

INTERFACING SIMULINK/MATLAB WITH V-REP FOR ANALYSIS AND
CONTROL SYNTHESIS OF A QUADROTOR

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ABSTRACT

INTERFACING SIMULINK/MATLAB WITH V-REP FOR ANALYSIS AND CONTROL SYNTHESIS OF A QUADROTOR

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The primary factor that restricts the new control systems developments for air vehicles and the implementation of various sensors for advanced algorithms is the deficiency of quick and cost-effective physical environment. Flight tests are costly and requires a long preparation process. The aim of this thesis is to improve the simulator infrastructure which easily implementable to the AscTec Hummingbird Quadrotor that is located in the University's lab and have interaction with the 3D physical environment. Firstly, quadrotor's mathematical model has been developed and this model is implemented on Matlab/Simulink environment. Afterwards, a basic PID controller is developed for attitude control. The quadrotor's physical model, the electric motor, the rotor and the IMU model have been modelled on Virtual Robotics Experimentation Platform (V-REP). Matlab / Simulink controller is synchronized with the V-REP and is used for the quadrotor's physical environment tests. The verification of the simulation is done by real experimental flight data of AscTec Hummingbird. The collision avoidance and wall following algorithms in empty room using ultrasonic distance sensors are implemented to show the usefulness of simulator infrastructure.

Keywords: Quadrotor, PID Controller, Simulink/Matlab, V-REP, Dynamic model, System verification, Ultrasonic distance sensors, Collision avoidance, Wall following

ÖZ

DÖRT ROTORLU HAVA ARACI ANALİZİ VE KONTROLCÜ SENTEZİ İÇİN SIMULINK/MATLAB VE V-REP ENTEGRASYONU

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Yüksek Lisans, Havacılık ve Uzay Mühendisliği Bölümü

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Hava araçlarındaki yeni kontrol sistemi denemeleri ve yeni sensör implementasyonunu kısıtlayan başlıca etken fiziksel olarak hızlı ve ucuz test yapamama durumudur. Uçuş testleri maliyetli ve uzun hazırlanma süreci istemektedir. Bu tez çalışmasındaki amaç üniversite labında bulunan AscTec Hummingbird dört rotorlu hava aracı için kolay uygulanabilen ve 3D fiziksel ortamla etkileşimde olan bir simülatör altyapısı geliştirmektir. İlk olarak dört rotorlu hava aracının matematik modelini çıkarılmış ve Matlab/Simulink ortamında simüle edilmiştir. Matematik model implemente edildikten sonra basit bir PID kontrolcü geliştirilmiştir. Dört rotorlu hava aracı fiziksel modeli, elektrik motor ve pervane ve IMU modeli Virtual Robotics Experimentation Platform (V-REP) 'de modellenmiştir. Matlab/Simulink kontrolcüsü V-REP ile senkronize edilmiş ve quadrotorun fiziksel ortam testleri için kullanılmıştır. Simülasyon sağlaması quadrotorun yazılımı kullanılarak yapılan deney verileri ile sağlanmıştır. Simülatör altyapısının uygulanabilirliğini göstermek amaçlı ultrasonik mesafe sensörleri kullanılarak engel sakınma ve boş odada duvar takibi çalışmaları yapılmıştır.

Anahtar Kelimeler: Dört rotorlu hava aracı, PID kontrolcü, Simulink/Matlab, V-REP, Dinamik model, Simülasyon sağlaması, Ultrasonik mesafe sensörü, Engel sakınma, Duvar takibi

to my parents...

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TABLE OF CONTENTS

ABSTRACT	v
ÖZ	vii
ACKNOWLEDGMENTS	x
TABLE OF CONTENTS	xi
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
NOMENCLATURE.....	xviii
CHAPTERS	
1. INTRODUCTION	1
1.1 Background Information	1
1.2 Present Approach.....	1
1.3 Major Objectives	9
1.4 Literature Survey	9
1.5 Outline of the Thesis	15
2. QUADROTOR SETUP	17
2.1 Quadrotor Properties	17
2.2 AscTec Simulink Toolkit Overview and Connections.....	19
3. MATHEMATICAL MODEL AND CONTROLLER DESIGN	23
3.1 Mathematical Model of Quadrotor	23
3.2 PID Controller Design.....	27
4. V-REP MODEL AND MATLAB/SIMULINK INTERFACING	31
4.1 Virtual Robot Experimentation Platform (V-REP)	31
4.2 Propeller Model in V-REP	36
4.3 Quadrotor Model in V-REP.....	37
4.4 Simulink/Matlab and V-REP Interfacing	39

5.	SIMULATION RESULTS.....	41
5.1	Simulation Results of Simulink/Matlab and V-REP Integration.....	41
5.2	Experimental Setup for Quadrotor Flight Test	47
5.3	Controller Design and Implementation on Real Quadrotor.....	51
5.4	Experimental Data and Case Comparison with Simulation Data.....	53
5.5	Collision Avoidance and Wall Following	59
6.	CONCLUSION AND FUTURE WORK.....	75
	REFERENCES.....	77

LIST OF TABLES

TABLES

Table 2.1. AscTec Hummingbird Properties [19].....	18
Table 5.1. Tuned PID gains.....	41

LIST OF FIGURES

FIGURES

Figure 1.1.STARMAC II [2].....	3
Figure 1.2.MARK II X4 Flyer [3].....	4
Figure 1.3.ETH Zurich research quadrotor [4].	4
Figure 1.4.Micro quadrotor in University of Pennsylvania Grasp Lab [5].	5
Figure 1.5.Variable pitch quadrotor in MIT [6].	6
Figure 1.6. Some popular commercial quadrotors in market	8
Figure 1.7. Flight test area built for AscTec Hummingbird experiments [13].....	11
Figure 1.8. Motor response to oscillating roll stick input [13].....	11
Figure 1.9. Motor response to oscillating pitch stick input [13].	12
Figure 1.10. Handlebar position ad vehicle linear speed response on real vehicle and V-REP simulation [14].....	13
Figure 1.11. The control and communication scheme of PyQuadSim [16].....	13
Figure 1.12. The V-REP, ROS and Simulink software flow diagram [17].....	14
Figure 1.13. Response of three axis fuzzy logic controller working together to step input in simulation [18].	15
Figure 1.14. Response of three axis fuzzy logic controller against disturbances in real [18].	15
Figure 2.1. AscTec Hummingbird quadrotor [13].	18
Figure 2.2. AscTec Autopilot general scheme [20]	19
Figure 2.3. The <i>onboard_matlab.mdl</i> Simulink model scheme	20
Figure 2.4. <i>UART_Communication.mdl</i> Simulink model scheme	21
Figure 3.1.Free body diagram of quadrotor [21].....	23
Figure 3.2.Yaw PID controller scheme	28
Figure 3.3.Roll PID controller scheme.....	28
Figure 3.4.Pitch PID Controller scheme	29
Figure 3.5.Altitude PID controller	29
Figure 4.1.The built-in V-REP robot models	33
Figure 4.2.The remote API communication modes: (a) blocking function call, (b) non-blocking function call [22].	35

Figure 4.3.(a) Thrust change w.r.t. the angular velocity of the rotor using BET in hovering flight, (b) Rotor torque change w.r.t. the angular velocity of the rotor using BET in hovering flight [27].....	36
Figure 4.4.Propeller model in V-REP	37
Figure 4.5.General AscTec Hummingbird quadrotor view in V-REP.....	38
Figure 4.6.General simulator operation diagram	40
Figure 5.1.Motor throttle command (%) and rotation speed (rpm) during hover flight simulation.....	42
Figure 5.2.Roll, pitch and yaw angles of quadrotor during hover flight simulation. The 10 degrees roll doublet input is shown in dashed lines.....	42
Figure 5.3.Roll, pitch and yaw angular rates change during hover flight simulation.....	43
Figure 5.4.The u, v and w velocities during hover flight simulation.	43
Figure 5.5. The x, y and z positions of the quadrotor during hover flight simulation. The z command is shown in dashed lines.	44
Figure 5.6.Motor throttle command (%) and rotation speed (rpm) during hover flight simulation with ground disturbance take-off.	44
Figure 5.7.Roll, pitch and yaw angles of quadrotor during hover flight simulation with ground disturbance take-off. The 10 degrees roll doublet input is shown in dashed lines.	45
Figure 5.8.Roll, pitch and yaw angular rates change during hover flight simulation with ground disturbance take off.....	45
Figure 5.9.The u, v and w velocities during hover flight simulation with ground disturbance take-off.....	46
Figure 5.10.x, y and z positions of the quadrotor during hover flight simulation with ground disturbance take-off. The z command is shown in dashed lines.....	46
Figure 5.11. The assembly view of experimental setup allowing movement in translation axes.....	47
Figure 5.12. Quadrotor mounted to the rod eye bearing which allows limited roll and pitch motion and full yaw rotation.....	48
Figure 5.13. The view of motion of quadrotor in flight tests	49
Figure 5.14. The assembly view of experimental setup with no movement in translation axes.....	50
Figure 5.15. The directional movement fixed type experimental setup.....	50
Figure 5.16. The Simulink model inside <i>Onboard_Matlab_Controller</i> subsystem. .	51
Figure 5.17. The Simulink model inside <i>Attitude Control</i> subsystem.	51
Figure 5.18. The Simulink Model inside <i>Rate Loop</i> subsystem.	52
Figure 5.19. The Simulink Model inside <i>Attitude Loop</i> subsystem.....	53

Figure 5.20. The roll angle (deg) response to roll stick input in directional motion free test setup.	54
Figure 5.21. The roll rate (deg/s) response to roll stick input in directional motion free test setup.	55
Figure 5.22. The pitch angle (deg) response to pitch stick input in directional motion free test setup.	55
Figure 5.23. The pitch rate (deg/s) response to roll stick input in directional motion free test setup.	56
Figure 5.24. The roll angle (deg) response to roll stick input in directional motion fixed test setup.	57
Figure 5.25. The roll rate (deg/s) response to roll stick input in directional motion fixed test setup.	57
Figure 5.26. The pitch angle (deg) response to pitch stick input in directional motion fixed test setup.	58
Figure 5.27. The pitch rate (deg/s) response to roll stick input in directional motion fixed test setup.	58
Figure 5.28. Maxbotix XL-MaxSonar-AE0 MB1300 [30].	59
Figure 5.29. Ultrasonic sensor orientation on quadrotor in V-REP	60
Figure 5.30. Roll, pitch and yaw angles of quadrotor during free flight and obstacle detection.	61
Figure 5.31. Motor throttle command (%) and rotation speed (rpm) during free flight and obstacle detection.	61
Figure 5.32. The u, v and w velocities during free flight and obstacle detection.	62
Figure 5.33. The x, y and z positions of the quadrotor during free flight and obstacle detection.	62
Figure 5.34. Roll, pitch and yaw angular rates change during free flight and obstacle detection.	63
Figure 5.35. The 10 m to 10 m room in V-REP	63
Figure 5.36. The general scheme of wall following mode with varying travel speed	64
Figure 5.37. The controller inside <i>State 1</i>	65
Figure 5.38. The controller inside <i>State 2</i>	65
Figure 5.39. 3D trajectory of wall following quadrotor in 10 m to 10 m room with varying travel speed.	66
Figure 5.40. 2D trajectory of wall following quadrotor in 10 m to 10 m room with varying travel speed.	66
Figure 5.41. Roll, pitch and yaw angles of wall following quadrotor in 10 m to 10 m room with varying travel speed.	67

Figure 5.42. Roll, pitch and yaw angular rates change of wall following quadrotor in 10 m to 10 m room with varying travel speed.	67
Figure 5.43. The u, v and w velocities of wall following quadrotor in 10 m to 10 m room with varying travel speed.	68
Figure 5.44. The x, y and z positions of wall following quadrotor in 10 m to 10 m room with varying travel speed.	68
Figure 5.45. Motor throttle command (%) and rotation speed (rpm) of wall following quadrotor in 10 m to 10 m room with varying travel speed.	69
Figure 5.46. The general scheme of wall following mode with constant distance to the wall.	70
Figure 5.47. The PD controller scheme inside <i>Velocity Controller</i>	70
Figure 5.48. 3D trajectory of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	71
Figure 5.49. 2D trajectory of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	71
Figure 5.50. Roll, pitch and yaw angles of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	72
Figure 5.51. Roll, pitch and yaw angular rates change of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	72
Figure 5.52. The u, v and w velocities of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	73
Figure 5.53. The x, y and z positions of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	73
Figure 5.54. Motor throttle command (%) and rotation speed (rpm) of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.	74

NOMENCLATURE

Latin Symbol	Description	Units
C_Q	Torque constant	Nm/rpm ²
C_T	Thrust constant	N/rpm ²
d	Distance between motor axes	M
$F_{g,i}$	Gravitational force in inertial frame	N
$F_{r,b}$	Force generated by rotors in body frame	N
$F_{d,b}$	Disturbance force in body frame	N
G	Gravity offset	-
I_B	Moment of inertia matrix of body	kg.m ²
I_m	Moment of inertia of motors	kg.m ²
$M_{gyro,b}$	Gyroscopic moment on body frame	Nm
$M_{r,b}$	Moment generated by rotors	Nm
K_p	P-Constant	-
K_i	Reduced frequency	-
K_d	Wing span	-
p	Roll change rate	rad/s
q	Pitch change rate	rad/s
Q	Torque generated by rotor	Nm
r	Yaw change rate	ad/s
R_{ib}	Transformation matrix	-
t	Time variable	s
T	Thrust force	N
U	Controller input	-
u	X axis velocity	m/s
v	Y axis velocity	m/s
w	Z axis velocity	m/s

x	X axis position	m
y	Y axis position	m
z	Z axis position	m

Greek Symbol	Description	Units
θ	Pitch angle	deg
$\dot{\theta}$	Pitch rate	deg/s
φ	Roll angle	deg
$\dot{\varphi}$	Roll rate	deg/s
ψ	Yaw angle	deg
$\dot{\psi}$	Dynamic viscosity of the fluid	deg/s
ω	Rotational speed	RPM

Abbreviations

2-D	Two-Dimensional
3-D	Three-Dimensional
IMU	Inertial Measurement Unit
PID	Proportional Integral Derivative Control

CHAPTER 1

INTRODUCTION

1.1 Background Information

The quadrotor is a Vertical Takeoff and Landing (VTOL) rotorcraft which is propelled by four fixed pitch rotor. Because of mechanical simplicity and high mobility, research related to the quadrotor topic are widespread. The use of area of quadrotors include military applications such as border patrolling, cartography, cost guards and also civilian applications such as mapping, search and rescue missions, agricultural applications, power and nuclear plants inspection etc.

1.2 Present Approach

In recent years, there are a wide range of academic studies related to quadrotor and quadrotor testbed were done.

One of the first successful quadrotor research platforms is the Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control (STARMAC) [1]. There are eight quadrotors currently and the platform is a multi-vehicle test setup to develop and implement new designs in multi agent control in real world platform. During the project, two models of quadrotor have been developed namely STARMAC I and STARMAC II.

STARMAC I have a total of 1 kg of thrust and can fly in hover with full throttle about ten minutes. As IMU, the Microstrain 3DM-G motion sensor was used, including accelerometer, 3-axis gyroscope and magnetometer. The Trimble Lassen Low Power GPS module is used for velocity and position measurement [1]. For the additional measurement of altitude SODAR the Devantech SRFO8 was used. The onboard sensing and calculations were done in two C programmed Microchip microcontrollers. The position estimation was done using Extended Kalman Filter (EKF) by combining GPS and IMU data. The rate of pose estimation is 10 Hz. Attitude control performed on board is 50 Hz and the communication with ground station was done via a Bluetooth Class II device over 150 ft. Ground station software was developed in LabView environment and manual and waypoint track control was done from this software using laptop. Linear Quadratic Regulator (LQR) technique was used to design attitude loop control. Also advanced controllers were implemented on STARMAC I such as sliding mode and reinforcement learning.

On STARMAC II several improvements have been made (Figure 1.1) [2]. The total of thrust capability has been increased up to 4 kg. The onboard controller has been divided on two parts. The low level controller was implemented on the Atmega128 microprocessor based board, which controls real-time execution loop and sends commands to motors. The high level controller and estimation implemented on embedded Linux based Crossbow Stargate 1.0 single board computer (SBC). This SBC controller can be replaced by Kubuntu Linux running ADL855 PC104, but due to the weight it will decrease flight time. The communication with ground station was replaced with WiFi network instead of Bluetooth communication. Novatel Superstar II GPS unit with position accuracy 1-2 cm was used for position and velocity measurement. Also in this platform, for replacing GPS in indoor flights USB camera was used. Blob tracking software was implemented with 1-2 cm position estimation accuracy at a rate of 10 Hz. For attitude, altitude and position control Proportional Integral Derivative (PID) was implemented.



Figure 1.1.STARMAC II [2].

Other successful custom-built quadrotor platform is MARK II X4 Flyer (Figure 1.2) which was developed in the Australia National University (ANU) [3]. The innovative parts of this quadrotor were using blade flapping and using inverted teetering rotors. The Mark II X4 Flyer weights 2 kg with a length of 70 cm and 11 inch diameter rotors. The X4 Flyer is larger construction and compromised from chassis, motors and power cells, and attitude control and communications avionics. The chassis of quadrotor was constructed from aluminum center frame with carbon fiber-foam sandwich arms mounted. The rotor mounts are teetering hubs which machined from aluminum. The rotors are capable of lifting beyond 30% of control margin. The design and manufacturing of rotors were made in ANU. Jeti Phasor 30-3 brushless motors were used to drive rotors. Custom motor controllers were developed by the CSIRO Queensland Centre for Advanced Technology ICT group. The Toshiba TB9060 brushless motor speed control chip and the Freescale HDC12D60A microprocessor were used in motor controller board development. The attitude readings were made using a CSIRO Eimu IMU which provides angular rate and acceleration measurements and angular position estimates at 50 Hz. The Eimu is a 6-axis IMU with magnetometer. The attitude control was implemented on onboard HC12 controller. The controller that implemented on X4 Flyer is a simple PID controller.



Figure 1.2.MARK II X4 Flyer [3].

In ETH Zurich, the main focus of studies are related to indoor flight tests. The Flying Machine Arena (FMA) is a portable platform that devoted to autonomous flight [4]. The platform with dimensions 10x10x10 meters, compromised of high motion capture system, a wireless network, and a strong software base that executes advanced algorithms for position estimation and controller implementation. The rate of motion capture system exceeds 200 frames per second for detecting multiple objects in space that move with 10 m/s speed. The system uses this data to execute advanced estimation and control algorithm and send commands via wireless links to the quadrotor. The quadrotor used in these studies is the hybrid one. As a frame of quadrotor AIRobots Quadrotor frame due to the modularity and low cost is selected (Figure 1.3). The onboard attitude controller is the controller of AscTec Hummingbird which is the product of Ascending Technologies. Advanced Iterative Learning Control study was made using the FMA.



Figure 1.3.ETH Zurich research quadrotor [4].

The study related to the swarm of an agile micro quadrotors was done in University of Pennsylvania Grasp Lab (Figure 1.4) [5]. The size of quadrotor from rotor tip to rotor tip is 21 cm and rotor diameter is 8 cm. The weight of micro quadrotor without battery is 50 grams and can flight around 11 minutes with 2-cell 400mAh 23 grams Lipo battery. For onboard attitude sensing there are a 3-axis accelerometer, a 2-axis 2000 deg/s rate gyroscope for roll and pitch axes, a 1-axis 500 deg/s rate gyro for yaw axis, and a 3-axis magnetometer. The onboard attitude sensing and control is done on 72 MHz ARM Cortex-M3 microprocessor. The communication is provided via Zigbee transreceivers. To sense the position of each quadrotor the Vicon motion capture system is used which sense at a rate of 100 Hz. This data is sent via ethernet network to the base station and high level control is done in Matlab on the high power base station. The quadrotor is very agile due to small inertias and reaches maximum angular velocity of 1850 deg/s. The number of twenty quadrotors were used in this study and advanced swarm tracking algorithms were implemented.

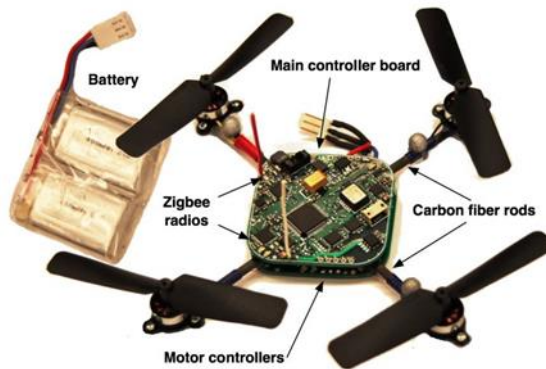


Figure 1.4. Micro quadrotor in University of Pennsylvania Grasp Lab [5].

One of the different type of project is realized in Massachusetts of Institute (MIT) by Cuttler (Figure 1.5) [6]. In study the addition of variable pitch propeller to a quadrotor and its benefits over fixed pitch propeller were analyzed. The variable pitch propeller system widens the control bandwidth which is restricted only to variable-pitch actuation speed. Also efficient reverse thrust is achievable with variable pitch propeller. On the other hand it is mechanically is challenging due to addition variable pitch actuation mechanism. Onboard attitude sensing and control is done by custom

MIT built controller board. Vicon motion capture system is used for external position and velocity estimation. A nonlinear quaternion-based controller is implemented on quadrotor. The control law and trajectory generation algorithms are developed.



Figure 1.5. Variable pitch quadrotor in MIT [6].

There are also commercially available quadrotors in market which generally related to high performance aerial media recording purpose. One of them is the PHANTOM 4 which is the product of DJI Company [7]. It has manual control flight and position hold flight modes. Its diagonal size excluding propellers is 350 mm and weight including battery and propellers is 1380 g. The product includes intelligent flight battery with 4-cell LiPo which is 5350 mAh 15.2 volts and the device has low voltage protector. With this battery configuration the maximum time that quadrotor can flight is approximately 28 minutes. There is also three axis camera stabilization gimbal for camera recording. The PHANTOM 4 can be controlled and take vision via Android and iOS devices.

Another market popular quadcopter is Draganflyer X4-P product [8]. This device is also developed for media recording missions but also can be used for public safety, industrial inspection and education purposes. The width and length of vehicle is 870 mm and height is 300 mm but it can pack up small and quickly assembled again. The weight of quadrotor is 1670 g with battery. The frame of quadrotor is patent folding mostly carbon fiber built design and has excessive weight to strength ratio. It has both

hardware and software custom developed autopilot unit featured eleven on-board sensors and which data can be controlled and viewed real time via monitoring unit. There is also on-board data logging option with removable micro-SD memory card. The vehicle has ability to auto-land at that position in the case of low battery or lost communication link condition.

The Microdrones MD4-200 is one of the high performance quadrotors in drone market [9]. It has wide range application area such as search and rescue, industrial inspections, security, surveillance, science and research, aerial media recording, mapping and unmanned cargo system. MD4-200 frame is carbon fiber built and from rotor hub to rotor hub dimension is 540 mm with 800 g weight. The propellers of vehicle are CFD optimized and maximum thrust is 15.5 N. The payload that quadrotor can carry is approximately 250 g. The approximate flight time depending on load, battery and wind condition is 30 minutes. The standard battery package used in quadrotor is 14.8 V 2300 mAh 4-cell LiPo battery. The MD4-200 has manual control flight mode and automatic mode which uses custom developed GPS Waypoint navigation software.

Another high performance media recording quadrotor is AR.Drone2.0 [10]. Its frame is carbon fiber tube build and weight is approximately 420 g. The onboard autopilot is custom design including Linux built 1 GHz 32 bit ARM Cortex processor with 800 MHz video DSP, 1 GB DDR2 200MHz RAM, 3 axis gyroscope, 3 axis accelerometer, 3 axis magnetometer, pressure sensor and ultrasound sensors. The AR.Drone2.0 can be controlled remotely and take shoots from Android and iOS devices. There is also director mode in which automatic movements can be programmed and great shootings is available.

The AscTec Hummingbird is one of the popular quadrotors and main object is to provide physical platform for research projects. In this thesis study the AscTec Hummingbird will be used and detailed information is given in Chapter 2.



