisfirstpresentedin[14]andfurtherdevelopedby otherresearchers[15].The RISE feedback controlcancompensateforexternaldisturbancesand modeling uncertaintieswhileensuring accurate tracking and semiglobalasymptoticconvergence.

Unmanned aerial vehicles (UAVs) especially quadrotor drones are becoming the standard in reconnaissance in both military and civilian applications. Object identification and tracking are the typical requirement of most of these missions. So much research is being done in this field. Paula et al. [17] described the phases of identification, dynamic modelling and control of an unmanned aerial vehicle of type quad-rotor intended to capture pictures and video in high definition with relatively low cost. Kim et al. [18] described wearable hybrid interface where eye motions and mental focus specifically impact the control of a quadcopter in three-dimensional space. Kim et al. [18] described wearable hybrid interface where eye motions and mental focus specifically impact the control of a quadcopter in three-dimensional space. This brief intends to explore object detection using a monocular camera which may prove useful as the size of these drones are getting smaller by the day and thereby payload capacity is reducing making a need for smaller and lesser sensory devices on board the quadrotor.

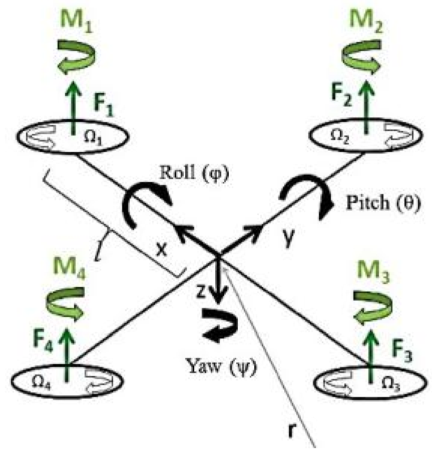


Fig 1. Quadcopter Moments

The paper is divided into four sections. Section II presents the modeling of the under actuated Quadrotor. Section III details control problem formulation and the controller development. Section IV mentions the feature identification methodologies using a monocular camera. Section V presents the simulation results of the attitude and altitude control loops. Finally a few conclusions and the possible improvements are listed in Section VI

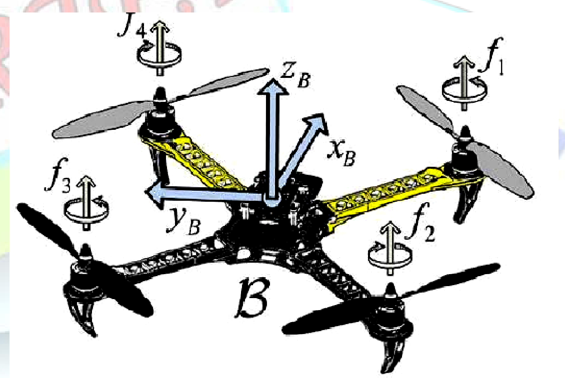


Fig 2. Quadcopter Axes

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## IIQUADROTOR MODELLING

A Quad rotor Helicopter or simply a Quadcopter is as mentioned previously an Unmanned Aerial Vehicle (UAV) which has four rotors or propellers producing thrust. It uses these rapidly spinning rotorstopush airdownwards,thuscreating athrustforce in the downward direction thereby keeping the quadcopter in hover. Fig. 1 shows the quadcopter moments during operation and Fig. 2shows thetwo reference frames. An inertial frame ℶ is taken to be stationary with respect to the earth and a body frame $\mathcal{B}$ is fixed to the center of mass of the object

Toflyaquadrotor helicopter,youhavetobalanceitsweightbygenerating anequivalentforce(Lift)andbalancemomentsaboutitsCentreofGravity (CG) by generating oppositemoments.Aquad-coptergeneratestheserequiredmomentsandlift forceusingitsfourrotors.Generatingliftisrestively easy,butthedifficult partisgenerating momentstostabilize the machineandgeneratingcontrolforcestomoveittoa desired locationoronadesiredpath.Tofly stableinanorientation,netmomentabouttheCG should alwaysbezeroorresultantofalltheforcesactingonthequadrotorshouldpass throughitsCG.Iftheresultantoftheliftgeneratedby alltherotorsdoesn'tpassthrough CG,itcreatesamomentabouttheCGandtendtotiltthequad-copteruntilliftagainpasses throughtheCG. Also,tobalancetheangularmomentumabouttheCG,tworotorsare made torotateclockwise andothertwoanti-clockwiseasshowninFig. 1

