Design and development of Intelligent Mobile Robots (IMRs) for disaster mitigation and firefighting

Second Deliverable

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Chapter 1. Introduction

This report is the second deliverable for the National ICTR&D funded research project titled "Design and development of Intelligent Mobile Robots (IMRs) for disaster mitigation and firefighting".

Chapter 2. Mechanical Structure of the IMR

2.1 Introduction

Mechanical Structure of IMR is being developed alongside the electronics and the power circuitry. As the mechanical structure design relies on all of the former developments. i.e. sensor placements, number of sensors, number of motors, tyre type, size dimensions, inner space requirements, power supply – all these parameters need to be finalized before the hardware design can be finalized. Hence the hardware design process is in a very variable state.

Additionally, the IMR hardware needs to be relaible enough to withstand high temperatures and some impact on the body. The body also needs to be somewhat waterproof to safeguard the inner batteries, motors and other circuitry, for these reasons, the IMR hardware design is broken into multiple stages, with the first stage being the development of a basic hardware chassis, which will serve as a testing ground to refine the final design and the actual IMR hardware will be developed ONLY after the initial beta hardware is tested thoroughly.

2.2 Initial beta hardware

The initial beta hardware is being designed to be manually controlled with a tread based design for movement and internal space for batteries and power and RF circuitry. On the top side of the robot a grasping arm will be fixed which will be used to test the load carrying and pulling ability of the robot, to see if it can even pull the hose or if we need to do changes to the design specs of the robot. Below pictures are provided of the development phases of the IMR robot hardware.

2.3 Specifications of the IMR Robot

The IMR Robot specifications are currently defined in terms of the capabilities the robot needs to have, these capabilities are then translated into the robot specifications like overall dimensions, weight, number of sensors and such. The capabilities of the robot are listed below followed by a list of the current specifications on paper.

2.3.1 Capabilities of IMR Robots

The robot capabilities as laid out in the project proposal are further clarified and listed below with specific details of the robot functionalities which we will be implementing as part of this project.

a) Should be able to traverse a rough plain autonomously
b) Should be able to establish wireless communication with other robot and with the base station
c) Should be able to develop a map of the surrounding area

2.4 IMR Robot 3D Model

For the current work being done on the IMR beta robot chassis, the 3D models are under development as the work is in progression. In this manner any design changes will be integrated into the 3D model. The preferred method of work by machine shops in Pakistan is that the work is carried out with consideration of the available materials, tools and facilities. Our robot chassis is being developed at a Machine shop in the Korangi industrial area of Karachi, with some of the work being done at the KIET Mechanical Workshop as well.

2.5 Grasping Arm for Hose

A grasping arm for water hose will be affixed on top for the robot which will allow the robot to douse any nearby fires with water or other chemicals as needed. This gripping arm is being designed to handle a standard size hose which is carried by fire fighters similar to what is available locally at the fire stations and in fire tenders. This arm is being designed to be able to move in a vertical manner, as the horizontal motion will be provided by the robot body itself.

Chapter 3. Electronic Circuitry of the IMR

3.1 IMR Circuit Layout

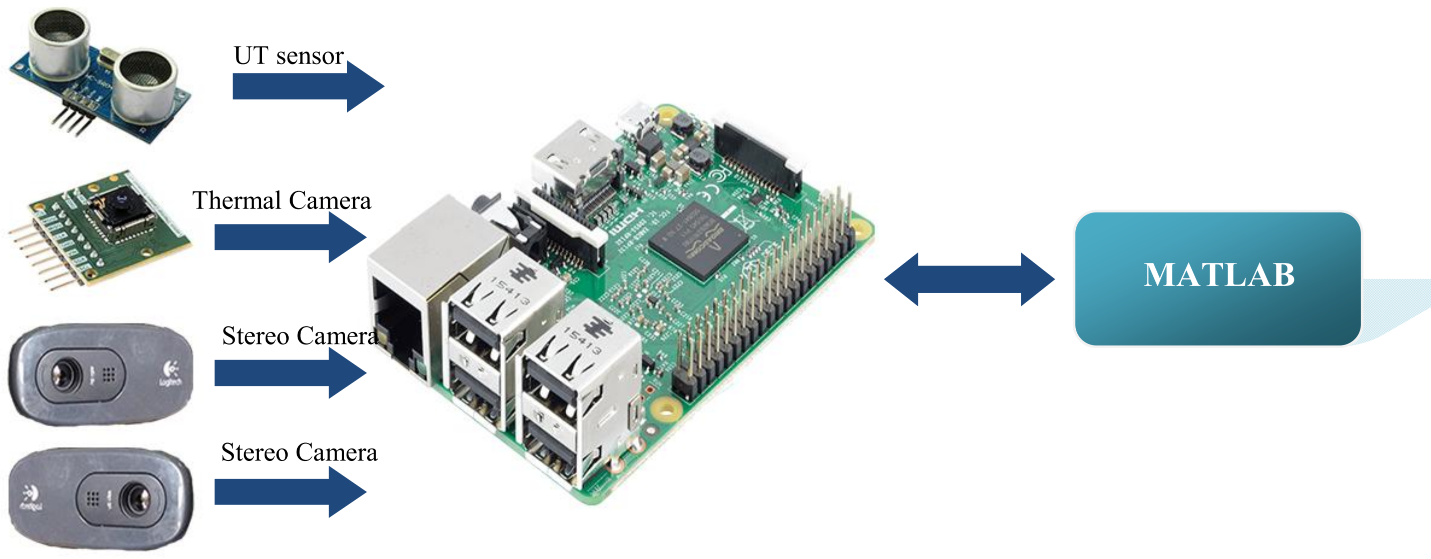
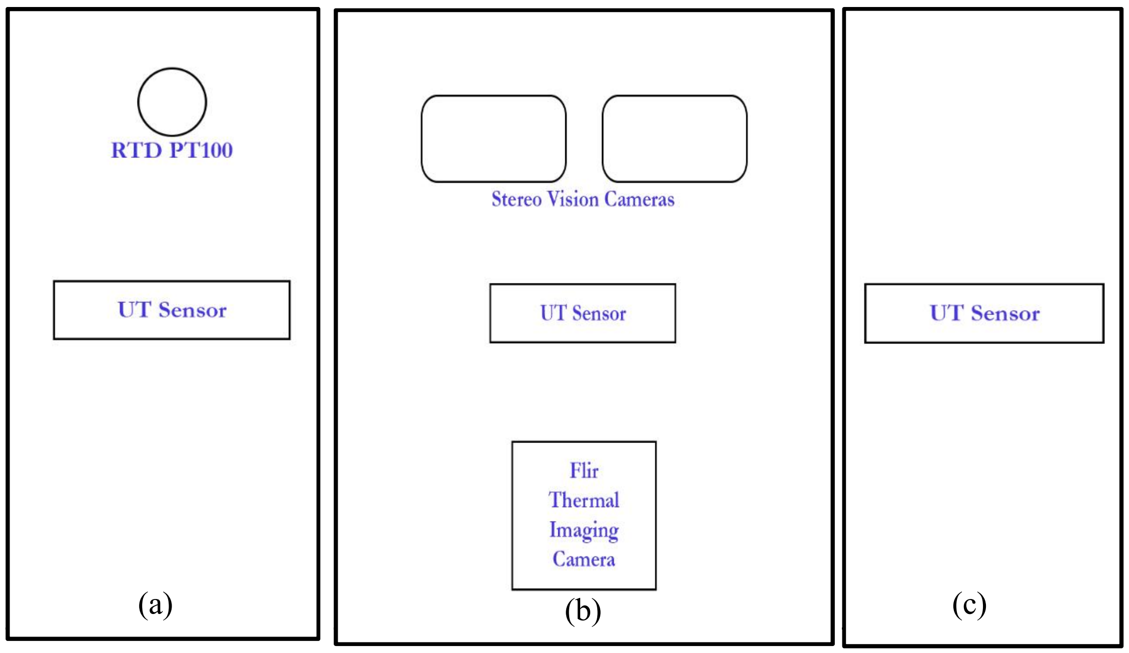


Figure 1 Block Diagram of IMR Circuit Layout

3.2 Sensor placement on the IMR



Where,

(a) => Right Side view of sensors on IMR
(b) => Front Side view of sensors on IMR
(c) => Left Side view of sensors on IMR

3.2.1 UT Sensors

Ultrasonic Senor (HC-SR04) are distance measuring sensors. They are designed to measure distance between source and target by the use of ultrasonic waves. Working voltage of these sensors is $5V_{dc}$. Their distance measuring range is from 2cm to 500cm with a resolution of approximately 0.3cm. These ultrasonic sensors operate at frequency of 40kHz and have cycle period of 50msec. these sensors do not cause disturbance since they are inaudible to human ear.

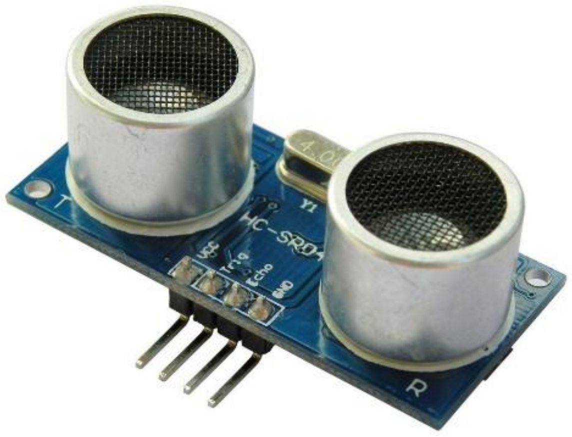


Figure 2 UT Sensor

3.2.1.1 Working of Ultrasonic Sensor (HC-SR04):

Ultrasonic Sensor uses a sonar for measuring the distance between source and obstacle with high accuracy and stability.

Ultrasonic Sensor (HC-SR04) has four pins which are as follows,

- **GND**-Ground
- **VCC**-Input power of 5V
- **ECHO**-Output ECHO
- **TRIG**-Input TRIG

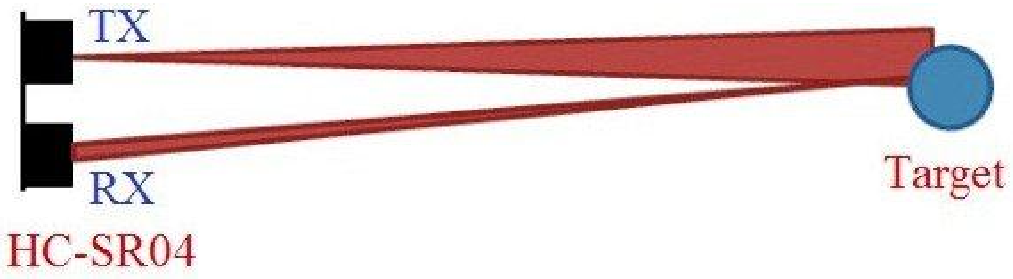


Figure 3 Working of UT Sensor

To make ultrasonic sensor working, we have to go with the following steps

1. TRIG input of Ultrasonic sensor requires High signal for atleast 10uS. That signal should be provided.
2. This enables the sensor to transmit ultrasonic wave at 40KHz.
3. In case of any obstacle in-front of sensor, ultrasonic wave will be reflected back
4. If signal comes back, the ECHO output of the sensor will then be high for a duration of time which is taken for sending and receiving ultrasonic signals.

3.2.1.2 Ultrasonic Sensor (HC-SR04) interface with raspberry pi:

3.2.1.2.1 Voltage Divider:

The output at ECHO pin of ultrasonic sensor is of 5V. While the GPIO pin of raspberry pi is rated at 3.3V. Therefore, 5V cannot be directly fed to GPIO pin of raspberry pi. To overcome this issue, we have to use a voltage divider circuit with appropriate resistors such that the output voltage can be brought down to 3.3V. This can be done using the following equation of voltage divider rule.

$$V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right)$$

3.2.1.2.2 Distance Calculation:

Since the time taken by the pulse is the time in which pulse starts from source strike the obstacle and then comes back and receive by sink (receiver) of UT sensor. Therefore the time which we need in our calculation will be half of the total time taken.

$$Distance = Speed \times \frac{Time}{2}$$

3.2.1.2.3 Circuit Assembling with raspberry pi:

For connecting Ultrasonic Sensor (HC-SR04) with raspberry pi, we have used four pins of raspberry pi:

- GPIO 5V (pin 2)
- GPIO GND (Pin 6)
- GPIO 23 (Pin 16)
- GPIO 24 (Pin 18)

These pins of raspberry pi were then connected to Ultrasonic sensor (HC-SR04) using the following detailed circuitry. Where, the values of resistors $R_1$and R_2were calculated using the voltage divider rule keeping V_{out}as 3.3V.

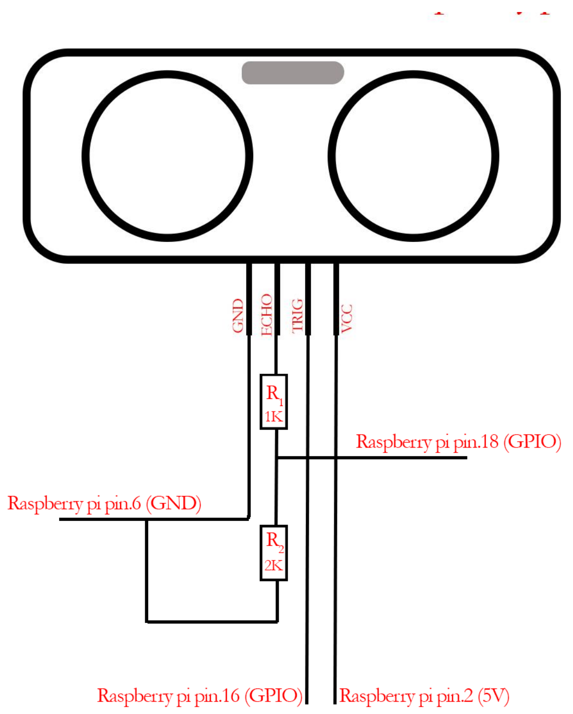


Figure 4 UT sensor interface with raspberry pi

The circuit was then designed on the breadboard for prototype development for ultrasonic sensor integration on raspberry pi.

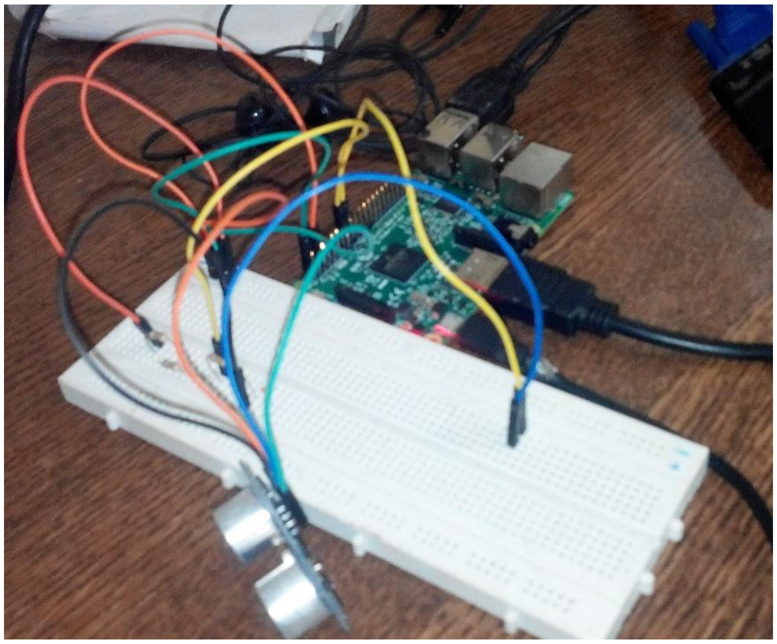
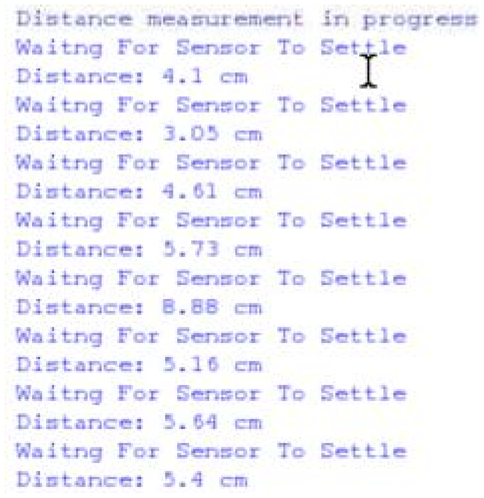


Figure 5 Circuit Development

Python code which we have used to make ultrasonic sensor work on raspberry pi is attached in **Annexure A.**

The result which we got by running this code on raspberry pi is as shown. Following image was taken while moving ultrasonic sensor towards and away from obstacles.



```
Distance measurement in progress
Waitng For Sensor To Settle
Distance: 4.1 cm
Waitng For Sensor To Settle
Distance: 3.05 cm
Waitng For Sensor To Settle
Distance: 4.61 cm
Waitng For Sensor To Settle
Distance: 5.73 cm
Waitng For Sensor To Settle
Distance: 8.88 cm
Waitng For Sensor To Settle
Distance: 5.16 cm
Waitng For Sensor To Settle
Distance: 5.64 cm
Waitng For Sensor To Settle
Distance: 5.4 cm
```

Figure 6 Results

3.2.2 Temperature Sensors (RTD-PT100)

RTD stands for Resistance Temperature detectors and PT means Platinum thermometers. These temperature sensors have temperature measuring range of -270°C up to 660°C. These temperature sensors are widely used in industries for measuring the temperatures of furnaces below 660°C. They are quite accurate in measuring temperatures. They have low drift, wide operating range and are quite useful for taking the precise values. They have linear response, and also provide the real time data. RTD-PT100 has steel body.

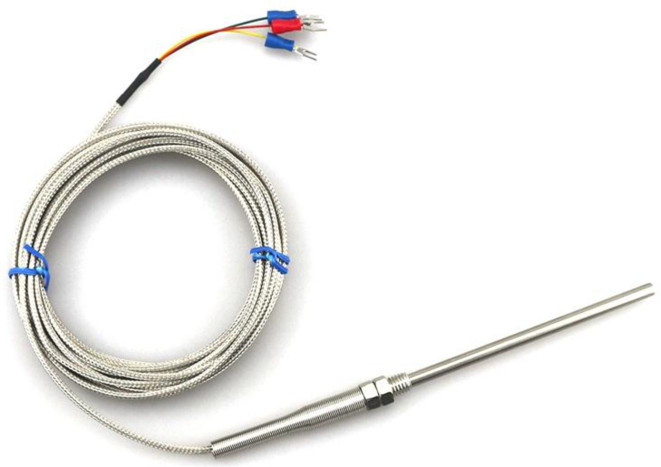


Figure 7 RTD PT100

3.2.2.1 Calculations

RTD-PT100 needs to be calibrated before using it for measuring the temperature of a region. For calibration at first we have to find the value of coefficient of RTD-PT100. This value is calculated using the equation,

$$\alpha = \frac{Rt - Ro}{T * Ro}$$

Where, Rt is the resistance at some known temperature T, Ro is the resistance at 0°C, while α is the coefficient of temperature. By this equation, we can find out the value of α which will be used for calculating the values of temperature in next measurements using the same equation, as mentioned above.