(a) PHANTOM 4 [7]



(b) Draganflyer X4-P [8]



(c) Microdrones MD4-200 [9]



(d) AR.Drone2.0 [10]

Figure 1.6. Some popular commercial quadrotors in market

1.3 Major Objectives

The design and implementation of control algorithms is not fast implantable always due to lack of physical test flights. The quadrotors are agile air vehicles and it is not always safe and cost effective to try new controller designs. Also for indoor flights and mapping algorithm designs, wide variety of 2D and 3D laser scanner, vision sensors are needed. Another challenge, to design swarm algorithms with some number of quadrotors or quadrotors with other robotic vehicles, is not always possible. Especially, the cost and not enough know-how restricts the development of new controller and algorithms. In our study goal is to design Simulink/Matlab model and controller for simulation. To test model and implement controller algorithms and observe 3-D physical interaction Simulink/Matlab is interfaced with V-REP directly. The physical model of the quadrotor and motor propeller combination is modeled in V-REP and accelerometer, gyroscope and GPS unit will be added to the model. The developed quadrotor model is tested experimentally and validation of the simulation is done. After this interfacing and experimental flights we will get simulation infrastructure where unlimited number of test flights, trial of new approaches and development of new algorithms can be possible for future works. Ability adding environment such as office furniture, building rooms or labyrinths give chance trying collision avoidance algorithms and path planning algorithms on quadrotor model. This ability also decreases the time to make the environment safe especially in indoor applications. Also the wide range sensor and environment objects of V-REP will not restrict us try sensors, developing swarm algorithms, get know how and confidently plan real applications.

1.4 Literature Survey

A quadrotor system is a simple structure but design and implementation of control algorithms is not always an easy task. Especially flight tests in the early stages of algorithm developments can be dangerous and costly. Besides the lack of technical hardwares such as indoor localization systems (Vicon cameras), 3-D scanner and

visual sensors etc. are reducing development ability. Another challenge the studies related to swarm flight algorithms requires number of quadrotors and technological infrastructure. Also especially in indoor applications the safety of environment is important and pillow, netting etc. safety precautions is needed in real flights. To avoid these types of problems simulator platform tests and implementations have been spread. Most of these simulator studies are generally developed in Matlab/Simulink platform. In his thesis Martinez modelled the quadrotor in Matlab/Simulink platform and his model based around Draganfly XPro quadrotor [11]. The model included detailed DC motor model and rotor model based on Blade Element Theory verified by wind tunnel experiments, equation of motions of quadrotor based on Newton-Euler formulation, horizontal and vertical gusts, and possible asymmetries due to motor property or rotor weight. The model simulations ran in variable-step solvers. In this thesis, the scope of the work is done according to the open loop flight dynamics of the quadrotor and no controller was implemented. The non-linear model of quadrotor was derived using classical mechanics and multiple control techniques such as PID, LQ and robust control techniques H_∞ and μ with DK-iteration were employed in Matlab/Simulink in Marcelo's thesis study [12]. The quadrotor parameters like inertia, aerodynamic drag coefficient and thrust coefficient were validated experimentally. Karwoski developed a model in Simulink based on AscTec Hummingbird quadrotor for design and analysis of variable control systems [13]. In his work, he built experimental safe area for the flight tests of quadrotor as shown in Figure 1.7.



(a) Flying area with pillows and net (b) Quadrotor after hitting net

Figure 1.7. Flight test area built for AscTec Hummingbird experiments [13].

Then non-linear dynamic model was derived and implemented in Simulink/Matlab platform and PID controller was designed by step-step starting from P-controller, then trying PD, PI and PID controllers in simulation environment. There were made experimental flights that measured quadrotor attitude loop response to remote stick input. Also motor command responses to roll and pitch stick input were also logged and analyzed as shown in Figure 1.8 and Figure 1.9 .

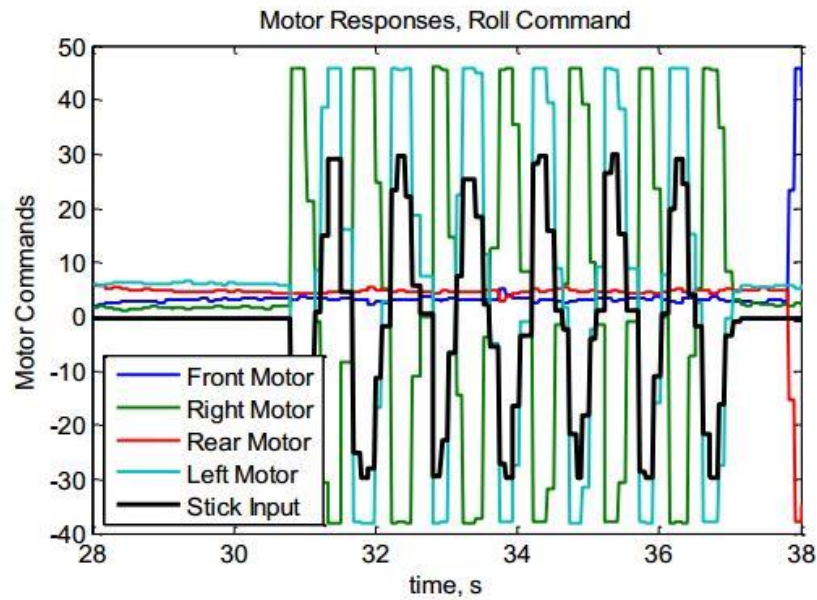


Figure 1.8. Motor response to oscillating roll stick input [13].

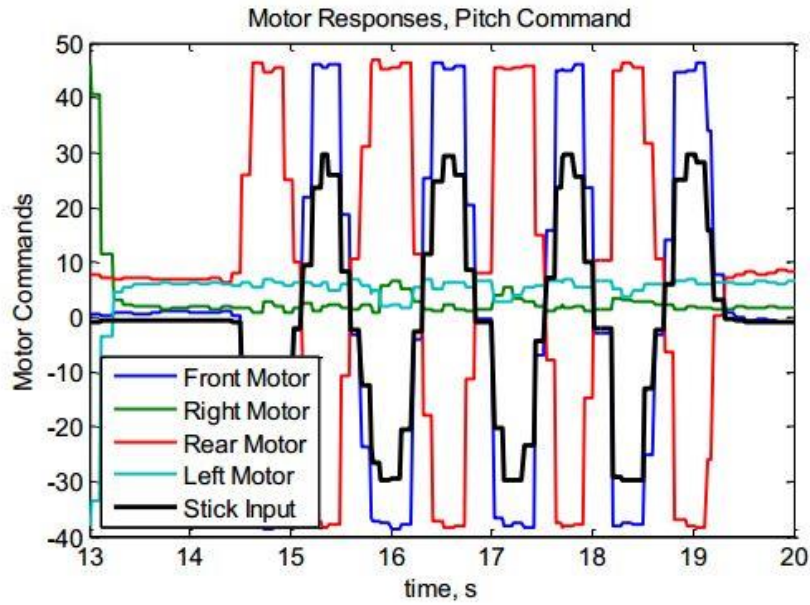


Figure 1.9. Motor response to oscillating pitch stick input [13].

The Matlab/Simulink environment is widespread and easy use for developing, debugging and testing complex control algorithms in a fast prototyping and testing. On the other hand Matlab lacks an easy to use 3D physical simulation engine for robotic applications. In this point Virtual Robot Experimentation Platform (V-REP) is one of the alternatives for 3D modeling and physical environment interaction testing. In Matteucci's study simulation environment was created for an autonomous all-terrain mobile robot in V-REP and validation experiments were presented in which the behavior of the real system was compared with the corresponding simulations [14]. The mobile robot was built on base of Yamaha Grizzly 700 and equipped with sensors like GPS unit, IMU, a stereo camera rig, two laser range-finder, and wheel and handlebar encoder. The physical model and Ackermann steering and suspension of the vehicle were modeled in V-REP. The actuator responses to step input on real and simulated vehicle is shown Figure 1.10 .

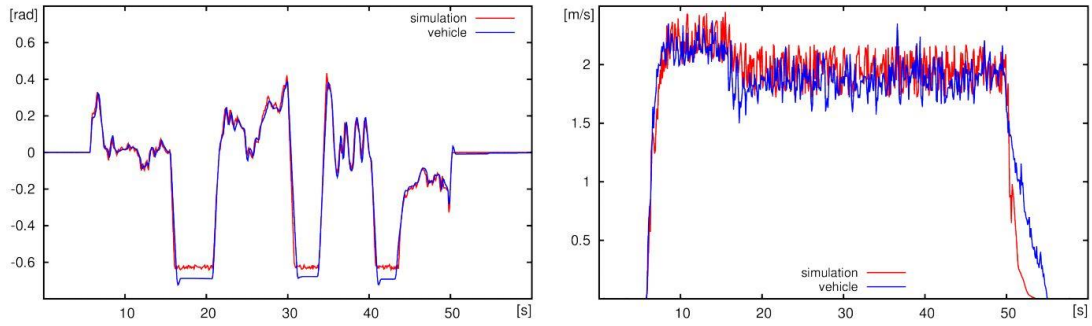


Figure 1.10. Handlebar position ad vehicle linear speed response on real vehicle and V-REP simulation [14].

There are also quadrotor modeling and control algorithm implementation studies in V-REP. One of them is PyQuadSim study in which quadrotor is controlled via joystick or gamepad, and the controller is written in Python and modeling is done in V-REP [15]. In this study default V-REP built quadrotor model is used and V-REP is client which sends the IMU readings and server side written in Python which PID controller implemented calculates thrust values for each rotor according to IMU readings and controller commands and send these data to client side. The scheme of the simulator is shown in Figure 1.11 .

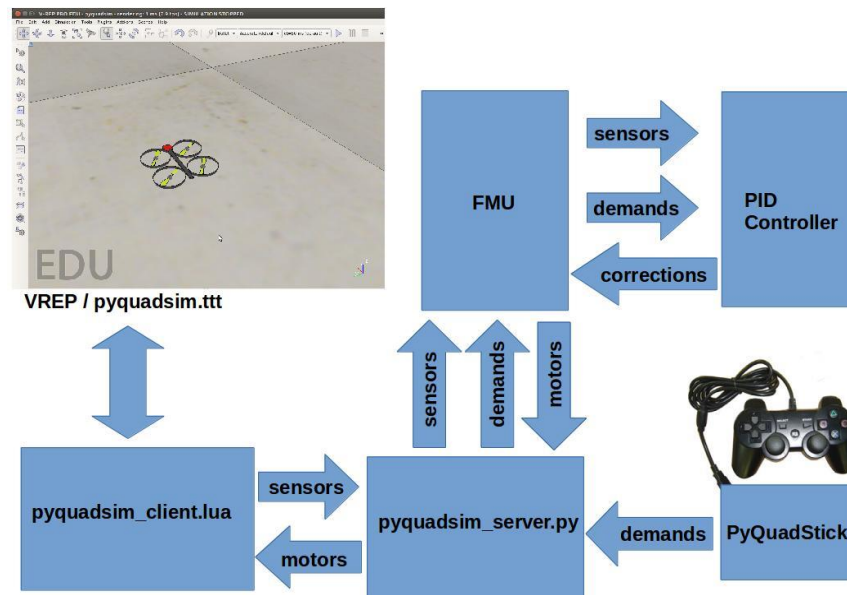


Figure 1.11. The control and communication scheme of PyQuadSim [16].

In Riccardo's study the interface of Matlab/Simulink with V-REP using ROS as communication middleware is done and the default V-REP quadrotor model control is done using visual servoing [17]. In this project the camera and quadrotor module of V-REP is used where images sent from V-REP to ROS node and processed using ViSP library. The tracked location data from ROS node is sent to Simulink and calculated thrust commands for each motor are sent back to V-REP. The software diagram is shown in Figure 1.12.

The configuration of V-REP and ROS to work in parallel, using ROS packages for pose estimation based on vision and for the design and use fuzzy logic control system in quadrotor is done in Mendez's study [18]. The experimental flights were set by a real Ar.Drone parrot power edition quadrotor and the results support virtual flight test data. As a conclusion of study three ROS packages were built which the first one is control part related to fuzzy logic controller, the second one is to process image and extract information from them in real world and simulation, and the third one is to link image process information to the controller in real world and simulation platform. The response of three axis fuzzy logic controllers to step signal input in simulation is shown in Figure 1.13 and the response of three controllers against disturbances in real life is shown in Figure 1.14.

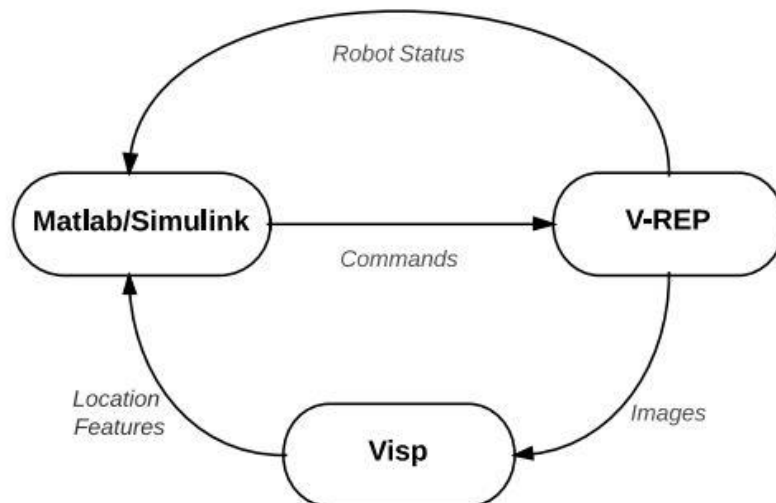


Figure 1.12. The V-REP, ROS and Simulink software flow diagram [17].

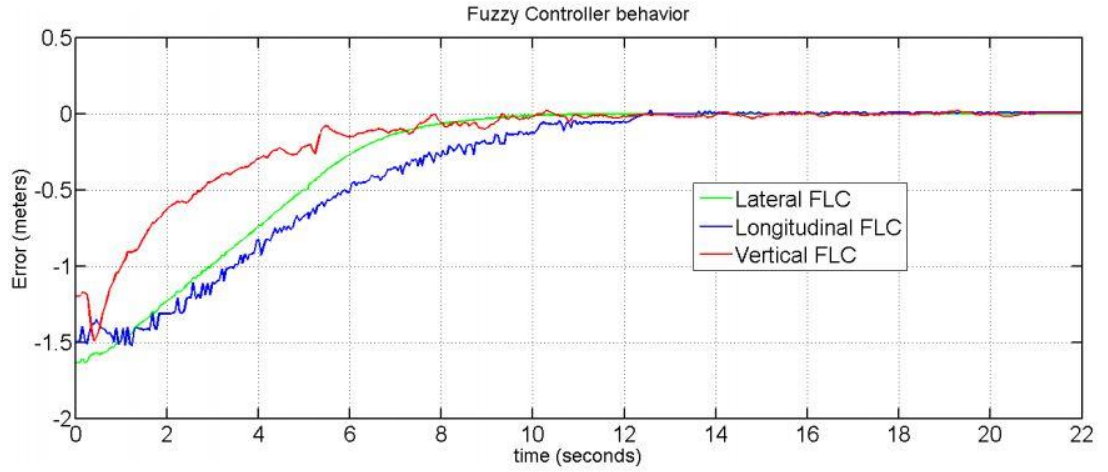


Figure 1.13. Response of three axis fuzzy logic controller working together to step input in simulation [18].

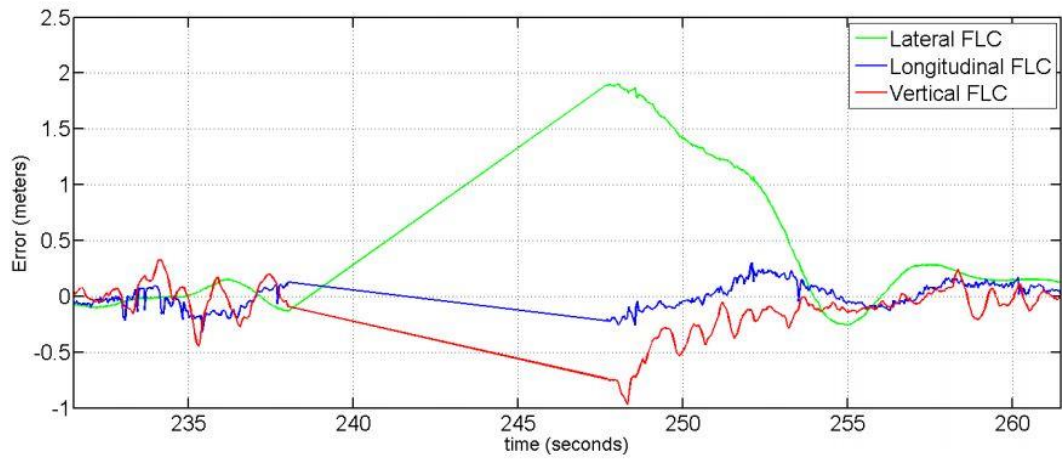


Figure 1.14. Response of three axis fuzzy logic controller against disturbances in real [18].

1.5 Outline of the Thesis

This study is comprised of six chapters to explain the scope of the thesis. In Chapter 1, brief background information is given, and then present approach related quadrotors is described. After mentioning objectives of work, the literature survey related to subject is presented. Chapter 2 describes the hardware and software toolkit properties

of quadrotor that will be used in this thesis. In Chapter 3, the mathematical model of quadrotor is derived and classical PID controller is designed. The first section of Chapter 4 describes the capabilities of V-REP, and then in related sections modeling of propeller and quadrotor in V-REP, Simulink/Matlab interfacing with V-REP are presented. Thereafter, some case simulation results are given in first section of Chapter 5. Then experimental setups and controller implementation on real quadrotor are described in the next sections of Chapter 5. In fourth section of Chapter 5 experimental and simulation data comparison is given. In final part of Chapter 5, the collision avoidance and wall following studies is presented to demonstrate the simulation infrastructure capabilities. Chapter 6 covers the general conclusion and future recommendations for the study.

CHAPTER 2

QUADROTOR SETUP

2.1 Quadrotor Properties

The quadrotor that is used in this study is an AscTec Hummingbird (Figure 2.1) which is equipped with the AscTec Autopilot [19]. The quadrotor, shown in Figure 2.1 is small, lightweight and an ideal platform for testing flights in indoor environments. The main frame of quadrotor is made out of sandwich material consisting of carbon fiber and balsa wood. Due to lightweight and small size control bandwidth does not restrict aggressive maneuvers significantly. The system has a pressure sensor, three axis compass, GPS unit, an acceleration sensor, and three gyroscopes (one for each axis). AscTec Autopilot main board consist of two ARM 7 60MHz, 32 Bit microcontrollers – a low level processor (LLP) and a high level processor (HLP). LLP collects IMU (accelerometer + gyroscopes) data, sends commands to the motor controller and is responsible from attitude control of quadrotor. The HLP controls the GPS and is free for user defined control algorithm designs. The control algorithms can be designed in Simulink/Matlab environment, the control system is then translated to the C code by the Real Time Workshop Embedded coder. The AscTec HL-SDK provides all necessary tools to program custom C code and to flash and debug the code on the processor. The communication of AscTec Hummingbird with ground is provided by a wireless Xbee model via serial port. The technical details of the quadrotor are summarized in Table 2.1.

Table 2.1. AscTec Hummingbird Properties [19].

Model	AscTec Hummingbird
Manufacturer	Ascending Technologies GmbH
Takeoff weight (2100 mAh TP battery)	480 g
Distance between motor axes	34 cm
Flight control and IMU board	AscTec Autopilot
Propeller	8" flexible standard propeller grey
Motors	AscTec X-BL 52s
Motor controller	AscTec X-BLDC
Thrust per Motor (standard propeller)	0,05 – 3,5 N
Radio control system	Futaba Fasst 2,4 GHz
Telemetry System	Xbee 2,4 GHz
Moment of inertia	$I_{xx} = I_{yy} = 5.6 \cdot 10^{-3} \text{ kg} \cdot \text{m}$; $I_{zz} = 8.1 \cdot 10^{-3} \text{ kg} \cdot \text{m}$



Figure 2.1. AscTec Hummingbird quadrotor [13].

The propellers used in quadrotor are fixed pitch propellers, so the control of quadrotor is done by changing the rotation speed of propellers. The front and rear propellers are rotating clockwise and the left and right propellers are rotating counter clockwise. Roll motion is controlled by manipulating the rotation speed of right and left propellers, pitch motion is controlled by varying the rotation speed of front and rear propellers. Yaw motion is controlled by speeding up the propellers rotating in one direction and

slowing down ones spinning in other direction. So the trust does not change, but change of angular momentum causes rotation in yaw axis.

2.2 AscTec Simulink Toolkit Overview and Connections

The AscTec Simulink Toolkit provides you chance to create your own controllers in Simulink and test them directly onboard of the quadrotor. The toolkit works compatible with AscTec SDK which is also provided by company. The custom design controller algorithm is running on HLP and in a case of any problem it can be switched to LLP for safety. The general scheme of AscTec AutoPilot is shown in Figure 2.2.

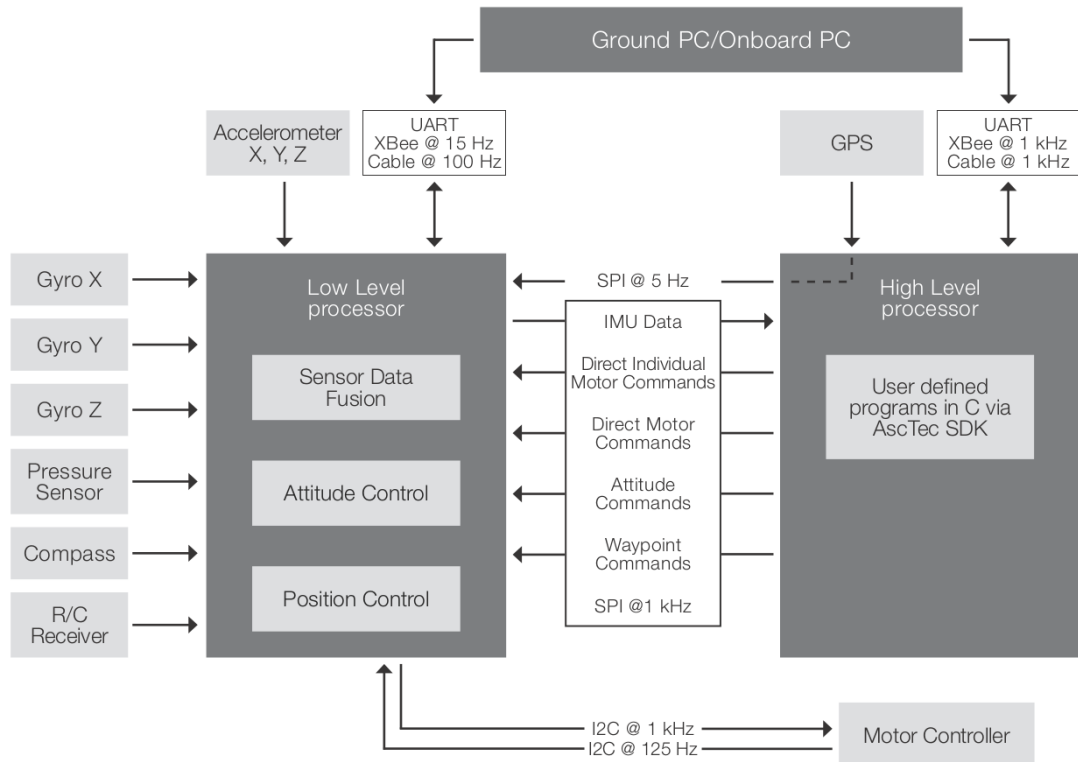


Figure 2.2. AscTec Autopilot general scheme [20]

The main part of the framework is *onboard_matlab.mdl* Simulink file and it needs to be compiled and built exactly with *onboard_matlab.mdl* name in *custom_mdl* named

subfolder. It is important due to the file name and locations that AscTec SDK uses. The model of *onboard_matlab.mdl* is shown in Figure 2.3.

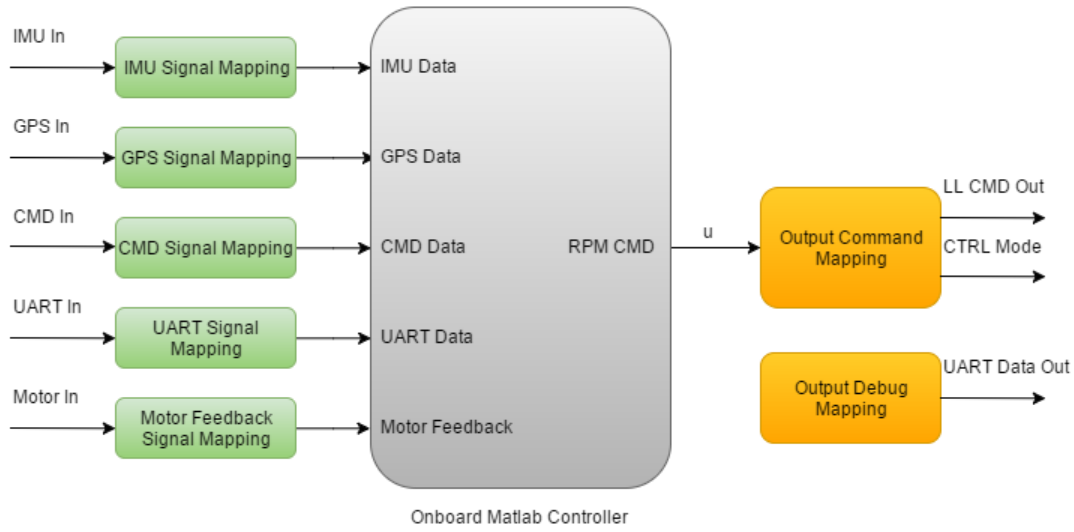


Figure 2.3. The *onboard_matlab.mdl* Simulink model scheme

The subsystem *Onboard_Matlab_Controller* is the place where you implement your control algorithm. *RC_Data_In* are remote control inputs which are roll, pitch, yaw, and thrust stick commands. There are also three point switch which switches between GPS mode, height mode and manual mode, and two point switch which provides transition between serial mode and manual mode. *UART_Data_In* are serial mode control inputs sent from ground PC. The *Output_Mapping_Debug* subsystem consists of debug channels that are set using the yellow colored “Go to” blocks. Before running Simulink model *InitOnboardMatlab.m* must be executed and constant parameters must be set. There are 40 numbers can be set for various purposes and tuning your controller. These parameters also must send via serial port when quadrotor powered, by running *parameter_send.m* file.