The Modelling of the dynamics of the Quadrotor is done following the Newton-Euler equations for a dynamic system. The quadrotor has six degrees of freedom namely the translational position (x,y,z) and attitude $(\theta, \emptyset, \varphi)$. The following assumptions are also considered while modelling the system equations

1. Thestructureis rigid and symmetrical.
2. The center ofgravityof thequadrotorcoincides with the bodyfixed frameorigin
3. The propellers are rigid
4. Thrust and drag areproportional to the squareofpropeller's speed.

The dynamics of the quadrotor were adopted from[2],[19].Afewassumptionsfrom[20]hasalsobeen adapted to obtain the model as required for our analysis

$$m\ddot{x} = -K_1\dot{x} + u_t[cos\emptyset sin\theta cos\varphi + sin\emptyset sin\varphi]$$

$$m\ddot{y} = -K_2\dot{y} + u_t[cos\emptyset sin\emptyset sin\theta - sin\emptyset cos\varphi]$$

$$m\ddot{z} = -K_3\dot{z} - mg + u_t[cos\emptyset cos\theta]$$

$$J_1\ddot{\emptyset} = -K_4 l\dot{\emptyset} + d_1(t) + l\tau_1 \qquad (1)$$

$$J_2\ddot{\theta} = -K_5 l\dot{\theta} + d_2(t) + l\tau_2$$

where $m\epsilon R^+$ denotes the mass , $J_i\,\epsilon R^+$ for i=1,2,3 are the moments of inertia, $K_i\,\epsilon R^+$ for i=1,2,3,4,5,6 denotes the aerodynamic damping coefficients , g is the acceleration due to gravity, $u_t(t)$,$\tau_1(t)$,$\tau_2(t)$,and$\tau_3(t)$ denote the total thrust and the three rotational forces produced by the four rotors and $c\epsilon R^+$represents a constant force-moment factor. The rotation from the body frame to inertial frame describes the orientation of the quadrotor.

$$R = \begin{bmatrix} c\theta c\varphi & s\theta s\emptyset c\varphi & s\theta c\emptyset c\varphi + s\emptyset s\varphi \\ c\theta s\varphi & s\theta s\emptyset s\varphi + c\theta c\varphi & s\theta c\emptyset c\varphi - s\theta c\varphi \\ -s\theta & c\theta s\emptyset & c\theta c\emptyset \end{bmatrix}$$

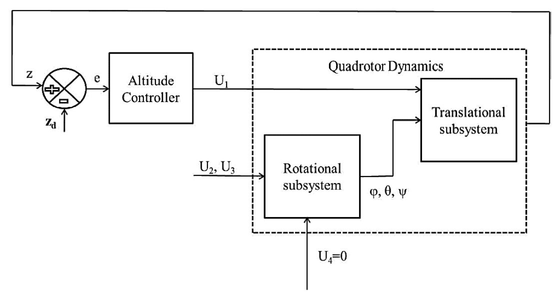


Fig. 3. Structure of Altitude-Attitude Control System

(2)

The rotation matrix is given by R (2),where s and c denote sin and cosine. The control inputs $U_1$, $U_2$, $U_3$, and U4 can be obtained from motor thrusts as

$U_1 = T_1 + T_2 + T_3 + T_4$

$U_2 = -T_1 - T_2 + T_3 + T_4$

$U_3 = -T_1 + T_2 + T_3 - T_4$(3)

$U_4 = -T_1 - T_2 + T_3 - T_4$

## III PROBLEM FORMULATION AND CONTROL DEVELOPMENT

The control development of a Quadrotor is a tad difficult process owing to the highly under actuated nature of the quadcopter meaning that the number of independent control inputs (which is in this case the thrust produced by the four rotors) is lesser than the number of variables that need to be controlled (which in case of a quadrotor are the three translational positions and the three attitude angles). Therefore it is always advisable to formulate a two loop control structure to control the two set of dynamics. Also from analyzing the quadrotor dynamics derived by Newton-Euler

Method we can see that the translational dynamics are dependent on the attitude but the attitude dynamics are completely independent of the translational dynamics. Therefore a good strategy would be to control the position of the quadrotor in the outer loop and generate the desired two attitude values theta ($\theta$) and phi ($\emptyset$) from the control outputs of the position controllers. The heading psi ($\varphi$) is given as the reference. The calculation of desired values of theta ad psi are not discussed in this brief as it is aims to develop only a non- linear controller for the attitude and an altitude controller.