The voltage across the resistance Rt can be calculated by using the following formula, where Vo is the output voltage or Rt and Vex is the supplied volage;

$$V_o = V_{ex}\left(\frac{R_3}{R_3 + R_4}\right) - V_{ex}\left(\frac{R_2}{R_1 + R_2}\right)$$

3.2.2.2 Circuitry to convert resistance to voltage

The circuit which we have used to convert the resistance we obtain from RTD-PT100 is a simple Wheatstone bridge and its diagram is as shown:

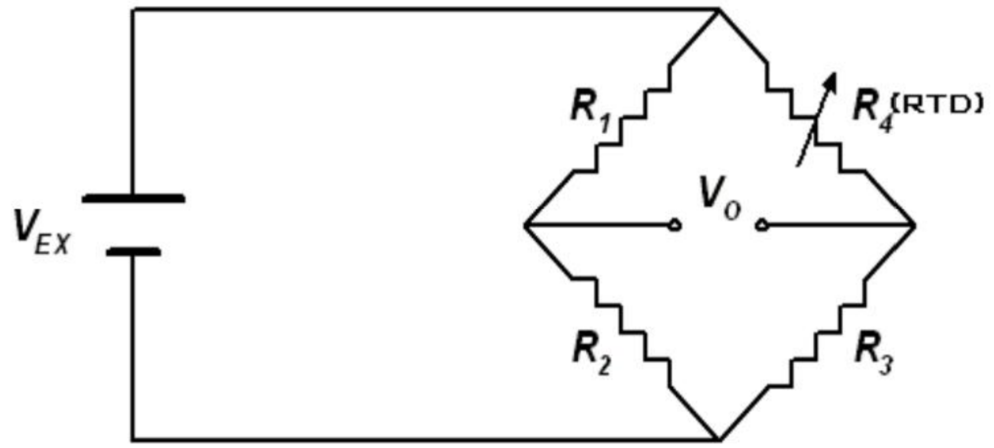


Figure 8 PT100 Circuitry

Where Vex is the supplied voltage, R1, R2 and R3 are the known resistances whereas, R4 is unknown or the resistance of RTD.

3.2.2.3 Sensor Testing and Debugging

RTD-PT100 was tested using some water inside a beaker and beaker was then heated and the values of the resistance of RTD were then noted

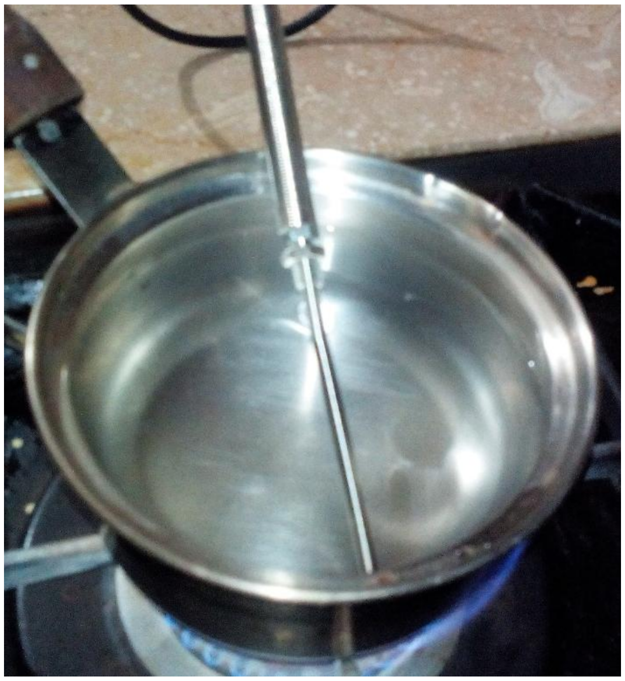


Figure 9a PT100 Testing

The values of resistance which came were:

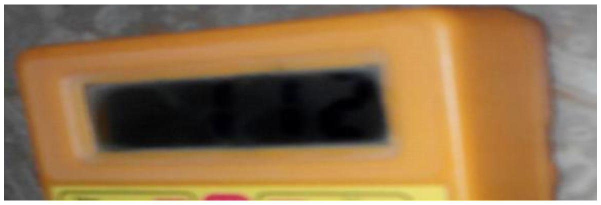


Figure 9b PT100 Testing

Above shown resistance was the resistance at start, when RTD was not inserted inside the beaker

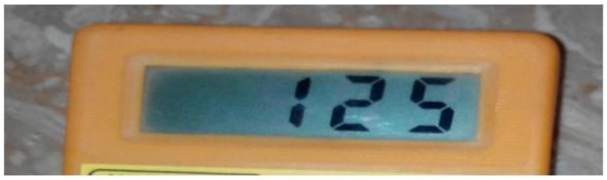


Figure 9c PT100 Testing

This was the values of resistance which came when the temperature of water was increased. These values of resistances were then compared with standard resistance values of RTD and the results of our resistances were quite close to the ideal values.

3.2.3 Thermal Camera

3.2.3.1 Electromagnetic Spectrum for Flir Thermal Imaging Camera

Electromagnetic radiations are available all around us and they are comprised of radiations ranging from Gamma radiations on the higher frequency side and radio waves on lower frequency side. Most of the sensors used for imaging purposes detect radiations only in visible region of spectrum (wavelength is from 380nm to 700nm), while infrared wave sensors detect radiations from 900nm to 14,000nm which is known as infrared spectrum. It accounts for most of the thermal radiations emitted by objects near room temperature.

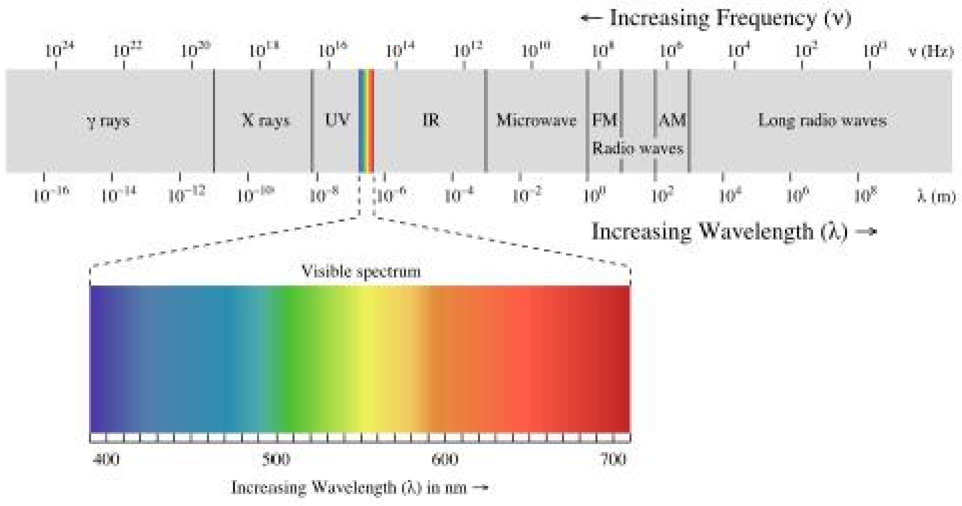


Figure 10 Spectrum of Thermal Imaging Camera

Microbolometer array is the sensor which is used insed the FLiR Lepton. Microbolometers are made from a material which changes its resistance when they are heated up by infrared radiations. By calculating this resistance, we can determine the temperature of that object which is emitting those radiations and create a false color image which encodes that data.

This type of thermal imaging technique is often used for inspection of buildings, to detect insulation leakage, automotive inspection and medical diagnosis. it has ability to produce the image with no visible light, therefore thermal imaging is considered ideal for night vision cameras.

3.2.3.2 Circuit Assembling with Raspberry pi

For connecting raspberry pi with Flir thermal imaging camera we have used the following connections,

- Pin 1 of raspberry pi (Vcc=3.3V) : Vin of Flir thermal imaging camera
- Pin 3 of raspberry pi : SDA pin of flir thermal imaging camera
- Pin 5 of raspberry pi : SCL pin of flir thermal imaging camera
- Pin 6 of raspberry pi (GND) : GND of flir thermal imaging camera
- Pin 19 of raspberry pi : MOSI pin of flir thermal imaging camera

- Pin 21 of raspberry pi : MISO pin of flir thermal imaging camera
- Pin 23 of raspberry pi : CLK pin of flir thermal imaging camera
- Pin 26 of raspberry pi : CS pin of flir thermal imaging camera

Visual representation of these connections is as shown;

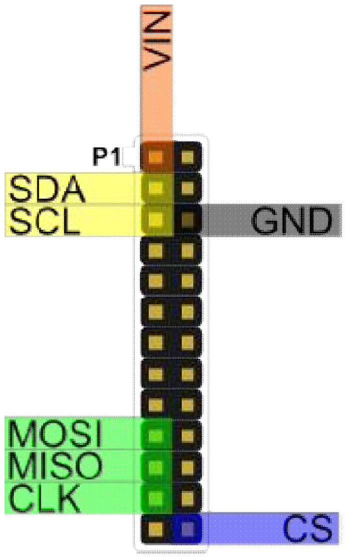


Figure 11 Connections for thermal camera and raspberry pi

3.2.3.3 Software used for Flir Imaging Camera interface with raspberry pi

Python software which we have made for Flir Imaging camera interface with raspberry pi is attached in **Annexure B.**

3.2.3.4 Results of Flir imaging Camera interface with raspberry pi

To test the code which we had developed and also to check the performance of Flir Thermal imaging camera, thermal imaging camera was then mount on a remote controlled toy car as shown below,

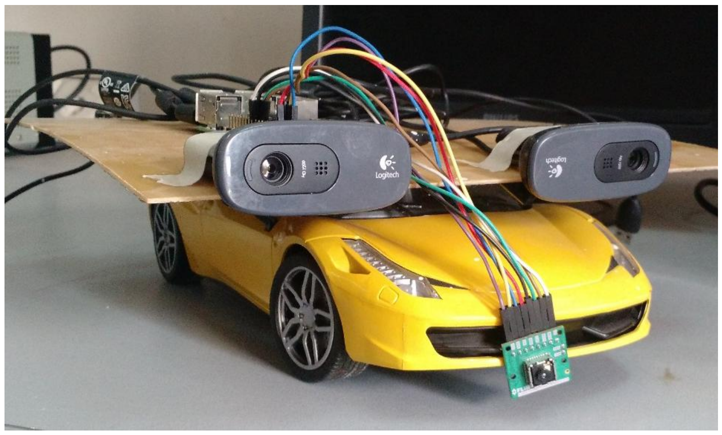


Figure 12 Sensors mount on toy car

In front of that car were two placed two glasses of water, one containing hot and other containing cold water. Some of the results which we got from Flir Thermal Imaging Camera on moving car are as,

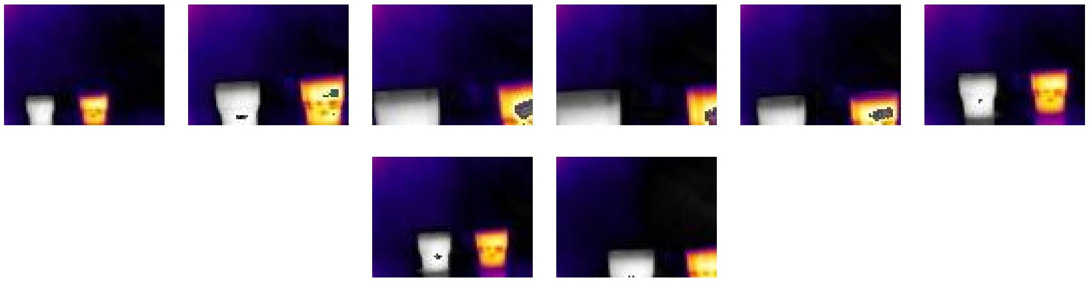


Figure 13 Thermal Imaging results

3.2.4 Stereo Camera

Two Stereo Vision cameras have been attached with raspberry pi module. The picture was taken only when the code is executed for each camera. The Figure 1shows the picture was taken with each camera with some base distance. The code for capturing the pictures run manually for each camera and the camera was at rest.

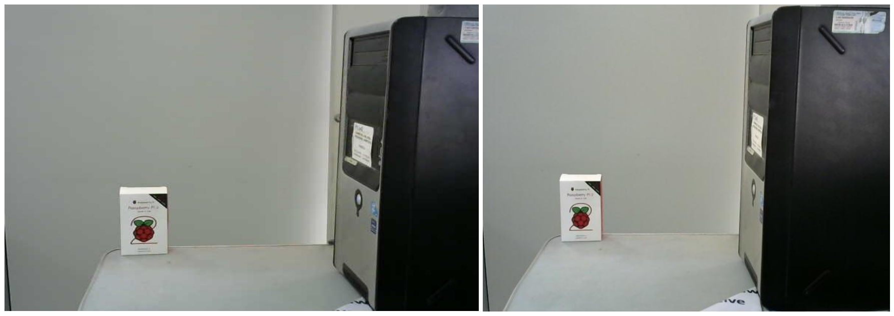


Figure 14 Pictures taken from Stereo vision camera

In order to make it work autonomously, a python code has been written. The Python code for stereo vision camera is attached in Annexure A. In the code the loop has been generated which run the capturing code for each camera after 2seconds. The difficult part in the code is to rename the file every time so that it cant be overwrite with the previous one. The issue of capturing the picture from both the camera at the same time is big challenge. This has also been removed as the speed of the robot is very slow which doest effect the disparity map acquired from stereo images. The Figure shows the connection of stereo vision camera with raspberry pi.

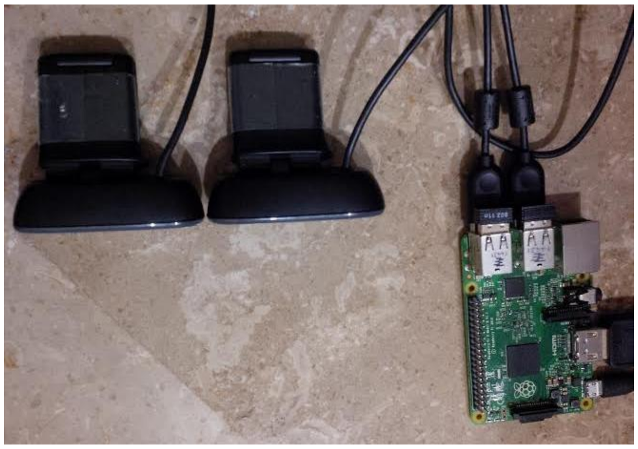


Figure 15 Stereo Vision camera with Raspberry pi

After writing the python code for capturing auto pictures. The next step is to run the code automatically during boot. For that the command has been written in “Profile”. A “Profile” is a directory in rapberry pi which executes during the boot.

At the end the complete system is placed on moving car. The car runs at the constant speed and takes the stereo vision pictures. The Figure shows the car with base mounted at the top. The car is used to check the IMR sensors.

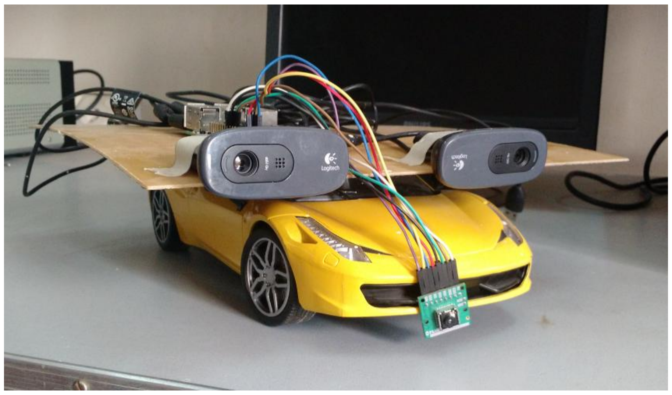


Figure 16 Moving care for testing sensors of IMR

3.2.5 Disparity Map

Stereo Vision computes the disparity map between two rectified images. The first step is to read in the color stereo image pair and convert the images to gray scale for the matching process. The stereo vision images used to compute the disparity map is shown in Figure .

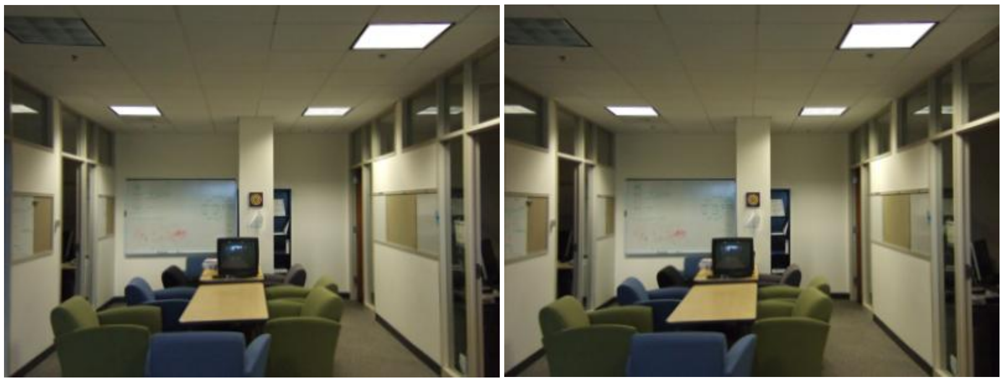


Figure 17 Stereo vision images

The next step is to perform the basic block matching. For every pixel in the right image, we extract the 7-by-7-pixel block around it and search along the same row in the left image for the block that best matches it. The basic block matching does well, as the correct shape of the stereo scene is recovered. However, there are noisy patches and bad depth estimates everywhere, especially on the ceiling. These are caused when no strong image features appear inside of the 7-by-7-pixel windows being compared. Then the matching process is subject to noise since each pixel chooses its disparity independently of all the other pixels. A noisy disparity image can be improved by introducing a smoothness constraint using dynamic programming.

Figure below shows the stereo result refined by applying dynamic programming to each row individually. Dynamic programming does introduce errors of its own by blurring the edges around object boundaries due to the smoothness constraint. Also, it does nothing to smooth "between" rows, which is why a striation pattern now appears on the left side foreground chair. Despite these limitations, the result is significantly improved, with the noise along the walls and ceiling nearly completely removed, and with many of the foreground objects being better reconstructed. The colour red indicates the object is near however blue indicates farther things.

3.2.1 Global Positioning System (GPS)

GPS is a global navigation satellite system that provides information of location and time in all weather conditions. GPS operated independently on any telephonic or internet reception. It provides critical positioning capabilities to military, civil and commercial users all around the world. Government of United States created this system, maintains it and makes it freely accessible to anyone who have GPS receiver.