The serial port communication is provided by XBee modules that come with quadrotor kit. One of the modules is XBee USB module which is connected to ground PC via USB cable and the other one is XBee Serial Module which is connected to HLP serial interface. If as in our case XBee modules are missing you can use your own XBee

modules and configure pairs by XCTU Tool software. The communication baud rate is 57600 (Data Bits: 8, Parity: None, Stop Bits: 1, Flow Control: None).

To communicate with ground PC in real time ***UART_Communication.mdl*** Simulink model must be executed. There are sixty debug channels under *Debug_Mapping_Extended* mask and each channel gets the values that assigned in ***onboard_matlab.mdl***. Also CPU load and battery voltage can be displayed continuously through display. There are twelve control channels to send data from ground PC to quadrotor and this channel values can be constants and as well as control signals. The ***UART_Communication.mdl*** debug channel mappings and control inputs can be seen in Figure 2.4. *Debug_Scopes* subsystem is area where received data is visualized and collected.

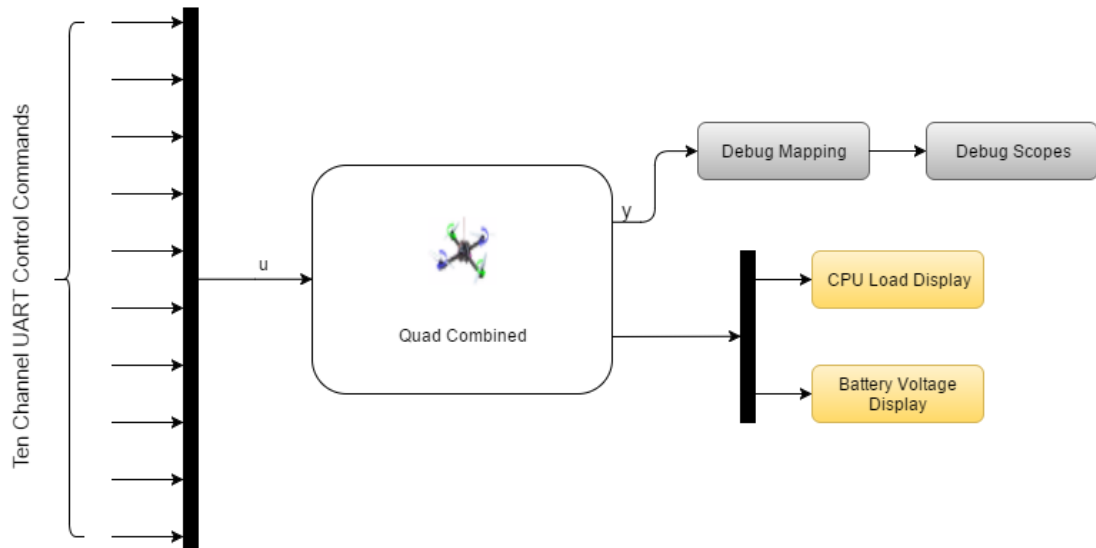


Figure 2.4. ***UART_Communication.mdl*** Simulink model scheme

After building your ***onboard_matlab.mdl*** Simulink model using Simulink Code Generation C-code must be generated and stored to *onboard_matlab_ert_rtw*. Then *asctec-sdk2.0.zip* package must be installed which comes with AscTec SDK. This package installs Eclipse, ARM-GCC, OpenOCD and JTAG drivers on your system.

AutoPilot_HL-Simulink_SDK_v2.0 project must be imported to the working workspace directory in AscTec Eclipse and built. Afterwards JTAG adapter must be connected to quadrotor and *OpenOCD AscTec-JTAG* must be selected as run option and code is uploaded to quadrotor HLP. After restarting quadrotor custom built controller code is running on quadrotor HLP onboard.

CHAPTER 3

MATHEMATICAL MODEL AND CONTROLLER DESIGN

3.1 Mathematical Model of Quadrotor

The quadrotor that we use in our study is fixed pitch propeller quadrotor. The angle of attack of fixed pitch propeller is constant and thrust force produced by propeller is adjusted by changing the rotational speed of corresponding rotor. The relation between thrust and rotational speed is as follows,

$$T = c_T \omega^2 \quad (3.1)$$

where c_T is motor-prop specified thrust constant that depends on used propeller model. The relation between propeller torque and rotational speed is as follows,

$$Q = c_Q \omega^2 \quad (3.2)$$

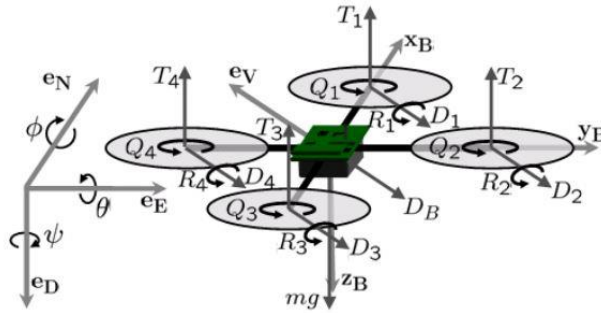


Figure 3.1. Free body diagram of quadrotor [21]

The control of quadrotor model is done by adjusting rotational speed of each propeller. Thus the four controller inputs for quadrotor control are as follows:

$$U_1 = T_1 + T_2 + T_3 + T_4 \quad (3.3)$$

$$U_2 = T_4 - T_2 \quad (3.4)$$

$$U_3 = T_3 - T_1 \quad (3.5)$$

$$U_4 = Q_2 + Q_4 - Q_1 - Q_3 \quad (3.6)$$

As it can be seen from equation (3.3) U_1 input is related to the z direction motion of the quadrotor and is equal to the sum of all thrust forces generated by four rotors. To realize x and y direction motion of the quadrotor is done by changing roll and pitch angles via adjusting orientation of U_1 . It is seen that roll motion of quadrotor is directly related to the U_2 input which is the thrust value difference between the right and left rotor (3.4). In similar way the pitch motion is achieved with the thrust value difference between the front and rear rotor which is defined in equation (3.5) as U_3 input. The units of U_1 , U_2 and U_3 are N, where the unit of U_4 is Nm. The input U_4 is related to the yaw motion of the quadrotor, which is torque value difference between the sum of right and left rotor torque values and the sum of front and rear rotor torque values (3.6). It must be noticed that the front and rear rotors rotate clockwise, while right and left rotors rotate counterclockwise.

The matrix describing the thrusts and torques is shown below (3.7):

$$\begin{bmatrix} \Sigma T \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} c_T & c_T & c_T & c_T \\ 0 & dc_T & 0 & -dc_T \\ -dc_T & 0 & dc_T & 0 \\ -c_Q & c_Q & -c_Q & c_Q \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \quad (3.7)$$

, where d is the distance between the propeller rotation axes.

Afterwards in this section the effect of external forces and moments acting on the quadrotor body is defined. For simplicity some of the forces and moments are ignored. The first important force acting on the center of gravitation (CG) of a quadrotor body is due to gravitation with constant gravitational acceleration $g = 9.81 \text{ m/s}^2$. The expression of gravity force in inertial frame is shown as follows (3.8)

$$F_{g,i} = -m \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \quad (3.8)$$

The expression of thrust force generated by rotors in body frame is written as below (3.9)

$$F_{r,b} = \begin{bmatrix} 0 \\ 0 \\ c_T \omega_1^2 + c_T \omega_2^2 + c_T \omega_3^2 + c_T \omega_4^2 \end{bmatrix} \quad (3.9)$$

Other external disturbance forces acting on quadrotor body frame are related to the aerodynamic, wind disturbance, ground effect etc. and are expressed as $F_{d,b}$. It must be noticed that, in quadrotors due to small size and low translational speeds (5-10 m/s) the effect of aerodynamic drag is considered for translational dynamics only.

Moment generated by the rotor on quadrotor body frame is expressed as below (3.10):

$$M_{r,b} = \begin{bmatrix} d(c_T \omega_2^2 - c_T \omega_4^2) \\ d(c_T \omega_3^2 - c_T \omega_1^2) \\ -c_Q \omega_1^2 + c_Q \omega_2^2 - c_Q \omega_3^2 + c_Q \omega_4^2 \end{bmatrix} \quad (3.10)$$

There are also gyroscopic moments on body due to governed by the inertia of each motor's rotating components (I_m), the rolling and pitching rates (p and q), as well as the speed of each rotor. The gyroscopic moment equation is shown below:

$$M_{gyro,b} = \begin{bmatrix} I_m q (\omega_1 - \omega_2 + \omega_3 - \omega_4) \\ I_m p (-\omega_1 + \omega_2 - \omega_3 + \omega_4) \\ 0 \end{bmatrix} \quad (3.11)$$

Afterwards defining forces and moments state equations can be derived. Considering forces and accelerations acting on the quadrotor body velocity state equations are derived which describes the acceleration of the center of mass of the quadrotor model:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = F_{r,b} - F_{d,b} + F_{g,b} - \Omega \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (3.12) \quad \text{where} \quad F_{g,b} = R_{bi} F_{g,i} \quad (3.13) \quad \text{and}$$

$$\Omega = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \quad (3.14)$$

It must be noticed that R_{bi} is rotation matrix to translate the translational velocity of quadrotor in the components of body fixed frame and inertial frame (3.15). The sequence of rotations of according to the aerospace rotation sequence is in order of yaw, pitch, and roll rotation. R_{ib} is the transpose of R_{bi} matrix.

$$R_{bi} = \begin{bmatrix} c(\theta) c(\psi) & c(\theta) s(\psi) & -s(\theta) \\ (-c(\phi) s(\psi) + s(\phi) s(\theta) c(\psi)) & (c(\phi) c(\psi) + s(\phi) s(\theta) s(\psi)) & s(\phi) c(\theta) \\ (s(\phi) s(\psi) + c(\phi) s(\theta) c(\psi)) & (-s(\phi) c(\psi) + c(\phi) s(\theta) s(\psi)) & c(\phi) c(\theta) \end{bmatrix} \quad (3.15)$$

Next position state equation is derived which describes the linear velocity of the center of mass of the quadrotor in the inertial frame.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = R_{ib} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (3.16)$$

Then angular velocity state equations are derived, which describe the change in roll, pitch, and yaw rates of the quadrotor by taking into account the inertia, angular velocity, and the moments applied by the rotors.

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = (I_B)^{-1} \left[M_{r,b} + M_{gyro,b} - \Omega I_B \begin{bmatrix} p \\ q \\ r \end{bmatrix} \right] \quad (3.17)$$

where I_B is inertia matrix. Next the rate of change of the Euler angles is determined in the inertial frame by multiplying quadrotor body angular rate changes by angular velocity transformation matrix:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & t(\theta) s(\phi) & t(\theta) c(\phi) \\ 0 & c(\phi) & -s(\phi) \\ 0 & s(\phi)/c(\theta) & c(\phi)/c(\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (3.18)$$

It must be noticed that there is a singularity at $\theta = \pm 90^\circ$ in (3.18).

3.2 PID Controller Design

Classical PID control is selected as the control method and in this section the basic theory of this controller is described.

The PID controller is composed of three components: Proportional, Integral and Derivative part. The proportional control reduces the rise time and there is always steady state error offset in response to a step input. Adding integral reduces the steady state error but may cause oscillatory response of slowly decreasing amplitude. Due to integrator windup there can be instability in controller, so saturation limits must be applied to the integrator. Adding only derivative control to proportional control improves the transient response and reduces overshoot of response to the step input. So the derivative control increases the stability of controller. There is no direct effect of derivative controller to the steady state error, but as it acts like damper, large proportional gains can be selected for decreasing the steady state error. Adding both integral and derivative controller to proportional controller results in PID controller, which reduces rise time, maximum overshoot and removes steady state error.

The tuning process is one of the challenging parts of PID controller. There are several tuning algorithms such as Ziegler-Nichols and Lambda tuning. In our study we used iterative hand tuning according to response analyzes.

Using this mathematical model PID controller is designed for the altitude and attitude control of the quadrotor. The hovering height and roll, pitch, and yaw angles have been controlled.

The yaw control is not so critical control among the quadrotor controls because it has no direct effect on the quadrotor's motion. The effect of disturbances on the yaw is relatively small, so there is no need to large controller gains. Also bandwidth of controller is also small. The control scheme of the controller is as below in Figure 3.2.

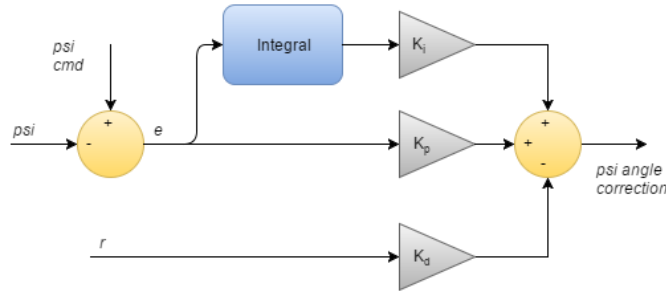


Figure 3.2. Yaw PID controller scheme

The roll and pitch controllers are same due to the quadrotor's symmetrical layout. Due to this, there is direct relationship with x and y direction acceleration the control bandwidth of controllers is higher relative to the yaw control. The controller schemes are in Figure 3.3 and Figure 3.4.

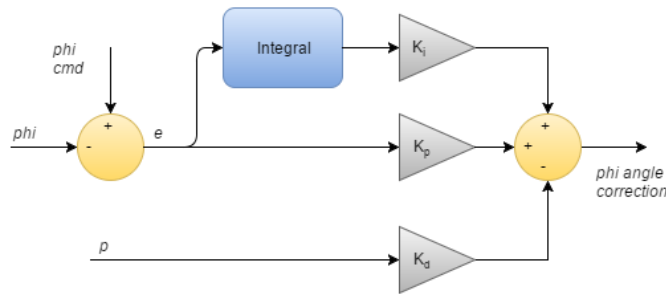


Figure 3.3. Roll PID controller scheme

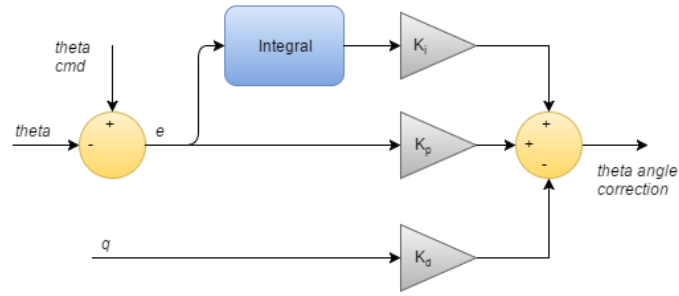


Figure 3.4. Pitch PID Controller scheme

In hover condition, above the ground effect, the control output is nearly proportional to the z axis acceleration on quadrotor body frame. To keep the hover altitude a large number of gravity offset (G) is required to defeat the gravity force. PID controller is needed to stabilize the altitude motion. The control scheme is described in Figure 3.5.

$$G = \frac{z_{cmd} + mg}{\cos \varphi \sin \theta} \quad (3.19)$$

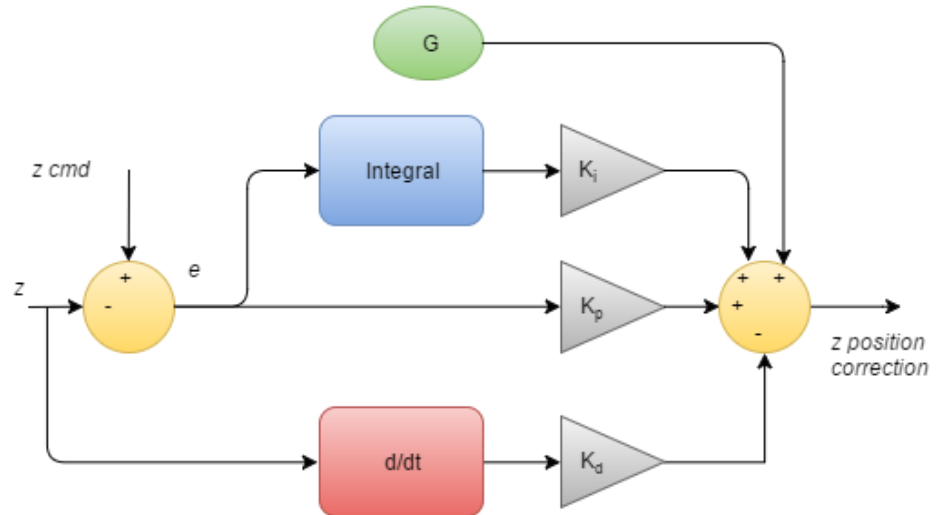


Figure 3.5. Altitude PID controller

CHAPTER 4

V-REP MODEL AND MATLAB/SIMULINK INTERFACING

4.1 Virtual Robot Experimentation Platform (V-REP)

In our study, we have used the Virtual Robot Experimentation Platform (V-REP), a physical simulator which provides an easy and intuitive environment to create your own virtual platform and to include some popular robots, objects, structures, actuators and sensors.

Virtual Robot Experimental Platform (V-REP) is the product of Coppelia Robotics that developed for general purpose robot simulation. Customized user interface and a modular structure integrated development environment are the main characteristics of the simulator. Modularity is in high level both for the simulation objects and control methods. The easy use of development environment inside the simulator provides the creation of robots and simulation cases. This capability permits for fast prototyping, algorithm design and implementation. During the active simulation this area acts as real 3D world and gives real time feedback according to the behavior of models. The objects that compose the scene, the control mechanism and the computing modules are the three main functionalities of the simulator. The following object types compose the V-REP simulation scene or model:

- **Shapes:** Shapes are triangular faced rigid mesh objects. These objects can be used in collision detections against other collidable objects and minimum distance calculations with other measurable objects. Shapes also can be

detected by proximity and vision sensors. Another property of shapes is that can be cut by mills.

- Joints: Joints are the tools used for building mechanisms and moving object, which has at least one Degree of Freedom (DOF). There are four types joints which are revolute, prismatic, and spherical and screw joints. The operation modes of joints are passive mode, inverse kinematic mode, dependent mode, motion mode and finally torque or force mode. Dynamic model of actuator can be modeled enabling torque or force mode which also has position control (PID) method.
- Proximity sensors: From ultrasonic to infrared nearly all type of proximity sensors can be modeled to simulate proximity sensors. They do an exact distance calculation between their sensing point and any detectable entity that interferes with its detection volume.
- Vision sensors: They will render all renderable objects in simulation scene (colors, objects sizes, depth maps, etc.) and extract complex image information. A built-in filter and image processing functions ease the use of vision sensors in simulation.
- Force sensors: Force sensor are objects that measures transmitted force and torque values between two or more objects. The force sensor working principle can be modeled as real one, so that they can even be broken in overshoot force and torque values.
- Graphs: Graphs are objects for to record, visualize and export data from a simulation. The graphs feature in V-REP are very powerful, so that time graphs, x/y graphs and 3D graphs can be generated for data types applied to specific objects to record.
- Cameras: Cameras are objects that you can monitor your simulation from different viewpoints. You can either add multi view windows in one view window or attach each view to separate windows.
- Lights: Lights are the objects that light the simulation scene and directly influence camera and vision sensors.
- Paths: Paths are objects that define a rotational, translational or combined path or trajectory in space.

- Dummies: A dummy is a type of object that can be defined as a reference frame or point of orientation attached to the object. They are useful especially for path-trajectory planning and following. Dummies are generally multipurpose helper object in combination with other objects. It must be noticed that alone they are not so useful.
- Mills: Using mills almost any type of cutting volumes as long as they are convex can be modeled. Mills always have a convex cutting volume; however they can be combined to generate a non-convex cutting volume or more complex volumes.

The combination of above described scene objects allow the creation of complex sensors (accelerometer, gyroscope, GPS, Kinect, etc.), and complex models from manipulators to wheeled robots. There is a wide sensor and robot model library in V-REP environment that can be added easily dragging to the scene. Also it must be noticed that these models are fully customizable.

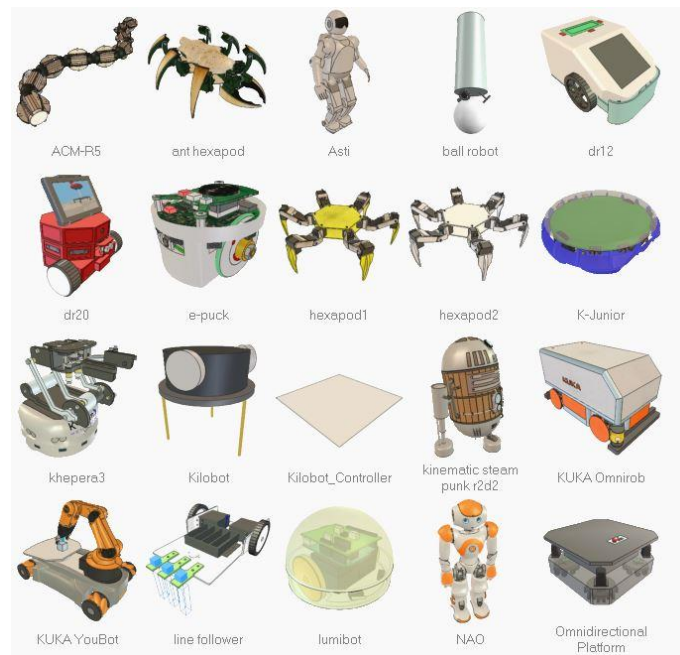
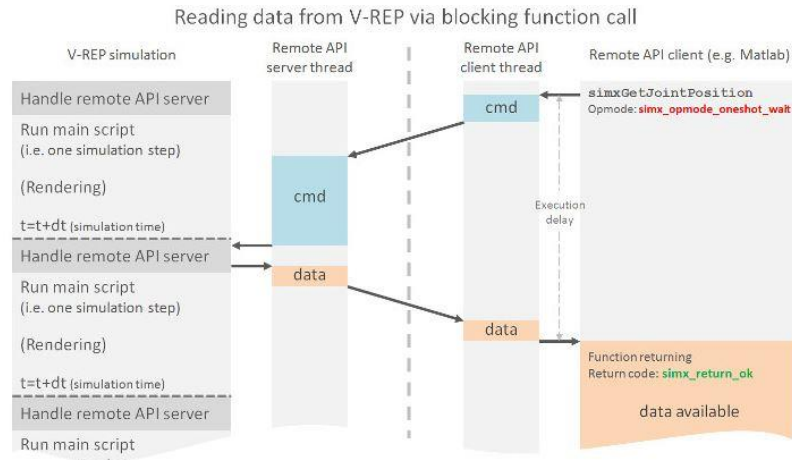


Figure 4.1. The built-in V-REP robot models

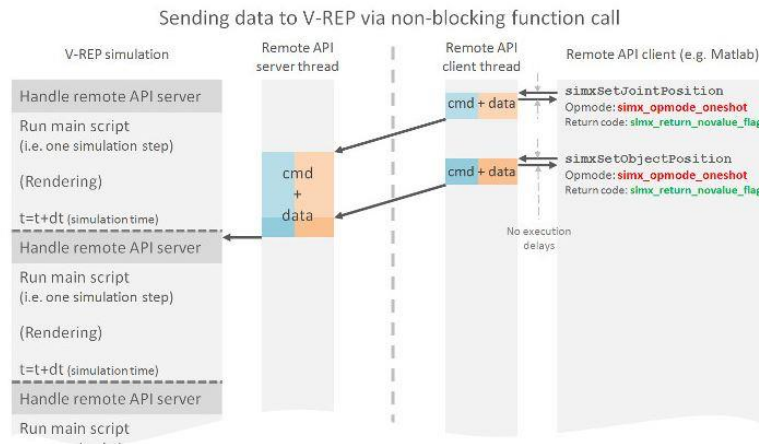
There are various control mechanisms to manage the behavior of each simulation objects. These controllers can be implemented not only inside of the simulation environment and also outside of the simulation environment. The main internal control mechanism is the use of child scripts, which can be associated with any element in the scene. The child scripts handle a particular part of the simulation and they are an integral part of their associated object. Due to that property they can be duplicated and serialized, together with them. Therefore, they are a single package containing the model parameters together with its control which makes them portable and scalable. Child scripts have two execution modes. Non-threaded child scripts are pass-through scripts which means every time they are called they execute some task and then return to control. Threaded child scripts launches in thread and is handled by main script code. Threaded child scripts require more advanced programming knowledge compared ton on-threaded child scripts. Also threaded child scripts can waste more processing power and time than non-threaded ones, and there some lag can be observed in response to a simulation commands. The main script handles both threaded and non-threaded child scripts. These embedded scripts open and handle communication lines start remote API servers, launch executables, load and unload plugins, and can register ROS publishers and subscribers.

