DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

CONTROL OF MOBILE ROBOTS VIA INTERNET AND WIRELESS COMMUNICATION

by
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November, 2013
İZMİR

CONTROL OF MOBILE ROBOTS VIA INTERNET AND WIRELESS COMMUNICATION

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"CONTROL OF MOBILE ROBOTS VIA INTERNET AND WIRELESS COMMUNICATION"** completed by **İSMET ATEŞ** under supervision of **ASSOC. PROF. ZEKİ KIRAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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İsmet ATEŞ

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ABSTRACT

In the scope of this thesis, a general-purpose mobile robot platform has been designed and produced. A serial robot manipulator produced in a previous study has been mounted on the designed mobile robot platform in order to increase workspace of the mobile robot. Also, required electronic circuit boards have been designed for being able to operate of mobile manipulator. Single Board Computer Raspberry Pi has been used as a main controller of the mobile manipulator and Linux based web server has been established on it in order to storage web interface page and sensory data. Arduino Leonardo has been used as a sub-controller. Web based user interface has been designed for controlling the mobile manipulator with teleoperation method over wireless internet, providing live camera stream and sensory information for operator. And finally, the determined implementation scenario, which is carrying various objects in a shelf to another shelving in a mini warehouse model, has been performed successfully.

Keywords: Mobile robot, teleoperation, single board computer, mobile web server.

MOBİL ROBOTLARIN İNTERNET VE KABLOSUZ İLETİŞİM ARACILIĞIYLA KONTROLÜ

ÖZ

Bu tez kapsamında, genel amaçlı bir mobil robot platformu tasarlanıp üretilmiştir. Robotun çalışma alanını artırmak için, önceki çalışmalarda üretilmiş bir robot manipülatörü tasarlanan mobil robot platformu üzerine monte edilmiştir. Ayrıca, mobil manipülatörü çalıştırabilmek için gereken elektronik devre kartları tasarlanmıştır. Tek kart bilgisayar Raspberry Pi mobil manipülatörün ana kontrolcüsü olarak kullanılmıştır, web arayüzünü ve algısal bilgileri depolayabilmek için üzerine Linux tabanlı web sunucusu kurulmuştur. Alt kontrolcü olarak Arduino Leonardo kullanılmıştır. Kablosuz internet üzerinden teleoperasyon metodu ile mobil manipülatörün kontrolü, operatör için algısal bilgileri ve canlı kamera görüntüsünü sağlamak için web tabanlı kullanıcı arayüzü tasarlanmıştır. Ve son olarak, küçük bir depo modelindeki, raf içerisinde bulunan çeşitli nesneleri başka raflara taşıma olarak belirlenen uygulama senaryosu başarıyla gerçekleştirilmiştir.

Anahtar kelimeler : Mobil robot, teleoperasyon, tek kart bilgisayar, mobil web sunucu.

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

The mobile robots and their systems go on developing day by day in robotics research community. There are many reasons for interesting with mobile robots such as object transporting, robotics manufacturing and assembly, investigation and mapping an unknown environment with data collecting. Mobile robots are electromechanical vehicles contain embedded systems, computer, sensors and actuators. Their wheels, tracks or other forms can ensure to move in their environment.

A mobile manipulator consists of a traditional robotic arm mounted on the mobile robot base and the mobile robot platform. This structure increases workspace of the manipulator and operation flexibility and capability. Today's mobile manipulators have been used lots of area such as education, industry and research. This combination has significant advantages but also it has disadvantages and challenges as well.

Lots of different control techniques and algorithms for the mobile manipulators have been developed to the present. One of them is teleoperation that have been used frequently to control mobile manipulators remotely with the wireless communication or internet connection. Teleoperation system has been used to perform tasks in a distant, inaccessible or dangerous environment. Teleoperation and robotics have created telerobotics field in research community. Research in internet telerobotics field has increased after improving internet technology during the last fifteen years.

1.2 Literature Review

Today, controlling of mobile manipulator is an important field of research.

Improvement of mobile manipulator has brought more complex mechanic, electronic and software structure. Thus, more complex control technique have been begun to need. This complexity has caused to develop more robust, accurate and precision control technique.

Internet teleoperation and telerobotics have developed quite a few to the present with improving internet technology. Internet communication is chosen in telerobotics applications for using advantages of internet but it sometimes causes unpredictable problems such as time delay, packet lost or error, connection rupture because internet doesn't Guarantee Quality of Service (QoS). Research in internet teleoperation and telerobotic is more about decreasing effect of these problems and improving new control technique under problems.

In this literature review, research in mobile manipulators, internet teleoperation and telerobotics, reducing their problems and various implementation areas have been mentioned.

Goldberg, Mascha, Gentner, Rothenberg, Sutter & Wiegley (1995) have developed The Mercury project is thought to be the first system that allowed users to manipulate various object with made of 6 Degrees of Freedom (DOF) tele-manipulator via internet. This project is the milestone on internet teleoperation and telerobotics.

Goldberg, Santarromana, et al. (1995) have extended internet telerobotics idea with The Telegarden allows users to look at and interact with a remote garden have in living plants by internet. User can water, dig and monitor the plants with 6 DOF robot arm.

Simmons, Fernandez, Goodwin, Koenig & O'Sullivan (1999) have developed a mobile robot Xavier have tended researchers to consider control algorithm of the internet telerobotics because internet caused unpredictable time delay when controlling the robots on web.

Slawinski, Postigo & Mutt (2006) have designed stable control scheme is composed a velocity controller and time-delay compensation between local and remote location of the teleoperation system.

Ogaki & Suzuki (2007) have presented adaptive teleoperation and autonomous behavior according to situation in order to overcome the communication time delay related internet.

Agis, Carrillo, Moran, Gonzalez, Morillas, Pelayo & Bernier (2005) have designed Hypertext Preprocessor (PHP) based web interface established on Apache web server for monitoring the mobile robot.

Wang & Liu (2005) have implemented interactive control which is used for internet based mobile robot teleoperation. They have used joystick commands and linguistic commands are for advanced telecommanding.

Kaber, Wright & Sheik-Nainar (2005) have designed multi-modal interface for Adaptive Automation (AA) of human control of telerobotics.

Nielsen, Goodrich & Ricks (2007) have used ecological interfaces that combined video and robot pose information in Three Dimension (3D) reality display for telerobotics.

Malysz (2011) has improved a general teleoperation framework for master and slave robots.

Dai & Li (2010) designed and implemented motion controller for an 8 DOF mobile manipulator that wanted to track a desired trajectory according to frame.

Frejek & Nokleby (2013) has intended to develop an algorithm facilitated teleoperation of mobile manipulators for the operator.

Commonwealth Scientific and Industrial Research Organization [CSIRO] (n.d.) has carried out Museum Mobile Telepresence Robot project allows visitors to do a virtual tour of places with mobie robot equipped 360 degree camera and panoramic viewer in National Museum of Australia.

Double Robotics (n.d.) has developed commercial telepresence robot controls personal tablets for offices, school campuses, retail stores, manufacturing facilities, families, museums and galleries.

1.3 Objective of Thesis

The mobile manipulators have been used frequently remote, inaccessible or dangerous environment for executing the task sent by operator or another system. One of the key topics is telerobotic for implementing this control structure.

The objectives of this thesis are to design and produce a 7 DOF mobile manipulator, develop web based user friendly interface established single board computer (SBC), control mobile manipulator by wireless internet communication and implement the scenario is that various objects in shelf are carried another shelving in a mini warehouse model.

The mobile manipulator and interface can be perform follows task in real time;

- Connecting to the mobile manipulator.
- Moving the mobile robot to four directions forward, backward, right and left
- Moving the robotic arm anywhere in workspace.
- Gripping object with robotic arm.
- Monitorization video from camera on the robot.
- Displaying battery status, current information of motors and robotic arm.
- Displaying velocity and displacement of mobile manipulator.

1.4 Organization of the Thesis

This thesis is organized as follows.

Chapter 2 presents briefly theoretical background about mobile robot, mobile manipulators, teleoperation, telerobotics and controlling via internet. In Chapter 3, mechanical and electronic hardware designs of the mobile manipulator are presented and all elements are explained. Chapter 4 includes explanations about infrastructure of low level and high level software in the system. In Chapter 5, implementation scenario is presented and web based real time user interface is explained. Chapter 6 includes thesis conclusion, discussion of results and things to do for future works.

CHAPTER TWO
THEORETICAL BACKGROUND

2.1 Mobile Robots

Mobile robots are in focus of current robotic research. Lots of university, independent researcher, company have studied on mobile robotics and many articles are published regularly about mobile robots. Mobile robots have been used often many field in today such as industry, military, medical, education, research, rescue entertainment, especially since development in electronics, computer science, communication and internet.

Mobile robot is electromechanic machine that is able to move in any environment. Mobile robot consist of embedded systems which execute low level processes such as collecting and processing sensors data, controlling actuators and base level communication, computer which carries out high level processes such as interpreting sensors data and determination of behavior, high level communication such as the internet and control of whole systems, mechanic systems and actuators that ensure mobile robot to move in given environment and perform given tasks.

2.1.1 Classification of Mobile Robots

Many mobile robots have been developed by using purpose and area. In generally, mobile robots can be classified according to the environment in which they travel and the locomotion mechanisms use to move (Wikipedia, n.d.).