The general structure of the control system is shown in Fig. 3. This section presents the attitude and altitude control for a quadrotor. The altitude control is separated from the attitude control loop and implements different controller as well.

The altitude controller used here is a traditional PID controller which has the general structure as given in (4). The proportional ($K_p$) accounts for the current values of error , the integral ($K_i$) term accounts for the past values of error and derivative term ($K_d$) compensates for future trends in error based on the rate of its change in the present

$$\mu_z = K_{pz}e_z + K_{dz}\dot{e_z} + K_{iz}\int_0^t e_z,\ e_z = z_d - z \quad (4)$$

However for the attitude control loop, a novel nonlinear controller is used which was first proposed in [19]. This nonlinear control methodology, named as RISE (robust integral of the signum of the error) feedback control, has fewer requirements for the dynamic model knowledge and maintains robustness with respect to structural or non-structural uncertainties and non-vanishing external disturbance.The objective is to design a robust controller that guarantee tracking of desired attitude for proper flight control. To formulate this control strategy the attitude errors are first calculated as follows

$$e_{\emptyset 1} = \emptyset_d - \emptyset\ , e_{\theta 1} = \theta_d - \theta\ , e_{\varphi 1} = \varphi_d - \varphi \quad (5)$$

Now we define the auxiliary errors of the above system as follows

$$e_{\emptyset 2} = e_{\emptyset 1} + \alpha_{\emptyset}\dot{e_{\emptyset 1}}$$

$$e_{\theta 2} = e_{\theta 1} + \alpha_{\theta}\dot{e_{\theta 1}} \quad (6)$$

$$e_{\varphi 2} = e_{\varphi 1} + \alpha_{\varphi}\dot{e_{\varphi 1}}$$

where $\alpha_{\emptyset}, \alpha_{\theta}, \alpha_{\varphi}$ are positive constants.Following the similar steps in [24], a continuous RISE feedback control law to attain the mentioned control objective is as follows

$$\mu_{\emptyset} = K_{s\emptyset}e_{\emptyset 2} + \int_0^t (K_{s\emptyset}\alpha_{\emptyset}e_{\emptyset 2} + \beta_{\emptyset} sgn(e_{\emptyset 2}(\tau)))d\tau$$

$$\mu_{\theta} = K_{s\theta}e_{\theta 2} + \int_0^t (K_{s\theta}\alpha_{\theta}e_{\theta 2} + \beta_{\theta} sgn(e_{\theta 2}(\tau)))d\tau$$

$$\mu_{\varphi} = K_{s\varphi}e_{\varphi 2} + \int_0^t (K_{s\varphi}\alpha_{\varphi}e_{\varphi 2} + \beta_{\varphi} sgn(e_{\varphi 2}(\tau)))d$$

DYNAMICS

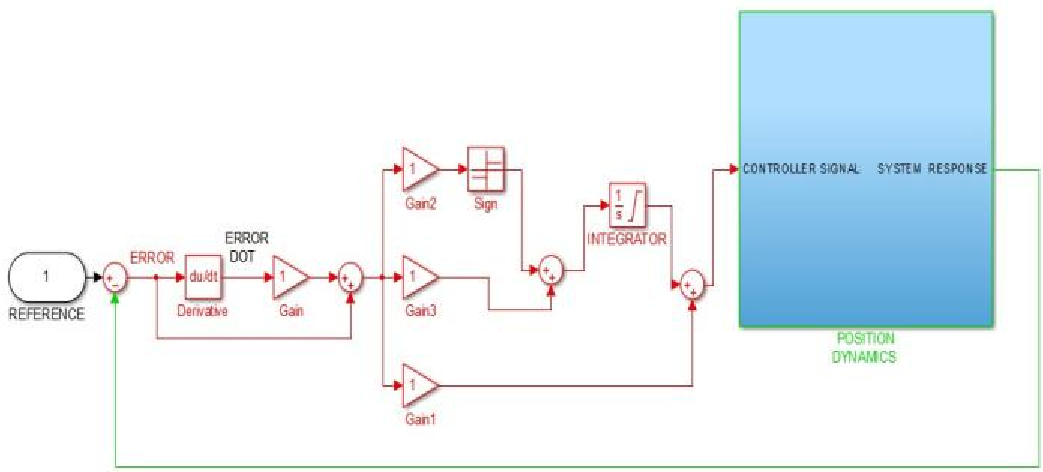


Fig 4. MATLAB Implementation of RISE Controller

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(7)