For simulator-in-the-loop configuration tests V-REP offers also a method to control the simulation from outside the simulator by external implied controller algorithm. The controller developed in remote API interface in V-REP communicates with the simulation scene using a socket communication. It is composed by remote API server services and remote API clients. The client side can be developed in C/C++, Python, Java, Matlab or Urbi languages, also embedded in any software running on remote control hardware or real robots, and it allows remote function calling, as well as fast data streaming. Functions support two calling methods to adapt to any configuration: blocking, waiting until the server replies, or non-blocking, reading streamed commands from a buffer. The schematic of this communication mode is shown in Figure 4.2. Plugins implement the API server inside V-REP for providing a simulation process with standard LUA commands. So they generally are used in combination with scripts. On the other hand, if there is need for either fast calculation case (compiled

languages most of the time are faster than scripts) or an interface to a real device (e.g. real robot), plugins provide special functionality.



(a)



(b)

Figure 4.2. The remote API communication modes: (a) blocking function call, (b) non-blocking function call [22].

The interaction between objects in the simulation scene is calculated by various calculation modes. V-REP's dynamics module currently supports four different physics engines: the Bullet physics library [23], the Open Dynamics Engine [24], the Vortex Dynamics engine [25] and the Newton Dynamics engine [26]. At any time, it is easy to switch from one engine to the other quickly according to the simulation needs. The reason for this diversity in physics engine data support is that physics simulation

is a complex task which can be achieved with various degrees of precision, speed, or with support of diverse features.

4.2 Propeller Model in V-REP

The propeller of AscTec Hummingbird quadrotor has been modeled in V-REP environment. The experimental data have been used in modeling study. The experimental values are obtained from [27]. The Figure 4.3 shows the experimental thrust and torque measurements of propeller with varying rotation speed (RPM).

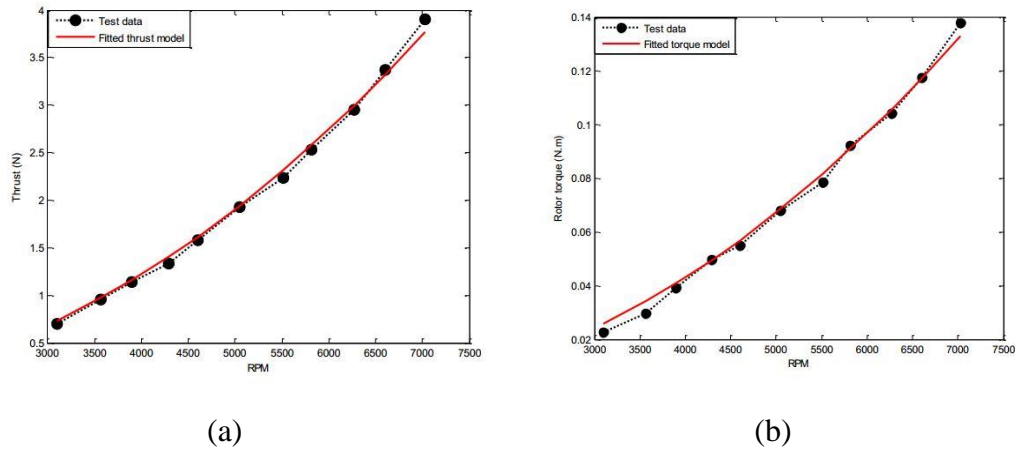


Figure 4.3.(a) Thrust change w.r.t. the angular velocity of the rotor using BET in hovering flight, (b) Rotor torque change w.r.t. the angular velocity of the rotor using BET in hovering flight [27].

The thrust constant (N/RPM^2) and rotor torque constant (Nm/RPM^2) parameters are found by using the method of least squares.

$$c_T = 7.6184 \times 10^{-8} N/RPM^2$$

$$c_Q = 2.6839 \times 10^{-9} Nm/RPM^2$$

The brushless DC motor used in quadrotor is modeled in Simulink part of simulator. The transfer function of motor is found experimentally in [27].

$$G_s = \frac{3.5}{0.0044s^2 + 0.08s + 1}$$

The estimated parameter then has been implemented in V-REP environment. The CAD model of propeller is imported to the platform and appropriate LUA embedded script has been written which gets the rotation speed and particle velocity from main script. Particle velocity is modeled for ground disturbance studies in future studies. In Figure 4.4 there is one example work of propeller at *3900 RPM* which attached to the cube and force and torque sensors have been mounted.

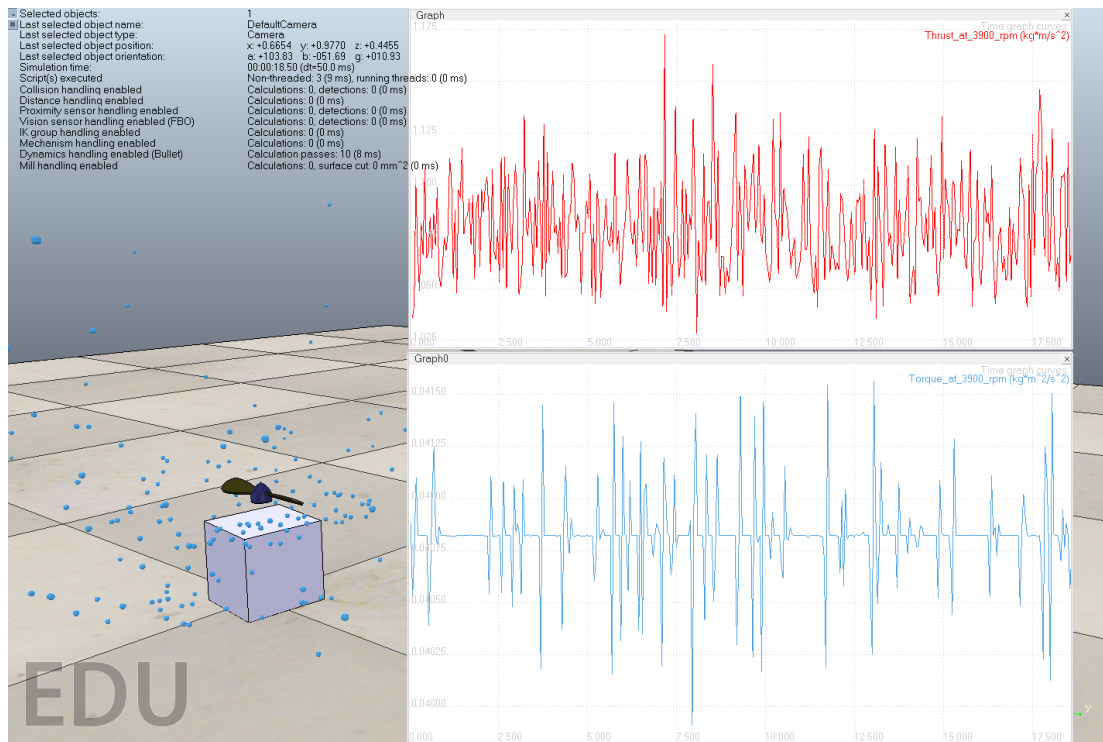


Figure 4.4. Propeller model in V-REP

4.3 Quadrotor Model in V-REP

V-REP provides a very powerful tool to create and modify mechanical model. It is comfortable that you assemble all the parts in your CAD program first and export the model into a single stl file. It is easy to import this stl file to V-REP and divide the

model into smaller parts and assign them own mechanical properties. The quadrotor model stl file for the AscTec Hummingbird quadrotor is downloaded from the AscTec wiki [28]. The stl file imported into the V-REP and a simplified dynamic model created for simulation. An appropriate mass and inertia value has been set. Then developed propeller model has been included to the model. This process is done by copy and paste between propellers designed scene and quadrotor model scene. In Figure 4.5 general view of quadrotor model can be seen.

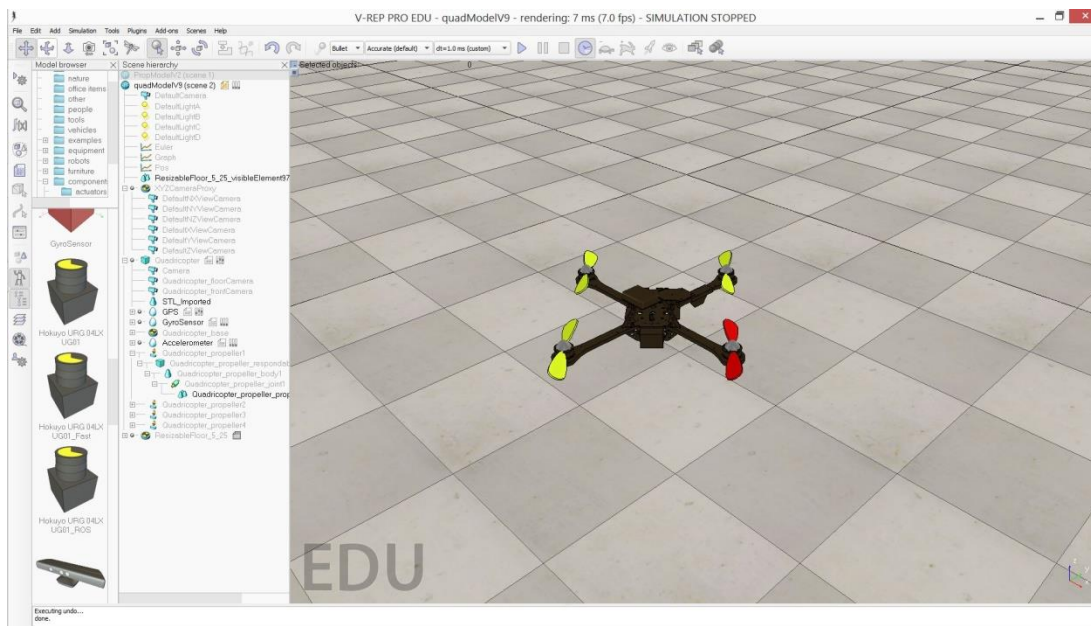


Figure 4.5. General AscTec Hummingbird quadrotor view in V-REP

Then sensor components like accelerometer, gyroscope and GPS unit has been added to simulation platform. In this point of study the accelerometer and gyroscope sensors have been used for calculation of roll and pitch angle. The sensors have their own embedded LUA scripts and using these scripts the data has been read in main script. To obtain angular position both accelerometer and gyroscope data can be used. Gyroscope can do this by integrating angular velocity over time, with accelerometer it can be done by determining the position of gravity vector by using *atan2* function. But in gyroscope due to integration over time, the measurement has tendency to drift and not returning to zero when it comes its original position, so gyroscope data is reliable in short term. On the other side, accelerometer all the small forces will disturb our

measurement completely, so accelerometer data is reliable in long term. Using complementary filter solves this problem because using this filter, on the short term data from the gyroscope have been used and on the long term data from accelerometer have been used. The weighting function of complementary filter in small angle changes – in short term looks like as below:

$$angle = 0.98 * (angle + gyroData * dt) + 0.02 * (accData)$$

Using formulation above the appropriate code has been developed in main script to calculate roll and pitch angle.

4.4 Simulink/Matlab and V-REP Interfacing

V-REP offers a remote API allowing to control a simulation from an external application. The V-REP remote API is composed by approximately one hundred functions that can be called from Matlab program. In our application the command and controller part is developed in Simulink and actuation and physical interaction part is created in V-REP. The general scheme of developed simulator can be seen in Figure 4.6.

In Simulink part controller gets commands and state data, makes corrections and sends this data to control mixing and motor speed calculation block. Then speed data is sent to Matlab S-Function where all communication process is done. In Matlab S-Function the remote API functions and Matlab functions are integrated. The remote API functions are interacting with V-REP via socket communication in a way that reduces lag and network load to a great extent. The synchronization with V-REP is also done in this part of simulation. Matlab S-Function sends motor speeds to V-REP and gets state data from V-REP and sends these data to controller and correction block in Simulink. In V-REP side main LUA script gets motor speeds from Matlab/Simulink and sends these values to appropriate propeller model child LUA scripts. Meanwhile, main LUA script read accelerometer and gyroscope data from child scripts, implement

complementary filter to these data and calculate roll and pitch angles. On the other hand, it also gets absolute positions (x,y,z) and absolute velocities (u,v,w) of quadrotor, combining them with angle (ϕ, θ, ψ) and angular velocity (p,q,r) data and sends them to Simulink/Matlab application. The visualization of processed data is done both in Simulink/Matlab and V-REP application.

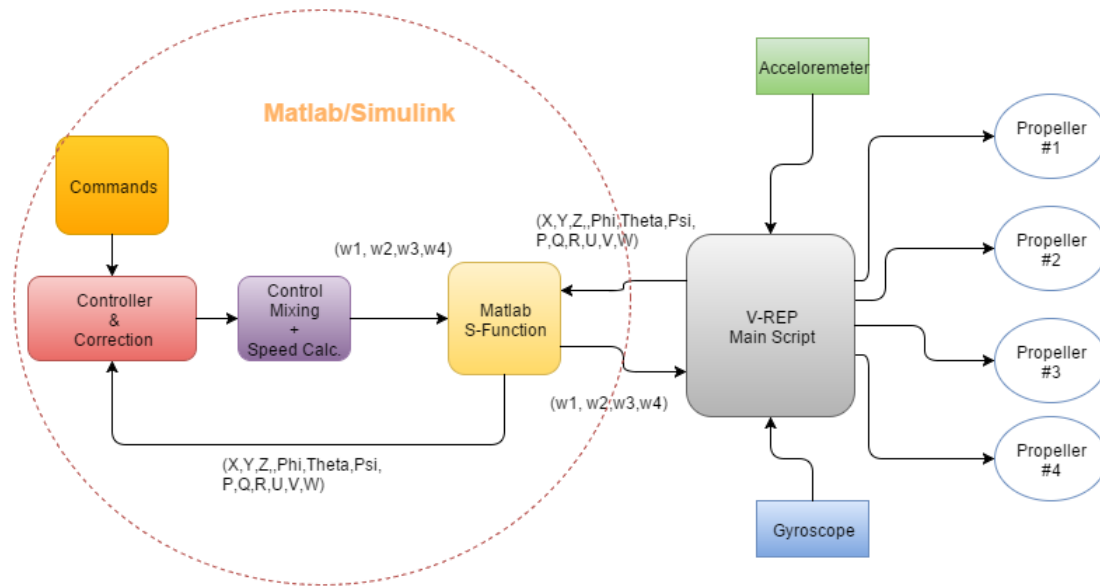


Figure 4.6. General simulator operation diagram

CHAPTER 5

SIMULATION RESULTS

5.1 Simulation Results of Simulink/Matlab and V-REP Integration

Afterwards interfacing the Simulink/Matlab with V-REP controller tuning and flight simulations trials have done. Processing with hand tuning and referring to Karwoski's studies [13] PID gains have been determined and can be seen in Table 5.1.

Table 5.1.Tuned PID gains

Gains	Hover	Roll Angle	Pitch
K_p	16	25	25
K_i	1	0	0
K_d	10	6	6

After tuning PID gains some flight conditions have been tested in simulator. One of them is to hover from 1 m to 1.5 m and 10 degree roll angle doublet input in 1 sec. The input command and motor command and state results can be seen in figures below.

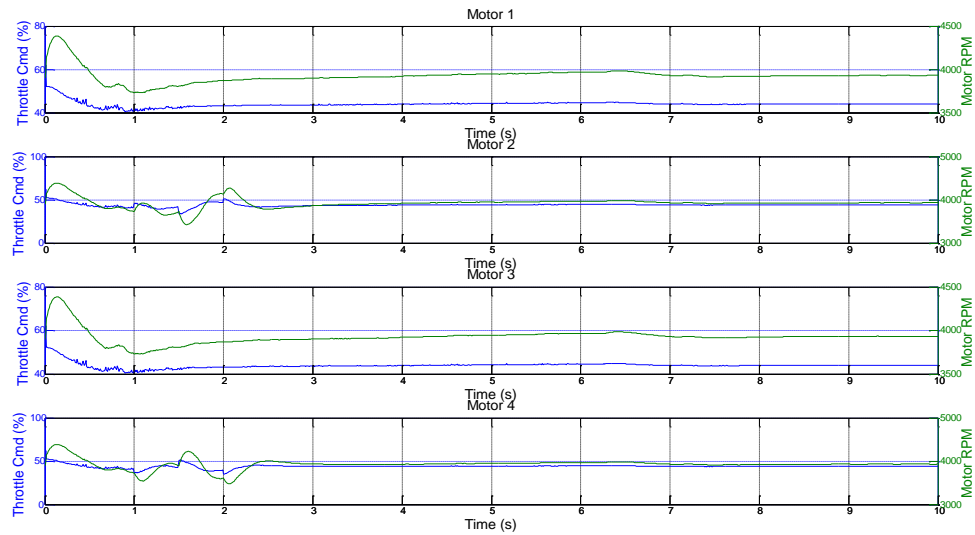


Figure 5.1. Motor throttle command (%) and rotation speed (rpm) during hover flight simulation.

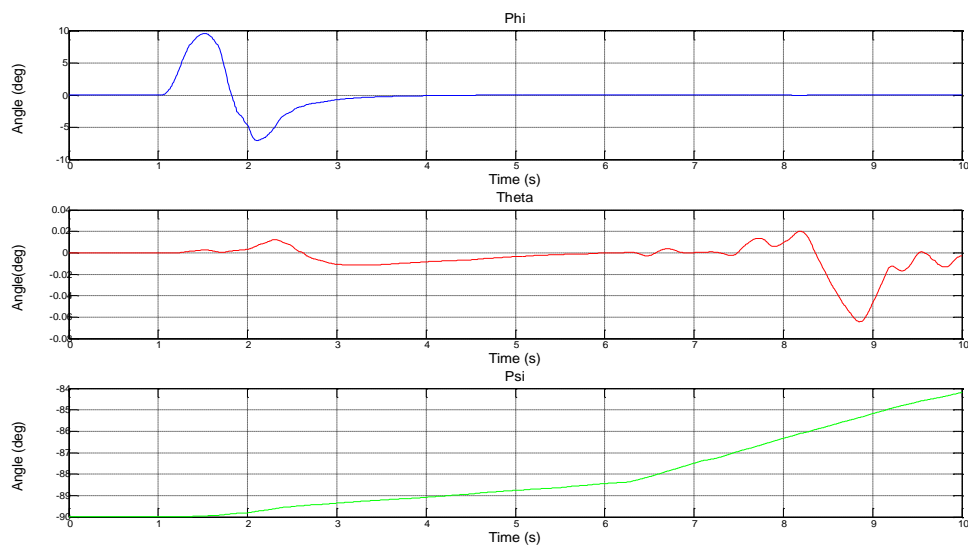


Figure 5.2. Roll, pitch and yaw angles of quadrotor during hover flight simulation.
The 10 degrees roll doublet input is shown in dashed lines.

The effect of roll angle doublet input to roll angular rate can be seen in Figure 5.3. Although the yaw angle controller does not affect directly the motion of quadrotor the lack of yaw angle controller can also be observed.

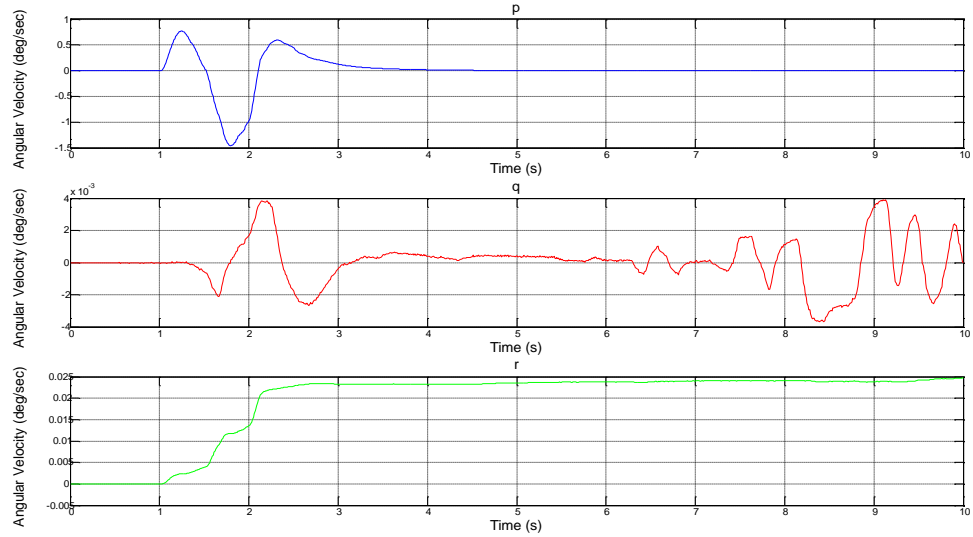


Figure 5.3. Roll, pitch and yaw angular rates change during hover flight simulation.

The effect of altitude command to the z axis velocity and effect of doublet roll angle command to the y axis velocity can be seen in Figure 5.4.

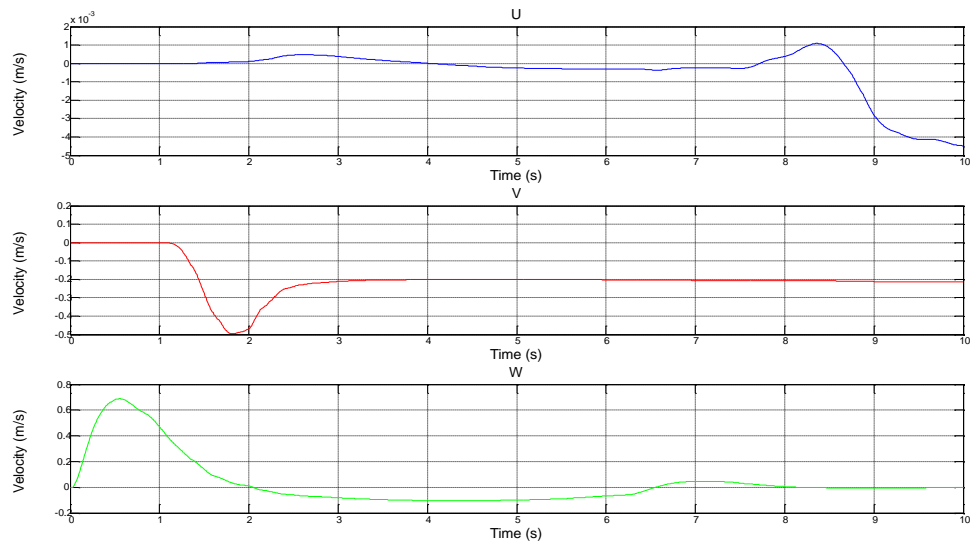


Figure 5.4. The u, v and w velocities during hover flight simulation.

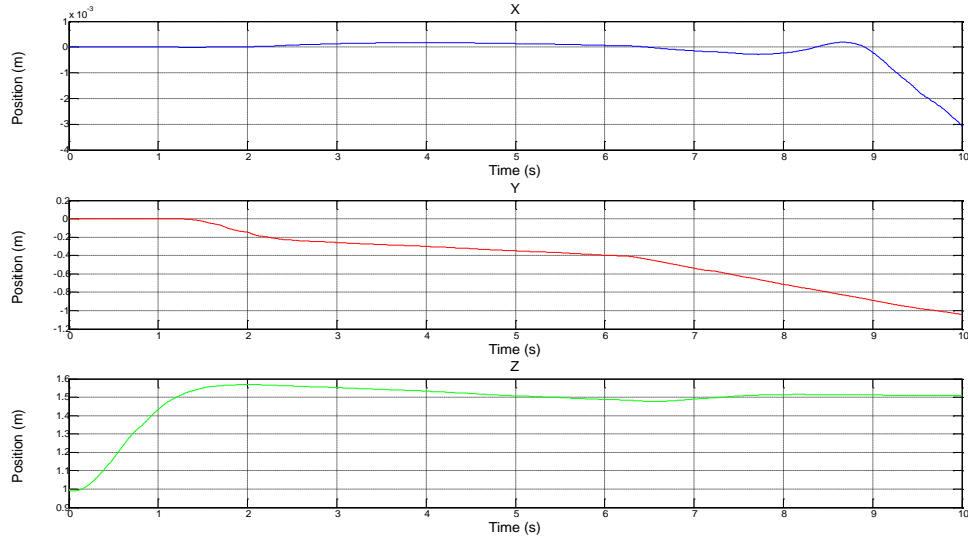


Figure 5.5. The x, y and z positions of the quadrotor during hover flight simulation. The z command is shown in dashed lines.