Classification of the locomotion mechanisms as follows;

- Legged robots: Mobile robots have one or many legs according to its structure for moving on terrestrial environment.

- Wheeled robots: The wheels are most popular locomotion mechanism in mobile robotics and their efficiencies are very good. The wheels number depends on drive technique and structure of robot.
- Tracked robots: The tracks are chosen especially for using mobile robots in rough terrain. Tracked locomotion mechanism ensures much larger ground contact and improves robot maneuverability.
- Robots with rotors: The rotors are used for aerial and underwater robots, its number changes design of mobile robots.

Classification of the environment in which they travel as follows;

- Land Robots: They are also called Unmanned Ground Vehicles (UGVs) and include locomotion mechanisms such as legs, wheels or tracks.
- Aerial robots: They are also referred to as Unmanned Aerial Vehicles (UAVs) and use rotors as locomotion.
- Underwater robots: They are also called Autonomous Underwater Vehicle (AUVs) and use rotors for moving in given environment.
- Polar robots: They are used crevasse, icy filled environments.

2.1.2 Structure of Mobile Robots

In generally, mobile robots consist of elements like seen in Figure 2.1

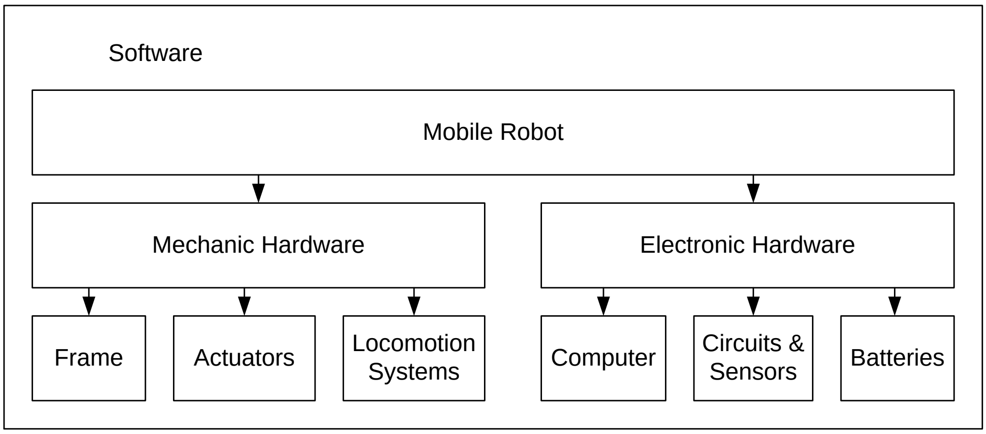


Figure 2.1 Structure of mobile robots

Mechanic hardware of mobile robot consists of a frame, actuators and the locomotion system. The frame encloses and carries whole electronic and mechanic systems. Designing, producing and assembly of frame is important issue for motion smoothness of mobile robots and influences directly path controlling of robot.

The actuators convert electronic energy to mechanic energy for being able to move mobile robot and operate their mechanic limbs for given tasks. The actuators are chosen according to mechanic power requirement, precision, speed and duty in mechanism of robot. The reductor mechanisms that increase torque are sometimes used with motors. Some of the actuators used are standard DC motors, stepper motors, servo motors and linear motors.

The locomotion mechanism as described in 2.1.1 can be legged, wheeled or tracked and are connected directly or indirectly with motors. The locomotion is one of the important issues for mobile robot as the frame

Electronic hardware is formed with computer, circuits, sensors and batteries. A computer acts as a major component no doubt. The computer carries out high level process related control, interpreting, planning, behavior, determination and communication of mobile robot. Development of electronic integrated circuit (IC) and microprocessor technology minimizes size of computers as SBC, which preferred to use often in mobile robots and manipulators, are significant examples but heavy processes like complex image processing tasks are required better computers like a laptop.

Electronic circuits are used to carry out subtask of the system such as driving motors, battery management, collecting and converting sensor data. There are many useful sensors has been improved for providing senses of robots. The sensors used mostly in mobile robot are that; shaft encoders, accelerometers, gyroscope, inertial measurement unit (IMU), inclinometers, compass, cameras, ultrasonic sensors, infrared sensors, micro switches, proximity switches, current sensors, sonar, lidar, laser, global positioning system (GPS), barometer and temperature sensors.

Batteries supply electronic energy for whole systems and batteries sometimes combines with renewable energy system especially in space robots as Solero (Michaud, Scheider, Bertrand, Lamon, Siegwart, Van Winnendael & Schiele, 2002)

As seen clearly in Figure 2.1, electronic and mechanic hardware cannot execute together given tasks without software. Software is major point for control of mobile robot. Control of subunits and subtasks are executed by the low level software in embedded systems. High level software such as computer programs, web interface in established on computers or servers controls whole systems.

2.1.3 Drive Techniques

The wheeled mobile robots have been by far the most popular robots in mobile robotics. Using the wheels in mobile robots has advantages and disadvantages (Ignell, Rasmusson & Matsson, 2012)

The advantages are;

- Very good efficiencies.
- Relatively simple mechanical implementation.
- Stable balance up to four wheeled robot.
- Generally cheap.
- Generally easy control up to four wheeled robot.

The disadvantages are;

- Balance and stability problems based weight.
- Frictional forces.
- Poor maneuverability for four or many wheels.

In generally, wheeled mobile robot researches tend to focus on problems of stability, maneuverability and control in given terrain with desired traction and stability. Wheeled mobile robot contacts to ground with a few point. Therefore, weight distribution in mobile robot is more important for stability and balance. This problem concerns four wheeled robots more and a suspension system is required all wheels to be able to contact with ground in given enjoinment for removal problem. (Siegward & Nourbakhsh, 2004)

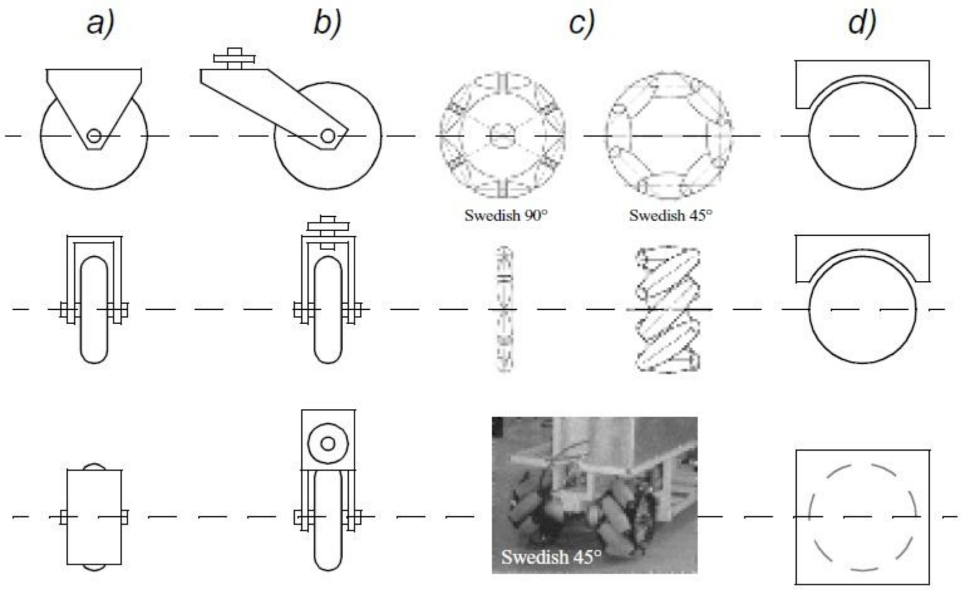


Figure 2.2 The four basic wheel types. a) Standard motorized wheel: 2 DOF. b) Castor wheel: 2 DOF c) Swedish motorized Wheel: 3 DOF. d) Ball or spherical wheel.(Siegward & Nourbakhsh, 2004)

There are four basic wheel types like seen in Figure 2.2. Depending on variety of wheels and environments, many drive techniques have been occurred, as shown in Figure 2.3, Figure 2.4 and Figure 2.5.