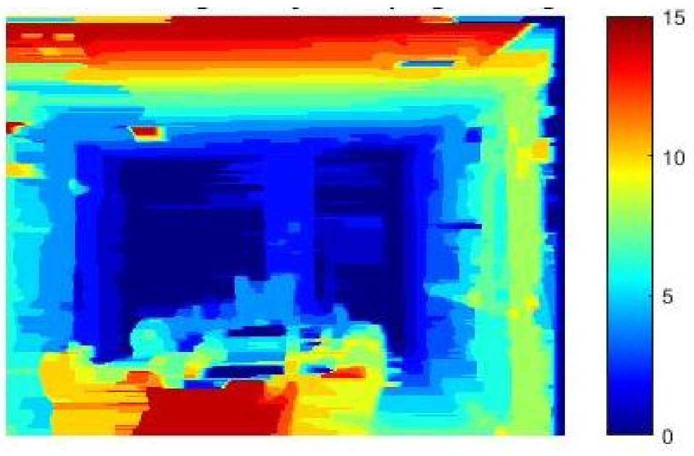


Figure 18 Block matching with dynamic programming

3.2.1.1 GPS interface with raspberry pi

3.2.1.1.1 Connection of GPS with raspberry pi

GPS module has only 4 wires and to connect GPS module with raspberry pi following connections are made;

- Vcc of GPS module to Pin 1 of raspberry pi (3.3V)
- TX of GPS module to Pin 10 of raspberry pi (RX / GPIO 15)
- RX of GPS module to Pin 8 of raspberry pi (TX / GPIO 14)
- GND of GPS module to Pin 6 of raspberry pi (GND)

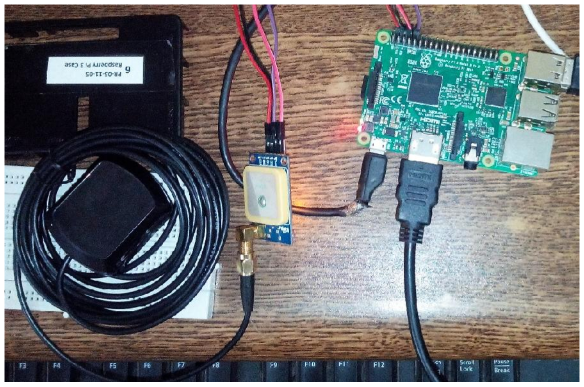
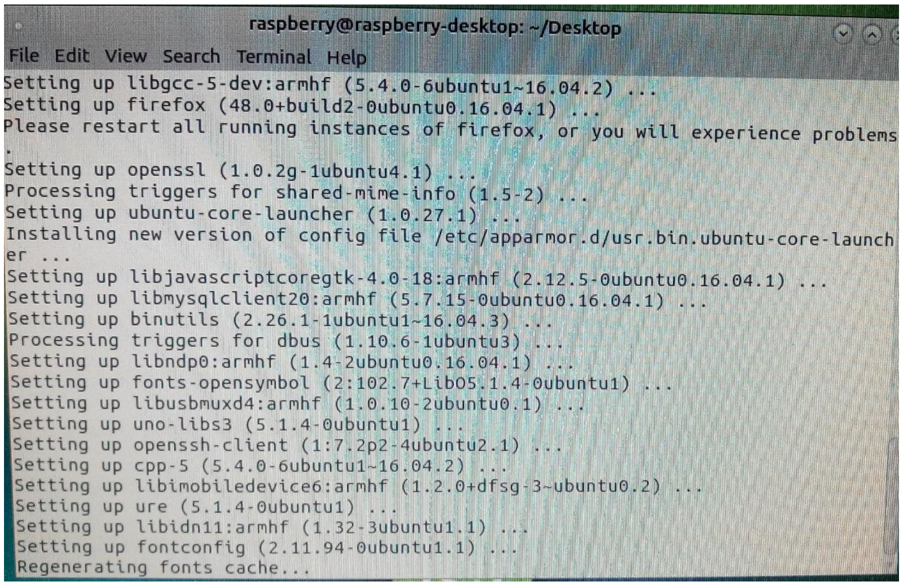


Figure 19 GPS interface with raspberry pi

3.2.1.1.2 Raspberry pi and GPS

Programming Language for raspberry pi is Python. Python is an interpreted programming language and is slightly different than something like Arduino or programming in C. Program you write is not compiled as a whole, into the machine code. In fact each line of program is sequentially fed into something called a Python interpreter. To make GPS module work on the raspberry pi some necessary libraries of *.gpsd* were to be installed on the raspberry pi board.


raspberry@raspberry-desktop: ~/Desktop
File Edit View Search Terminal Help

```
Setting up libgcc-5-dev:armhf (5.4.0-6ubuntu1~16.04.2) ...
Setting up firefox (48.0+build2-0ubuntu0.16.04.1) ...
Please restart all running instances of firefox, or you will experience problems
.
Setting up openssl (1.0.2g-1ubuntu4.1) ...
Processing triggers for shared-mime-info (1.5-2) ...
Setting up ubuntu-core-launcher (1.0.27.1) ...
Installing new version of config file /etc/apparmor.d/usr.bin.ubuntu-core-launch
er ...
Setting up libjavascriptcoregtk-4.0-18:armhf (2.12.5-0ubuntu0.16.04.1) ...
Setting up libmysqlclient20:armhf (5.7.15-0ubuntu0.16.04.1) ...
Setting up binutils (2.26.1-1ubuntu1~16.04.3) ...
Processing triggers for dbus (1.10.6-1ubuntu3) ...
Setting up libndp0:armhf (1.4-2ubuntu0.16.04.1) ...
Setting up fonts-opensymbol (2:102.7+LibO5.1.4-0ubuntu1) ...
Setting up libusbmuxd4:armhf (1.0.10-2ubuntu0.1) ...
Setting up uno-libs3 (5.1.4-0ubuntu1) ...
Setting up openssh-client (1:7.2p2-4ubuntu2.1) ...
Setting up cpp-5 (5.4.0-6ubuntu1~16.04.2) ...
Setting up libimobiledevice6:armhf (1.2.0+dfsg-3~ubuntu0.2) ...
Setting up ure (5.1.4-0ubuntu1) ...
Setting up libidn11:armhf (1.32-3ubuntu1.1) ...
Setting up fontconfig (2.11.94-0ubuntu1.1) ...
Regenerating fonts cache...
```

Figure 20 Ubuntu Mate Config.

After successful update of Ubuntu Mate configuration '*dpkg config—a*' to run Pythonscript file on GPS mogule, setting of new *.liboffice* and *.libpurple* files and installation of *.gpsd libraries* following results were obtained from GPS Module but there were quite some errors in the readings which we got from GPS module on which we are working to make it accurate.

3.2.2 MAP Generation

The initial MAP for the IMR will be generated using the sensor measurements. The stereo vision sensor or camera can determine the objects and their relative distance in the scene. However in fire scenario, the stereo vision camera will not be able to determine the objects and their distances because of the smoky environment. The disparity map from stereo vision images cannot be generated because of the noisy measurements.

To handle this problem, Thermal imaging and Ultrasonic sensors are also used to determine the distance and the temperature of the objects in the fire environment. The measurements from all the sensors are fused together in order to generate more precise MAP. The overall MAP will be generated after the data fusion as shown in figure 3-6.

The MAP generated using these three sensor measurements contains the information of the objects in the scene as well as their temperature and distance from the IMR. This information helps the IMR in their movement.

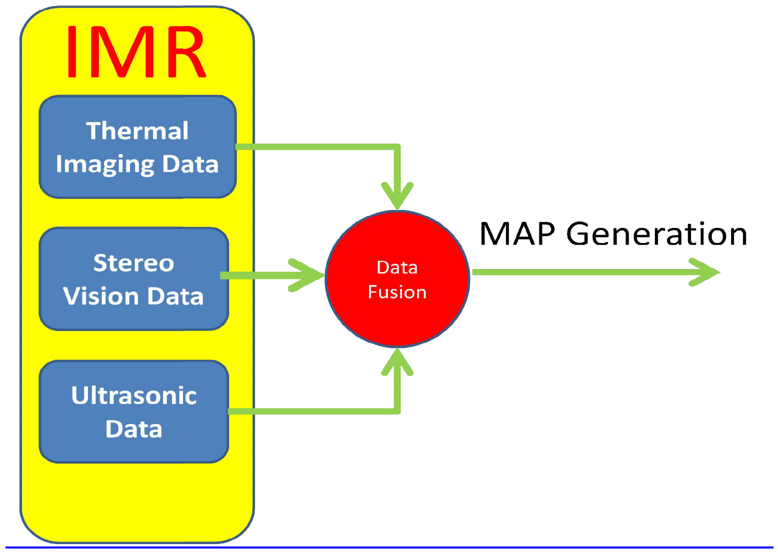


Figure 21 Data Fusion using diffenet sensors

The prior Probability Density Function (PDF) for each of the sensor measurement will be handled individually. Equations (3.1),(3.2) and (3,3) is showing the prior PDF's of the Thermal Imaging sensor, Stereo Vision sensor and Ultrasonic sensor respectively.

$$P\left({}^{Thermal}\!/_{Observation}\right) \tag{3.1}$$

$$P\left({}^{Stereo}\!/_{Observation}\right) \tag{3.2}$$

$$P\left({}^{Ultrasonic}\!/_{Observation}\right) \tag{3.3}$$

Chapter 4. Design of Robotic Platform (MUSAFIR)

4.1 Motivation

MUSAFIR is an Urdu word, which means Traveler. In order to design and build robots for the IMR project, we need to test several algorithms and work on several different sensing techniques. In order to be able to reliably and repeatedly test the algorithms, we needed a test robotic platform. Musafir is the result of that need.

The Musafir design is mainly inspired from some similar academic commercial bots, which are too expensive Khepera (I, II, III and now IV) and e-Puck Robot, the 2 Commercial Academic Research Mobile Robotic Platforms are the 2 prime example robotic platforms that we have studied. We selected to mimic Khepera robots as these robots are also the ones used by other robotics labs around the world and also included in the online course CONTROL OF MOBILE ROBOTS - https://www.coursera.org/learn/mobile-robot

For comparison, the cost of Khepera IV is 2650CHF which is about 2695 USD and 282,554 PKR and cost of e-puck, another similar robot is 950 CHF, which is 966USD and 101,293 PKR. This is excluding the customs and shipping expenses.

Musafir robot is expected to be built in a fraction of the cost and we are working to make 4 such robots, so that most of the collaborative control, SLAM and swarm algorithms can be tested, most configurations require at least 3 to 4 robots.

4.2 Desired MUSAFIR Specifications

In order to design and build a new robotics platform, specifications need to be written and laid out before starting the work. Musafir robots are expected to have several built-in sensors and communication methods.

- Re-Chargeable Battery
- Round/Circular/Symmetric Design
- IR/Sonar sensor skirt around the bot
- Differential Drive Motors with Encoders
- IMU (Gyro + Accelerometer) + Compass Sensor
- Wireless Communication
- Motor Driver - MOSFET Based
- On-board computer/camera for further processing and SLAM – OPTIONAL

With these specifications, the design was broken into 3 main steps, initially a very basic robotic platform with motors and wireless control and minimum sensors will be implemented, then the design will be refined and more sensors (sensor skirt) will be added to the bot, finally, in the third stage the robot will be equipped with a computer (Raspberry Pi) and a camera, given time and budget constraints, this step will be done last and is optional.

4.3 3D Design of Musafir

Musafir robot was first designed in SolidWorks, however as the main body work of the robot was needed to be done with Acrylic Plastic Sheets, which are cut by laser cut CNC machines, the design was also re-done in SketchUp and then further refined in CorelDraw for final sending to the Laser Cut shop.

The designs are provided below which serve as a reference and show how the design evolved over time.

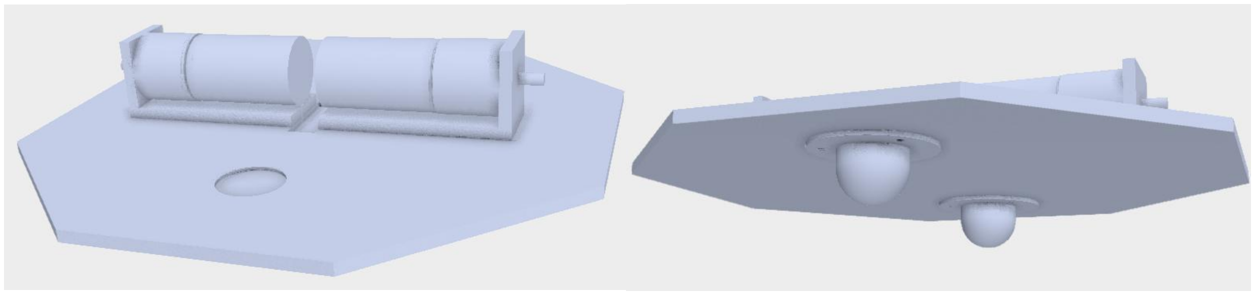


Figure 4-1: Initial Sketch of Robot base, showing Motors and Ball Caster Wheels

The initial design shape was selected to be Octagon, as that enables us to put 8 sensor max in symmetry across the robot to form a sensor skirt, the octagonal shape also helps in the LASER cut process, as the straight edges are easier to join and work with as compared to a circular robot. As shown in Figure 4-2, the robot body was designed to have range sensors (Ultra Sonic) and proximity sensors (IR) on all 8 sides.

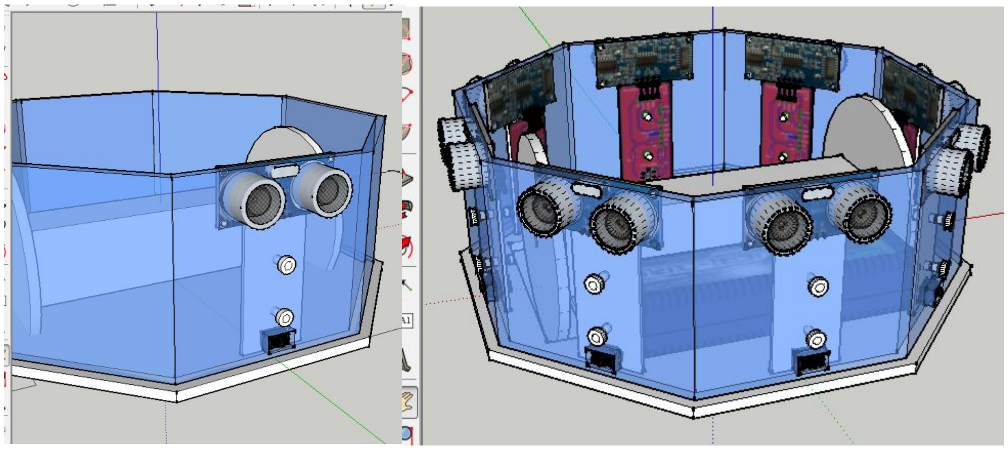


Figure 4-2: Robot 3D Design with Sensor placements shown

4.4 Final LASER Cut Design

For first iteration, the Musafir design was minimized to a Minimum working Prototype Stage (without computer and sensor skirt) and re-designed in Corel Draw for LASER Cut work, the final design 2D planar top view is shown in Figure 4-3 (not to scale).

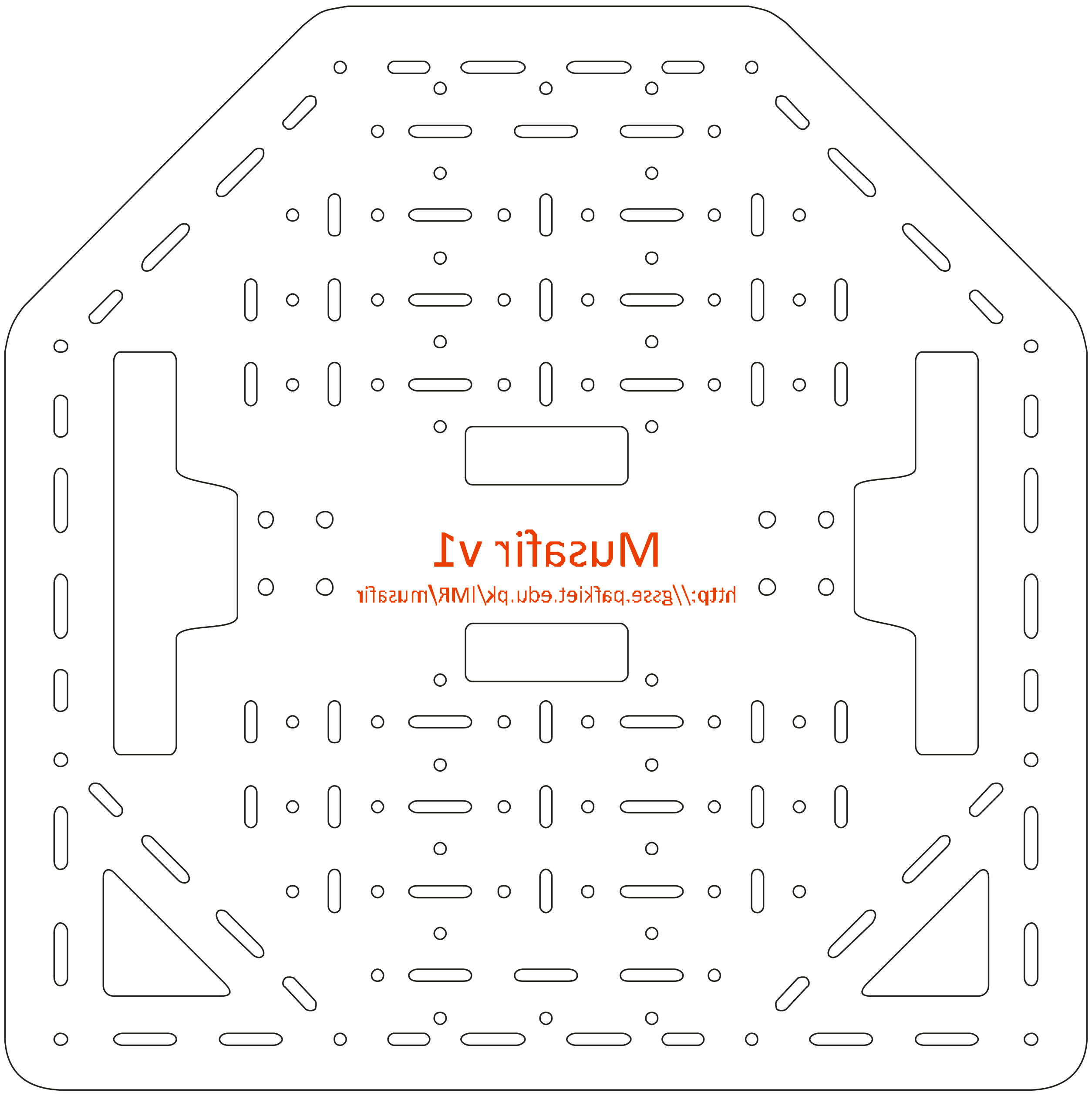


Figure 4-3: Profile for LASER Cutting – Size: 256x256mm – Thickness 5mm Acrylic

4.5 Motor Selection and Wheels

The motors selected to be used in Musafir are DC Gear motors with built-in encoders, these motors were selected after a thorough selection process and criteria refining, we needed the motor to run at 12V and have strong torque with slow outer speed. For odometry calculation, encoders were necessary. Encoders can be externally connected to a motor as well, but with built-in encoders, high precision is achieved in determining motor shaft rotation. The selected motors were then imported from china.