Another simulation condition is the take off quadrotor from ground and the ground disturbance is modeled by particles in V-REP. The roll angle doublet input was also given, and the z command was 1.5 m from ground. The results are shown figures in below.

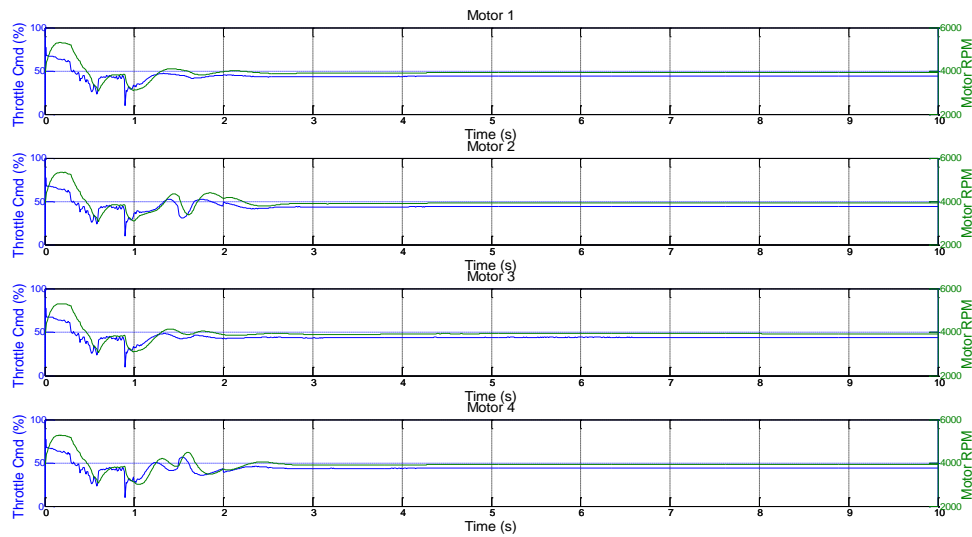


Figure 5.6. Motor throttle command (%) and rotation speed (rpm) during hover flight simulation with ground disturbance take-off.

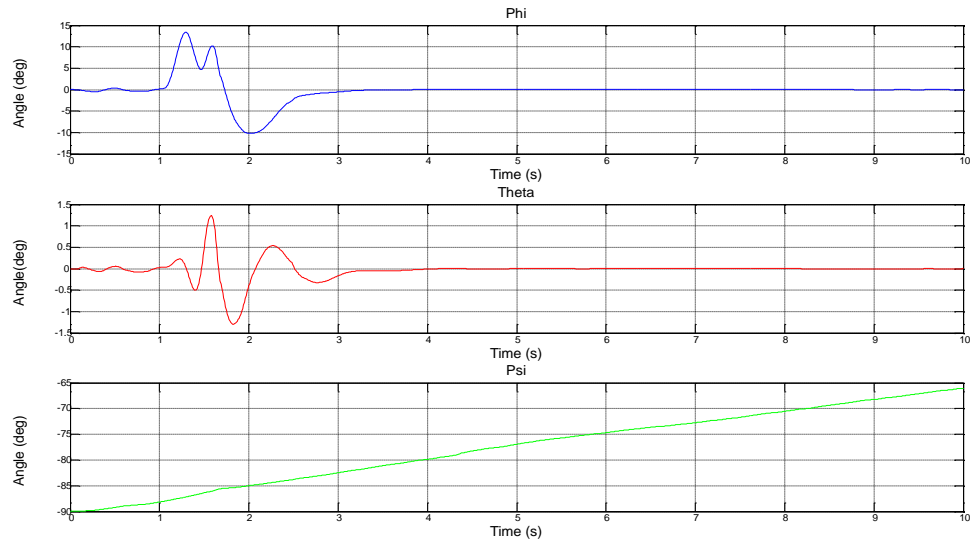


Figure 5.7. Roll, pitch and yaw angles of quadrotor during hover flight simulation with ground disturbance take-off. The 10 degrees roll doublet input is shown in dashed lines.

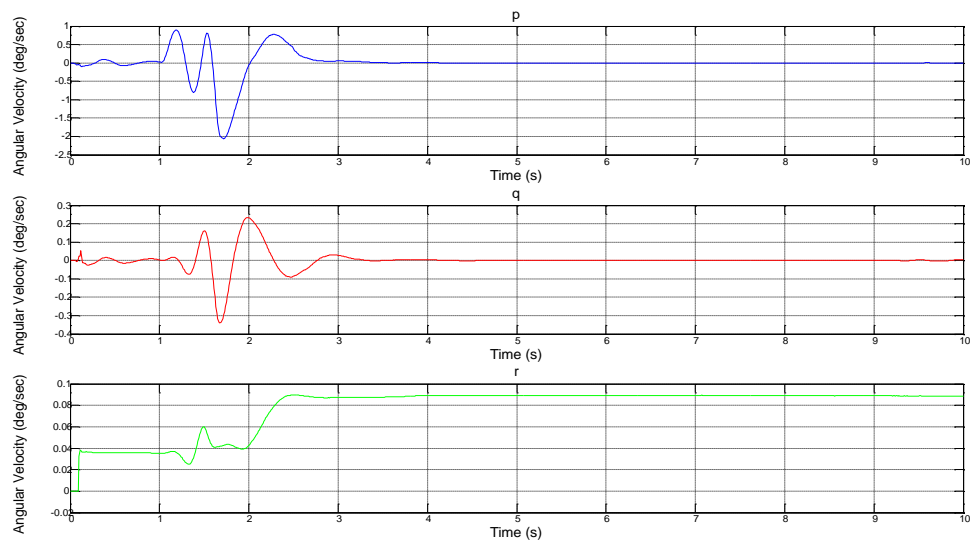


Figure 5.8. Roll, pitch and yaw angular rates change during hover flight simulation with ground disturbance take off.

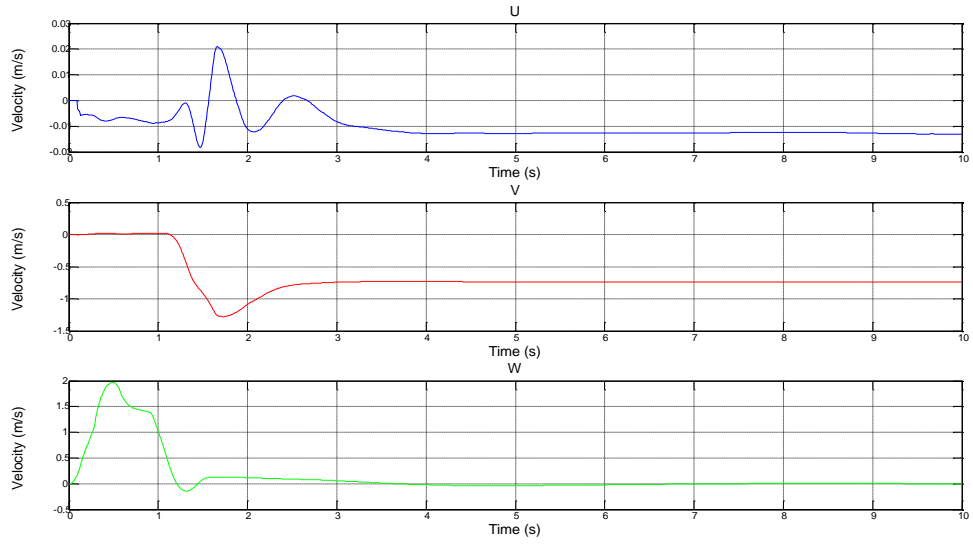


Figure 5.9. The u , v and w velocities during hover flight simulation with ground disturbance take-off.

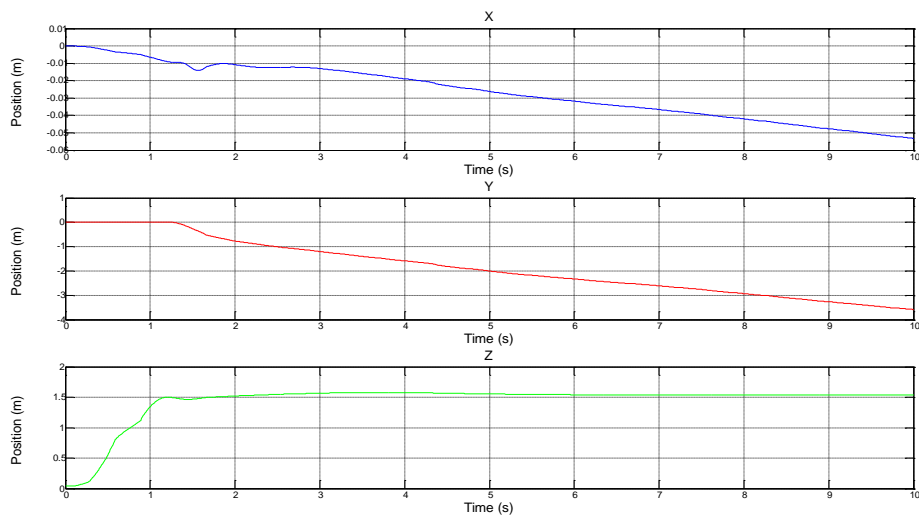


Figure 5.10. x , y and z positions of the quadrotor during hover flight simulation with ground disturbance take-off. The z command is shown in dashed lines.

5.2 Experimental Setup for Quadrotor Flight Test

After simulation results there is need to validate the dynamic, sensor data and control algorithm of a quadrotor. For this purpose basic experimental setup was built. The similar experimental setup was built in [29] for test of vertical take-off and landing (VTOL) air vehicle. In this part explanation of this experimental setup is given with illustrations. The quadrotor that is used in these experiments is AscTec Hummingbird. The quadrotor test were made in indoor conditions. So there were need to take safety cautions and limit the range of motion of a quadrotor. Experimental test setup was built with limited motion range.

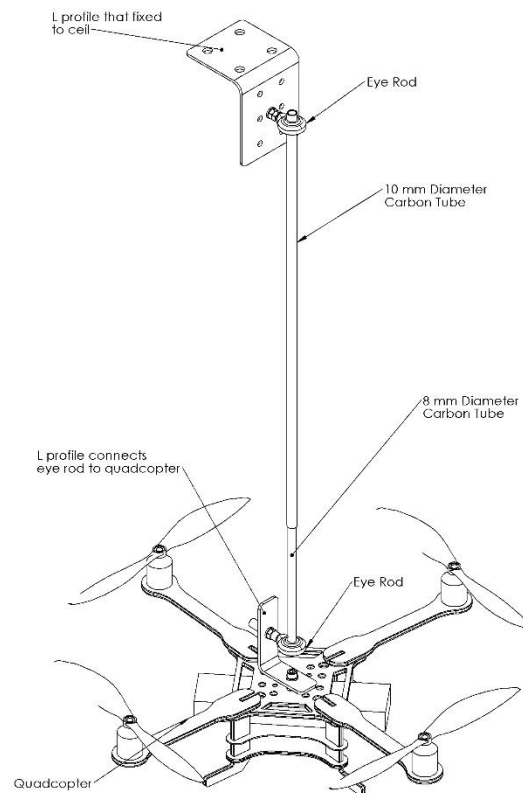


Figure 5.11. The assembly view of experimental setup allowing movement in translation axes.

The main parts of experimental setup were two rod eye bearings with 10 mm and 8 mm inner diameters respectively and two carbon fiber tubes. The carbon fiber tube with 10 mm outer diameter was inserted in 10 mm inner diameter rod eye bearing and the axial motion of the tube was locked.

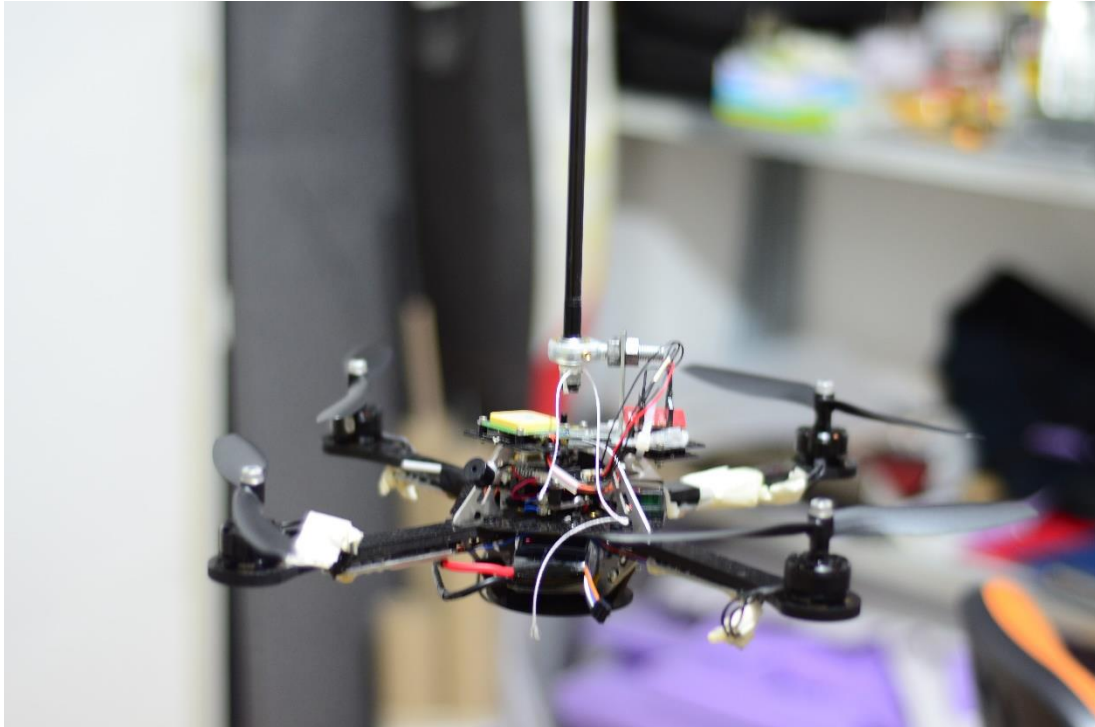


Figure 5.12. Quadrotor mounted to the rod eye bearing which allows limited roll and pitch motion and full yaw rotation.

This assembly was mounted to the ceiling of room using steel L profile and it had nearly $40\text{-}45^\circ$ freedom in pitch and roll axis and full rotation in yaw axis. The one side of carbon fiber tube with 8 mm outer diameter was tied up with parachute rope, the rope was carried through bigger tube and tightened to steel L profile in ceiling and smaller carbon fiber tube can travel inside the bigger one nearly 300 mm as shown in Figure 5.11. Other side of smaller carbon fiber tube was carried through 8 mm inner diameter rod eye bearing and also its movement through bearing in axial direction was locked. The threaded end of the smaller rod eye bearing was assembled to steel L profile which is mounted to the center of quadrotor frame as shown in Figure 5.12. The roll and pitch angles again were restricted to approximately $40\text{-}45^\circ$ and there was

full rotation in yaw axis. The height that quadrotor can travel from its hanger position was approximately 300 mm. The quadrotor can also move in limited range in lateral and longitudinal directions due to bigger rod eye bearing. In Figure 5.13 the visual is shown from flight tests.



Figure 5.13. The view of motion of quadrotor in flight tests

There also fixed type experimental setup was built. In this setup the lateral, longitudinal and altitude motions of quadrotor was locked. There were only roll and pitch motions which were limited to approximately $40\text{-}45^\circ$ and full range yaw motion was allowed. The setup comprise the stiff wood which was mounted to the ceiling of room using steel L profile. The carbon fiber with 8 mm outer diameter was fixed to the wood with steel bracelets and ensured that no movement and rotation in any direction (Figure 5.14). The rod eye bearing with 8 mm inner diameter was mounted to the end of carbon tube and movement along the altitude direction was locked. The threaded end of the smaller rod eye bearing again was assembled to steel L profile which was mounted to the center of quadrotor frame as shown in Figure 5.15.

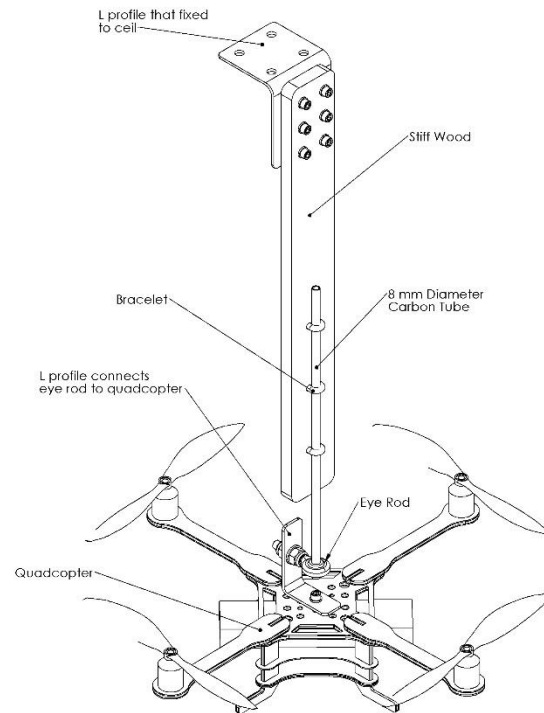


Figure 5.14. The assembly view of experimental setup with no movement in translation axes.



Figure 5.15. The directional movement fixed type experimental setup.

5.3 Controller Design and Implementation on Real Quadrotor

To make flight tests PD controller is designed in Simulink using AscTec Simulink Toolkit. The custom *onboard_matlab.mdl* Simulink is used which is provided by toolkit. The *Onboard_Matlab_Controller* subsystem in Simulink model is the place where control algorithm is implemented. In this study the PD controller is used with the attitude gains according to the Table 5.1. The model under *Onboard_Matlab_Controller* is shown Figure 5.16.

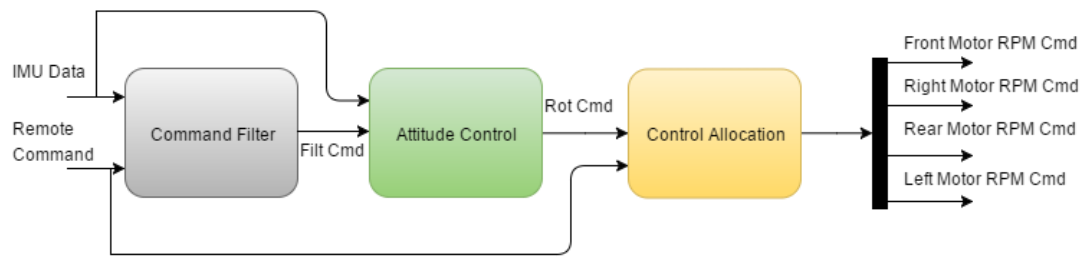


Figure 5.16. The Simulink model inside *Onboard_Matlab_Controller* subsystem.

In *Command Filter* subsystem the remote control input yaw rate command is integrated to a commanded yaw angle. In integration process the flip at 360° and resetting of the IMU yaw measurement at zero thrust is taken account. Also roll and pitch commands are scaled to $\pm 30^\circ$ under this subsystem. The controller is implemented under *Attitude Control* subsystem as shown in Figure 5.17.

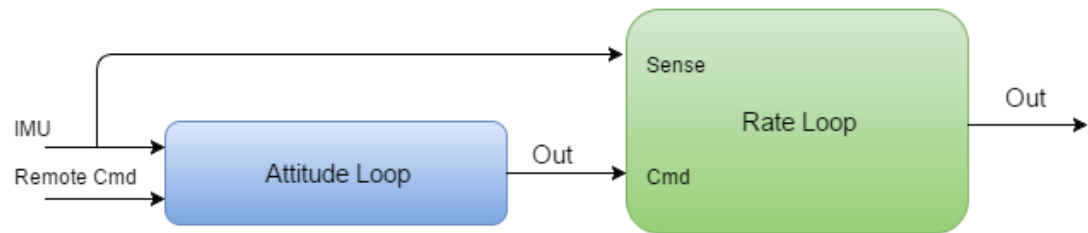


Figure 5.17. The Simulink model inside *Attitude Control* subsystem.

The *Rate Loop* is inner loop and *Attitude Loop* is outer loop. The Simulink models inside the *Rate Loop* and *Attitude Loop* are shown in Figure 5.18 and in Figure 5.19 respectively. The constants in orange blocks are controller gains which are setting by first running *InitOnboardMatlab.m* code for initialization and sending parameters via serial port when quadrotor is powered by running *parameter_send.m* file. In *Control Allocation* block the four signals; thrust, roll, pitch and yaw signals are mixed to send to the four motors. The value of signals are ranged from 1 to 200 which are mapped from 1075 rpm to 8600 rpm rotational speed in motor controllers.

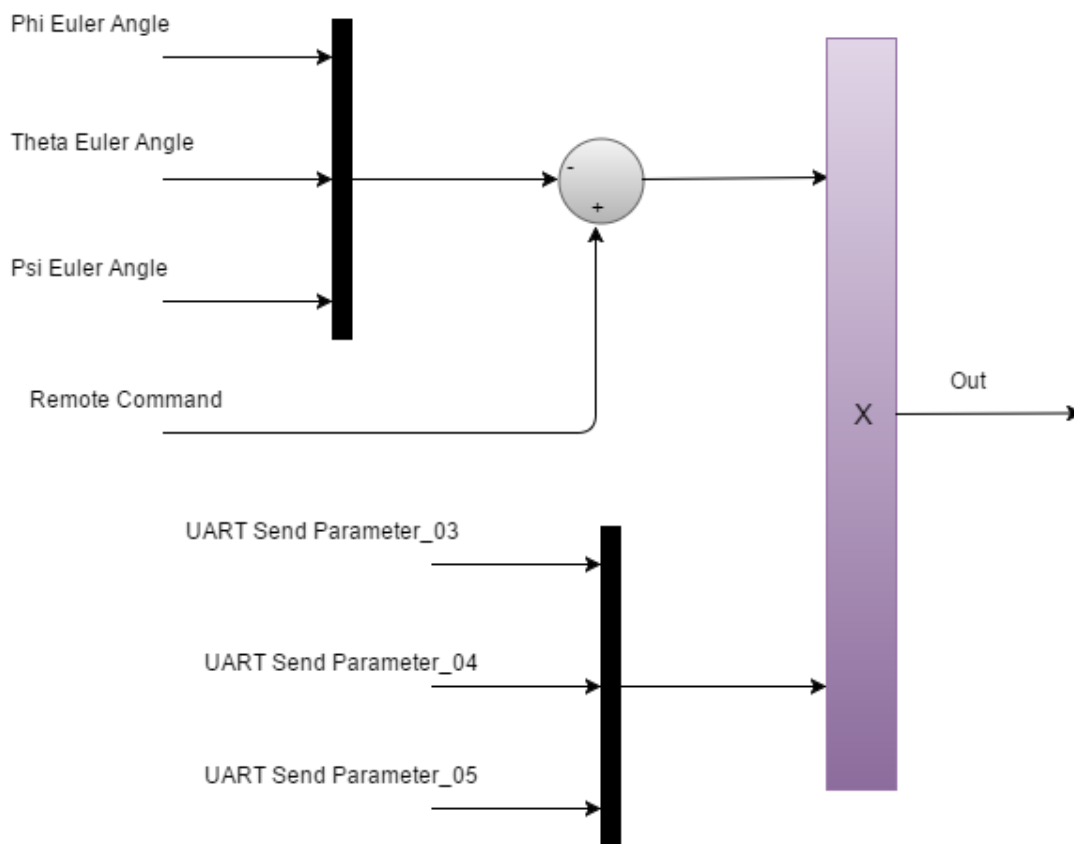


Figure 5.18. The Simulink Model inside *Rate Loop* subsystem.