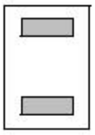
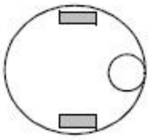
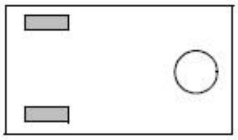
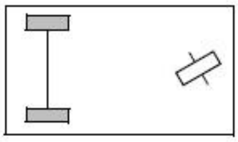
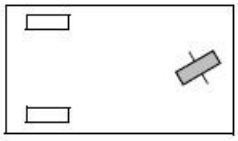
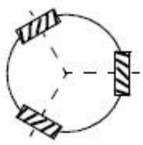
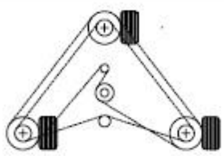
# of wheels	Arrangement	Description	Typical examples
2		One steering wheel in the front, one traction wheel in the rear	Bicycle, motorcycle
		Two-wheel differential drive with the center of mass (COM) below the axle	Cye personal robot
3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRob EPFL
		Two independently driven wheels in the rear/front, 1 unpowered omnidirectional wheel in the front/rear	Many indoor robots, including the EPFL robots Pygmalion and Alice
		Two connected traction wheels (differential) in rear, 1 steered free wheel in front	Piaggio minitrucks
		Two free wheels in rear, 1 steered traction wheel in front	Neptune (Carnegie Mellon University), Hero-1
		Three motorized Swedish or spherical wheels arranged in a triangle; omnidirectional movement is possible	Stanford wheel Tribolo EPFL, Palm Pilot Robot Kit (CMU)
		Three synchronously motorized and steered wheels; the orientation is not controllable	"Synchro drive" Denning MRV-2, Georgia Institute of Technology, I-Robot B24, Nomad 200

Figure 2.3 Drive technics with two and three wheels (Siegward & Nourbakhsh, 2004)

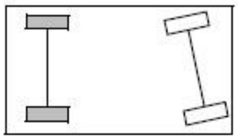
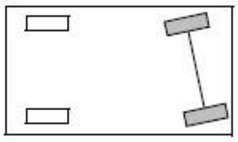
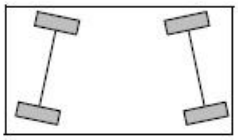
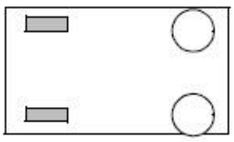
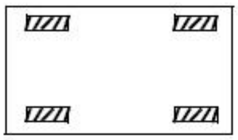
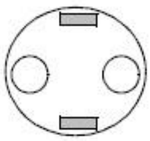
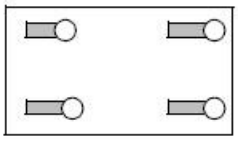
# of wheels	Arrangement	Description	Typical examples
4		Two motorized wheels in the rear, 2 steered wheels in the front; steering has to be different for the 2 wheels to avoid slipping/skidding.	Car with rear-wheel drive
		Two motorized and steered wheels in the front, 2 free wheels in the rear; steering has to be different for the 2 wheels to avoid slipping/skidding.	Car with front-wheel drive
		Four steered and motorized wheels	Four-wheel drive, four-wheel steering Hyperion (CMU)
		Two traction wheels (differential) in rear/front, 2 omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)
		Four omnidirectional wheels	Carnegie Mellon Uranus
		Two-wheel differential drive with 2 additional points of contact	EPFL Khepera, Hyperbot Chip
		Four motorized and steered castor wheels	Nomad XR4000

Figure 2.4 Drive technics with four wheels (Siegward & Nourbakhsh, 2004)

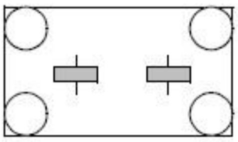
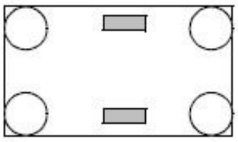
# of wheels	Arrangement	Description	Typical examples
6		Two motorized and steered wheels aligned in center, 1 omnidirectional wheel at each corner	First
		Two traction wheels (differential) in center, 1 omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)
Icons for the each wheel type are as follows:			
	unpowered omnidirectional wheel (spherical, castor, Swedish);		
	motorized Swedish wheel (Stanford wheel);		
	unpowered standard wheel;		
	motorized standard wheel;		
	motorized and steered castor wheel;		
	steered standard wheel;		
	connected wheels.		

Figure 2.5 Drive technics with six wheels and icons (Siegward & Nourbakhsh, 2004)

2.2 Mobile Manipulators

The manipulator is defined as a mechanical device that manipulates the object in the environment, and is frequently called robotic arm in robotics. The robotic arm is similar to human arm, consists of several links, the joints connect the links and the motors that are connected to the joints, shown in Figure 2.6. Aim of this structure is placement an end effector to given position with translating and rotating the links have the motorized joints.

Figure 2.6 The robot manipulator

In the last decade, increasing of operational capability and flexibility of mobile robots are a significant interest with combining static manipulators and mobile platforms in research. Mobile manipulators have been used many teleoperation implementations such as military operations, dangerous material carrying, research and rescue operations. These robots have been designed in order to be used in complex tasks with combining the mobile platform and the advantages of a robotic arm. As shown clearly in Figure 2.7, the mobile manipulator consists of the mobile platform and the robotic arm mounted upon the mobile platform.

Figure 2.7 The mobile manipulator

2.2.1 Advantages and Disadvantages

There are advantages as well as disadvantages when the mobile manipulators are used (Frejek, 2009)

The advantages are;

- Workspace increment: The workspace increases naturally because the manipulator placed on mobile platform can move desired anywhere.
- Usage expanding: Lots of manipulators have been placed naturally on fixed position. This means that the manipulator can be used virtually environment. After its mounting on the mobile platform, the robot system can be used unknown or dangerous environment.
- Reduction of cost: The mobile manipulator can be used to perform different tasks in different areas with workspace increment. This situation can reduce number of fixed manipulators so the cost can be decreased.

The disadvantages are;

- Redundancy: The end effector of mobile manipulator can be placed desired position with infinite number of configurations. This is called as redundancy. It is needed to choose which solution is the best solution. In generally, redundancy complicates operating and controlling of the mobile manipulators.
- Vibrations and stability loss: Changes in speed and acceleration of mobile platform or travelling on rough terrain caused to the vibrations may be transferred to mounted manipulator and cause accuracy loss. Vibrations can occur the manipulator as well as the mobile platform. Also, carrying large amount of load with the manipulator may cause the mobile platform to lose its stability.
- Response time: In generally, the mobile platform slower than the manipulator mounted on it thus different response times occur and cause control problems.

2.2.2 Kinematic of a Mobile Manipulator

Kinematic describes the relationship between moving points, moving bodies and fixed bodies (Wikipedia, n.d.). Kinematic consists of two significant sub-methods that are forward and inverse kinematics.

In this thesis, kinematic equations have not been used for control of mobile manipulator. Mobile platform and each joints of manipulator have been controlled manually with wireless internet communication. The thesis concentrates to control the mobile manipulator that will be able to execute given command with using internet teleoperation.

2.3 Telerobotics

Telerobotics took place because of need to exciting operations where it is difficult and dangerous area for human working. Telerobotics can be defined as controlling robots remotely with wireless connection such as radio frequency (RF), bluetooth, Internet. The robot is responsible for low level directive at a distance, while the human operator carries out the high level control such as perception and planning. Telerobotics consist of teleoperation and robotic fields.

2.3.1 Teleoperation

Teleoperation can be defined executing an operation at a distance. Also, meaning of teleoperation is similar to remote control. First principles of teleoperation system were developed in the time beginnings of radio communication by Nikola Tesla. U.S. patent US 613809 A describes it (Tesla,1898).

2.3.2 Classification of Telerobotics

Following classification of telerobotic control scheme is defined by Conway (Conway, Volz & Walker, 1990)

Direct continuous control: The remote device follows the input from the controller; also known as master/slave control.

Shared continuous control: Control is at a higher level than direct position servoing; i.e. the device may vary from course if it encounters an obstacle.

Discrete command control: The controller is able to carry out discrete commands without intervention. This implies a higher level of capability in the remote portion of the controller as it must be able to carry out the command without help.

Supervisory control: The remote device operates in a largely autonomous mode and only interacts with the human when it encounters and unexpected situation.

Learning Control: The remote device is given intelligence that allows it to learn from human inputs and sensor information and subsequently to generate behavior in similar situations without human intervention.

Figure 2.8 shows classification of telerobotic control schemes that are in increasing sophistication from manual to autonomous control as a parallel of Conway's classification.