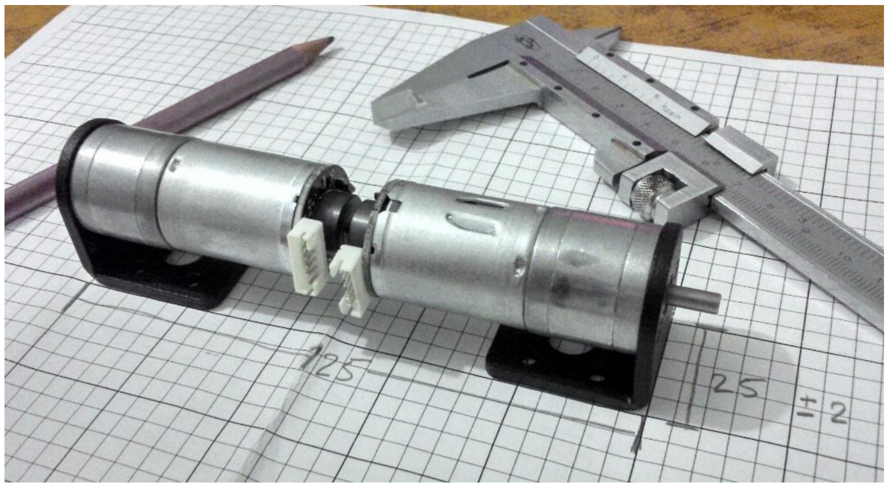


Figure 4-4: Selected Motors

For the motors, wheels were also designed in Corel Draw and then LASER Cut and affixed on the motors.

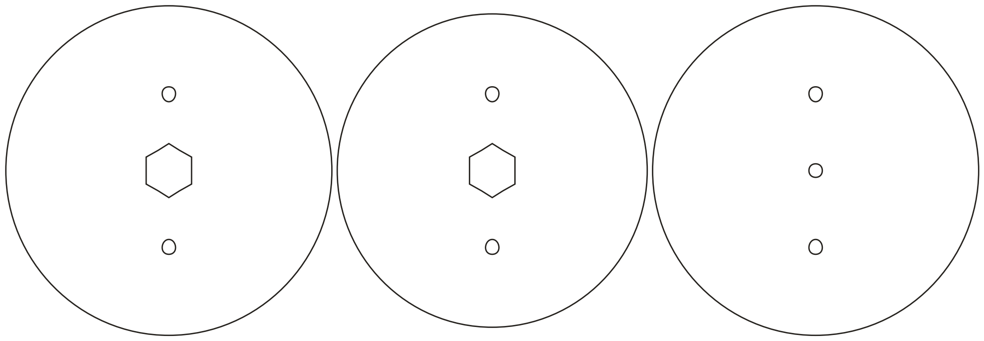
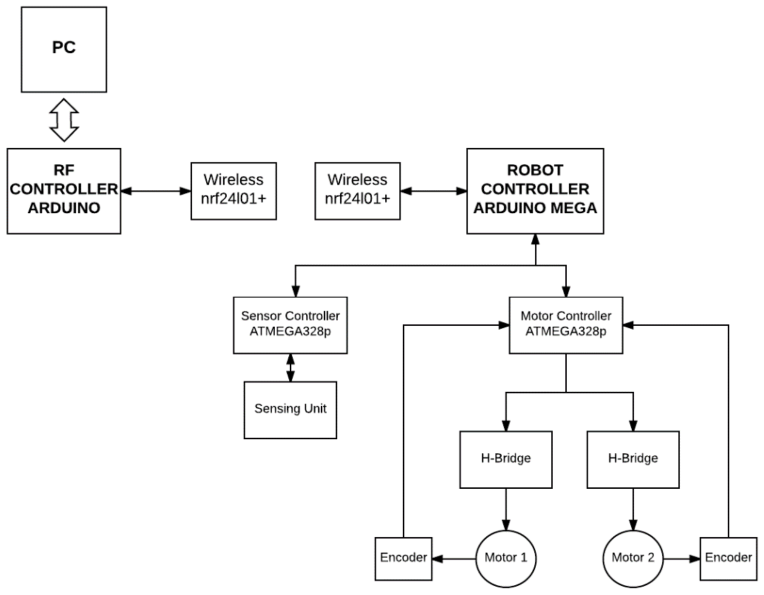


Figure 4-5: Wheel Design, 3 part design, fixed with screws and an O-ring

4.6 Musafir Electronics

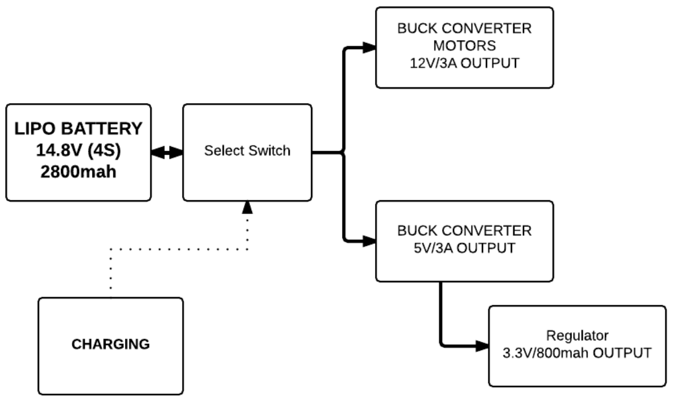
The Musafir electronics were designed in a very modular manner with the ease of usage and assembly in mind along with separation of tasks among boards and the different controllers, so that programming the firmware would then be distributed as separate tasks. The electronics is basically distributed into Power, Motor Drivers, Motor Controller, Sensor Controller, Main Controller and RF Controller (on PC Side).

A basic block diagram of the whole system is provided first which shows the different systems and how they are connected in a functional manner.



4.6.1 Power Circuitry

The power circuitry involves the battery, power regulation, and power switch and charge connectors. These were put on a separate board, the input is the battery which is a LiPo 4S battery giving 14.8V with current capacity of more than 2000mAh. The battery supply is regulated to 12V for motor drivers and to 5V for the control circuitry by two separate buck converter modules.

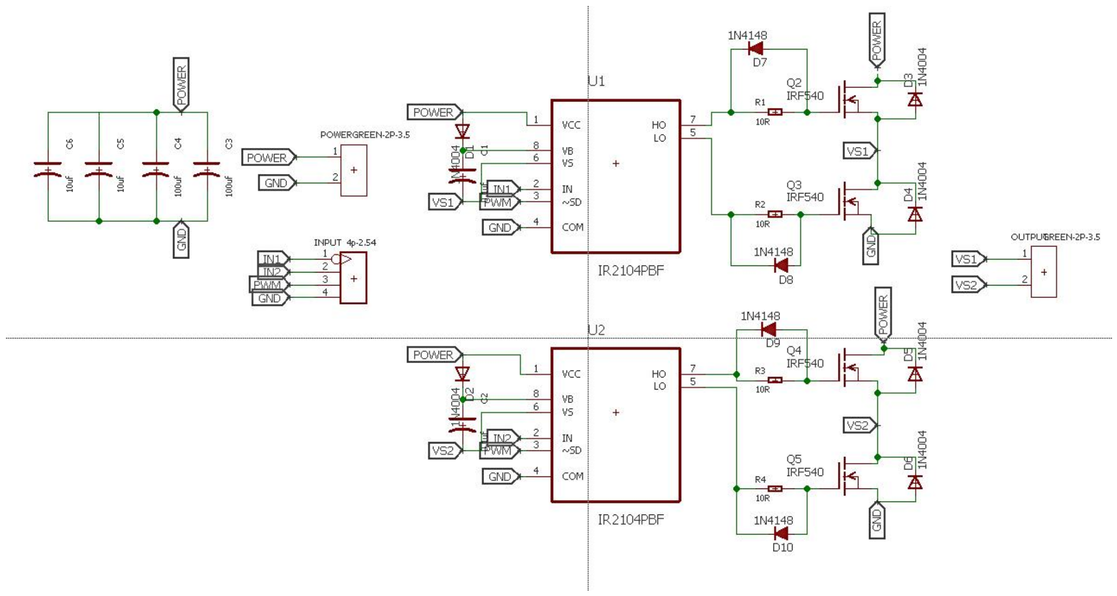

BUCK CONVERTER MOTORS 12V/3A OUTPUT
LIPO BATTERY 14.8V (4S) 2800mah
Select Switch
BUCK CONVERTER 5V/3A OUTPUT
CHARGING
Regulator 3.3V/800mah OUTPUT

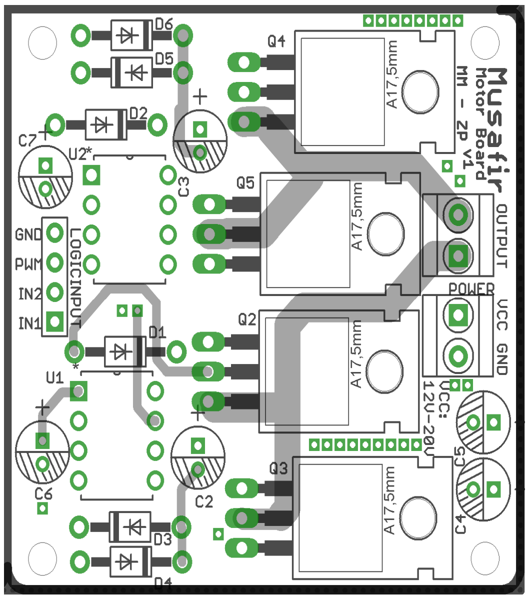
4.6.2 Motor Drivers

MUSAFIR contains Two H-bridge MOSFET driver board to drive it. These PCBs are capable to carry 5A current with voltage rating from 10V to 20V through it. 4pin input header use to control its functionality.

MOSFET: IRF540/IRF3205

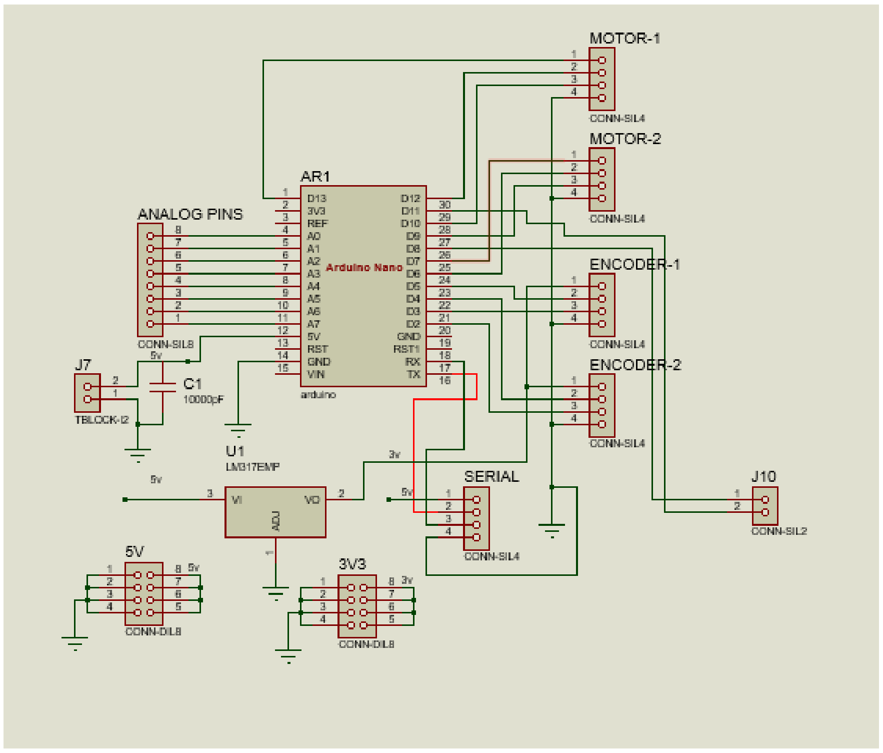
MOSFET Driver: IR2104

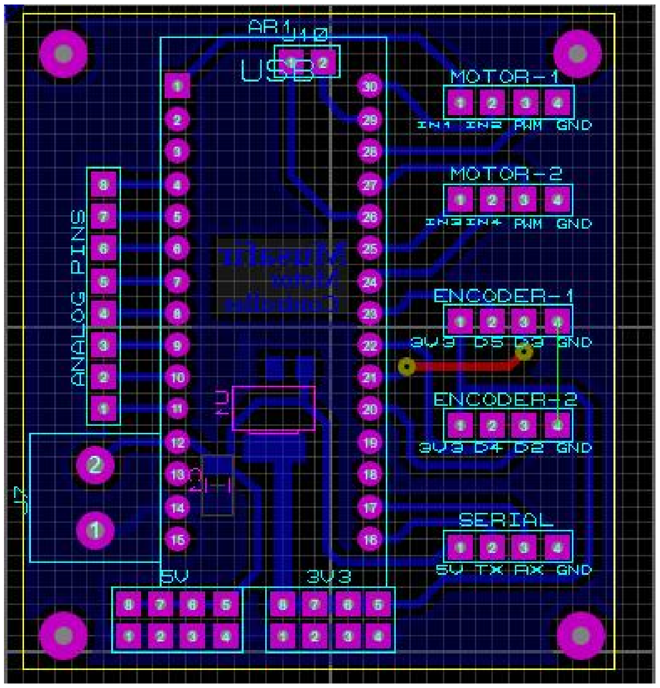




4.6.3 Motor Controller Board

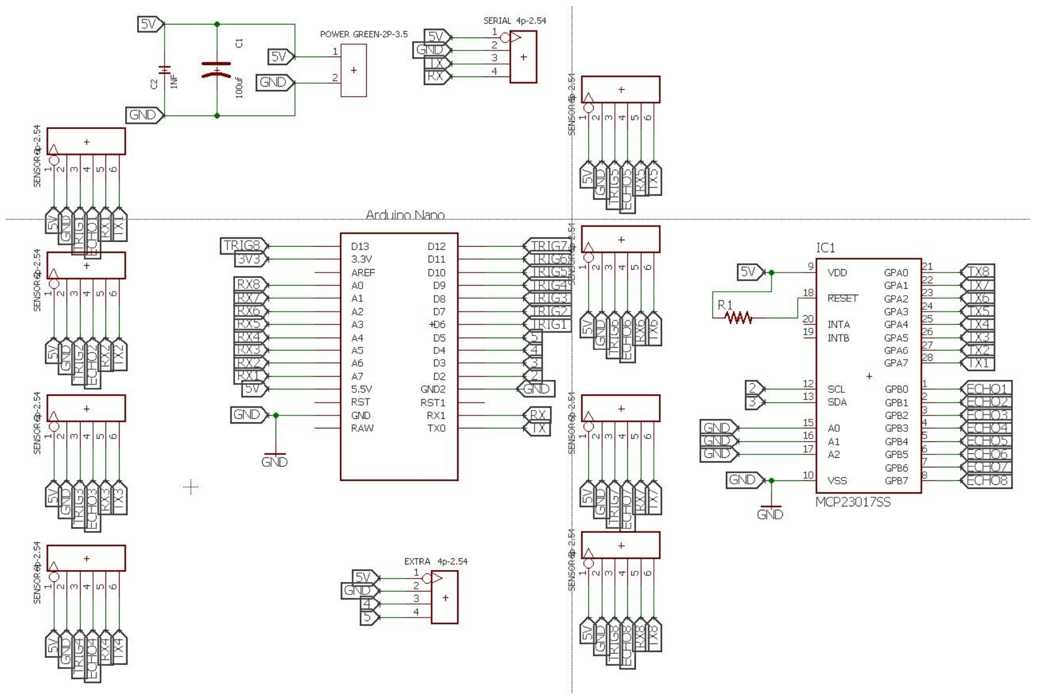
MUSAFIR contain the Motor Controller to control the motors. The separate PIDs has been implemented to control the motors. The encoder has also been read by this motor controller to control its close loop operation. Our motor controller is bound to take directions from on robot Mega board through serial communication. The predefined set of commands has been set up to implement this communication. These command will be discussed later in section 4.7.

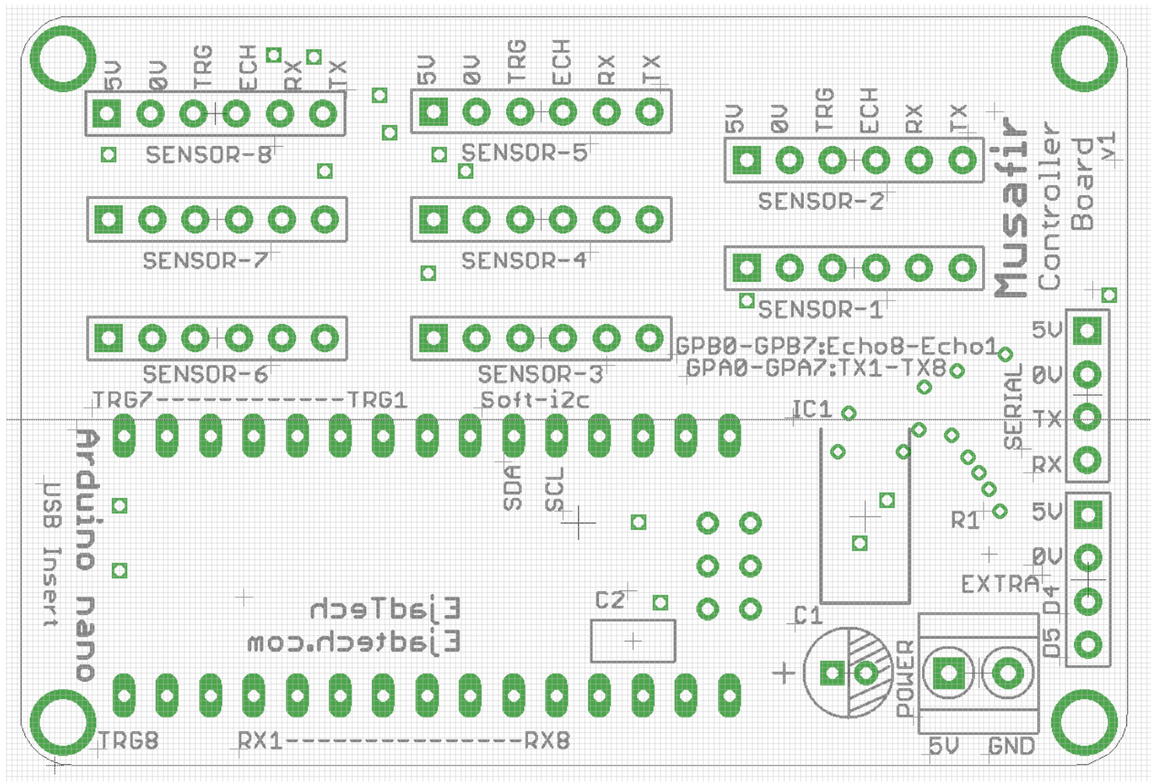




4.6.4 Sensor Controller

A separate controller board is designed which uses a digital IO multiplexer IC to interface with maximum 8 range sensors and 8 proximity sensors at the same time. This same controller is responsible for doing basic filtration and sanity checking on the sensor readings, so that the main controller only needs to poll this controller and get all the sensor reading either individually or all in one go. As the first iteration of Musafir does not include the sensor skirt, this board was designed but not implemented in the design.