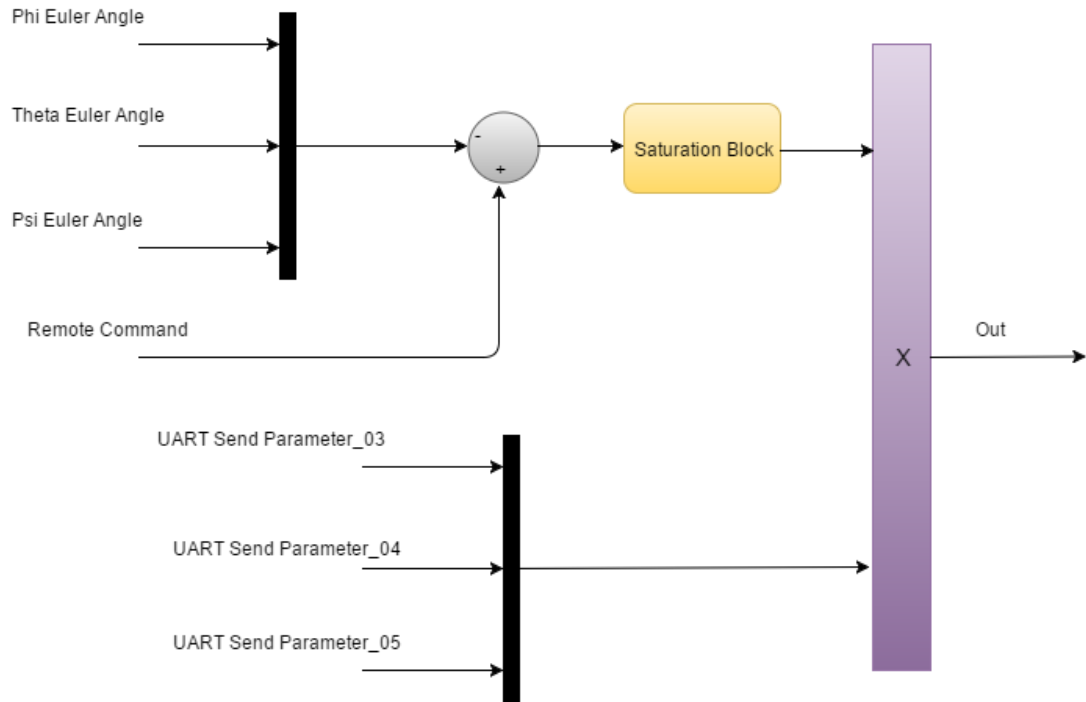


Figure 5.19. The Simulink Model inside *Attitude Loop* subsystem.

After building model and generating C code as described in Chapter 2, the code is uploaded via JTAG using AscTec Eclipse. As the quadrotor is ready to test the data visualization and logging is made by using *UART_Communication.mdl*. In this study flight test were made for both experimental setup cases and command inputs were given by remote controller.

5.4 Experimental Data and Case Comparison with Simulation Data

The flight tests were made within described experimental setups. First flights were made in test setup which allowed a limited motion in lateral, longitudinal and altitude. The experiments in this scenario were made at hover condition with rotation speed approximately 3900 rpm. The input commands were set by remote controller, and first experiment was stick roll inputs. After collecting angle, angular velocity and stick input command data, the collected data is visualized using Excel. Then roll stick

command is imported to Simulink model using *Signal Builder* tool. The Simulink model is interfaced with quadrotor model that created in V-REP, then simulation had ran and data were collected. The roll stick input and according real quadrotor measured roll angle and V-REP quadrotor model logged angle are shown in Figure 5.20.

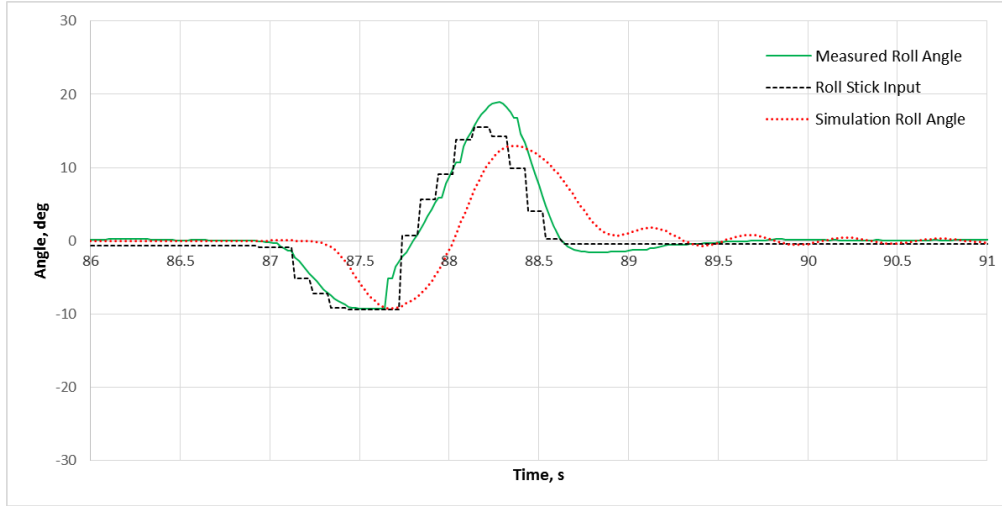


Figure 5.20. The roll angle (deg) response to roll stick input in directional motion free test setup.

From the graph it is seen that there is delay between measured and simulated roll angle. The one of the main reasons of that is the difference between real quadrotor IMU and the IMU that picked up from sensor models of V-REP. Also in V-REP scene the quadrotor is in free mode and not hanged to any tube. The moment of inertia of rod eye bearings, carbon tubes and small L profile can cause this type small changes in response dynamics. The response of roll angular velocity to this roll stick input in real quadrotor and V-REP quadrotor model is visualized in Figure 5.21. Again the delay and oscillation difference in the measurement of real and simulated roll angular velocity shows the minor differences between IMU models.

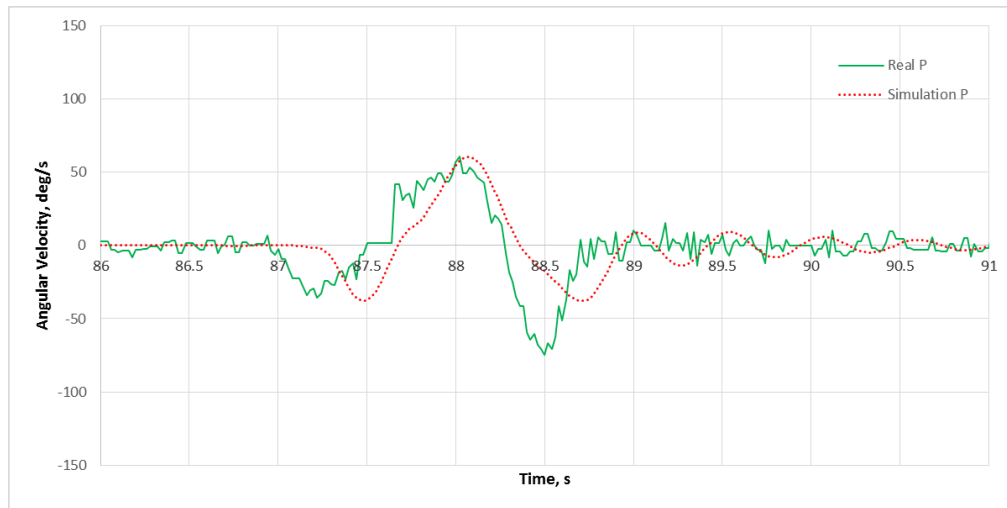


Figure 5.21. The roll rate (deg/s) response to roll stick input in directional motion free test setup.

The same experimental condition were applied and this time remote control pitch stick input were given to real quadrotor and data were collected. The collected pitch stick command was imported to Simulink interfaced V-REP quadrotor model. After running simulation pitch angle data is collected and graph has been created with real quadrotor pitch angle data, pitch stick command and V-REP modeled quadrotor pitch angle as shown in Figure 5.22.

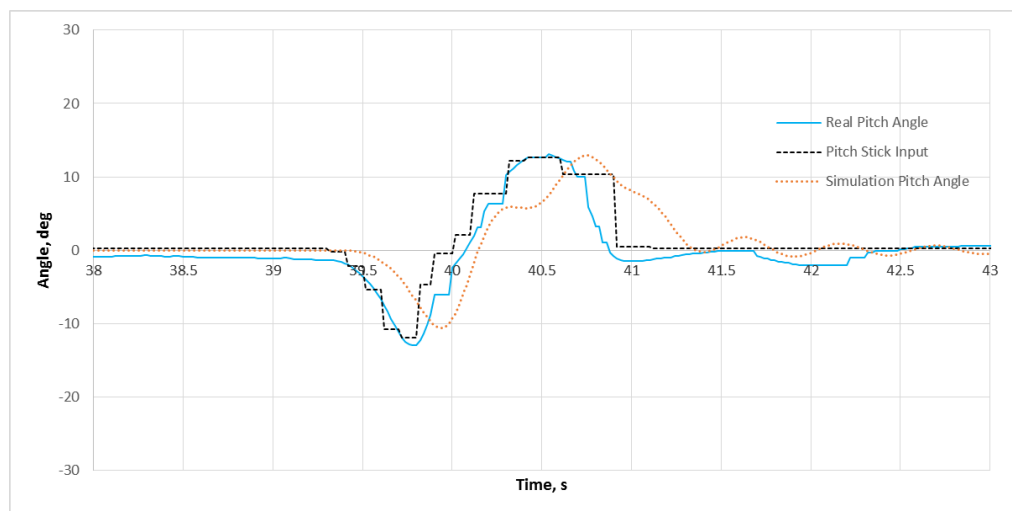


Figure 5.22. The pitch angle (deg) response to pitch stick input in directional motion free test setup.

The response of pitch angular velocity to this pitch stick input in real quadrotor and V-REP quadrotor model is visualized in Figure 5.23.

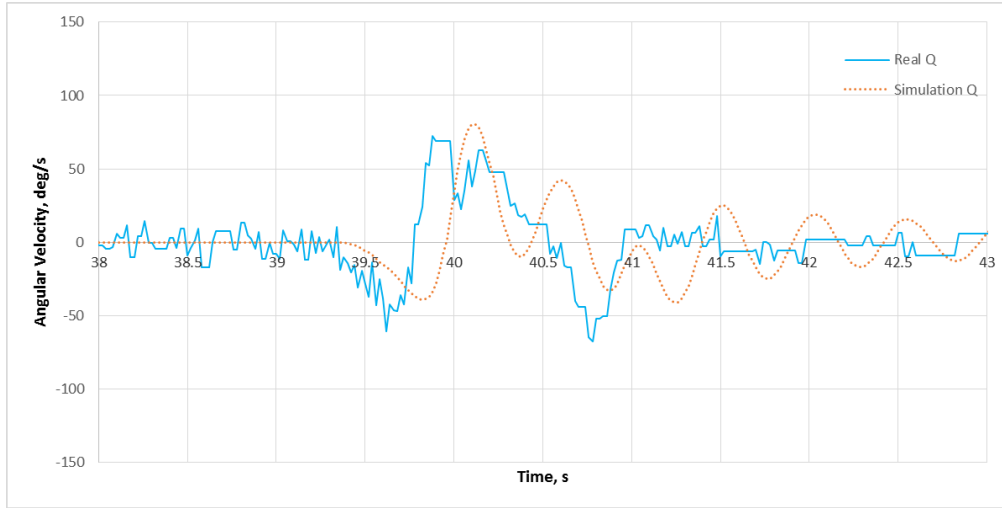


Figure 5.23. The pitch rate (deg/s) response to roll stick input in directional motion free test setup.

The same scenario experiment were made in test setup which all directional motions were fixed. The flight condition again was hover and approximate rotating speed of motors were 3900 rpm. First again roll stick input was given, the appropriate data were collected. Then collected roll stick input data were imported to Simulink and V-REP interfaced simulation was done. The comparison of collected real and simulated roll angle data and roll stick input is shown Figure 5.24. Again approximately the same amount of delay (~150 ms) and oscillations were observed. The response of roll angular velocity to this roll stick input in real quadrotor and V-REP quadrotor model can be seen in Figure 5.25. In experiment setup that all directional motions are fixed the only one rod eye bearing and small L profile can cause these minor changes in response dynamics. The difference between real and simulated IMU is presumed to be major factor between measurements.

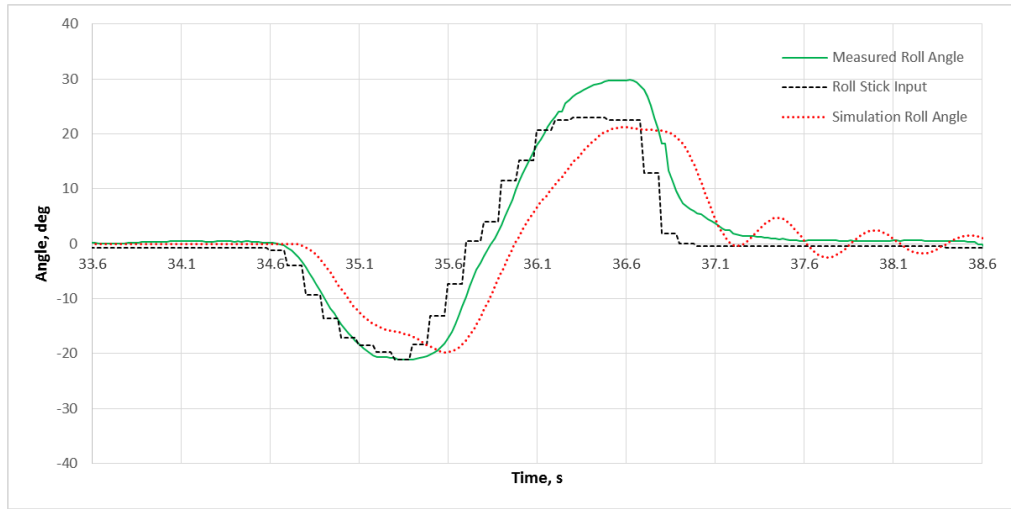


Figure 5.24. The roll angle (deg) response to roll stick input in directional motion fixed test setup.

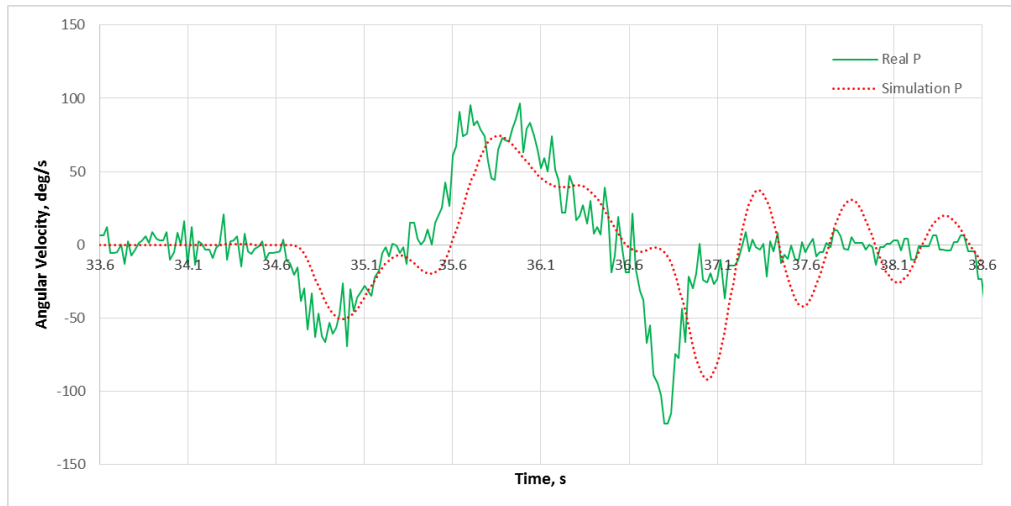


Figure 5.25. The roll rate (deg/s) response to roll stick input in directional motion fixed test setup.

The same experiment conditions in directional motion fixed experiment setup were applied and this time pitch stick input was given. From collected data pitch stick input signal was imported to Simulink model which is interfaced with V-REP built quadrotor model. The response of real and simulated pitch angles and angular rates can be seen in Figure 5.26 and in Figure 5.27 respectively.

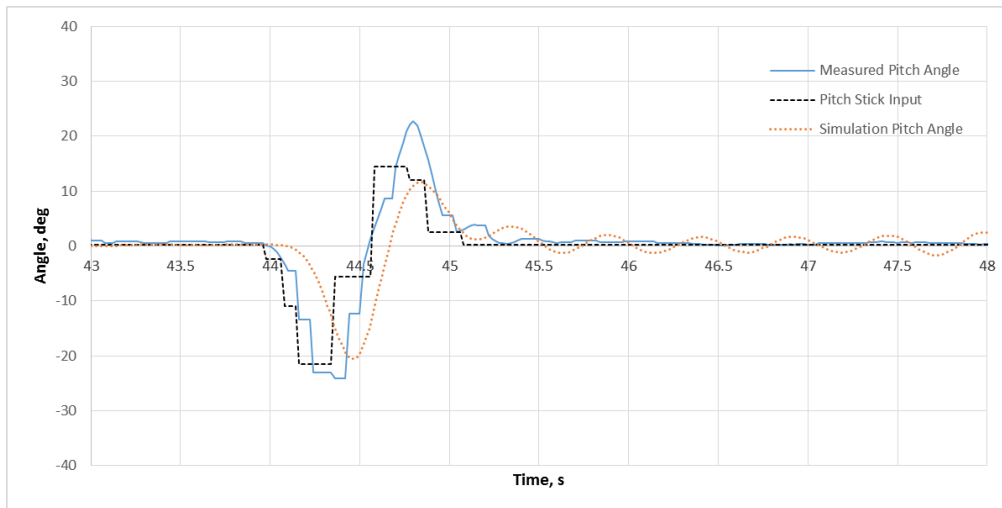


Figure 5.26. The pitch angle (deg) response to pitch stick input in directional motion fixed test setup.

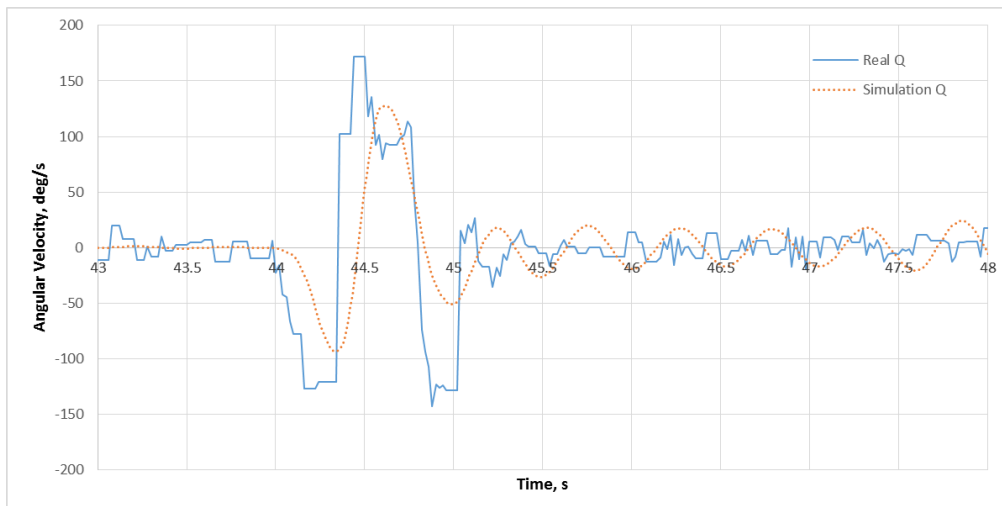


Figure 5.27. The pitch rate (deg/s) response to roll stick input in directional motion fixed test setup.

5.5 Collision Avoidance and Wall Following

After the verification of the quadrotor in V-REP environment the study has been done regarding to use the sensor capability of V-REP. According to this study the collision avoidance subject has been selected and final object is simple wall following controller design. The ultrasonic sensor has been chosen for object detection due to its application simplicity and the possibility of fast real life implementation in near future. As a sensor Maxbotix XL-MaxSonar-AE0 MB1300 has been selected [30] and the sensor is modeled in V-REP using proximity sensor specifications.



Figure 5.28. Maxbotix XL-MaxSonar-AE0 MB1300 [30].

Four ultrasonic sensors have been inserted on quadrotor model in V-REP in perpendicular manner in four directions for sensing the obstacles or wall in 2D. The fifth ultrasonic sensor has been inserted for measurement of altitude from the ground. The orientation of the sensors on quadrotor model is shown in Figure 5.29. Afterwards adding wall model into V-REP simulation environment has been completed. On the controller side in outside loop the velocity has been controlled in x and y directions. According to the commands coming from outside control loop in inner loop the roll, pitch, yaw and altitude have been controlled. In design stages of controller, obstacle avoidance and wall following algorithms, step by step implementations and trials have been done in Simulink/Matlab interfaced V-REP environment. This type of implementation shows the usefulness of 3D physically modeled environment (V-REP) and easy design and implementation of controller platform (Simulink/Matlab).

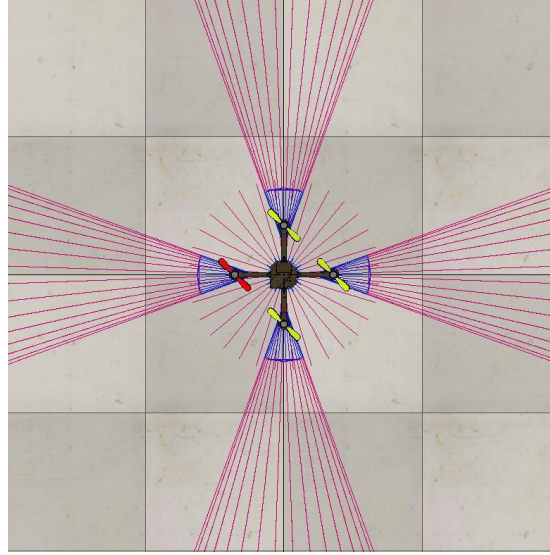


Figure 5.29. Ultrasonic sensor orientation on quadrotor in V-REP

The velocity data in x and y directions has been gathered from four ultrasonic sensors in V-REP LUA script. The velocity in one direction has been calculated by dividing ultrasonic distance measurement difference between current and previous loop to simulation time step. The range of ultrasonic sensor used in this study is 7.65 m and it has 1 cm resolution. In velocity calculation algorithm quadrotor assumes middle of the room as origin, if the quadrotor is in positive x direction side it uses the measurement of ultrasonic sensor that is mounted in that direction and if it is in negative x direction side it uses the measurement of ultrasonic sensor that is mounted in that direction. The same procedure has been applied to y direction also. The velocity calculation algorithm considers the roll, pitch and yaw angles corrections while evaluating the measured distances.

In the first step of the development process aim was to make velocity control and stop after referenced wall distance. The initial command was pitch angle that to travel in positive x direction. The pitch angle command was the function of the distance to the wall and decreased as it got closer to the wall. After referenced distance to the wall was reached, the quadrotor slowed down and stopped with referenced constant distance (3 m) to the wall. The velocity control was done using PD controller. The

change of roll, pitch, and yaw angles due to velocity command and response of the motors can be seen in figures below.

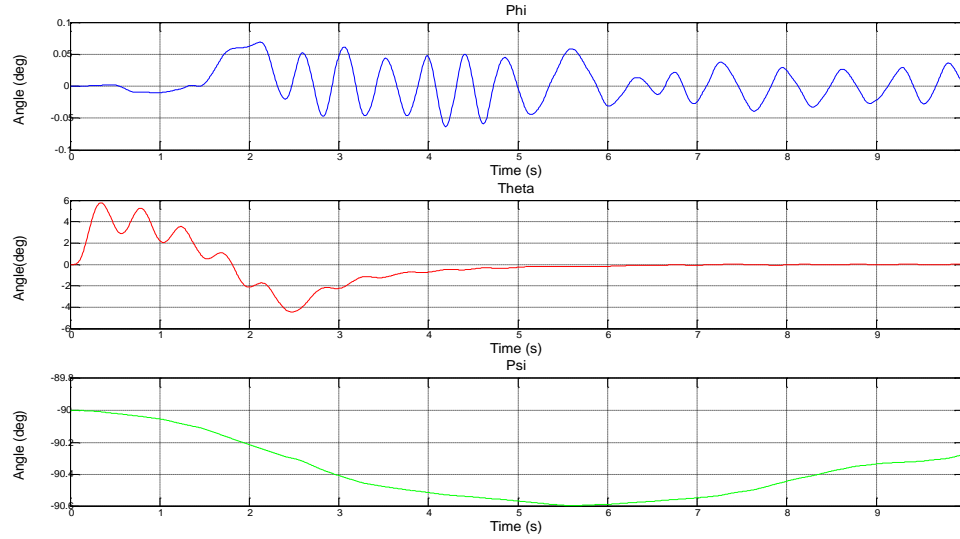


Figure 5.30. Roll, pitch and yaw angles of quadrotor during free flight and obstacle detection.