where $K_{s\theta}$,$K_{s\emptyset}$,$K_{s\varphi}$are positive constants and sgn(.) represents the signum function. The MATLAB implementation of the RISE controller is given in Fig.4. This control technique may also be extended to any other similar system. The stability analysis for the above controller is mentioned in [14]

## IV OBJECT DETECTION AND VISUAL ODOMETRY

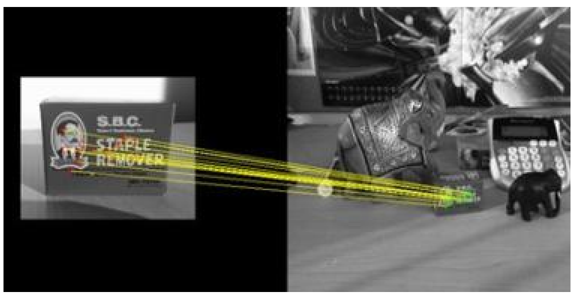


Fig 5. Feature Extraction using RANSAC

Object detection is the process of finding instances of real-world objects such as people, faces, buildings or some other object of importance to the particular application wherein the UAV is being used. It is particularly essential in military and search and rescue missions. Object detection algorithms typically use extracted features and learning algorithms to recognize instances of an object category. Object identification is used in military missions wherein the UAV can be used to track a particular vehicle or object or film a category of building or objects. People detection can especially be useful in search and rescue mission in the aftermath of a disaster where the presence of people can be determined without having to unnecessary risk the life of another human. This section shows light into a few of the applications of object identification methodologies with MATLAB as the experimental platform. [6] proposed a principle in which another NN yield input control law was created for an under incited quad rotor UAV which uses the regular limitations of the under incited framework to create virtual control contributions to ensure the UAV tracks a craved direction. Utilizing the versatile back venturing method, every one of the six DOF are effectively followed utilizing just four control inputs while within the sight of un demonstrated flow and limited unsettling influences.

### A. DETECTION METHODOLOGIES

A few of the object detection methodologies are mentioned below

- Feature-based object detection
- Viola-Jones object detection
- SVM classification with histograms of oriented gradients (HOG) features
- Image segmentation and blob analysis

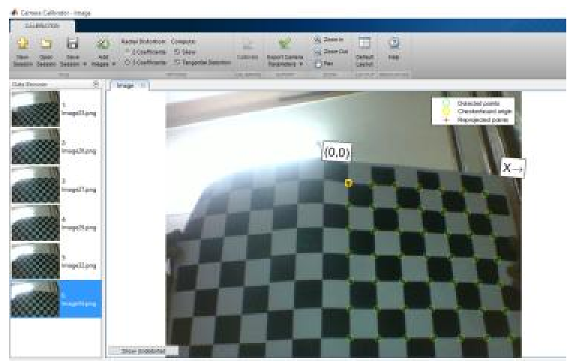


Fig 6. Camera Calibration App(MATLAB)

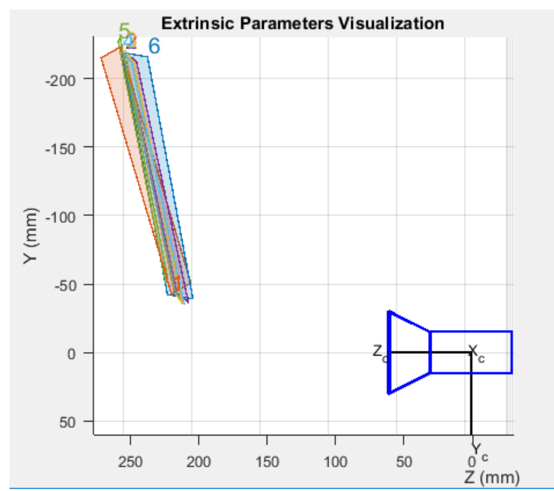


Fig 7. Extrinsic Parameter Visualization


Fig 8. Mean Projection Error

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Feature-based object detection aims at detecting a reference object in a crowded scene using feature extraction and matching using a preloaded reference data bank. RANSAC is used to estimate the location of the object in the crowded scene. Viola-Jones detection is used in Face detection algorithms. Human detection is made possible using pretrained SVM with HOG features. Image segmentation using background subtraction is also an effective method in achieving human tracing and feature identification. Other methods for detecting objects with computer vision include using gradient-based, derivative-based, and template matching approaches.