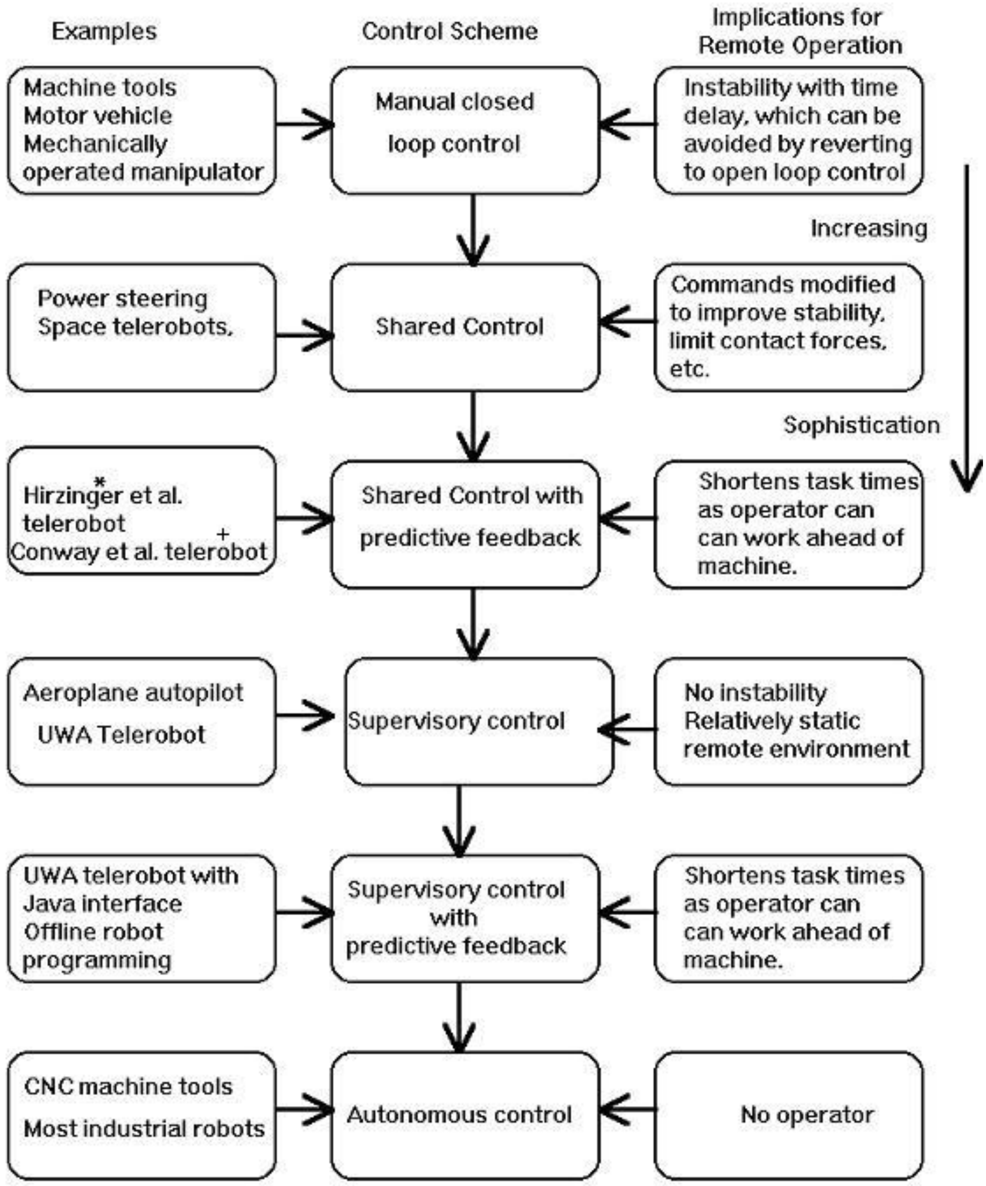


Figure 2.8 Classification of telerobotic control schemes (Taylor, 1999)

2.3.3 Telerobotics with Internet

Wikipedia describes Internet as; "The Internet is a global system of interconnected computer networks that use the standard Internet protocol suite (TCP/IP) to serve several billion users worldwide. It is a network of networks that consists of millions of private, public, academic, business, and government networks, of local to global scope, that are linked by a broad array of electronic, wireless and optical networking technologies. The Internet carries an extensive range of information resources and services, such as the inter-linked hypertext documents of the World Wide Web (WWW)" (Wikipedia, n.d.). In Today, the internet has become very popular in robotic applications.

Telerobotics with internet or internet telerobotics can be defined control of robots remotely over internet. Using internet communication has following advantages while the robots are controlled to perform tasks.

- Easy requirement for system infrastructure.
- User-friendly interface for understand and control.
- Worldwide expanding network.
- Low cost service and cheap equipment requirement.
- Fast and cheap development with improvement of new technologies.

Internet telerobotics have disadvantages as well as above many advantages. Using internet in telerobotic can cause unpredictable problems such as time delay, packet lost or error, connection rupture. Most important problem in these is the unavoidable time delays depend on structure of transmission control protocol (TCP)(Alvares, Romariz Jr., 2002), bandwidth, technical equipment, physical distance (Monteiro, Rocha, Menezes, Silva, Dias, 1997). Effects of others for teleoperation have decreased with continuous developing of internet technology.

A simple blog diagram of structure for internet teleoperation is shown Figure 2.9.

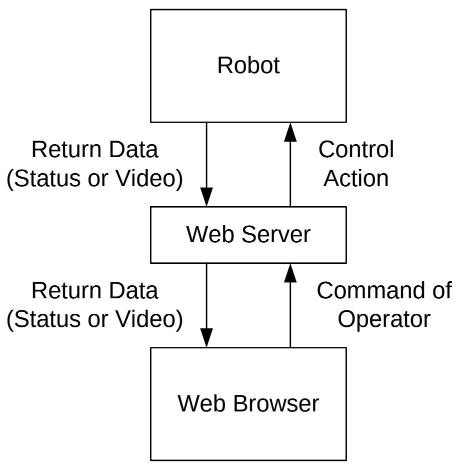


Figure 2.9 Structure for internet teleoperation

CHAPTER THREE
HARDWARE DESIGN

In this chapter, mechanic and electronic hardware of the designed and produced mobile manipulator will be presented thoroughly.

3.1 Mechanic Hardware

More mobile manipulators have been designed to use in research studies to the present. Before designing of mobile manipulator, previous designs in research have been surveyed; on the other hand, needs for project have been determined and future works have been taken into account. Thus, design criterions are occurred. One of the significant criterion for me is that developing general-purpose mobile platform for research studies in University. Mechanic 3D model of the mobile manipulator is designed in Solidworks with considering all of these.

3.1.1 Frame

Frame is first step of design. Lots of frame structures and materials have been searched but aluminum sigma profile for frame structure has been preferred due to its mechanic property and ease of assembly without mechanical processing. However, it has higher cost than other mechanic structures and materials.

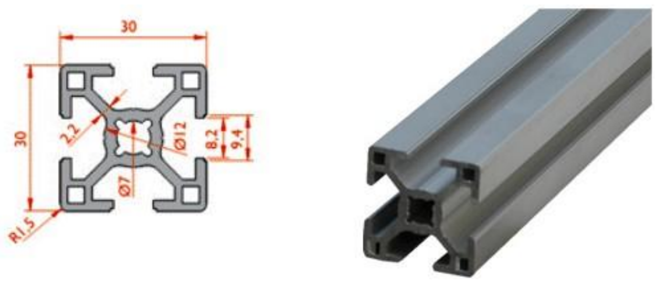


Figure 3.1 Aluminum sigma profile

Frame sizes has been decide as 640x400x140 mm and 30x30 Al sigma profile, shown in Figure 3.1, has been used in frame design with considering heavy load capability for future works. As shown in Figure 3.2, there are two sigma profiles layer for covering motors, pulleys, batteries and electronic circuits in frame because of protecting equipments in mobile platform from impact and providing resistance. An interval in each of the inner edge in the bottom layer has been designed for settling of the pulley-belt mechanisms which couple either motors with the shaft of wheels. Also, there are profiles in the middle for mounting of motors and resistance.

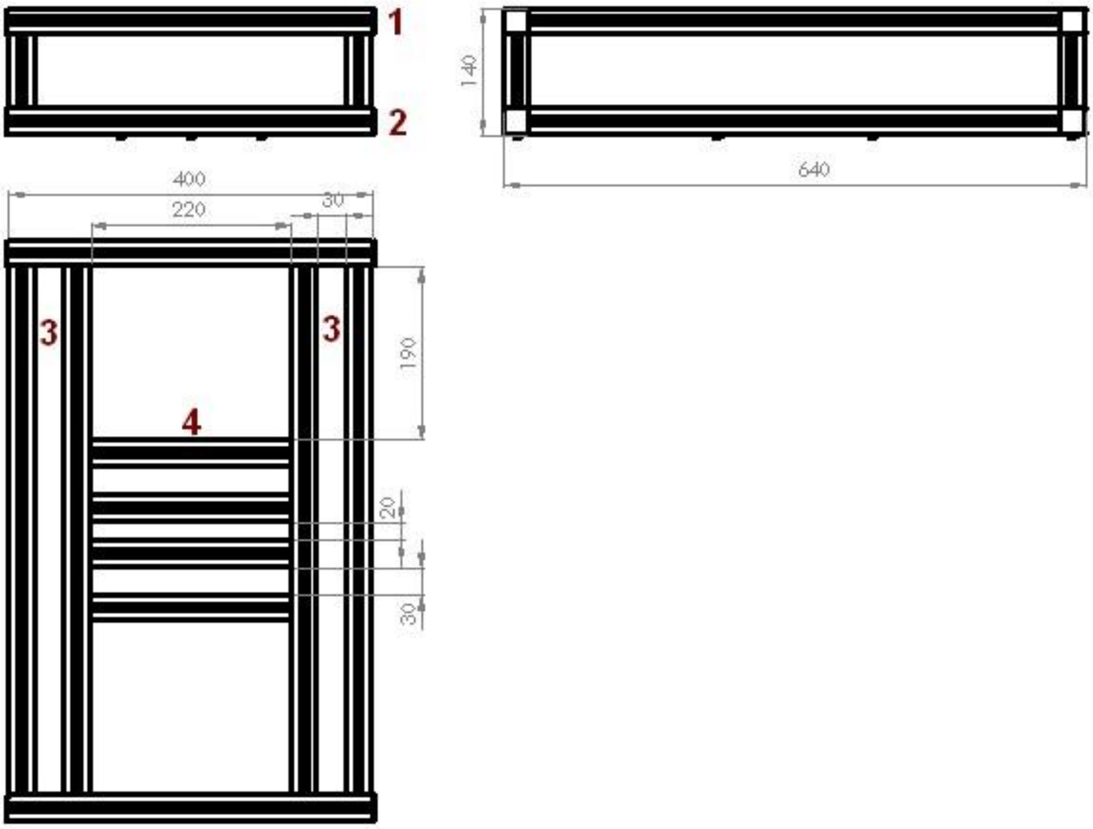


Figure 3.2 Three view of frame and its sizes. 1 is top sigma profile layer, 2 is bottom sigma profile layer, 3 is interval for pulley-belt mechanisms, 4 is profile group for motor mounting and resistance.