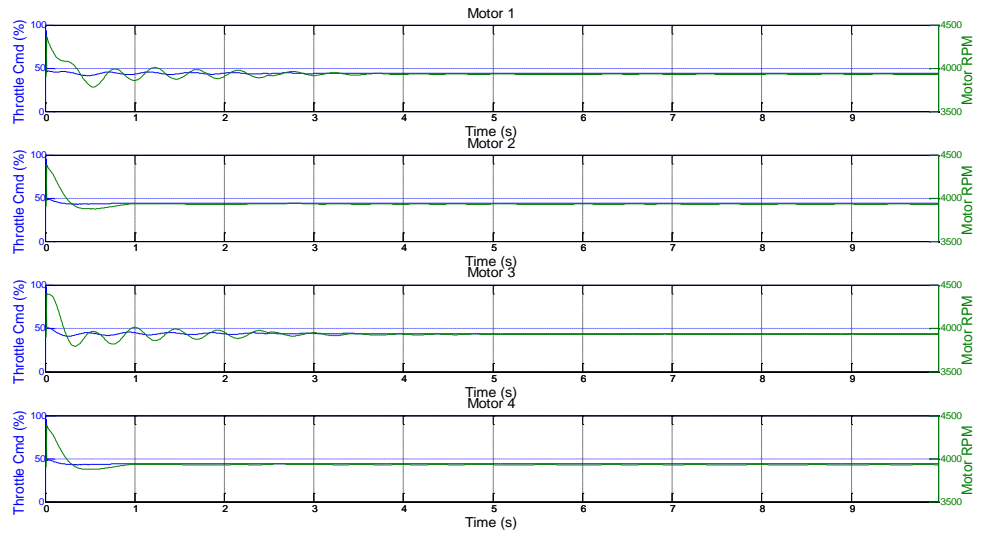


Figure 5.31. Motor throttle command (%) and rotation speed (rpm) during free flight and obstacle detection.

As it is shown in Figure 5.32 the x direction velocity first increased in free flight, and decreased after obstacle detection and set to zero finally. In Figure 5.33 the position states of quadrotor and in Figure 5.34 the change of angular rates are shown.

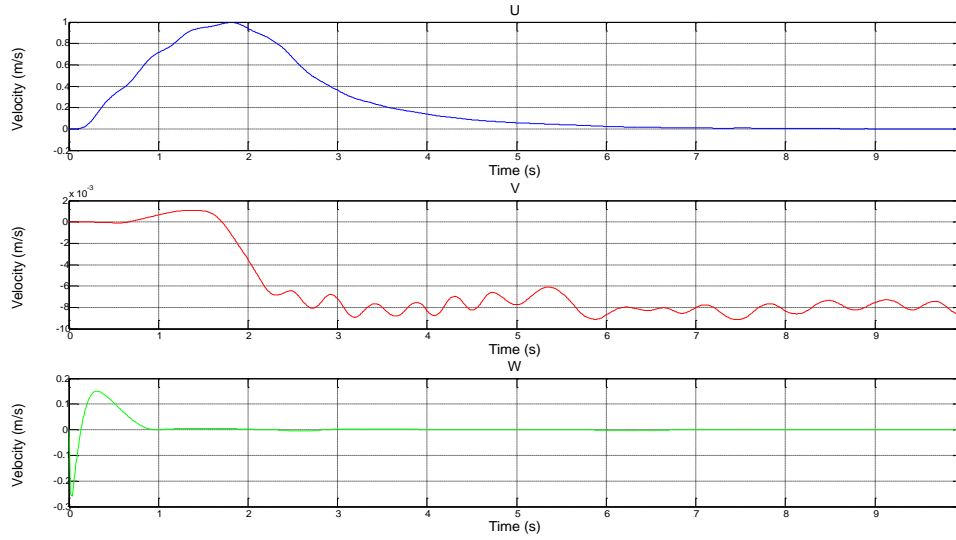


Figure 5.32. The u , v and w velocities during free flight and obstacle detection.

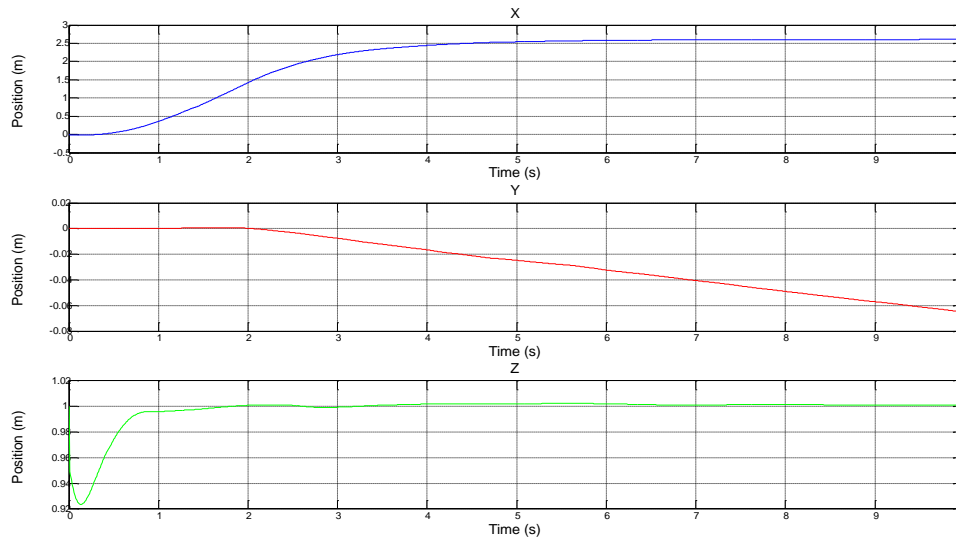


Figure 5.33. The x , y and z positions of the quadrotor during free flight and obstacle detection.

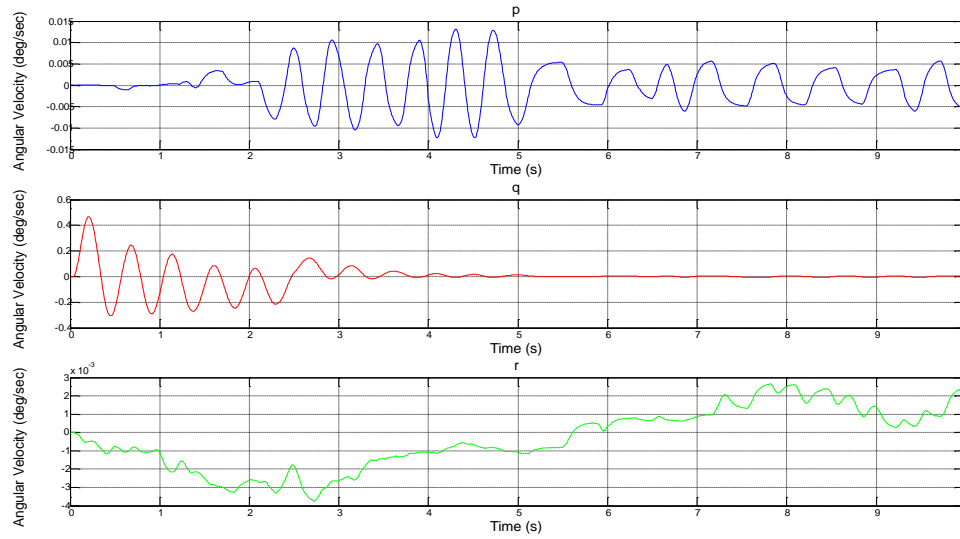


Figure 5.34. Roll, pitch and yaw angular rates change during free flight and obstacle detection.

After challenging the wall detection and succeed to stop the next aim was the wall following with quadrotor equipped with four ultrasonic sensors in four directions. The 10 m to 10 m empty room was created in V-REP and the middle of the room assumed as the origin (Figure 5.35)

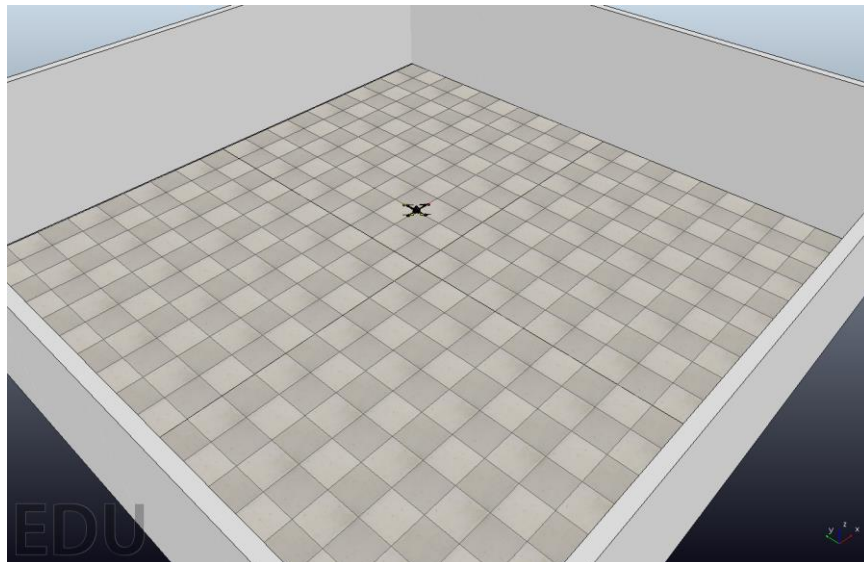


Figure 5.35. The 10 m to 10 m room in V-REP

Using four sensor data the logic algorithm was developed with five states. The algorithm developed in Simulink gets roll, pitch and yaw angles, ultrasonic sensors data and velocities from V-REP. The general scheme of algorithm is shown in Figure 5.36.

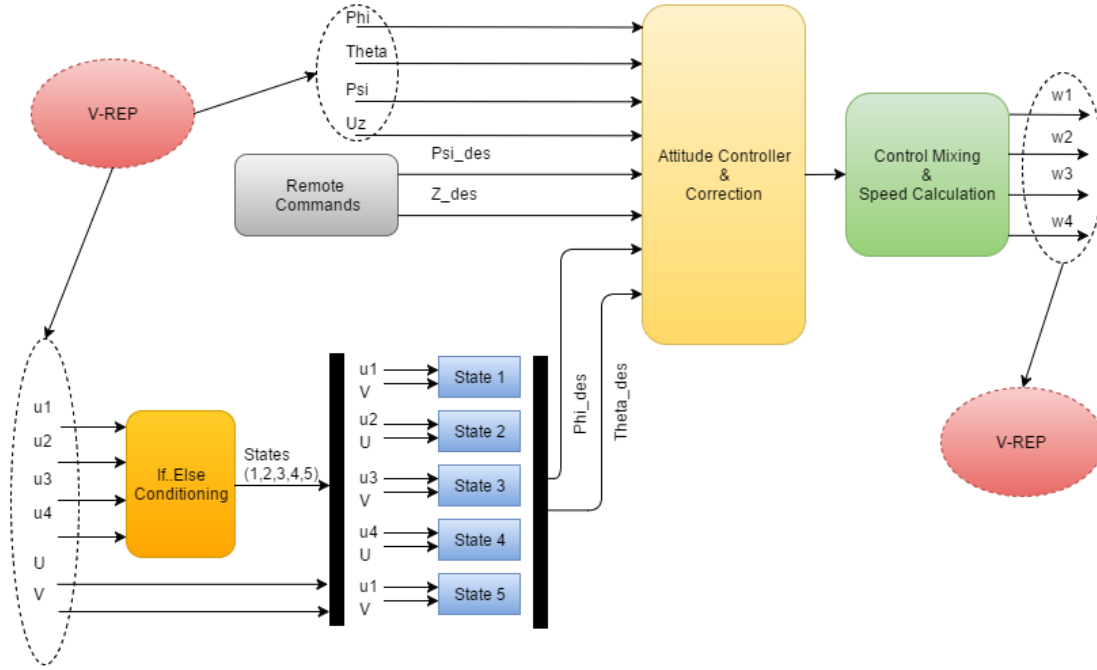


Figure 5.36. The general scheme of wall following mode with varying travel speed

In *State 1* the quadrotor is in the middle area of the room and it is in free flight mode. In free flight mode the quadrotor travel in positive x direction with pitch angle command and sets its y direction velocity to zero by PD controller. The pitch angle command is the function of the distance to the wall that measured by the ultrasonic sensor mounted on move direction and decreases as it got closer to the wall (Figure 5.37). After the referenced 3 m wall distance is reached algorithm switches to *State 2*. In *State 2* this time the quadrotor starts to move in negative y direction and sets its x direction velocity to zero by PD controller. The roll angle command like in *State 1* is the function of the distance to the wall that measured by the ultrasonic sensor mounted on move direction and decreases as it got closer to the wall (Figure 5.38). The algorithm continues with the same logic by following *State 3*, *State 4* and *State 5*. The controllers inside the *State 3* and *State 4* are like *State 1* and *State 2* respectively with

opposite movement direction and ultrasonic sensors. The controller inside the *State 5* and *State 1* are same.

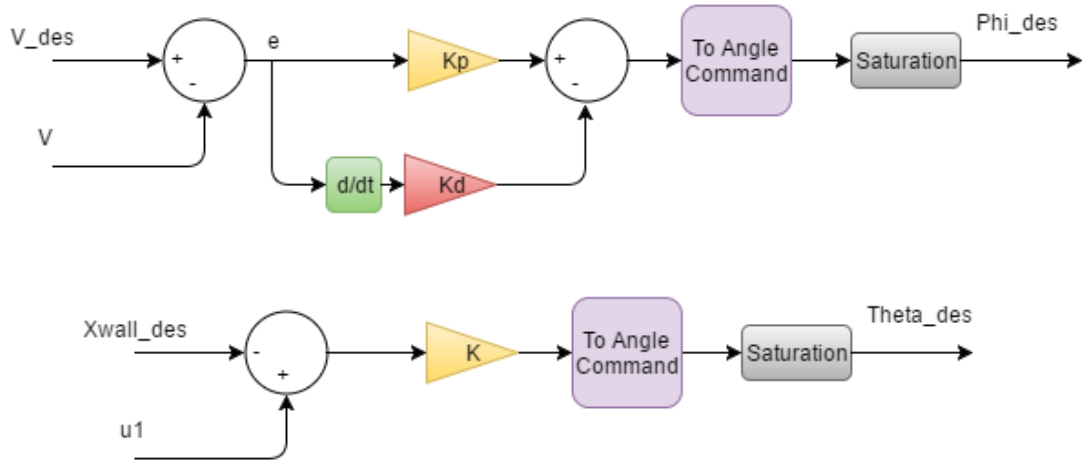


Figure 5.37. The controller inside *State 1*.

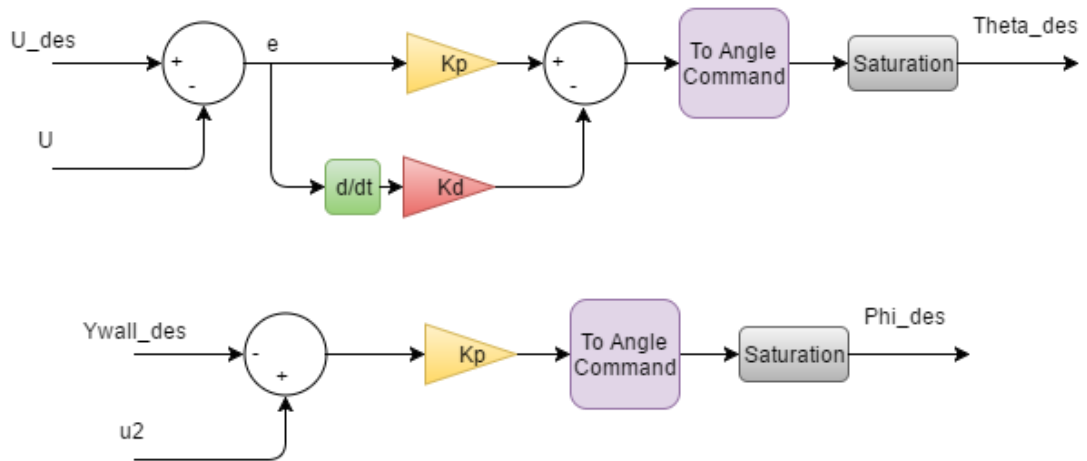


Figure 5.38. The controller inside *State 2*.

Afterwards development of wall following algorithm, it was implemented in Simulink interfaced V-REP environment. The 3D and 2D movement trajectory of quadrotor are shown in Figure 5.39 and Figure 5.40 respectively. From trajectories it can be seen that the quadrotor follows the wall and avoid collisions but it does not keep its distance to walls constant.

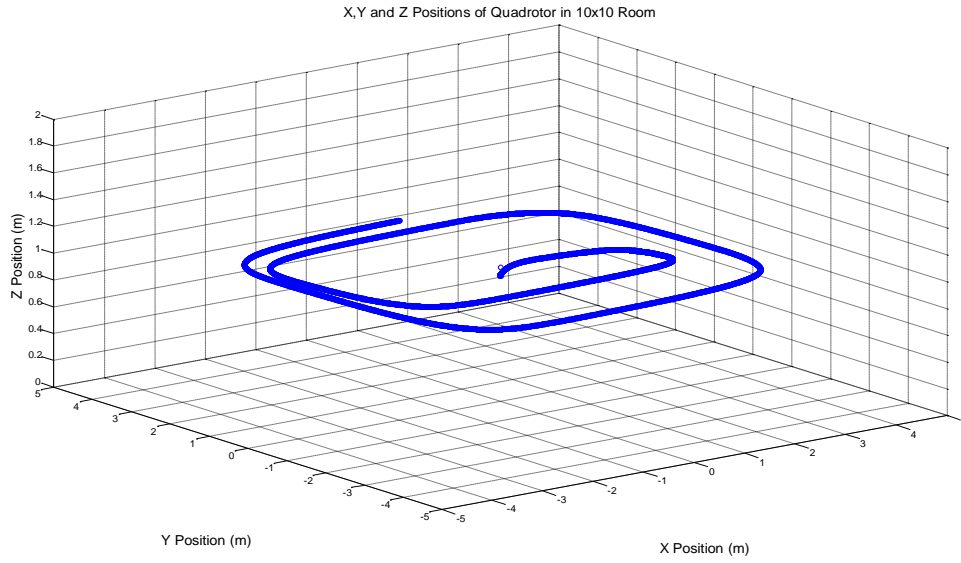


Figure 5.39. 3D trajectory of wall following quadrotor in 10 m to 10 m room with varying travel speed.

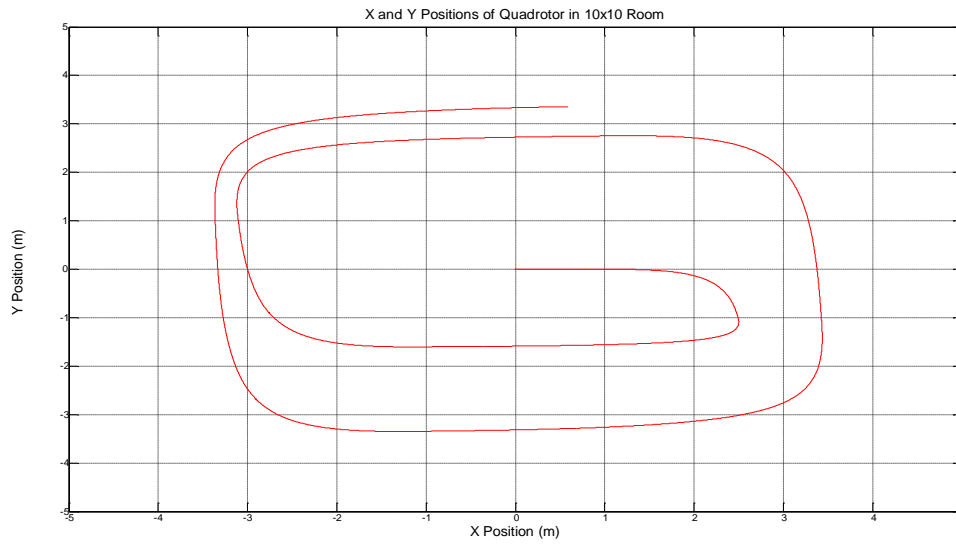


Figure 5.40. 2D trajectory of wall following quadrotor in 10 m to 10 m room with varying travel speed.

The change of roll, pitch and yaw angles and angular rates according to the trajectory shown above are shown in Figure 5.41 and Figure 5.42 respectively.

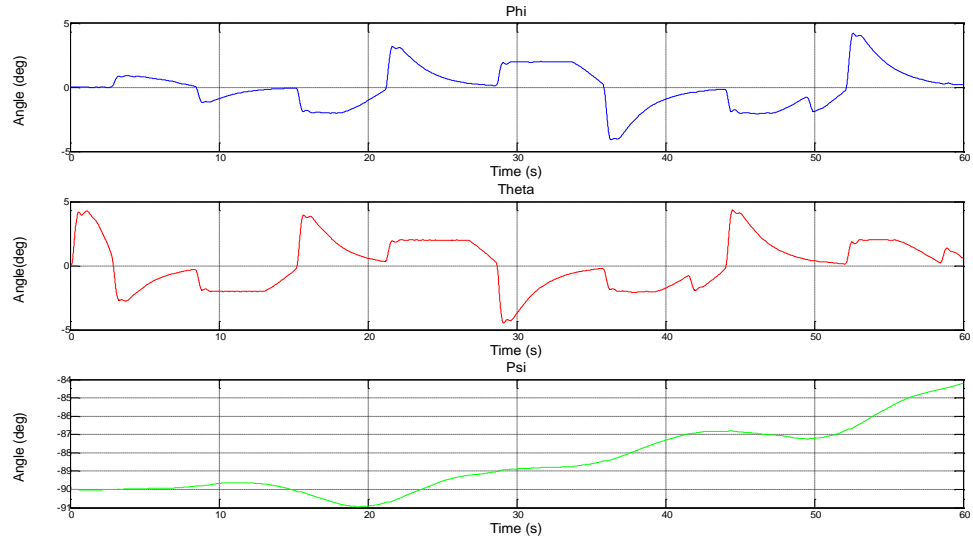


Figure 5.41. Roll, pitch and yaw angles of wall following quadrotor in 10 m to 10 m room with varying travel speed.

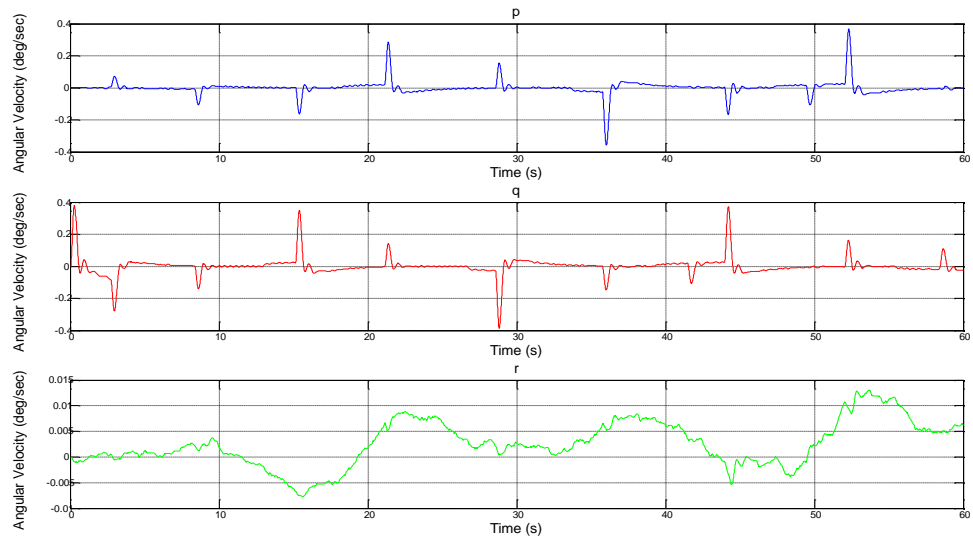


Figure 5.42. Roll, pitch and yaw angular rates change of wall following quadrotor in 10 m to 10 m room with varying travel speed.

The variation of velocities in x and y directions can be observed from Figure 5.43. The positions of quadrotor response to these velocity variations are shown in Figure 5.44.