### B. ODOMETRY

Apart from detection of objects, visual from a camera can also be used to approximate size of objects and distance from the center of the camera to enable obstacle avoidance. The first step in any such case is to calibrate the camera to enable the transformation from pixels to real world units. In this brief the calibration is done using the MATLAB mono camera calibration app in the toolbox list using a pair of custom print checkered board. The real world size of the checkerboard is known which can be used to calculate the size of a pixel on the video feed coming in from the camera. Fig 5 shows the camera calibrator app. Once calibrated the images from the camera can be used to localize the quadrotor or calculate the distance of the quadrotor from the obstacle and keep track of it or avoid collision. The calculation of distance from an obstacle is shown in Fig 9.

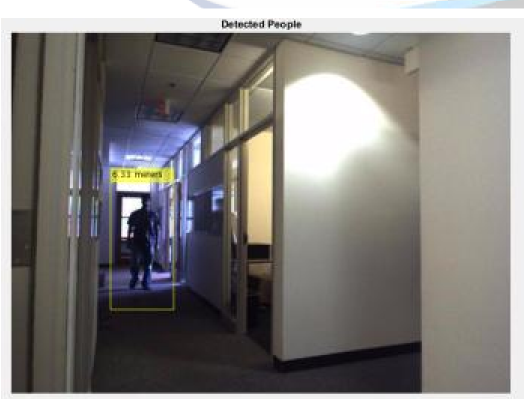


Fig 9. Distance Measurement Using Camera

## V SIMULINK VALIDATION

The attitude and altitude controllers were implemented in MATLAB Simulink platform to verify the effectiveness of the same. The Quadrotor dynamics were first simulated in open loop to verify the performance. The quadrotor parameters were adopted from [16]. The rotors speed required for the quadrotor to hover was calculated using thefollowing equation

$$mg = 4F_i = 4K_f\omega^2 \quad (7)$$

Where $K_f$ is the motor constant and $\omega$ is the propeller velocity. The input to the quadrotor dynamics is steadily increased in parts to check whether the increase in applied thrust only causes variation to the altitude. If so the system modelling is satisfactory. The other dynamics can be checked by providing respective inputs to the various channels to verify the model accuracy. Then an altitude controller is introduced followed by an attitude controller as the resulting structure is as in Fig 3.

In order to analyze the tracking capability of the system a reference signal is designed which zero value at the start of simulation and followed by both positive and negative peaks and the system is made to follow the trajectory using the controllers. The reference are given individually for each of the controllers. It should be noted that yaw angle should be preferably kept as low as possible if not zero. Therefore simulations are also done with yaw reference as zero which is shown in Fig 14. The control output of altitude is given to the attitude loop for the desired value of thrust in the system dynamic equations as given is (1)

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The above results from Simulink Implementation shows that the suggested controller is capable of accurately tracking the attitude angles of the quadrotor to the best possible extend. The pitch, roll and yaw dynamics were subjected to varying trajectories to studythe tracking capability of the controller. The pitch and roll response are … owing to the almost equal dynamics due to the symmetry of the system. Pitch response is characterized by a rise time of 1.2 seconds with a constant steady state error of 12 percent. The roll response is much faster with a rise time of about 0.3 seconds and steady state error less than 1 percent. The yaw moment maintains a constant error