Designing and assembly of frame is important issue for motion smoothness of mobile platform and direct influences path controlling of robot so aluminum sigma profiles have been cutted accurately in an aluminum market according to design and the profiles have been assembled carefully with measuring. Hidden connection parts with setscrew have been used to connect profiles in edges, seen in Figure 3.3, for being able to assembly without mechanical process like hole drilling.

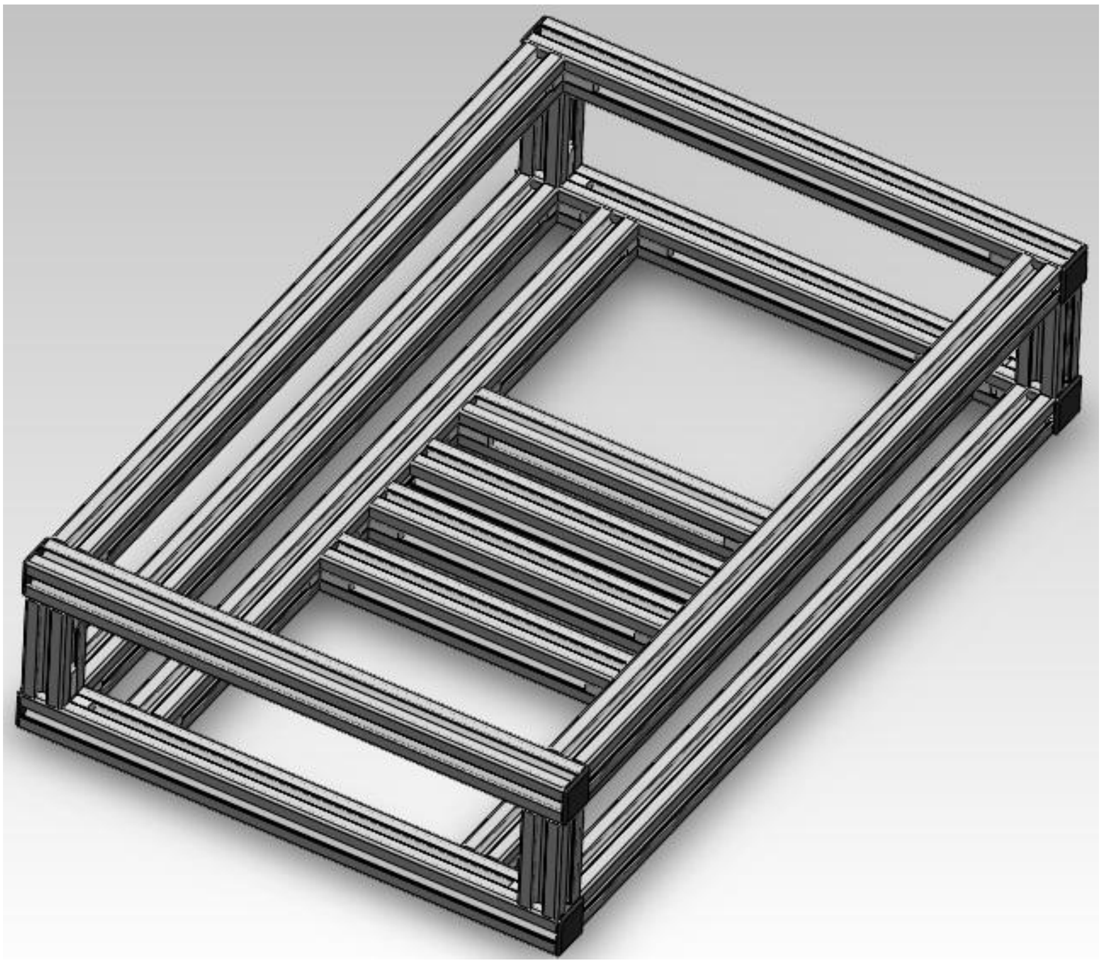


Figure 3.3 3D model of designed frame

3.1.2 Locomotion System

In this study, locomotion system of mobile platform consists of motors, the pulley-belt mechanisms, shafts and wheels. Each components of locomotion system will be explained one by one to detail in this section.

Before designing locomotion system, drive technique of mobile robot is needed to decide. VolksBot® RT 4 (Volksbot, n.d.) has been effectived for this deciding. Drive technique of mobile robot designed in this thesis is similar to differential drive and tracked drive but it is a little different. The mobile robot has four wheels and two motors however wheels coupled motors have been located diagonally like seen in Figure 3.4

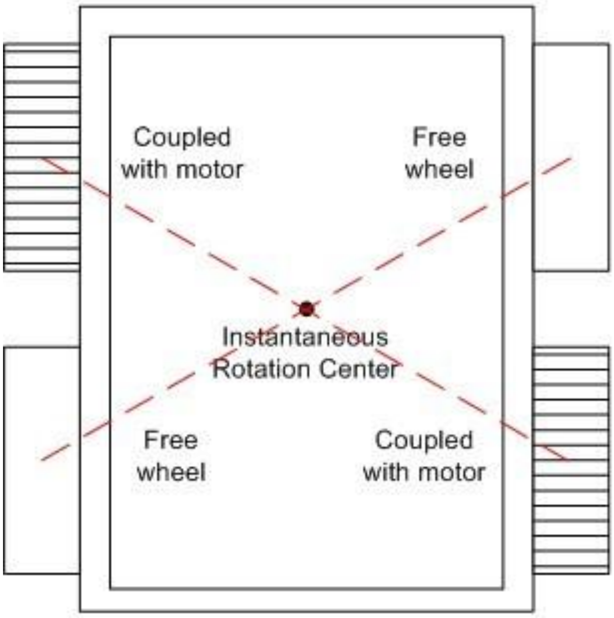


Figure 3.4 Drive technique of mobile robot

Instantaneous rotation center of mobile robot is center of robot thus mobile robot can turn its own axis in place but it depends on weight distribution of mobile robot. Purpose of using this drive technique is facilitation rotation mechanism with standard locomotion structure. Behavior of mobile robot have this drive technique has been observed throughout this study.

After deciding drive technique, the motors have been chosen objective criterions. Using brushless DC (BLDC) motors in mobile robot has been seen fit for these advantages; long life, less required maintenance, high efficiency, high output power according size, higher speed range, enables speed/torque control for given load with in hall position sensor and low noise. In this way, Daehwa E/M’s the BLDC motors ,which have B630-30B1 code, have been chosen to use in mobile robot. This BLDC motor have the technical specification shown in Figure 3.5 and performance curve seen in Figure 3.6. Its outline drawing shown in Figure 3.7 and its picture shown in Figure 3.8.

MODEL NO.	Voltage	No Load		Rated Load				Stall	
		Speed	current	Output	Speed	torque	current	torque	current
	(V)	(r/min)	(A)	(W)	(r/min)	(kgf-cm)	(A)	(kgf-cm)	(A)
B630-30B	24	4000	0.8	30	3100	0.974	2	11.5	23

Figure 3.5 Specification of chosen BLDC motor (ExceM, p.9, n.d)

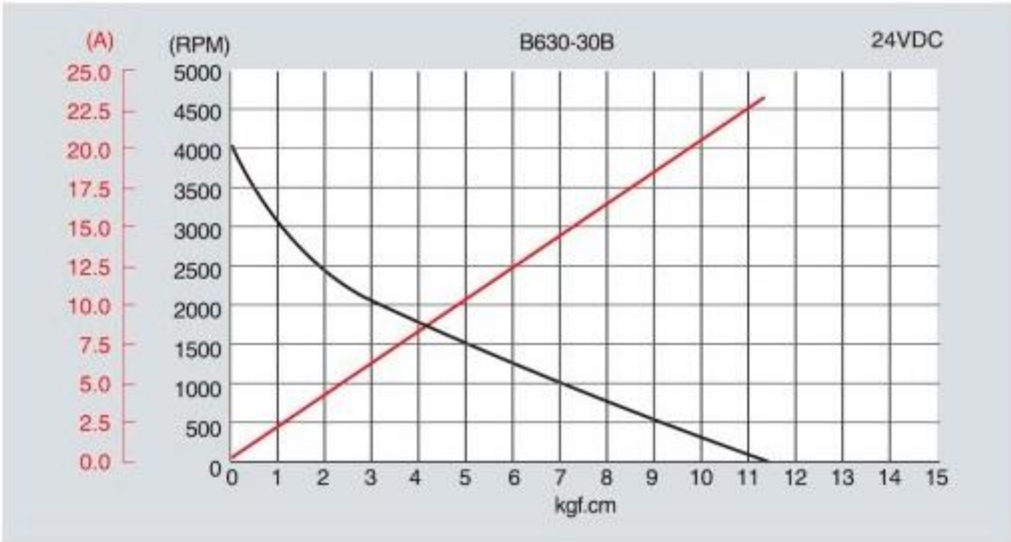


Figure 3.6 Performance curve of chosen BLDC motor (ExceM, p.9, n.d)