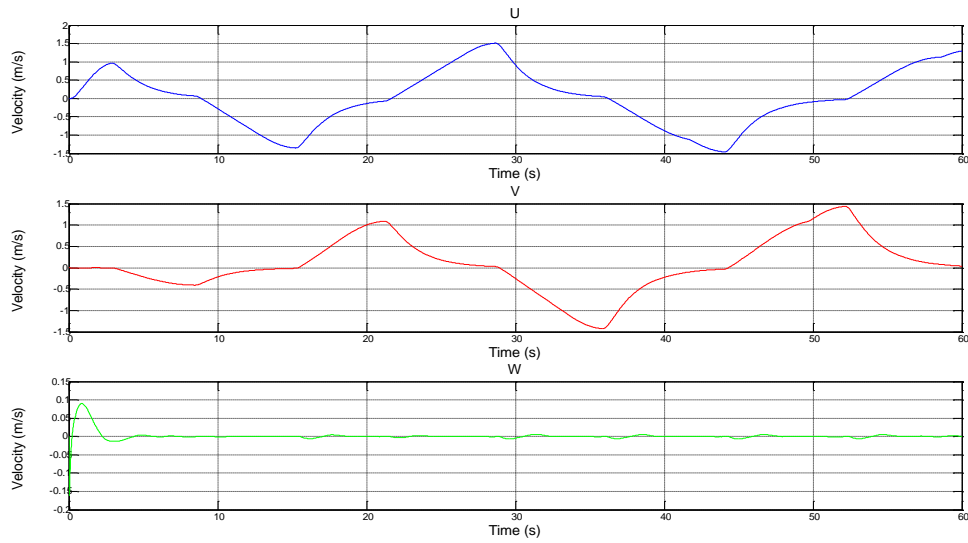


Figure 5.43. The u , v and w velocities of wall following quadrotor in 10 m to 10 m room with varying travel speed.

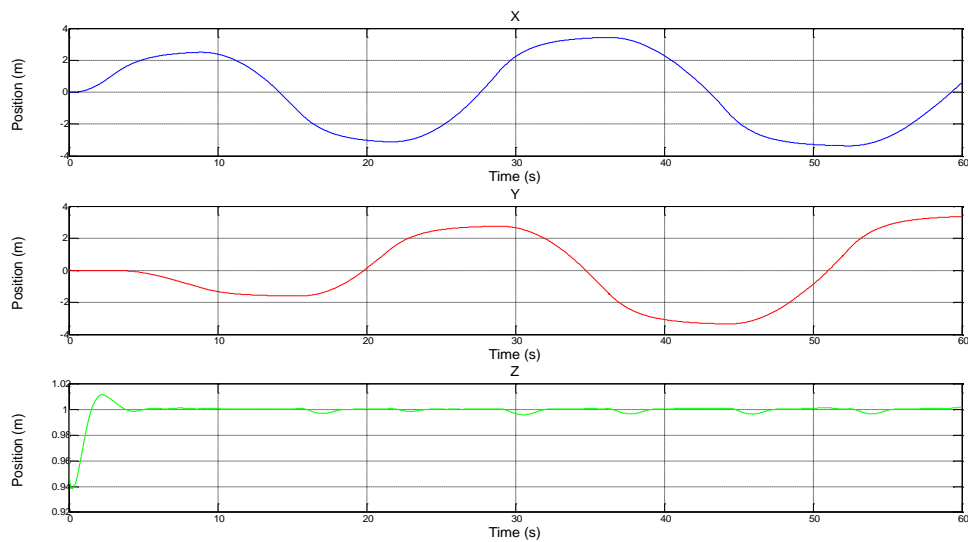


Figure 5.44. The x , y and z positions of wall following quadrotor in 10 m to 10 m room with varying travel speed.

The response of the motors according this varying velocity travel mode is shown in Figure 5.45.

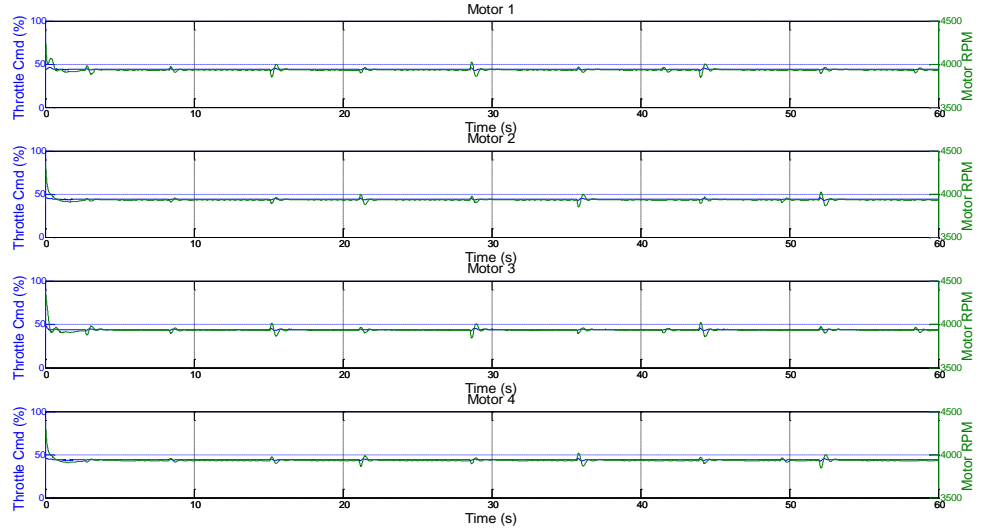


Figure 5.45. Motor throttle command (%) and rotation speed (rpm) of wall following quadrotor in 10 m to 10 m room with varying travel speed.

The final development objective was again following the wall with approximately 3 m constant distance to the wall. The control logic is similar with previous one but this time velocity commands are constant, and in state switches the set value of velocity commands change. The general scheme of the developed algorithm is shown in Figure 5.46. The *If..Else Conditioning* block switch states according to the distance to the wall and outputs of block are velocity commands in x and y directions. The *Velocity Controller* block contains two PD controller for u and v velocity commands. The scheme of controllers is shown in Figure 5.47.

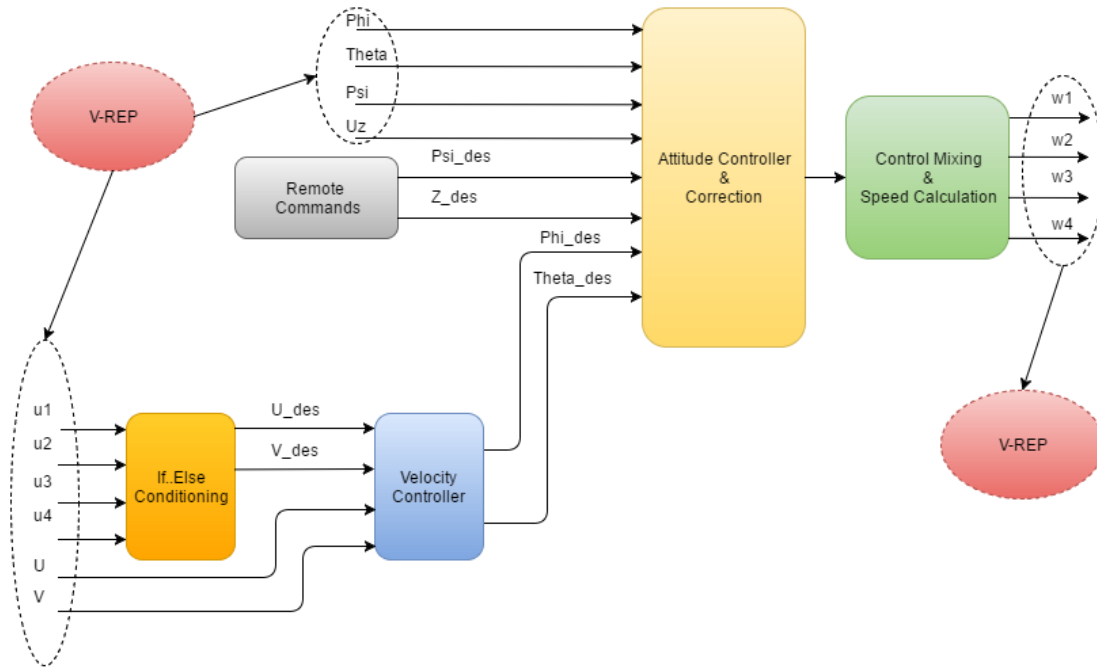


Figure 5.46. The general scheme of wall following mode with constant distance to the wall.

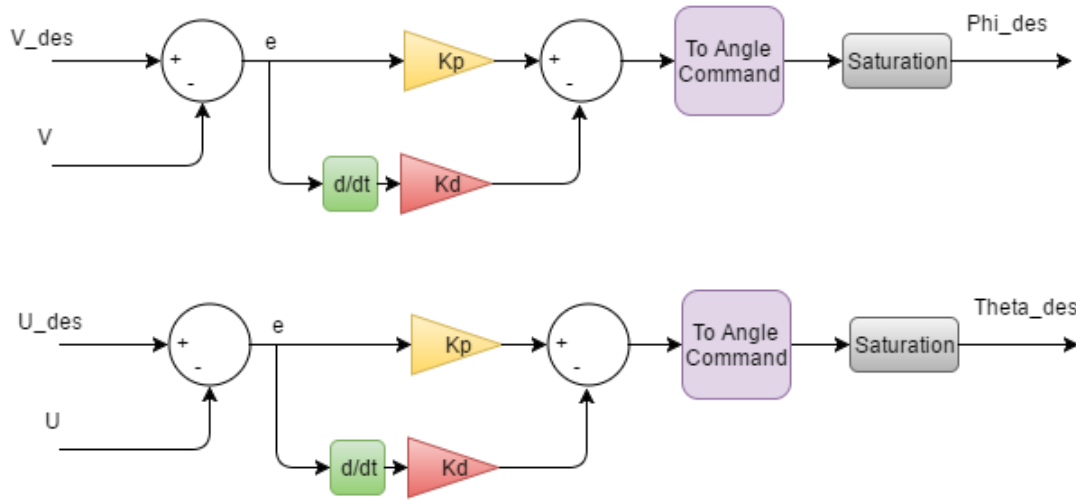


Figure 5.47. The PD controller scheme inside *Velocity Controller*.

Afterwards implementation of developed algorithm to Simulink interfaced V-REP the simulation results have been gathered. The 3D and 2D move trajectories of quadrotor inside a 10 to 10 m room are shown in Figure 5.48 and Figure 5.49 respectively. It can be observed that the quadrotor is approximately in constant distance to the wall.

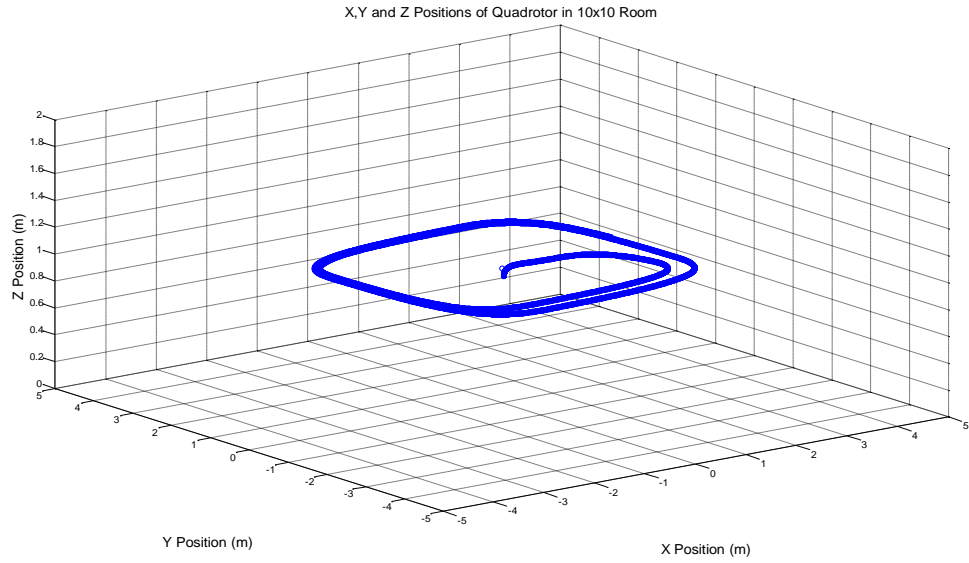


Figure 5.48. 3D trajectory of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

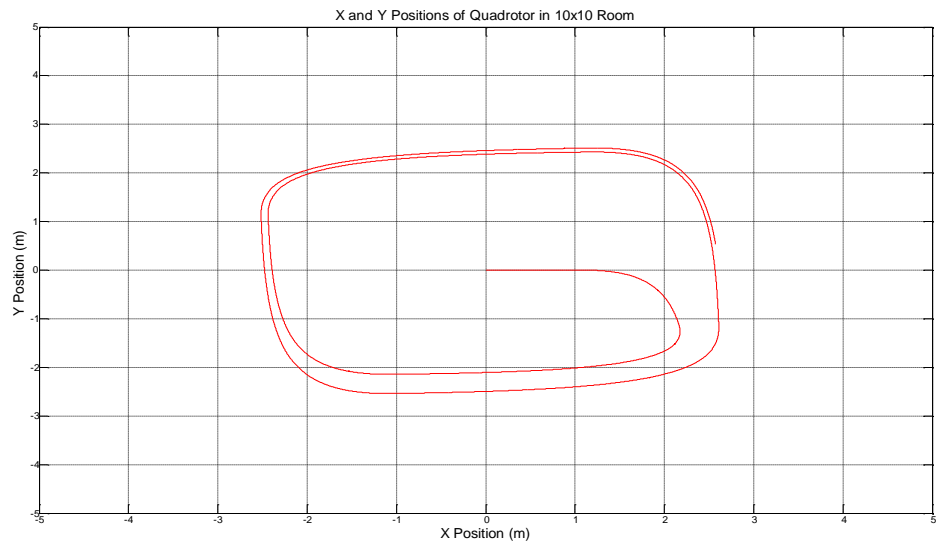


Figure 5.49. 2D trajectory of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

The change of roll, pitch and yaw angles and angular rates according to the trajectory shown above are shown in Figure 5.50 and Figure 5.51 respectively.

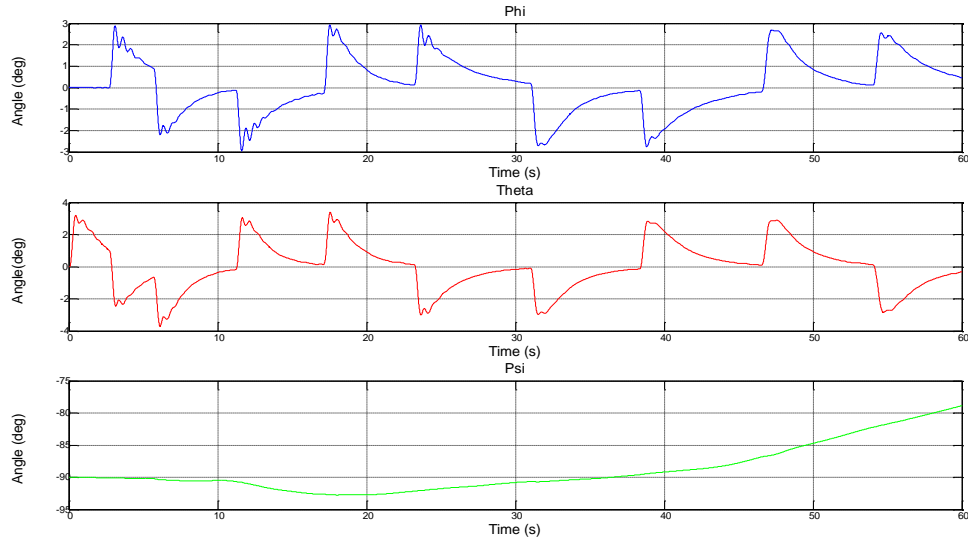


Figure 5.50. Roll, pitch and yaw angles of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

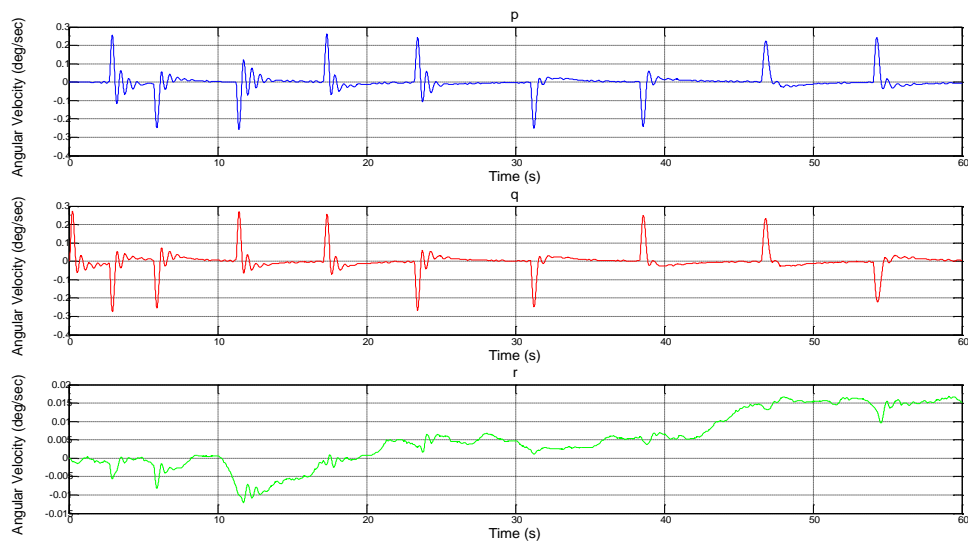


Figure 5.51. Roll, pitch and yaw angular rates change of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

The constant and repetitive switches of velocities in x and y directions can be observed from Figure 5.52. The positions of quadrotor response to these velocities are shown in Figure 5.53.

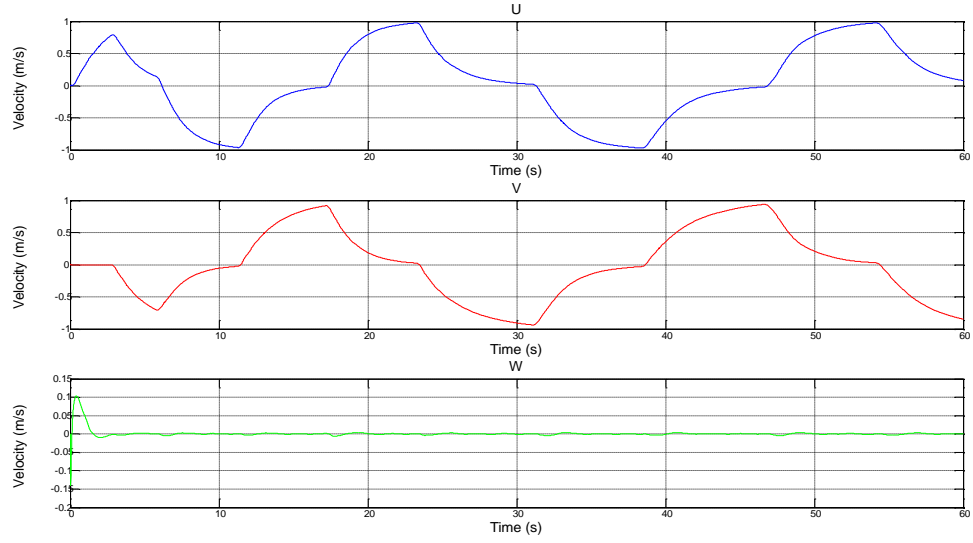


Figure 5.52. The u , v and w velocities of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

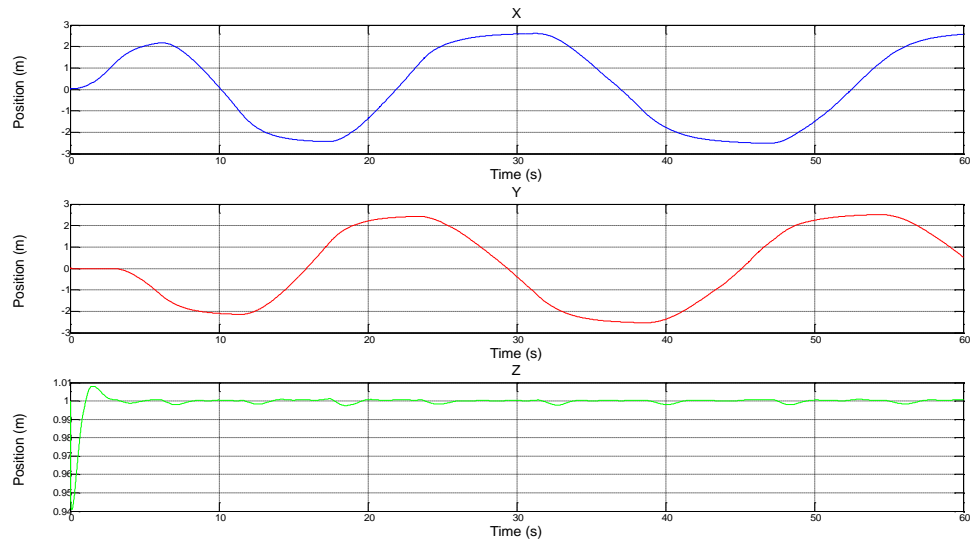


Figure 5.53. The x , y and z positions of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

The response of the motors according to this constant distance travel mode is shown in Figure 5.54

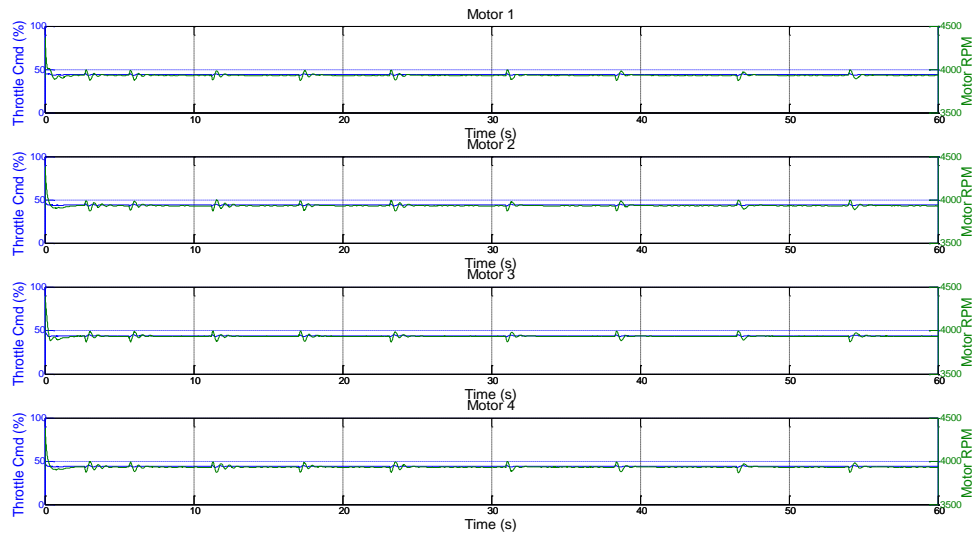


Figure 5.54. Motor throttle command (%) and rotation speed (rpm) of wall following quadrotor holding constant distance to the wall in 10 m to 10 m room.

CHAPTER 6

CONCLUSION AND FUTURE WORK

In this thesis the easy use 3-D simulator is designed for the test of variety control algorithms in AscTec Hummingbird quadrotor. First the dynamic model of the quadrotor is derived and PID controller is designed in Simulink/Matlab platform. Afterwards propeller model is created in V-REP relying on real test data and experimental transfer function of motor propeller. The 3-D model of quadrotor is also designed and accelerometer, gyroscope sensors, and GPS unit are added to quadrotor model in V-REP. Then the controller in Simulink/Matlab is interfaced with quadrotor model in V-REP and three dimensional physical environment interacted tests become easier in this combined simulator. The first flight tests have been made in simulator. In first case doublet input is given and the stabilization of vehicle in simulator is satisfied in hover condition. Next step quadrotor is taken off from ground to commanded height and again doublet input command is given and stabilization is satisfied. In this simulation ground disturbance is modeled where random moved air particles of V-REP included to propeller model. Then two case experimental setup has been built for real quadrotor test flights. In first case experimental setup the directional movements were settled free and input commands were given from remote controller, and data were collected. Then stick commands were imported to Simulink interfaced V-REP quadrotor model and regarding data were collected. In comparison of real and simulated there approximately 150 ms delay was observed. One possible reason is the difference between real and simulated IMU model. The next possible reason is addition of some stuff on real quadrotor model due to experimental setup which can effect dynamic response. It must be mentioned that simulations in V-REP was done in free flight hover conditions. In second case experimental setup the directional motions were fixed only rotational motions were allowed. The same test procedure was applied.

The results were similar and again approximately 150 ms delay was observed. As a result the 3-D Simulink interfaced physical simulator for quadrotor is achieved and its experimental validation has been done. The collision avoidance and wall following studies were carried to show the capabilities of simulator infrastructure which is the main object of this thesis. Ultrasonic distance sensors have been used for object or wall detection. Step by step controller algorithm has been developed totally in safe and easy manner. Using PD type velocity controller the wall following of quadrotor with approximately constant distance to the wall is achieved.

For future author can recommend addition of more detailed IMU model. Other classical and nonlinear control algorithms can be implemented in this simulator. Adding 2-D, 3-D vision sensor can create chance for localization and mapping algorithm tests. Advanced collision avoidance algorithms could also be developed in this simulator infrastructure. After developing these algorithms the costly sensors can be achieved and simulator based developed algorithms can be implemented on real quadrotor.

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