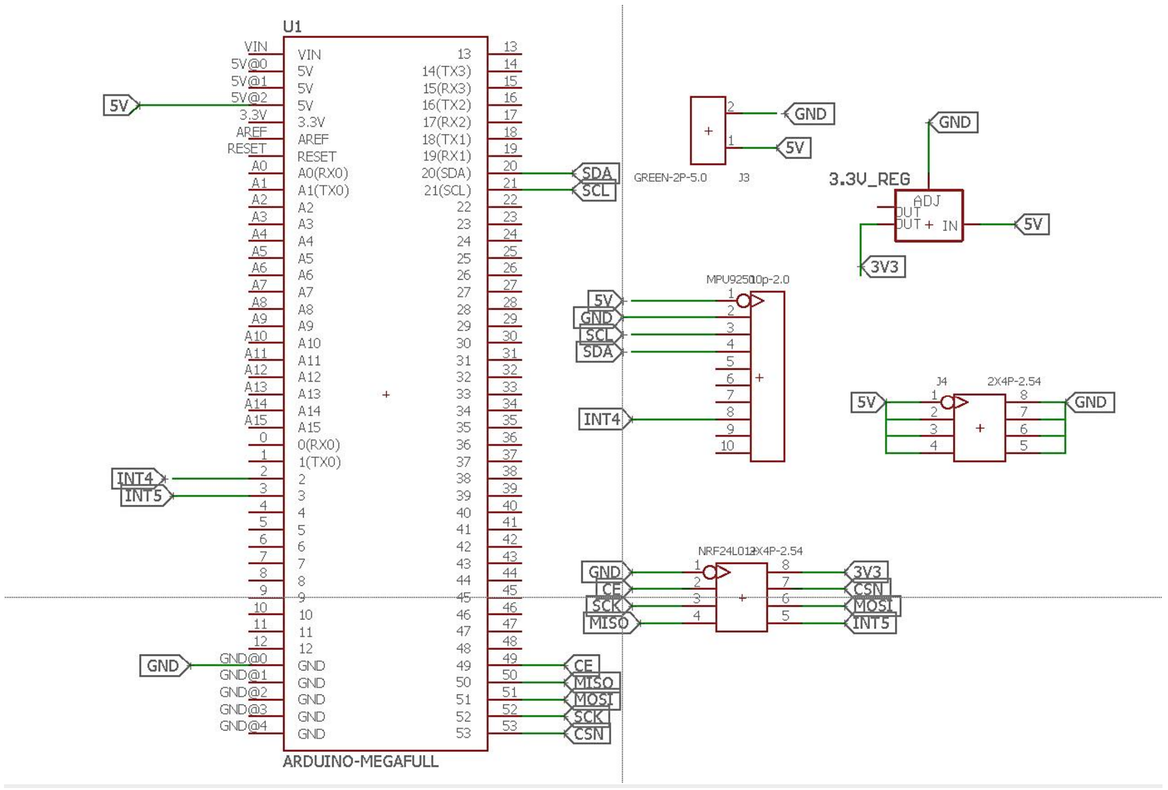


4.6.5 Main Controller Board

Arduino Mega is used to control Musafir by taking directions wirelessly from PC to implement the desired algorithm. Currently Mega is used for

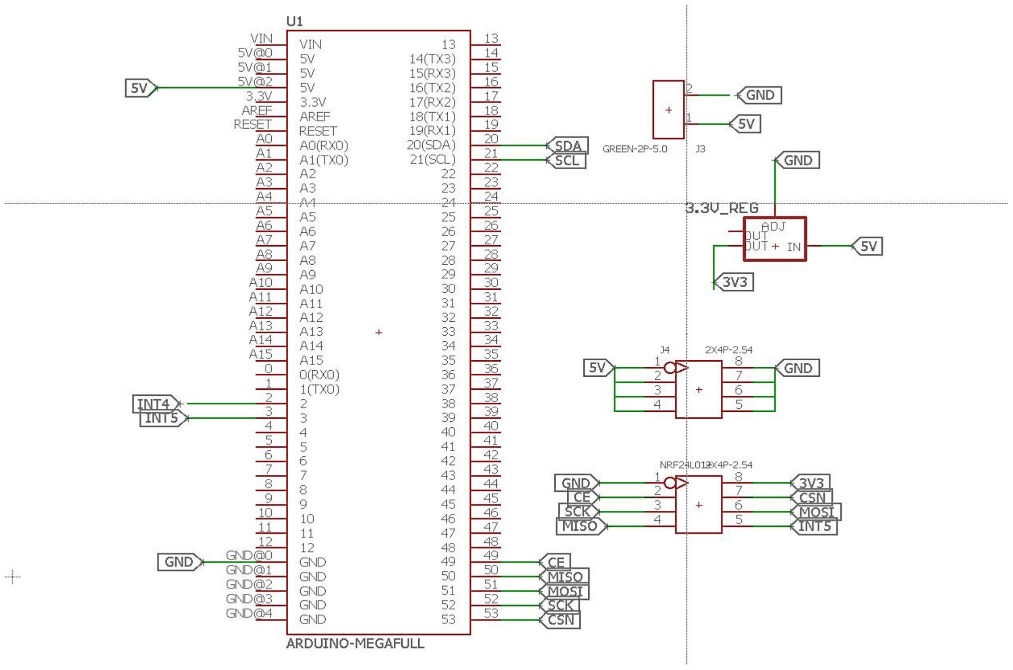
- Control the Motor controller.
- Control the Sensor Controller
- Communication through RF
- Compute the IMU data.

So on Robot all the modules is in control of Arduino Mega.



4.6.6 RF Controller Board (PC Side)

RF control board is much similar to Main control borad except it does not have IMU. This board is for sending the data packet of PC to Musafir or vice versa, through nrf24l01+ (Wireless Communication Module).



4.7 Musafir API and Control Methodologies

As the different controllers on the Musafir are responsible for their own separate tasks, we developed an API, which is implemented on each controller and each controller responds to the commands that it can handle. The main controller receives commands from the RF and then sends the command to the appropriate controller.

For example, if MOTOR command is received, that is sent to the Motor controller board and the response of the Motor controller is then transmitted back via RF. Similar for Sensor command, IMU command, etc.

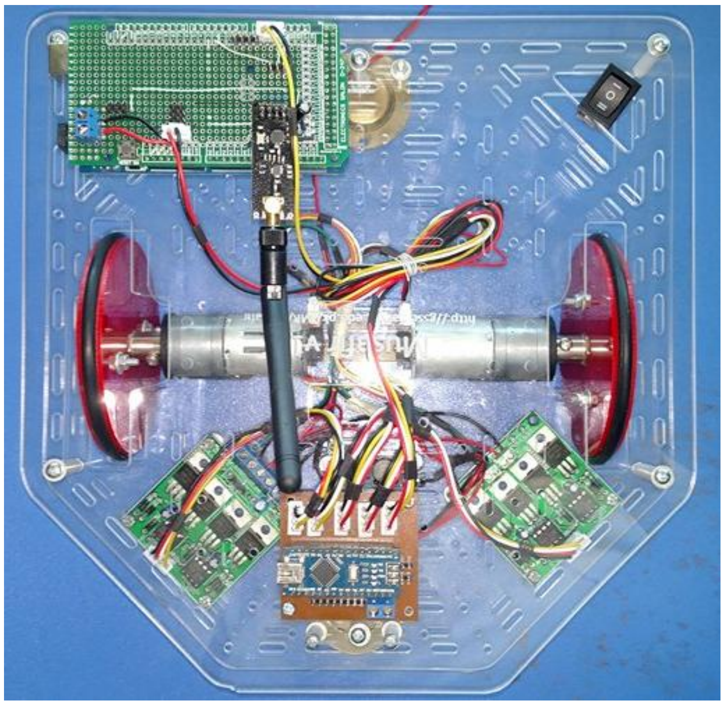
A basic brief of the API is given below with the commands, the relevant paramters and the response.

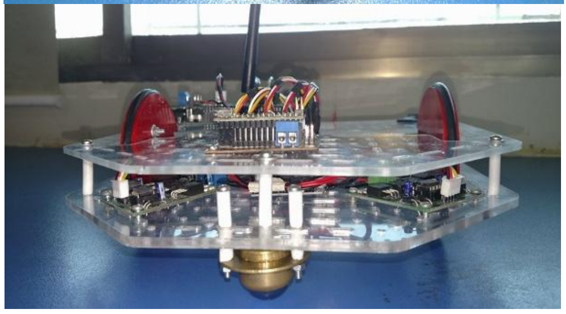
Command	Description, Usage and Response
L	Motor PWM control, OPEN LOOP L,leftPWM,rightPWM\n Response: l leftPWM and rightPWM are the speeds from 0 to 255, negative sign sets the direction.
D	Motor velocity Control (mm/s), close loop D,leftVelocity,rightVelocity\n Response: d LeftVelocity and rightVelocity are the speeds from 0 to 800mm/s
M	Motor max Achievable PWM M,maxPWM,minPWM,1/2\n Response: m Motor Maximum and minimum PWM could be set through it. (left motor = 1, Right Motor=2)
R	Read The Motor Encoder

	R,1/2\n Response: r,leftMotorEncoder,rightMotorEncoder\n The motor controller will feedback the current encoder values
I	Reset Encoder I\n Response: i The encoder will then be set to zero
H	Set the PID parameters H,kp,ki,kd,1/2\n Response: h This command will set the PID values, (left motor = 1, Right Motor=2)
S	Read PID parameters S, 1/2\n Response: s,kp,ki,kd,1/2\n The motor controller will respond the current pid values of Desired Motor

4.8 Musafir Actual Robot Images

Below are provided images of the first variant of Musafir (before installation of battery and ower circuit). These images show that the RF Controller as well, which is used on the PC side.





Chapter 5. Testing Environment for MUSAFIR

When developing robotic control algorithms, the algorithms need to be tested very thoroughly, analytical and completeness of the algorithm are tested by mathematical proofs, however until an algorithm is tested in real world scenarios, it cannot be fully verified. However real world testing requires design and development of hardware and also of test sites and test environments. There is a middle ground testing of algorithms as well, which is physics simulation environments in computers which test an algorithm by applying it on real world modeled 3d robots in a simulated 3d world with simulated physics.

Our process for testing of algorithms involves testing in MATLAB/Simulink environments, where robots are treated as point-bots, then the same algorithm is tested with 3D simulation software where real world 3d physics is applied. However, for actual testing of physical bots, real world testing is necessary which is why we needed to design a lab test environment to allow us to monitor and log the working of algorithms on actual robots.

5.1 Test Environment Setup

Our lab test environment consists of a camera and a computer which keep track of robot pose in the lab test environment, such a setup allows to monitor the activity of the robots from a top-view and the information is available for other software MATLAB/Simulink etc to determine the next course of action for the robots.

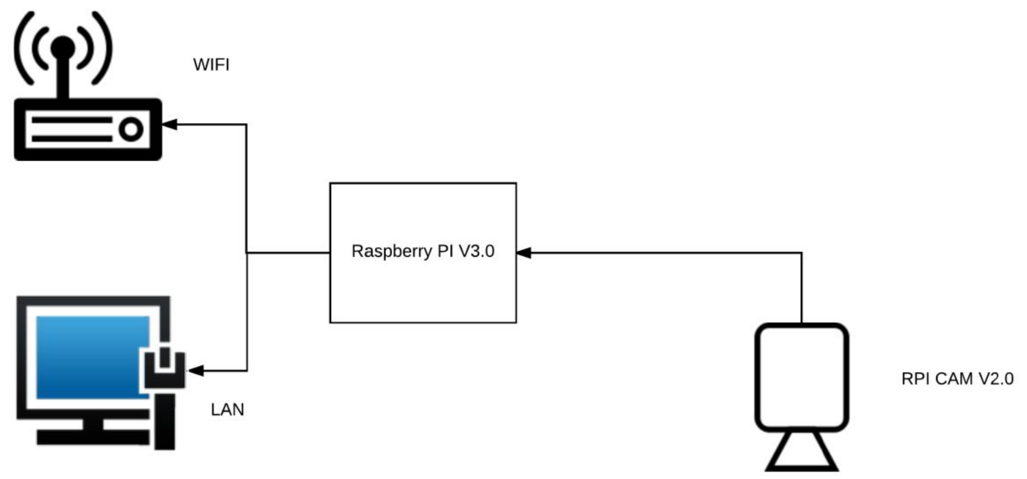
The Test Environment also is useful as a way to measure the effectiveness of localization and trajectory algorithms, by measuring the difference in pose of the robot as reported by running algorithm and from the test environment camera setup. A block diagram of the lab test setup is provided below to show the main components of the test environment.

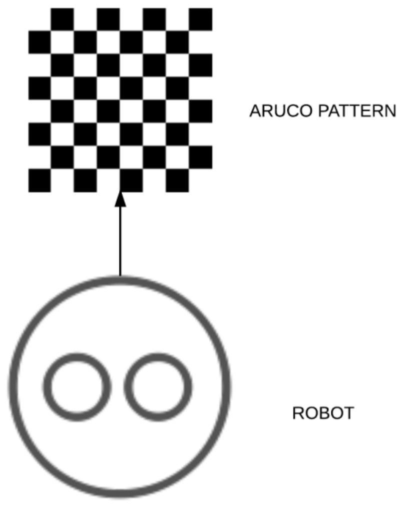
As this test environment is basically a system which is observing the robots move and for our case, the robots are Musafir bots, the Test Environment System is named MUBASSIR, urdu for observer.

5.2 Mubassir – Sub-Components

The lab test environment, Mubassir consists of mainly 3 components:

- Camera
- Computer System
- Tags on Robots





5.2.1 Camera

For Mubassir to be able to see the robots on the floor, a camera is needed, positioned in such a way to be able to have the whole test environment in its field of view, this camera needs to have high fps and good resolution, for these reasons a Raspberry Pi Camera, v2 was selected, as this camera is connected directly to the raspberry pi processor and has 8MP resolution which is much higher than what is needed. This camera also affords small size and low power consumption.

Specifications of the RaspiCam v2 are provided below in table 5-1.

Lens	Fixed focus
Megapixels:	8 megapixel native resolution sensor
Camera Resolution:	3280 x 2464 pixel stills
Video Resolution:	1080p30, 720p60 and 640x480p90 video
Dimensions:	25mm x 23mm x 9mm
Weight:	~3g
Connector:	ribbon connector
Interface:	CSI

5.2.2 Computer System

In order to process the video feed coming from the camera, a computer system is needed which acts as the brains of the Mubassir, as we selected RaspiCam v2 as the camera, the obvious choice for the computer system was a Raspberry Pi v3 single board computer, which serves our needs exceptionally well as it is small in size, takes less power, has network LAN and Wifi capability and supports Linux with openCV.

Specifications of the Raspberry Pi v3 are provided below in table 5-2.

CPU	Quad Cortex A53 @1.2Ghz
Instruction Set	ARM v-8A
GPU	400 Mhz VideoCore IV
RAM	1GB SDRAM
SoC	BCM2837
Stoarge	Micro-SD
Ethernet	10/100
Wireless	802.11n/Bluetooth 4.0
Video Output	HDMI/Composite
Audio Output	HDMI/Headphone
GPIO	40

5.2.3 Tags on Robots

In order for the camera and the computer system to identify individual robots and determine their location and heading, we need to put some sort of marker or fiducials on the robots, for this purpose, black and white tags are used which are available as part of augmented reality systems and the tags are printed and put on robots. Every tag is uniquely identified and the system can thus keep track of the complte pose of a robot by virtue of these tags. The library used for detection and tracking of these tags is called ARUCO.

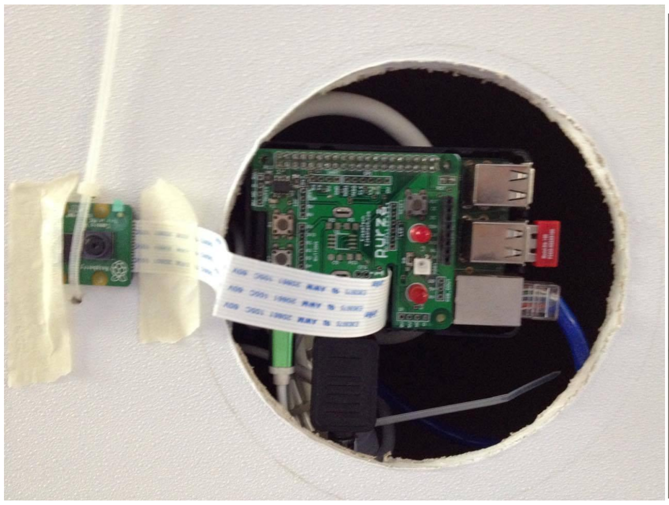
The ARUCO library has several features which are very essential for the test setup to be implemented, which are provided below:.

- Easy to use C++ library based on Opencv.

- It can detect square planner marker from various libraries which having valid code called dictionary.
- Can determine pose of camera .
- Integrated with OpenGL.
- Fast, less computational cost, and cross platform.

5.3 Mubassir Implementation

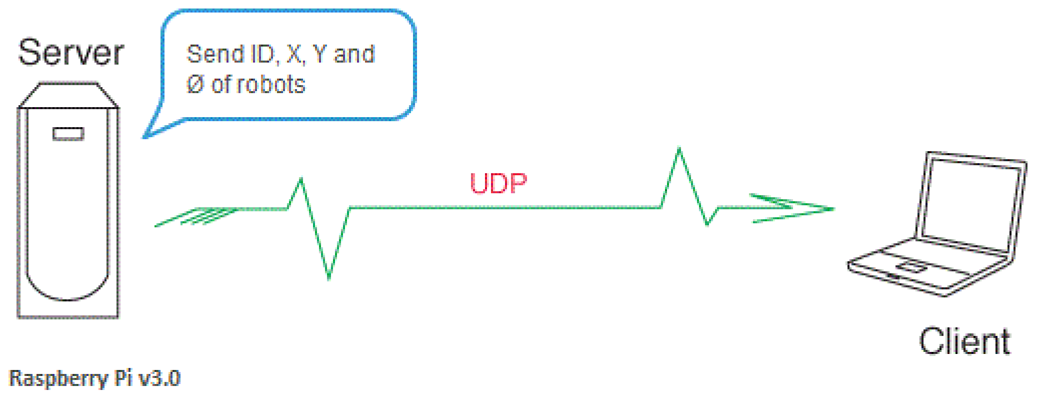
We implemented Mubassirwith a Raspberry Pi v3 with a RaspiCam v2 and ARUCO tags on robots, as the pi allows for LAN networking and WiFi, the whole system camera and pi wereput together on the roof of the lab in the center to have the most view of the lab floor where the robots will be moved and their mvoements detected and tracked by the system. Figure 5-1 shows the Mubassirsetup on the roof and figure 5-2 shows what the camera sees on the lab floor.



5.4 Software environment

The Lab Test setup software environment consists of Raspbian, Debian Linux running on raspberry Pi v3 with OpenCv, RaspiCam C++ and ARUCO libraries installed. A complete program was written by us to integrate the ARUCO library with RaspiCam v2 and do the detection and tracking. The robot pose related data is then simply multicasted on the network as packets on UDP sockets.

Every packet contains the information about how many robots were detected, pose of each robot, frame rate, current time and the packet number.



5.5 Accessing Mubassir Data

The Mubassir data is available on UDP and any system can listen to the UDP packets if it connects to the right port with UDP. The port number selected is 10001. For MATLAB, the connection commands were tested. A basic Data viewer CLI and GUI are also being developed which will help in visualization of the data, another application for the logging of the data is also being developed.