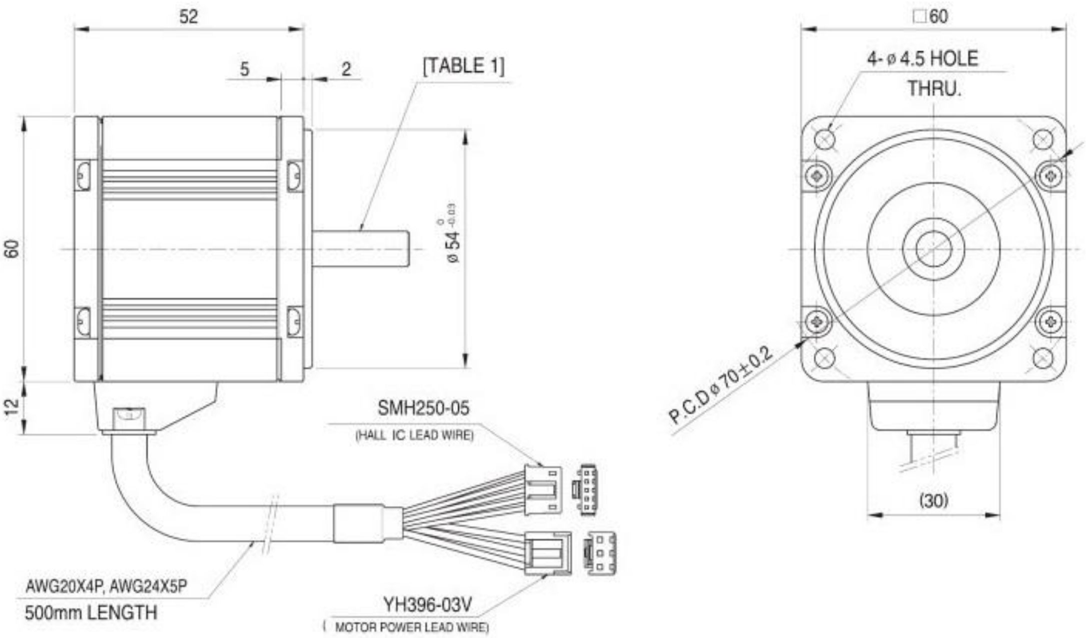


Figure 3.7 Outline drawing of chosen BLDC motor (ExceM, p.9, n.d)

Figure 3.8 Chosen BLDC motor (Directindustry, n.d.)

Seen in Figure 3.5, chosen BLDC motor have 30W output power, 3100 r/min speed and 0.974 kgf-cm torque output. Output torque is not high enough for move of mobile robot; on the other hand, output speed is too high for motion control. Therefore usage of the reductor mechanism that increases torque is inevitable. The 1:10 gear ratio 60 mm gearbox, shown in Figure 3.9, which has B6HK010 code, has been chosen for using with motor. Thus, permissible torque value have been 6.2 kgf-cm, speed out have been decreased naturally by 1:10 ratio as well, shown in Figure 3.10. Also, Figure 3.11 shows outline drawing of gearbox.

Figure 3.9 Chosen gearbox (Directindustry, n.d.)

UNIT = $\times 10^{-4}$ kg · m² (oz-in²)

Gear Ratio / Package Model	5	10	15	20	30	50	100	200
60mm	1.55(8.5)	6.2(34)	14(77)	24.8(136)	55.8(310)	155(850)	155(850)	155(850)

Figure 3.10 Torque value of gearbox (ExceM, p.16, n.d)

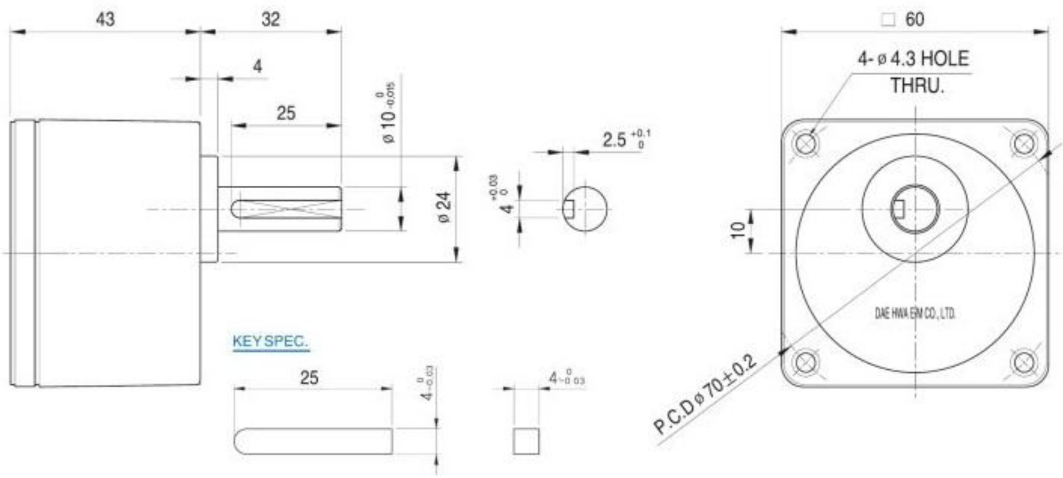


Figure 3.11 Outline drawing of gearbox (ExceM, p.16, n.d)

Figure 3.12 shows bent sheet bracket for being able to connect motor on the sigma profiles.

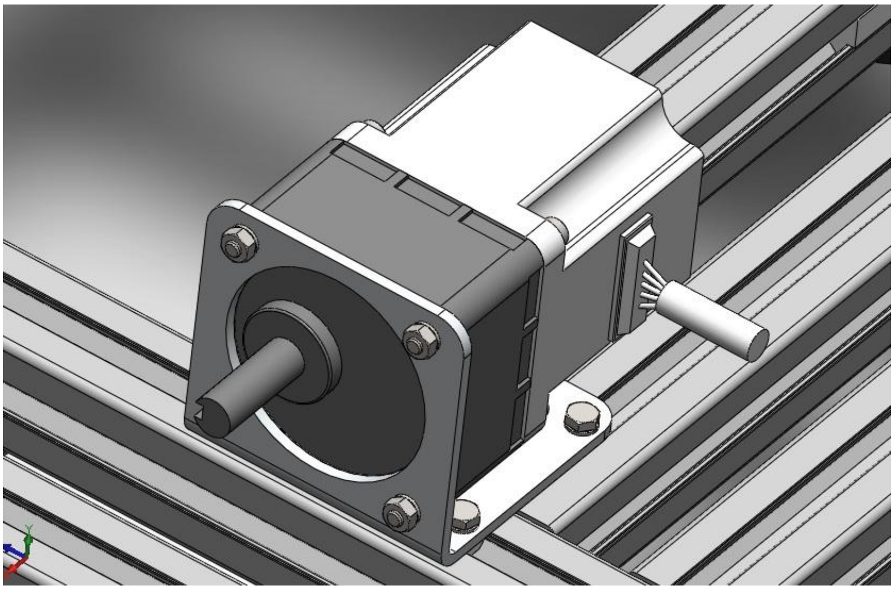


Figure 3.12 The motor bracket

UP 002 pillow blocks, shown in Figure 3.13, have been chosen to use for bearing shafts. The reason is that UP 002 can be mounted easily thanks to bolt holes on edge of block.

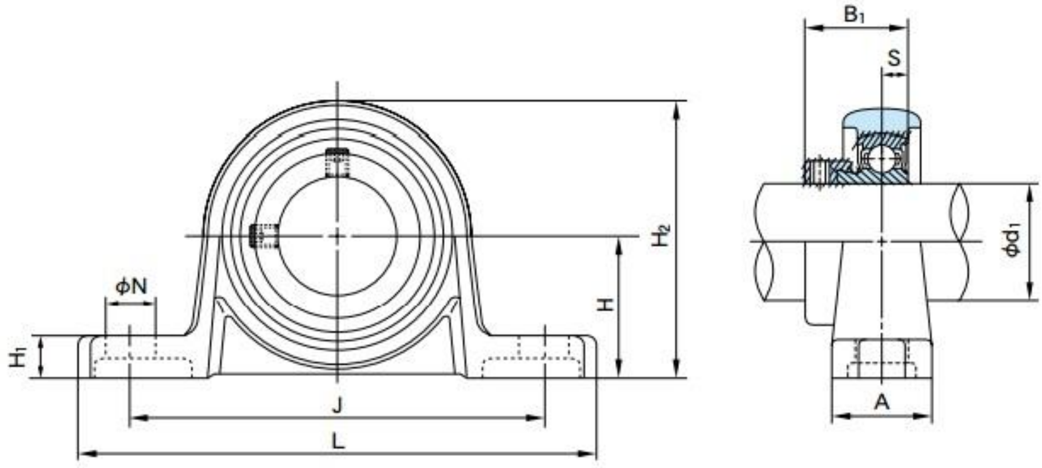


Figure 3.13 UP 002 pillow block

The bearing is more significant issue for locomotion system of mobile platforms because used bearings affect directly smoothness of drive. This importance has been taken into account and bearing from two points technique has been used in bearing of all shafts, shown in Figure 3.14. Thus, lateral forces effects on the locomotion could be decreased.