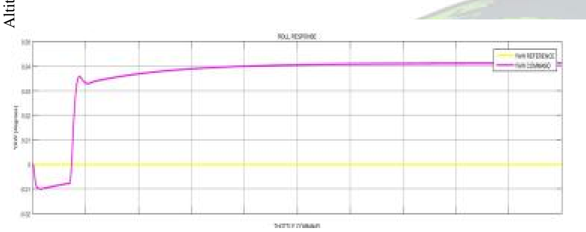

Fig 14. Yaw being tracked to zero

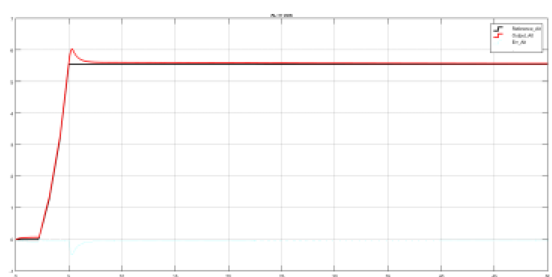

Fig 15. Altitude Tracking

which is owing to the inherent non linearity of the system. The response of the yaw dynamics to zero tracking gives you a clearer pictureof the above mentioned case in Fig 14. In order to check the ability of the PID controller to achieve a required height it's a subject to step input which forces the quadrotor from an initial height of zero meters from the ground to about 5.5 meters above the ground. Fig 15 gives the response characteristics of the altitude controller and as seen has very fast tracking abilities. It has a rise time of about 0.4 seconds and overshoots to about 9 percent more than the required value before settling to the desired altitude in less than 0.3 seconds after overshoot and with almost zero steady state error.

Thus the proposed control structure with nonlinear RISE controller for the attitude control and PID controller for the altitude is capable of providing better

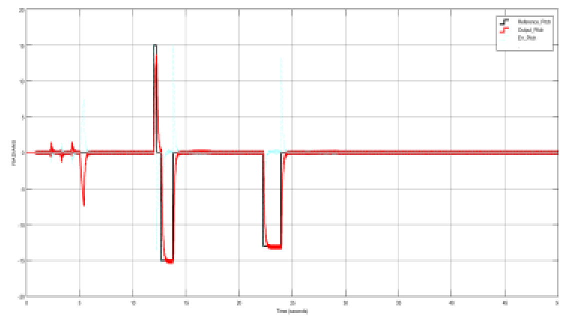

Fig 11. Pitch Response to Varying trajectory

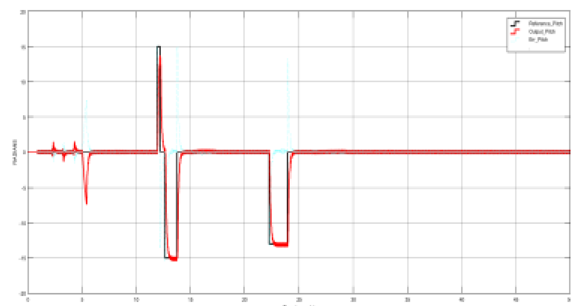

Fig 12. Roll Response to Varying trajectory

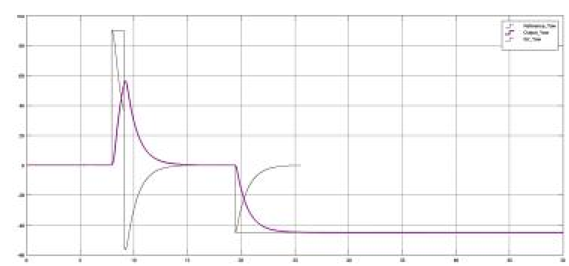

Fig 13. Yaw Response to Varying trajectory

tracking performance. The response characteristic of RISE has been compared with PID response characteristic from the reference and is found to have better tracking capabilities and disturbance tolerance.

## VI CONCLUSION

This brief aimed to point out the importance of non-linear controllers in designing tracking algorithms for under actuated nonlinear systems. The system considered was a highly under actuated Quadrotor system and it was modelled using Newton- Euler equations. A fairly novel controller named RISE was studied and formulated for the attitude control of the quadrotor and a traditional PID controller was implemented for the altitude control. The modelling and controllers were implemented in MATLAB/Simulink and results analysed.It has been found that the nonlinear controller has very good tracking capabilities and is less susceptible to disturbances. The PID controller was also sufficient to track the system to the desired altitude. A little light has also been shed on object detection and mono visual odometer using the help of MATLAB/Simulink toolboxes and exposes the method as the solution to many military and civilian exercises and thereby emphasizes the need for research in the area. Further advancements to the work may include a complete tracking control of the quadrotor using a nonlinear two loop structure and use of visual odometry and object detection for complete autonomous flight of the Quadrotor.

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