Chapter 6. Control Algorithm Development

6.1 Introduction

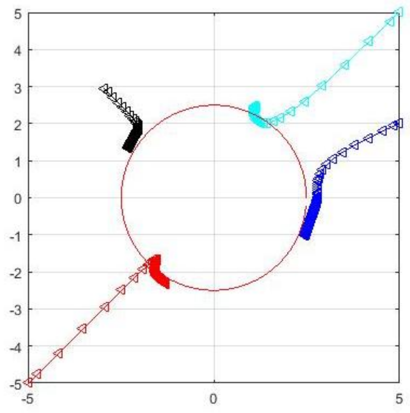
The basic objectives was to reproduce the results of the journal paper titled *"A Decentralized Cooperative Control Scheme With Obstacle Avoidance for a Team of Mobile Robots"* by Hamed Rezaee & Farzaneh Abdollahi.

It is worth mentioning that we didn't have access to any of the materials (simulation or hardware) related to the aforementioned paper other than the paper itself.

First and foremost, Dynamical equation of the kth mobile robot is modeled and solved using ode45 solver in MATLAB. The Electrostatic forces equation from (6) is substituted into Equation (8) and the resultant is substituted into Equation (7). Finally, the dynamics and state of the kth mobile robot in the proposed virtual structure is addressed. The algorithm has been tested on a team of mobile robots having minimum of 3 robots to as much as 8 robots.

6.2 Simulation Results

Given the coordinates to four robots, the result of formation algorithm is as follows:

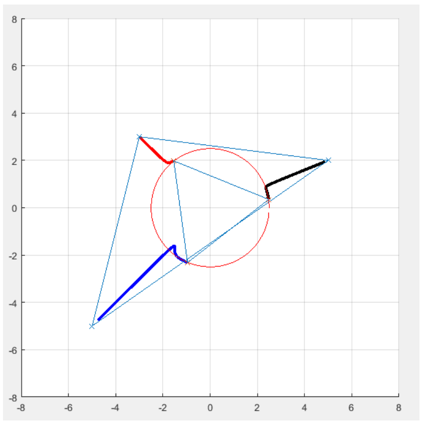


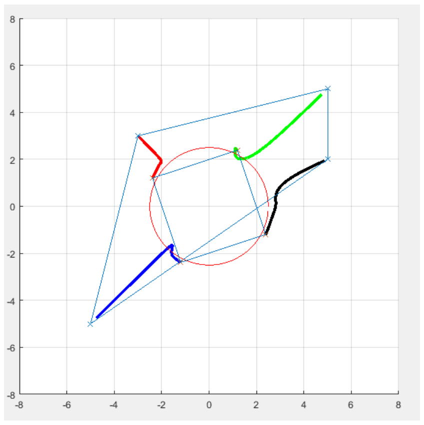
```
Configuration Parameters:
M = 1; (Mass of kth Robot)
B = 1;
Kd = 9;
ksk = 1;
kr = 0.15;
alpha = 2;
qk = 2.5; (Charges on kth Robot)
```

K = 10; (Electrostatic Constant)

Formation with 3 Robots:

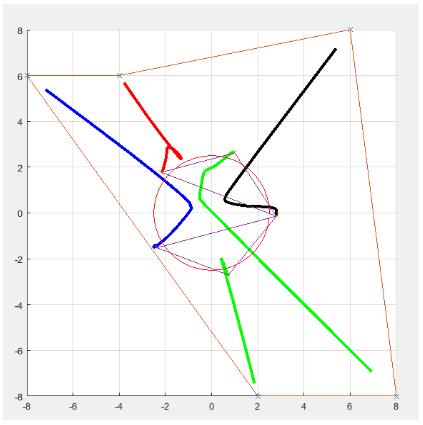
Formation with 4Robots:

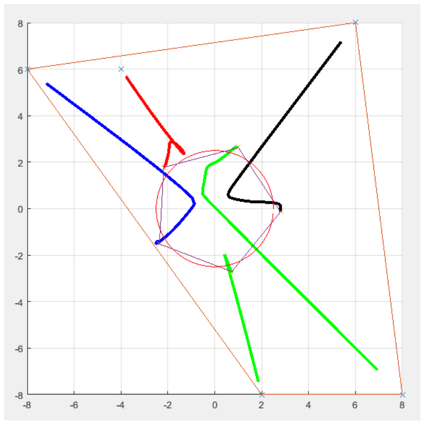




Formation with 5 Robots:

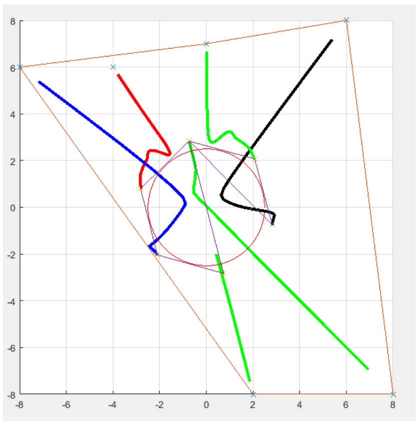
Formation with 5 Robots (Corrected):

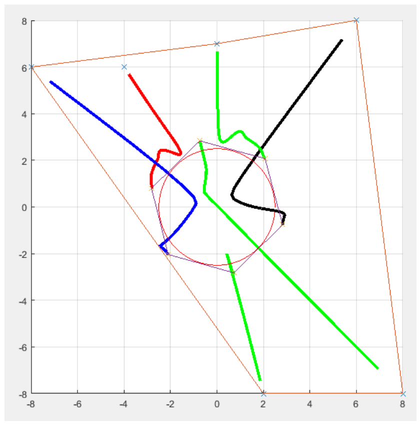




Formation with 6 Robots:

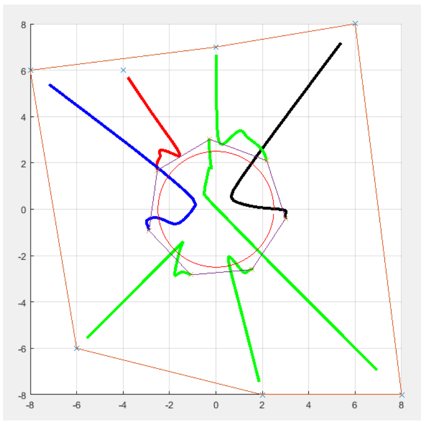
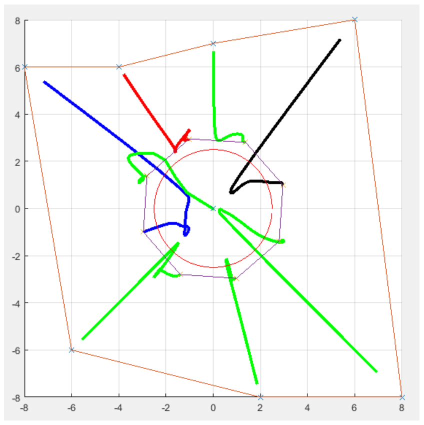
Formation with 6 Robots (Corrected):



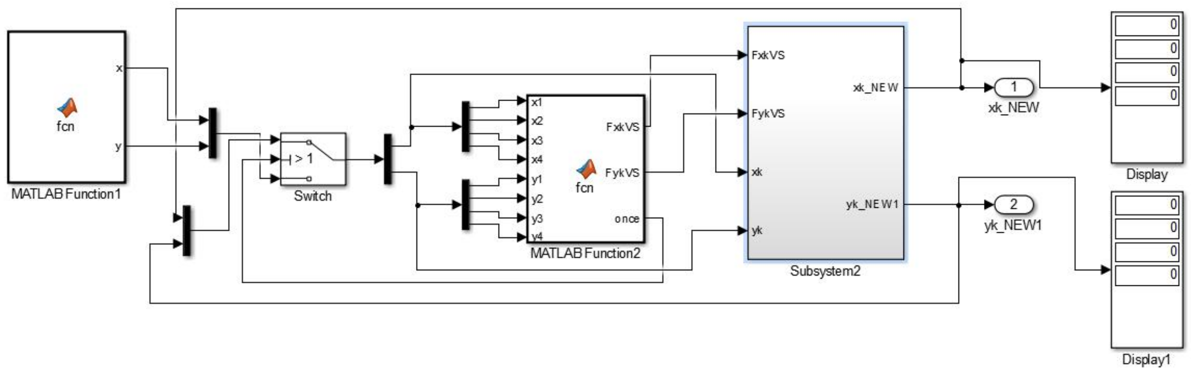


Formation with 7 Robots:

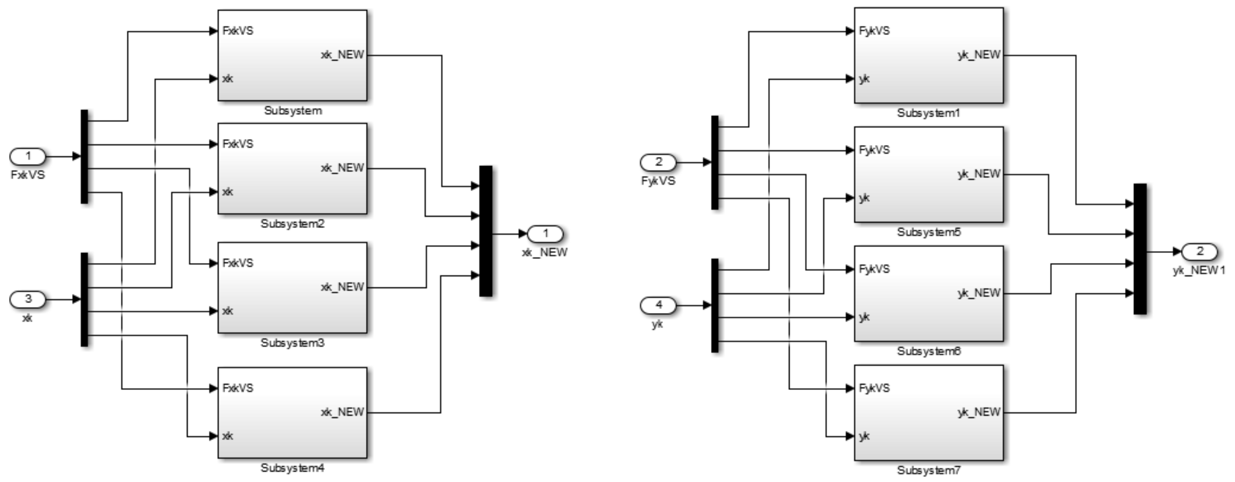
Formation with 8 Robots:

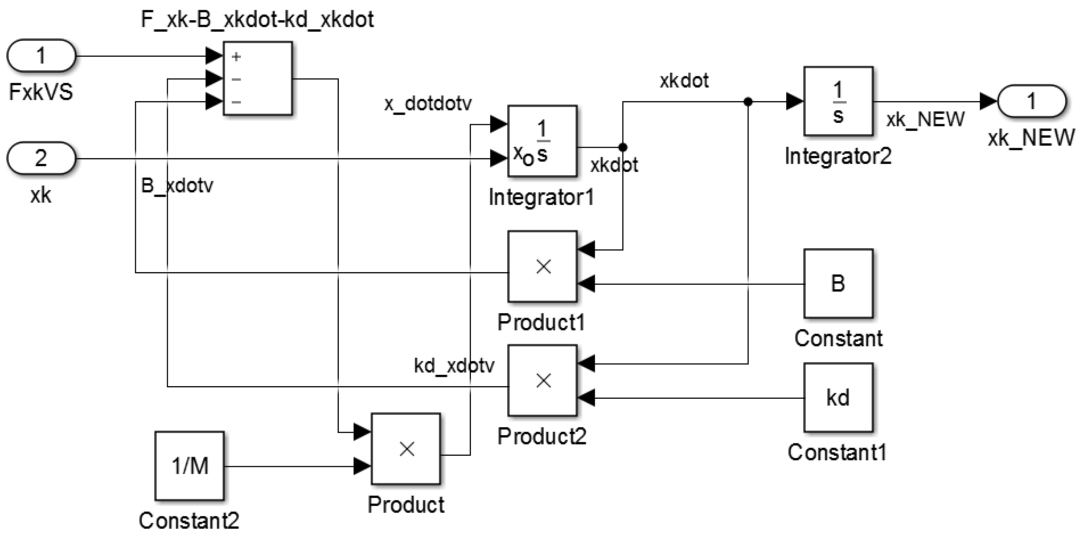
6.3 Simulink Model Approach:



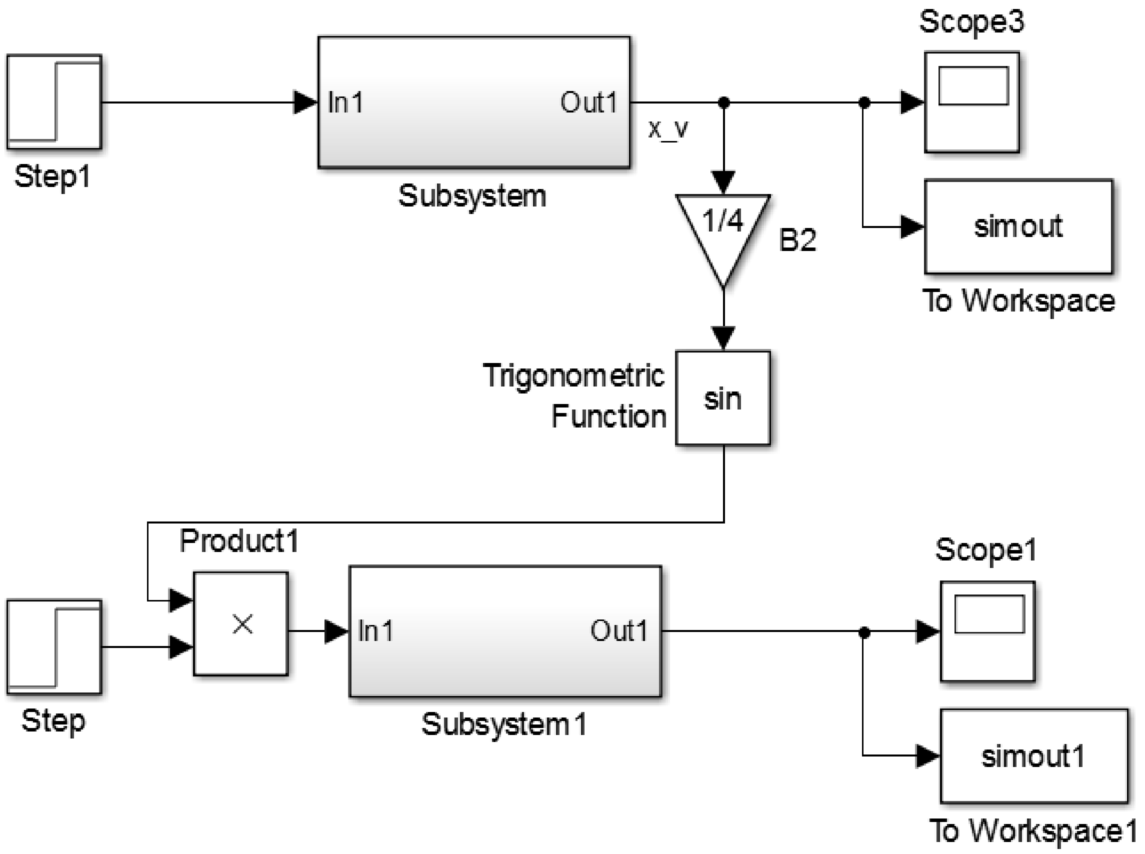
Inside Subsystem2:



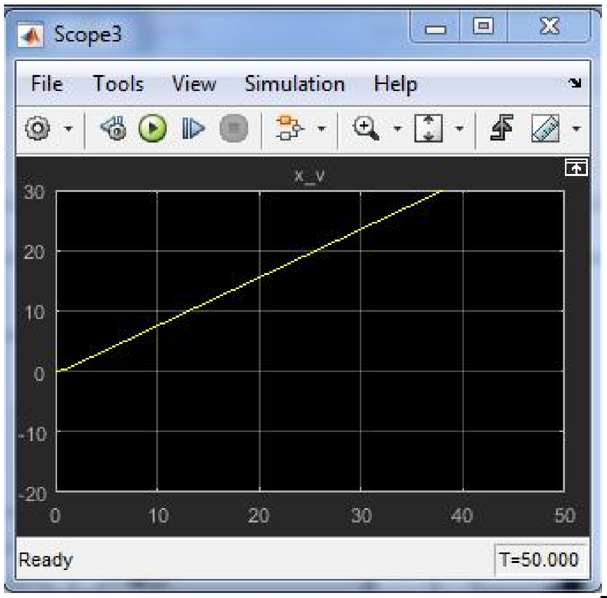
Inside Each Subsystem:

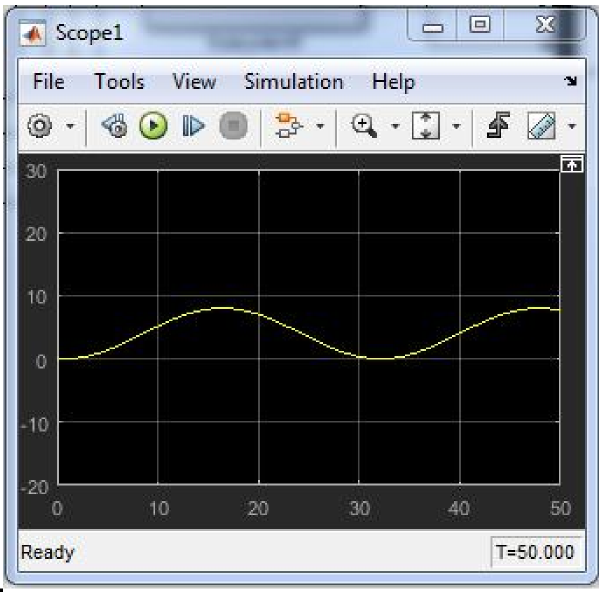


6.4 Mobile Robots Swarm (Trajectory for Virtual Only)



Scope Plot Data for x and y:





MATLAB Command for (x,y) plot of Swarm Trajectory for Virtual Mobile Robot:

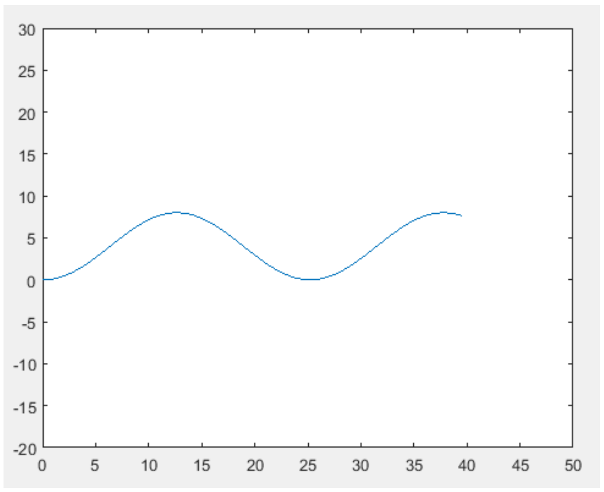
```
>> x=simout.signals.values;

>> y=simout1.signals.values;

>> plot(x,y)

>> axis([0,50,-20,30])
```

(x,y) Plot of Virtual Robot:



Codes for Formation:

MATLAB Code:

```
clc;
clear all;
close all;

number_of_robots=5;
robot=cell(1,number_of_robots+1);
POSITIONS=zeros(2,number_of_robots);

%Initial Position of the robots
robot{1}=[-4,6];
robot{2}=[-8,6];
robot{3}=[6,8];
robot{4}=[8,-8];
robot{5}=[2,-8];
robot{6}=[0,7];
robot{7}=[-6,-6];
robot{8}=[0,0];
robot{number_of_robots+1}=robot{1};

figure;
hold on; grid on;
rLine = [animatedline('Color','r','LineWidth',3);
         animatedline('Color','b','LineWidth',3);
         animatedline('Color','k','LineWidth',3);
         animatedline('Color','g','LineWidth',3);
         animatedline('Color','g','LineWidth',3);
         animatedline('Color','g','LineWidth',3);
         animatedline('Color','g','LineWidth',3);
         animatedline('Color','g','LineWidth',3);
         animatedline('Color','g','LineWidth',3);
         ];
axis([-8 8 -8 8]); axis square;

xdot = zeros(number_of_robots,1);
ydot = zeros(number_of_robots,1);

M=1;
B=1;
kd=9;
ksk=1;
kr=0.15;

xc=0;
yc=0;
hyp_robot=[xc,yc];

alpha=2;
qk=2.5;

%Vector to hold the position history
robot_Vec=[];

%Charges on each robot
```

```
q(1:number_of_robots)=qk;

%Mass of each robot
m(1:number_of_robots)=M;

%Electrostatic Constant
K=10;

%drawing a circle of radius=alpha
count=1;
for theta=0:0.1:2*pi
x_circle(count)=(alpha+0.5)*cos(theta);
y_circle(count)=(alpha+0.5)*sin(theta);
count=count+1;
end

x_circle=x_circle+hyp_robot(1);
y_circle=y_circle+hyp_robot(2);
plot(x_circle,y_circle,'r-')
for i=1:number_of_robots+1
    dummy=robot(i);
    xy_pos=cell2mat(dummy);
    x_pos=xy_pos(1);
    y_pos=xy_pos(2);
    POSITIONS(i,1) = x_pos;
    POSITIONS(i,2) = y_pos;
end
% scatter(POSITIONS(:,1),POSITIONS(:,2),'X')
% line(POSITIONS(:,1),POSITIONS(:,2))

xPOINTS = POSITIONS(:,1);
yPOINTS = POSITIONS(:,2);
plot(xPOINTS,yPOINTS,'X')
k = boundary(xPOINTS,yPOINTS,0);
plot(xPOINTS(k),yPOINTS(k));

pause
for t=1:150  %total simulation time
    %Computing distance of individual robot from all other robots
    r=zeros(number_of_robots,number_of_robots);
    for i=1:number_of_robots
        for j=1:number_of_robots
            a=robot{i}-robot{j};
            r(i,j)=sqrt(a(1)^2+a(2)^2);
        end
    end

    %Computing orientation of individual from all other robots
    theta=zeros(number_of_robots,number_of_robots);
    for i=1:number_of_robots
        for j=1:number_of_robots
            if i==j
                theta(i,j)=0;
            elseif i~=j
                a=robot{i}-robot{j};
                theta(i,j)=atan2(a(2),a(1));
            end
        end
    end

%     Computing Electrostatic forces (Repulsive) on individual robot
%     from all other robots
    Electrostatic_Forces=zeros(number_of_robots,number_of_robots);
    for i=1:number_of_robots
        for j=1:number_of_robots
            if i==j
                Electrostatic_Forces(i,j)=0;
            elseif i~=j
                Electrostatic_Forces(i,j)=(K*q(i)*q(j))/(r(i,j)^2);
            end
        end
    end

    %Decomposition of Electrostatic forces in x and y components
    for i=1:number_of_robots
        for j=1:number_of_robots
            Fxk_dist(i,j)=Electrostatic_Forces(i,j)*cos(theta(i,j));
            Fyk_dist(i,j)=Electrostatic_Forces(i,j)*sin(theta(i,j));
        end
    end

    for i=1:number_of_robots
        Fxk(i)=sum(Fxk_dist(i,1:number_of_robots));
        Fyk(i)=sum(Fyk_dist(i,1:number_of_robots));
    end

    %Computing x and y components of Attractive Force (Equation 8 in JP)

    for i=1:number_of_robots
        a=robot{i}-hyp_robot;
        Attractive_Force_x(i)=ksk*(a(1)*(a(1)^2+a(2)^2-alpha^2));
        Attractive_Force_y(i)=ksk*(a(2)*(a(1)^2+a(2)^2-alpha^2));
    end

    %Computing resultant forces on each robot
    for i=1:number_of_robots
        FxkVS(i)=Fxk(i)-Attractive_Force_x(i);
        FykVS(i)=Fyk(i)-Attractive_Force_y(i);
    end

    for i=1:number_of_robots
        dummy=robot(i);
        xy_pos=cell2mat(dummy);
        x_pos=xy_pos(1);
        y_pos=xy_pos(2);

        fx = @(t,x) [x(2); (FxkVS(i)-(B+kd)*x(2))/M];
        [T,X]=ode45(fx,[0,0.05],[x_pos;xdot(i)]);
        fy = @(t,y) [y(2); (FykVS(i)-(B+kd)*y(2))/M];
        [T,Y]=ode45(fy,[0,0.05],[y_pos;ydot(i)]);
        [m,z] = size(X);
        x_pos_new=X(m,1);
        xdot(i)=X(m,2);
        [m,z] = size(Y);
        y_pos_new=Y(m,1);
        ydot(i)=Y(m,2);
        robot{i}=[x_pos_new y_pos_new];
        addpoints(rLine(i),x_pos_new,y_pos_new);
        robot_Vec=[robot_Vec;robot];
    end
    drawnow
end


robot{number_of_robots+1}=robot{1};
for i=1:number_of_robots+1
    dummy=robot(i);
    xy_pos=cell2mat(dummy);
    x_pos=xy_pos(1);
    y_pos=xy_pos(2);
    POSITIONS(i,1) = x_pos;
    POSITIONS(i,2) = y_pos;
end
% scatter(POSITIONS(:,1),POSITIONS(:,2),'O')
% line(POSITIONS(:,1),POSITIONS(:,2),'color','m','LineWidth',3)

xPOINTS = POSITIONS(:,1);
yPOINTS = POSITIONS(:,2);
plot(xPOINTS,yPOINTS,'X')
k = boundary(xPOINTS,yPOINTS,0);
plot(xPOINTS(k),yPOINTS(k));
```

MATLAB Function 1 Code:

```
function [x,y]=fcn()
%#codegen
number_of_robots=4;
x = zeros(1,number_of_robots);
y = zeros(1,number_of_robots);
x = [-3,1,5,5];
y = [3,1,2,5];
```

MATLAB Function 2 Code:

```
function [FxkVS,FykVS,once]= fcn(x1,x2,x3,x4,y1,y2,y3,y4)
%#codegen
number_of_robots=4;
robot=cell(1,number_of_robots);

%Initial Position of the robots
robot{1}=[x1,y1];
robot{2}=[x2,y2];
```

```
robot{3}=[x3,y3];
robot{4}=[x4,y4];

M=1;
B=1;
kd=9;
ksk=1;
kr=0.15;

xc=0;
yc=0;
hyp_robot=[xc,yc];

alpha=3;
qk=10;

%Vector to hold the position history
robot_Vec=[];

%Charges on each robot
q = zeros(1:number_of_robots);
q(1:number_of_robots)=qk;

%Mass of each robot
m = zeros(1:number_of_robots);
m(1:number_of_robots)=M;

%Electrostatic Constant
K=10;

% for t=1:250  %total simulation time
    %Computing distance of individual robot from all other robots
    r=zeros(number_of_robots,number_of_robots);
    for i=1:number_of_robots
        for j=1:number_of_robots
            a=robot{i}-robot{j};
            r(i,j)=sqrt(a(1)^2+a(2)^2);
        end
    end

    %Computing orientation of individual from all other robots
    theta=zeros(number_of_robots,number_of_robots);
    for i=1:number_of_robots
        for j=1:number_of_robots
            if i==j
                theta(i,j)=0;
            elseif i~=j
                a=robot{i}-robot{j};
                theta(i,j)=atan2(a(2),a(1));
            end
        end
    end

%     Computing Electrostatic forces (Repulsive) on individual robot
%     from all other robots
```

```
    Electrostatic_Forces=zeros(number_of_robots,number_of_robots);
    for i=1:number_of_robots
        for j=1:number_of_robots
            if i==j
                Electrostatic_Forces(i,j)=0;
            elseif i~=j
                Electrostatic_Forces(i,j)=(K*q(i)*q(j))/(r(i,j)^2);
            end
        end
    end

    Fxk_dist = zeros(number_of_robots,number_of_robots);
    Fyk_dist = zeros(number_of_robots,number_of_robots);

    %Decomposition of Electrostatic forces in x and y components
    for i=1:number_of_robots
        for j=1:number_of_robots
            Fxk_dist(i,j)=Electrostatic_Forces(i,j)*cos(theta(i,j));
            Fyk_dist(i,j)=Electrostatic_Forces(i,j)*sin(theta(i,j));
        end
    end

    Fxk = zeros(1,number_of_robots);
    Fyk = zeros(1,number_of_robots);
    for i=1:number_of_robots
        Fxk(i)=sum(Fxk_dist(i,1:number_of_robots));
        Fyk(i)=sum(Fyk_dist(i,1:number_of_robots));
    end

    %Computing x and y components of Attractive Force (Equation 8 in JP)
   Attractive_Force_x = zeros(1,number_of_robots);
   Attractive_Force_y = zeros(1,number_of_robots);
    for i=1:number_of_robots
        a=robot{i}-hyp_robot;
        Attractive_Force_x(i)=ksk*(a(1)*(a(1)^2+a(2)^2-alpha^2));
        Attractive_Force_y(i)=ksk*(a(2)*(a(1)^2+a(2)^2-alpha^2));
    end

    FxkVS = zeros(1,number_of_robots);
    FykVS = zeros(1,number_of_robots);
    %Computing resultant forces on each robot
    for i=1:number_of_robots
        FxkVS(i)=Fxk(i)-Attractive_Force_x(i);
        FykVS(i)=Fyk(i)-Attractive_Force_y(i);
    end

once = zeros(1,1);
once = 3;
```

Chapter 7. Robot Localization by sensor fusion of GPS, Odometer and INS

- Introduction:

This chapter discusses how data from three sensors namely INS (Inertial Navigation System), GPS (Global Positioning System) and Odometer is combined to get accurate position of robot. The data from these sensors is combined using sensor fusion scheme such as the Kalman Filter, (KF) and weighting scheme.

Using the above mentioned sensor fusion scheme, the position of robot can be determined in indoor as well as outdoor applications.

7.2- The Sensor Fusion Scheme:

Fig 7.1 shows the sensor fusion scheme in block diagram. The data from INS and odometer is fused together to get correct position estimate using Kalman filter algorithm. The GPS data and KF filtered data is then weighted (using the weighting parameter,‘α’) using appropriate/best weights based on whether GPS data is available or not.

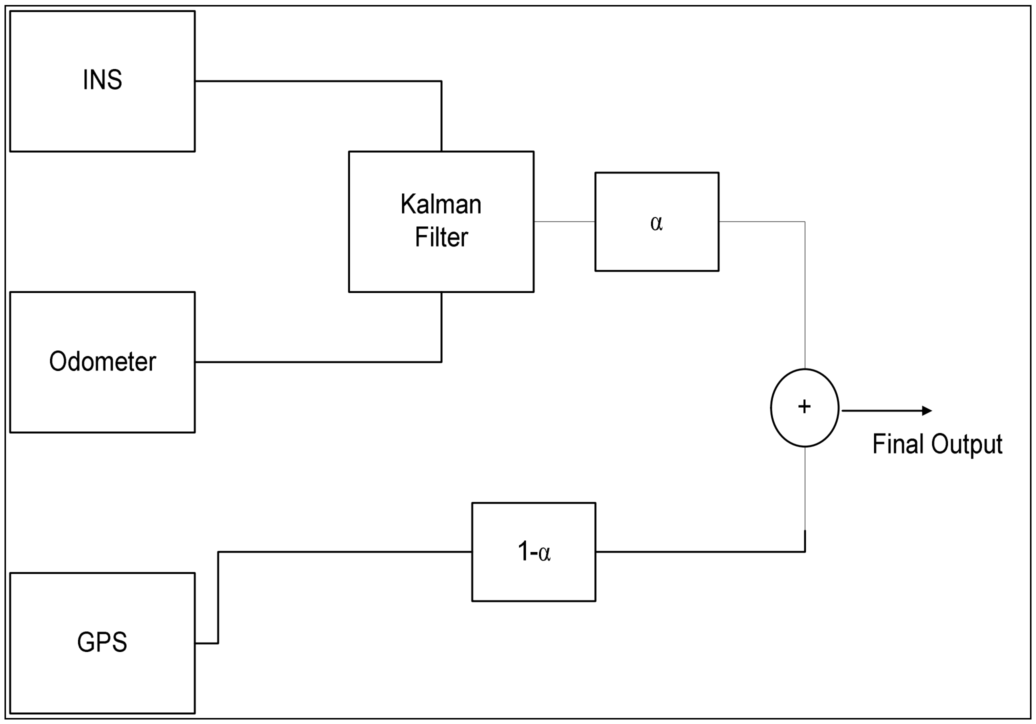


Fig7.1.The Sensor Fusion Scheme

7.3-Kalman Filter for Sensor Fusion:

The Kalman Filter is used to fuse the data from odometer and INS. Since the INS consists of accelerometers and gyroscopes. Accelerometers data contains many kinds of errors such as bias and random noise.

When the accelerometer data is double integrated to get position, there is error drift increasing with time and produces wrong position results. Therefore, odometer position data is combined with INS with Kalman filter to utilize the advantages of both the sensors and to get a correct estimate of position.

Kalman Filter algorithm:

The Kalman Filter algorithm consists of the following steps:

1. Prediction and
2. Correction.

The algorithm consists of the following steps:

1. Set the initial values of states and error covariance

Matrix:

$$x\hat{o}, Po$$

2. Predicting state and error covariance matrix.

$$\hat{x}_k = A\hat{x}_{k-1}$$

$$P_k^- = AP_{k-1}A^T + Q$$

Where,

A is the state transition matrix or the system model and

Q is the process noise covariance matrix

3. Compute the Kalman Gain

$$K_K = P_K^- H^T (HP_K^- H^T + R)^{-1}$$

Here,

H is the observation matrix

R is the measurement noise covariance matrix

4. Calculate the state estimate:

$$\hat{x}_k = \hat{x}_k^- + K(z - \hat{H}x_k^-)$$

5. Calculate the error covariance:

$$P_k = P_k^- - KHP_k^-$$

And the above steps are repeated iteratively.

7.4- Weighting using weighting parameter 'α':

The weighting parameter is used to assign appropriate weights to KF filtered signal (INS+ Odometer) and the GPS and the final output after data fusion is calculated as:

Output = α (KF filtered signal) + (1-α) GPS signal

Case –I:

The value of weighting parameter 'α' depends on the availability of GPS signals. If GPS signals are available, then:

$$\mathbf{0 \le \alpha \le 0.1}$$

Case-2:

If the values of GPS are not available, then the weighting parameter 'α' is assigned the following values:

$$\mathbf{0.9 \le \alpha \le 1}$$

7.5-Implementation:

To test the above sensor fusion algorithm, simulations were carried out in MATLAB / Simulink environment. Mathematical models of, INS, GPS and Odometer were used to generate simulated data from sensors. The following matrices were used in applying Kalman Filtering to INS and Odometer data:

Here, a six state Kalman Filter is implemented for sensor fusion. The system state vector is:

$X = [ax \quad ay \quad vx \quad vy \quad x \quad y]'$

Where,

'ax' is the robot acceleration in x – direction.

‘ay’ is the robot acceleration in y-direction.

‘vx’ is the robot velocity in x – direction.

‘vy’ is the robot velocity in y – direction.

‘x’ is the robot position x- co-ordinate.

‘y’ is robot position y – co-ordinate.

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ t & 0 & 1 & 0 & 0 & 0 \\ 0 & t & 0 & 1 & 0 & 0 \\ 0.5t^2 & 0 & t & 0 & 1 & 0 \\ 0 & 0.5t^2 & 0 & t & 0 & 1 \end{bmatrix}$$

The sensor measurements are:

$$Z = [ax\_acc \quad ay\_acc \quad x\_od \quad y\_od]$$

Where ax_acc and ay_acc are accelerations measured from accelerometers, and x_od and y_od are x and y positions determined from odometer readings.

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The observation matrix is:

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Process Noise Covariance matrix:

$$Q=\begin{bmatrix} 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \end{bmatrix}$$

The measurement noise covariance matrix is:

$$R=\begin{bmatrix} \sigma^2_{ax\_acc} & 0 & 0 & 0 \\ 0 & \sigma^2_{ay\_acc} & 0 & 0 \\ 0 & 0 & \sigma^2_{x\_od} & 0 \\ 0 & 0 & 0 & \sigma^2_{y\_od} \end{bmatrix}$$

The error covariance matrix P is initialized to:

$$P_0 = Q$$

The system states are initialized to:

$X = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$

The weighting parameter'α' is assigned a value '0.5' to test the effect of both KF filtered signals and GPS signals on the final output.

The simulation results are shown in Fig7.2 and Fig7.3.

7.6- Simulation Results:

The simulation results are presented in Fig7.2 and Fig7.3.The actual path of robot in both x and y direction are shown in red. The KF estimated output is shown in green. The weighted output from GPS and KF is shown in blue. It can be seen from Fig7.2 and Fig7.3 that since the initial values of x and y were initialized to zero, that is we do not know initial values of x and y, the KF estimate therefore takes time to converge to acceptable values. The weighted data from GPS and KF produces a better estimate of the robot's location. The proposed scheme produces estimates of the actual x and y location with minimum error and takes less time to converge than the KF output which is evident from the two graphs in Fig7.2 and 7.3.