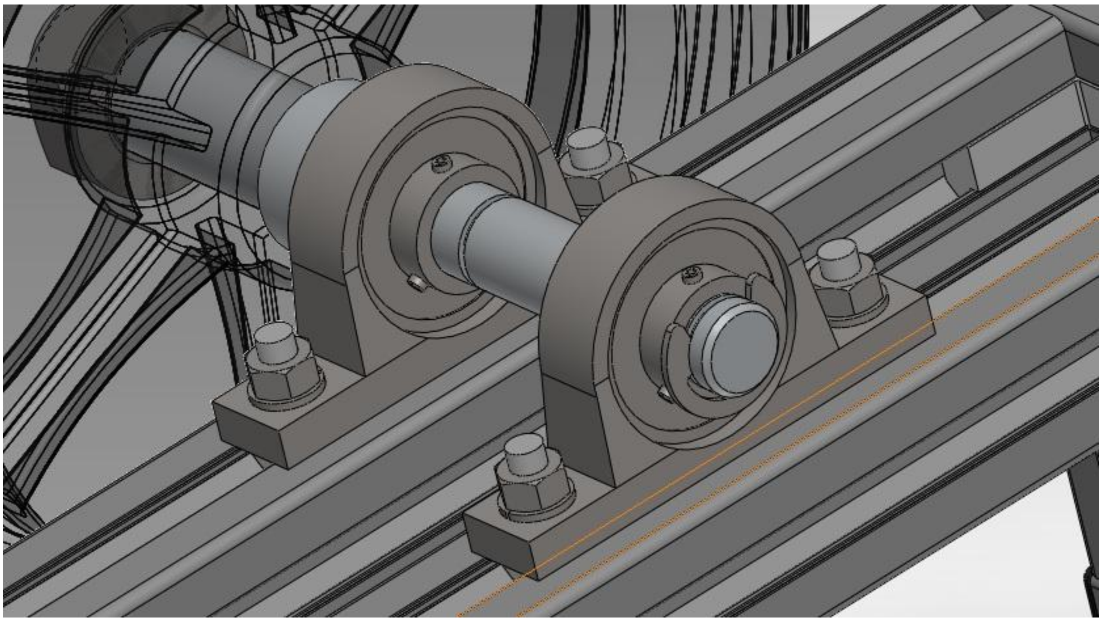


Figure 3.14 The shaft bearing

The shafts have cascade surface for wheel lean from outside and bearing lean from inside, shaft is seen in Figure 3.15. Metric 20 (M20) thread has been formed in heading of the shafts for pressing the wheel to cascade surface by M20 nut. Another process is retaining ring groove has been formed in other heading because the retaining ring prevents the shaft to go out from bearings. Figure 3.16 shows the shaft assembled with wheel and bearings.

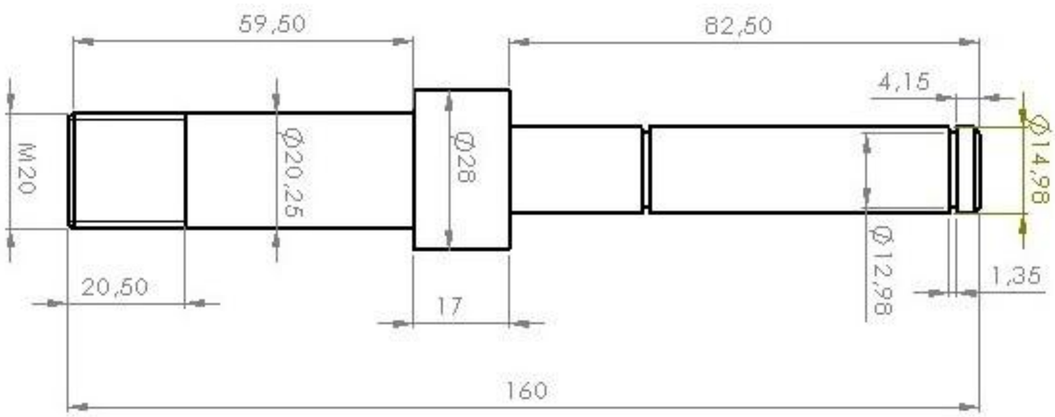


Figure 3.15 Outline drawing of shaft

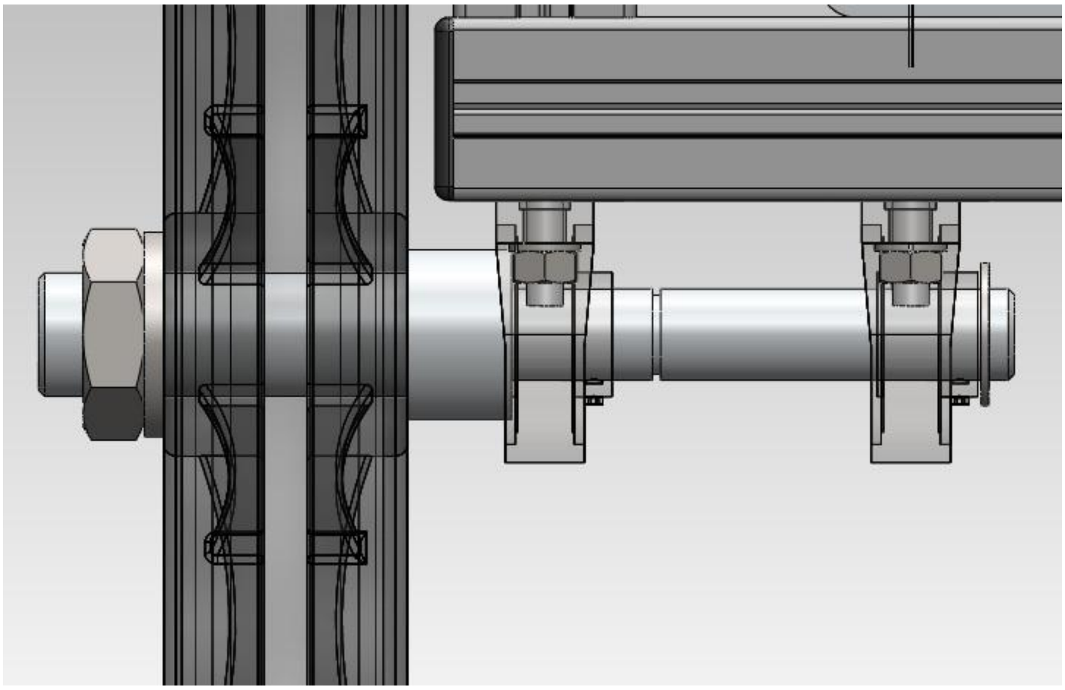


Figure 3.16 Mounted shaft

There are four shafts coupled with wheels in locomotion system of mobile robot, seen in Figure 3.17. Two of them were assembled to pulleys, which propelled with connection of belts and the pulleys of motors, with close fitting. However, other two shafts coupled the wheels are free as well. Sonlok 3638 strength retainer liquid (Parson Adhesives, n.d.) was used in coupling process of the shaft and the pulley. Also, it was used between motor shaft and the pulley.

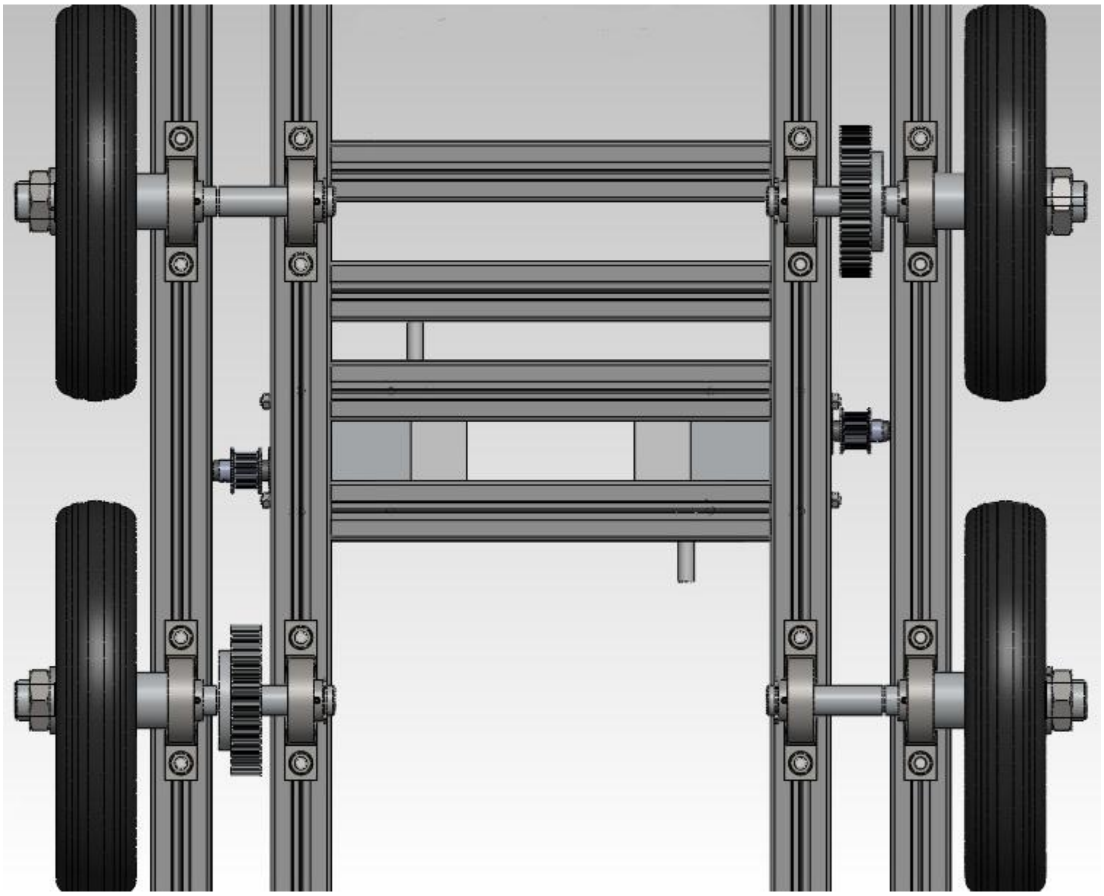


Figure 3.17 Locomotion system of mobile robot

In the design, the belt drive has been preferred for transfer the torque generated by motors because of geometric size of motors and decreasing motor speed. The Pulley-belt system consists of 12-T5-10F (12 teethes, 15 mm width) pulley, 48-T5-10 (48 teethes, 15 mm width) pulley and 450-T5 (90 teethes, 450mm length, 10mm width) belt, shown in Figure 3.18 and Figure 3.19. T5 is a code of the metric timing pulley and belt standard. Reasons of choosing T5 metric timing pulley and belt are that; locomotion system of the mobile robot has low torque according to other pulley-belt application and this standard is common in market. The belt length, which depends on locating of pulleys coupled with motor and shaft in design, has been calculated easily via 3D model of mobile robots.