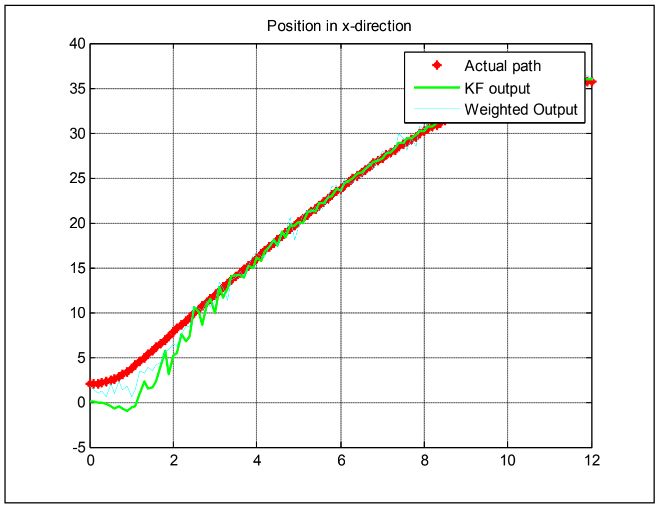


Fig. 7.2 – Position in x-direction (α=0.5)

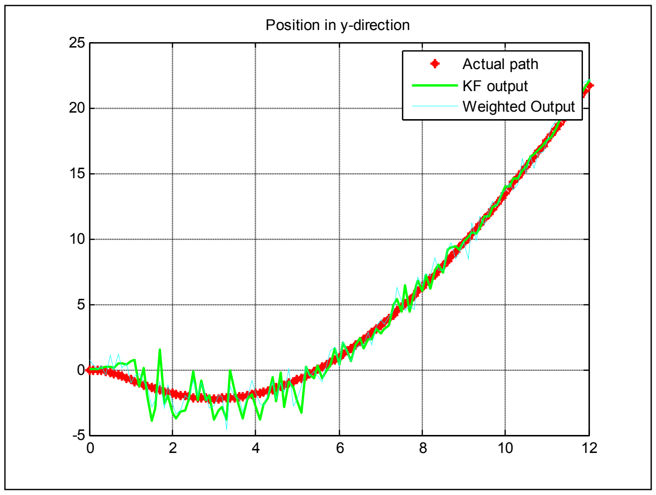


Fig. 7.3 – Position in y-direction (α=0.5)

Chapter 8. Annexure A

```
import RPi.GPIO as GPIO

import time

GPIO.setmode(GPIO.BCM)


TRIG = 23

ECHO = 24


print "Distance measurement in progress"


GPIO.setup(TRIG,GPIO.OUT)

GPIO.setup(ECHO,GPIO.IN)

while True:


  GPIO.output(TRIG, False)

  print "Waitng For Sensor To Settle"

  time.sleep(2)


  GPIO.output(TRIG, True)

  time.sleep(0.00001)

  GPIO.output(TRIG, False)


  while GPIO.input(ECHO)==0:

    pulse_start = time.time()
```

```
while GPIO.input(ECHO)==1:
  pulse_end = time.time()


pulse_duration = pulse_end - pulse_start
distance = pulse_duration * 17150
distance = round(distance, 2)


if distance > 2 and distance < 400:
  print "Distance:",distance - 0.5,"cm"
else:
  print "Out Of Range"
```

Chapter 9. Annexure B

Main.h File

```
#ifndef MAINWINDOW_H

#define MAINWINDOW_H


#include <QMainWindow>

#include <QImage>


class QLabel;

class LeptonThread;

class QGridLayout;


class MainWindow : public QMainWindow {

   Q_OBJECT


   enum { ImageWidth = 320, ImageHeight = 240 };


   static int snapshotCount;


   QLabel *imageLabel;

   LeptonThread *thread;

   QGridLayout *layout;


   unsigned short rawMin, rawMax;
```

```
    QVector<unsigned short> rawData;
    QImage rgbImage;

public:
    explicit MainWindow(QWidget *parent = 0);

public slots:
    void saveSnapshot();
    void updateImage(unsigned short *, int, int);
};

#endif // MAINWINDOW_H
```

<u>Main.cpp File</u>

```
#include "mainwindow.h"
#include <QLabel>
#include <QPushButton>
#include <QGridLayout>
#include <QImage>
#include <QPixmap>
#include <QPainter>
#include <QFile>

#include "LeptonThread.h"

int MainWindow::snapshotCount = 0;
```

```
MainWindow::MainWindow(QWidget *parent)
    : QMainWindow(parent)
    , rawData(LeptonThread::FrameWords)
    , rgbImage(LeptonThread::FrameWidth, LeptonThread::FrameHeight,
QImage::Format_RGB888)
 {




    QWidget *mainWidget = new QWidget();
    setCentralWidget(mainWidget);

    layout = new QGridLayout();
    mainWidget->setLayout(layout);

    imageLabel = new QLabel();
    layout->addWidget(imageLabel, 0, 0, Qt::AlignCenter);

    QPixmap filler(ImageWidth, ImageHeight); filler.fill(Qt::red);
    imageLabel->setPixmap(filler);

    thread = new LeptonThread();
    connect(thread, SIGNAL(updateImage(unsigned short *,int,int)), this,
SLOT(updateImage(unsigned short *, int,int)));
```

```
  //QPushButton *snapshotButton = new QPushButton("Snapshot");

  //layout->addWidget(snapshotButton, 1, 0, Qt::AlignCenter);

  //connect(snapshotButton, SIGNAL(clicked()), this, SLOT(saveSnapshot()));




   thread->start();


}



// Rainbow: const int colormap[] = {1, 3, 74, 0, 3, 74, 0, 3, 75, 0, 3, 75, 0, 3, 76, 0, 3, 76, 0, 3, 77,
0, 3, 79, 0, 3, 82, 0, 5, 85, 0, 7, 88, 0, 10, 91, 0, 14, 94, 0, 19, 98, 0, 22, 100, 0, 25, 103, 0, 28,
106, 0, 32, 109, 0, 35, 112, 0, 38, 116, 0, 40, 119, 0, 42, 123, 0, 45, 128, 0, 49, 133, 0, 50, 134, 0,
51, 136, 0, 52, 137, 0, 53, 139, 0, 54, 142, 0, 55, 144, 0, 56, 145, 0, 58, 149, 0, 61, 154, 0, 63,
156, 0, 65, 159, 0, 66, 161, 0, 68, 164, 0, 69, 167, 0, 71, 170, 0, 73, 174, 0, 75, 179, 0, 76, 181, 0,
78, 184, 0, 79, 187, 0, 80, 188, 0, 81, 190, 0, 84, 194, 0, 87, 198, 0, 88, 200, 0, 90, 203, 0, 92,
205, 0, 94, 207, 0, 94, 208, 0, 95, 209, 0, 96, 210, 0, 97, 211, 0, 99, 214, 0, 102, 217, 0, 103, 218,
0, 104, 219, 0, 105, 220, 0, 107, 221, 0, 109, 223, 0, 111, 223, 0, 113, 223, 0, 115, 222, 0, 117,
221, 0, 118, 220, 1, 120, 219, 1, 122, 217, 2, 124, 216, 2, 126, 214, 3, 129, 212, 3, 131, 207, 4,
132, 205, 4, 133, 202, 4, 134, 197, 5, 136, 192, 6, 138, 185, 7, 141, 178, 8, 142, 172, 10, 144,
166, 10, 144, 162, 11, 145, 158, 12, 146, 153, 13, 147, 149, 15, 149, 140, 17, 151, 132, 22, 153,
120, 25, 154, 115, 28, 156, 109, 34, 158, 101, 40, 160, 94, 45, 162, 86, 51, 164, 79, 59, 167, 69,
67, 171, 60, 72, 173, 54, 78, 175, 48, 83, 177, 43, 89, 179, 39, 93, 181, 35, 98, 183, 31, 105, 185,
26, 109, 187, 23, 113, 188, 21, 118, 189, 19, 123, 191, 17, 128, 193, 14, 134, 195, 12, 138, 196,
10, 142, 197, 8, 146, 198, 6, 151, 200, 5, 155, 201, 4, 160, 203, 3, 164, 204, 2, 169, 205, 2, 173,
206, 1, 175, 207, 1, 178, 207, 1, 184, 208, 0, 190, 210, 0, 193, 211, 0, 196, 212, 0, 199, 212, 0,
202, 213, 1, 207, 214, 2, 212, 215, 3, 215, 214, 3, 218, 214, 3, 220, 213, 3, 222, 213, 4, 224, 212,
4, 225, 212, 5, 226, 212, 5, 229, 211, 5, 232, 211, 6, 232, 211, 6, 233, 211, 6, 234, 210, 6, 235,
210, 7, 236, 209, 7, 237, 208, 8, 239, 206, 8, 241, 204, 9, 242, 203, 9, 244, 202, 10, 244, 201, 10,
245, 200, 10, 245, 199, 11, 246, 198, 11, 247, 197, 12, 248, 194, 13, 249, 191, 14, 250, 189, 14,
251, 187, 15, 251, 185, 16, 252, 183, 17, 252, 178, 18, 253, 174, 19, 253, 171, 19, 254, 168, 20,
254, 165, 21, 254, 164, 21, 255, 163, 22, 255, 161, 22, 255, 159, 23, 255, 157, 23, 255, 155, 24,
255, 149, 25, 255, 143, 27, 255, 139, 28, 255, 135, 30, 255, 131, 31, 255, 127, 32, 255, 118, 34,
255, 110, 36, 255, 104, 37, 255, 101, 38, 255, 99, 39, 255, 93, 40, 255, 88, 42, 254, 82, 43, 254,
77, 45, 254, 69, 47, 254, 62, 49, 253, 57, 50, 253, 53, 52, 252, 49, 53, 252, 45, 55, 251, 39, 57,
251, 33, 59, 251, 32, 60, 251, 31, 60, 251, 30, 61, 251, 29, 61, 251, 28, 62, 250, 27, 63, 250, 27,
65, 249, 26, 66, 249, 26, 68, 248, 25, 70, 248, 24, 73, 247, 24, 75, 247, 25, 77, 247, 25, 79, 247,
26, 81, 247, 32, 83, 247, 35, 85, 247, 38, 86, 247, 42, 88, 247, 46, 90, 247, 50, 92, 248, 55, 94,
248, 59, 96, 248, 64, 98, 248, 72, 101, 249, 81, 104, 249, 87, 106, 250, 93, 108, 250, 95, 109,
250, 98, 110, 250, 100, 111, 251, 101, 112, 251, 102, 113, 251, 109, 117, 252, 116, 121, 252,
121, 123, 253, 126, 126, 253, 130, 128, 254, 135, 131, 254, 139, 133, 254, 144, 136, 254, 151,
140, 255, 158, 144, 255, 163, 146, 255, 168, 149, 255, 173, 152, 255, 176, 153, 255, 178, 155,
255, 184, 160, 255, 191, 165, 255, 195, 168, 255, 199, 172, 255, 203, 175, 255, 207, 179, 255,
211, 182, 255, 216, 185, 255, 218, 190, 255, 220, 196, 255, 222, 200, 255, 225, 202, 255, 227,
204, 255, 230, 206, 255, 233, 208};
```

```
const int colormap[] = {255, 255, 255, 253, 253, 253, 251, 251, 251, 249, 249, 249, 247, 247,
247, 245, 245, 245, 243, 243, 243, 241, 241, 241, 239, 239, 239, 237, 237, 237, 235, 235, 235,
233, 233, 233, 231, 231, 231, 229, 229, 229, 227, 227, 227, 225, 225, 225, 223, 223, 223, 221,
221, 221, 219, 219, 219, 217, 217, 217, 215, 215, 215, 213, 213, 213, 211, 211, 211, 209, 209,
209, 207, 207, 207, 205, 205, 205, 203, 203, 203, 201, 201, 201, 199, 199, 199, 197, 197, 197,
195, 195, 195, 193, 193, 193, 191, 191, 191, 189, 189, 189, 187, 187, 187, 185, 185, 185, 183,
183, 183, 181, 181, 181, 179, 179, 179, 177, 177, 177, 175, 175, 175, 173, 173, 173, 171, 171,
171, 169, 169, 169, 167, 167, 167, 165, 165, 165, 163, 163, 163, 161, 161, 161, 159, 159, 159,
157, 157, 157, 155, 155, 155, 153, 153, 153, 151, 151, 151, 149, 149, 149, 147, 147, 147, 145,
145, 145, 143, 143, 143, 141, 141, 141, 139, 139, 139, 137, 137, 137, 135, 135, 135, 133, 133,
133, 131, 131, 131, 129, 129, 129, 126, 126, 126, 124, 124, 124, 122, 122, 122, 120, 120, 120,
118, 118, 118, 116, 116, 116, 114, 114, 114, 112, 112, 112, 110, 110, 110, 108, 108, 108, 106,
106, 106, 104, 104, 104, 102, 102, 102, 100, 100, 100, 98, 98, 98, 96, 96, 96, 94, 94, 94, 92, 92,
92, 90, 90, 90, 88, 88, 88, 86, 86, 86, 84, 84, 84, 82, 82, 82, 80, 80, 80, 78, 78, 78, 76, 76, 76, 74,
74, 74, 72, 72, 72, 70, 70, 70, 68, 68, 68, 66, 66, 66, 64, 64, 64, 62, 62, 62, 60, 60, 60, 58, 58, 58,
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40, 38, 38, 38, 36, 36, 36, 34, 34, 34, 32, 32, 32, 30, 30, 30, 28, 28, 28, 26, 26, 26, 24, 24, 24, 22,
22, 22, 20, 20, 20, 18, 18, 18, 16, 16, 16, 14, 14, 14, 12, 12, 12, 10, 10, 10, 8, 8, 8, 6, 6, 6, 4, 4, 4,
2, 2, 2, 0, 0, 0, 0, 0, 9, 2, 0, 16, 4, 0, 24, 6, 0, 31, 8, 0, 38, 10, 0, 45, 12, 0, 53, 14, 0, 60, 17, 0, 67,
19, 0, 74, 21, 0, 82, 23, 0, 89, 25, 0, 96, 27, 0, 103, 29, 0, 111, 31, 0, 118, 36, 0, 120, 41, 0, 121,
46, 0, 122, 51, 0, 123, 56, 0, 124, 61, 0, 125, 66, 0, 126, 71, 0, 127, 76, 1, 128, 81, 1, 129, 86, 1,
130, 91, 1, 131, 96, 1, 132, 101, 1, 133, 106, 1, 134, 111, 1, 135, 116, 1, 136, 121, 1, 136, 125, 2,
137, 130, 2, 137, 135, 3, 137, 139, 3, 138, 144, 3, 138, 149, 4, 138, 153, 4, 139, 158, 5, 139, 163,
5, 139, 167, 5, 140, 172, 6, 140, 177, 6, 140, 181, 7, 141, 186, 7, 141, 189, 10, 137, 191, 13, 132,
194, 16, 127, 196, 19, 121, 198, 22, 116, 200, 25, 111, 203, 28, 106, 205, 31, 101, 207, 34, 95,
209, 37, 90, 212, 40, 85, 214, 43, 80, 216, 46, 75, 218, 49, 69, 221, 52, 64, 223, 55, 59, 224, 57,
49, 225, 60, 47, 226, 64, 44, 227, 67, 42, 228, 71, 39, 229, 74, 37, 230, 78, 34, 231, 81, 32, 231,
85, 29, 232, 88, 27, 233, 92, 24, 234, 95, 22, 235, 99, 19, 236, 102, 17, 237, 106, 14, 238, 109,
12, 239, 112, 12, 240, 116, 12, 240, 119, 12, 241, 123, 12, 241, 127, 12, 242, 130, 12, 242, 134,
12, 243, 138, 12, 243, 141, 13, 244, 145, 13, 244, 149, 13, 245, 152, 13, 245, 156, 13, 246, 160,
13, 246, 163, 13, 247, 167, 13, 247, 171, 13, 248, 175, 14, 248, 178, 15, 249, 182, 16, 249, 185,
18, 250, 189, 19, 250, 192, 20, 251, 196, 21, 251, 199, 22, 252, 203, 23, 252, 206, 24, 253, 210,
25, 253, 213, 27, 254, 217, 28, 254, 220, 29, 255, 224, 30, 255, 227, 39, 255, 229, 53, 255, 231,
67, 255, 233, 81, 255, 234, 95, 255, 236, 109, 255, 238, 123, 255, 240, 137, 255, 242, 151, 255,
244, 165, 255, 246, 179, 255, 248, 193, 255, 249, 207, 255, 251, 221, 255, 253, 235, 255, 255,
24};


void MainWindow::updateImage(unsigned short *data, int minValue, int maxValue){
   // Record the raw data and min/max values
   memcpy(&rawData[0], data, 2*LeptonThread::FrameWords);
   rawMin = minValue; rawMax = maxValue;


   // Map "rawData" to rgb values in "rgbImage" via the colormap
   int diff = maxValue - minValue + 1;
   for (int y = 0; y < LeptonThread::FrameHeight; ++y) {
      for (int x = 0; x < LeptonThread::FrameWidth; ++x) {
         int baseValue = rawData[LeptonThread::FrameWidth*y + x]; // take input value in [0,
65536)
         int scaledValue = 256*(baseValue - minValue)/diff; // map value to interval [0, 256), and
set the pixel to its color value above
         rgbImage.setPixel(x, y, qRgb(colormap[3*scaledValue], colormap[3*scaledValue+1],
colormap[3*scaledValue+2]));
      }
   }
   // Update the on-screen image
```

```
    QPixmap pixmap = QPixmap::fromImage(rgbImage).scaled(ImageWidth, ImageHeight,
Qt::KeepAspectRatio);

    QPainter painter(&pixmap);

    // ... mark up pixmap, if so desired

    imageLabel->setPixmap(pixmap);


saveSnapshot();

}

void MainWindow::saveSnapshot() {


usleep(2000000);

   ++snapshotCount;

    // Raw file format: binary, one word for min value, one for max value, then 80*60 words of
raw data

    QFile rawFile(QString("raw%1.bin").arg(snapshotCount));

    rawFile.open(QIODevice::Truncate | QIODevice::ReadWrite);

    QDataStream rawOut(&rawFile);

    rawOut << rawMin << rawMax;

    rawOut.writeRawData((char *) &rawData[0], 2*rawData.size());

    rawFile.close();


    // JPG image, top quality

    rgbImage.save(QString("rgb%1.jpg").arg(snapshotCount), "JPG", 100);


}
```

Chapter 10. Annexure C

```
# program to take a series of pictures
import os
import string
import datetime
import time
from threading import Thread
first_pic =  "fswebcam --device /dev/video0 -r 640x480 --no-banner /home/pi/test0.jpg"
second_pic = "fswebcam --device /dev/video1 -r 640x480 --no-banner /home/pi/test2.jpg"
ii = "0"
jj = "2"
aa = "test"
def picfun():
   os.system(first_pic)
   os.system(second_pic)
t=5      # initialise the pause between pictures in seconds
count=10 # initialise the number of pictures to be taken
i=1       # initialise (reset) the counting sequence
totalTime=(t*count) # Calculate the time in seconds
# Take a series of pictures one every t seconds
while(i<count):
    leftTimeH = 0
    leftTimeM = 0
    leftTimeS = 0
```

```
# taking a picture by calling a command line prompt
    x = Thread(target = picfun)
    x.start()
    totalTime = (t*(count-i))   # Calculate the time in seconds
    print(i)                    # print the current count value to show progress
    while(totalTime>=3600):
        leftTimeH = leftTimeH + 1
        totalTime = totaTime-3600
    while(totalTime>=60):
        leftTimeM = leftTimeM + 1
        totalTime = totaTime-60
    leftTimeS = totalTime
    percentDone = (( i / count ) * 100)
    percentDone = round(percentDone,2)
    message1 = ("Time left to finish " +repr(leftTimeH) +" Hours " + repr(leftTimeM) + "
Minutes and " + repr(leftTimeS) + "Seconds")
    message2 = (" "+repr(percentDone) + " %Completed! ")
    print(message1)
    print(message2)
    i = i+1
    if(i>count):     # leave the loop when count fulfilled (not really necessary)
      break
    time.sleep(t)     # wait the defined time t(s) between pictures
    bb = "test" + ii
    ii = int(ii)
```

```
   ii = ii + 1
   ii = str(ii)
 first_pic = string.replace(first_pic, bb, aa+ii)
   cc = "test" + jj
   jj = int(jj)
   jj = jj + 1
   jj = str(jj)
   second_pic = string.replace(second_pic, cc, aa+jj)
   print("Finished!")   # print to show when finished
```