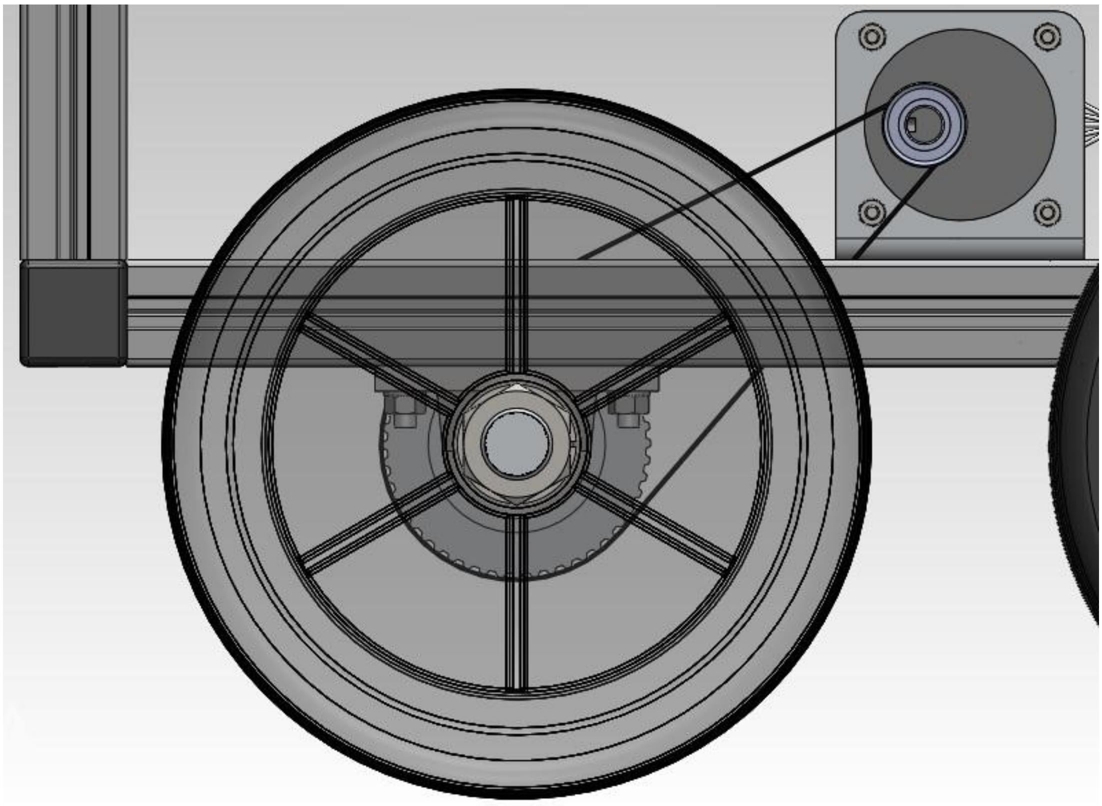


Figure 3.18 Pulley-Belt system

Teeth number of pulley has been chosen different consciously from each other because of creating another reduction ratio after the gearbox. Thus, shaft speed has been decrease with 1:4 reduction ratio and so control of mobile robot will be slower for being able to perform the tasks needed precision.

The wheels shown in Figure 3.18 have 200 mm diameter and 40 mm thickness. Filled wheels were used firstly in locomotion system but filled wheels caused difficult rotation and vibration so they were changed with pneumatic wheels. Thus, the problems disappeared.

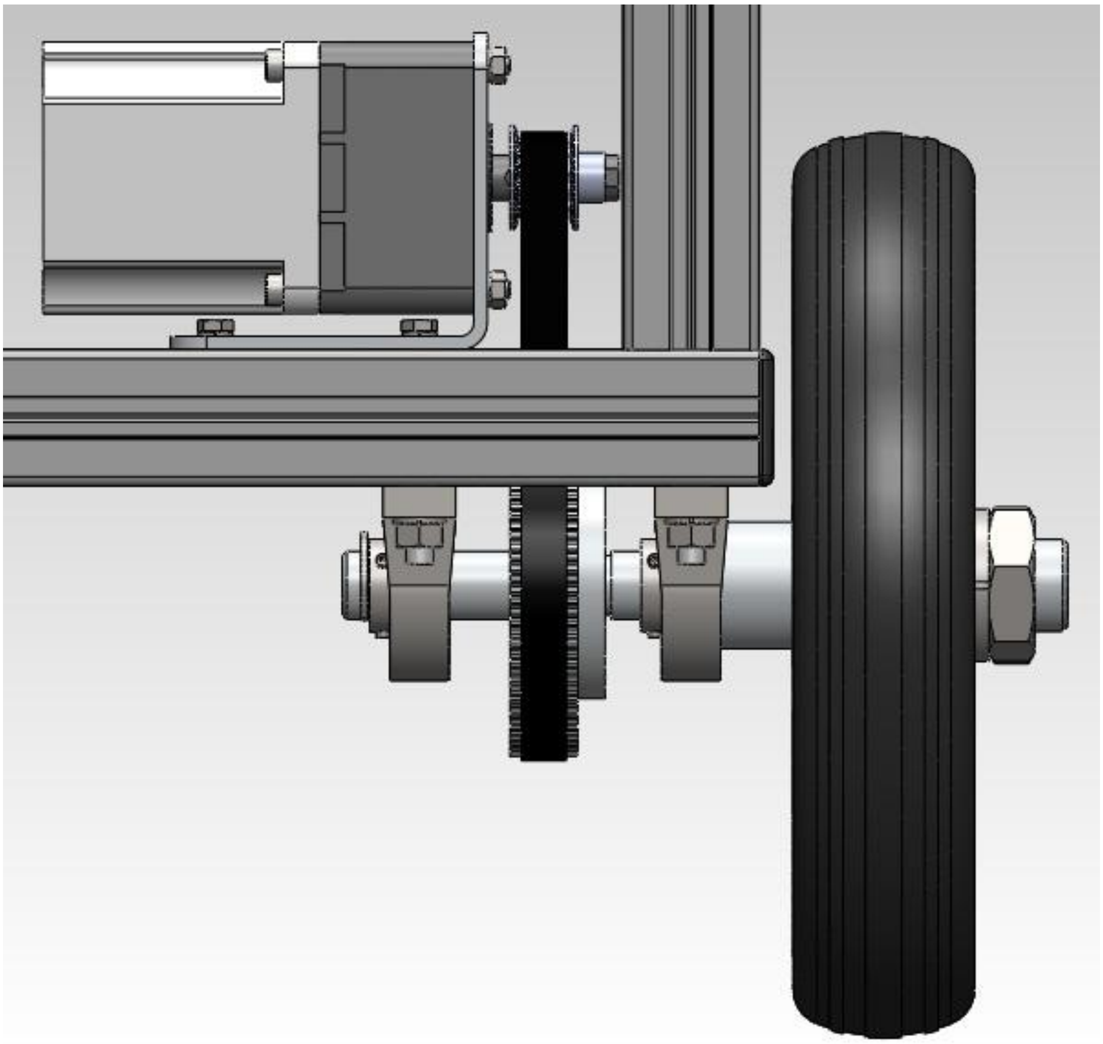


Figure 3.19 Assembled locomotion system of mobile platform

In these study, wheels of mobile robots have been adducted each other on the sigma profile. One of the advantages of this frame is flexible. In this way, changes can be performed easily, if belt length doesn’t vary. Finally, plexiglas has been assembled on top and bottom layer of frame for being able to mount electronic equipment and robotic arm on it.

3.1.3 Mobile Platform

In this section, final drawing and general dimensions after assembly of mobile platform will be shown and the some photographs that were taken while mounting will be shared.

Figure 3.20, 3.21, 3.22 show drawing and dimension of mobile platform. 3D isometric view is seen in Figure 3.23. Figure 3.24 shows mounted shaft, pulleys and pillow blocks. First test drive of locomotion system is shown in Figure 3.25. Mobile platform seem in Figure 3.26 after mounting of wheels and motor. Figure 3.27 and 3.28 show pulleys-belt-motor connection. The mobile robot equipped with electronic hardware is shown Figure 3.29 after finishing of whole assembly

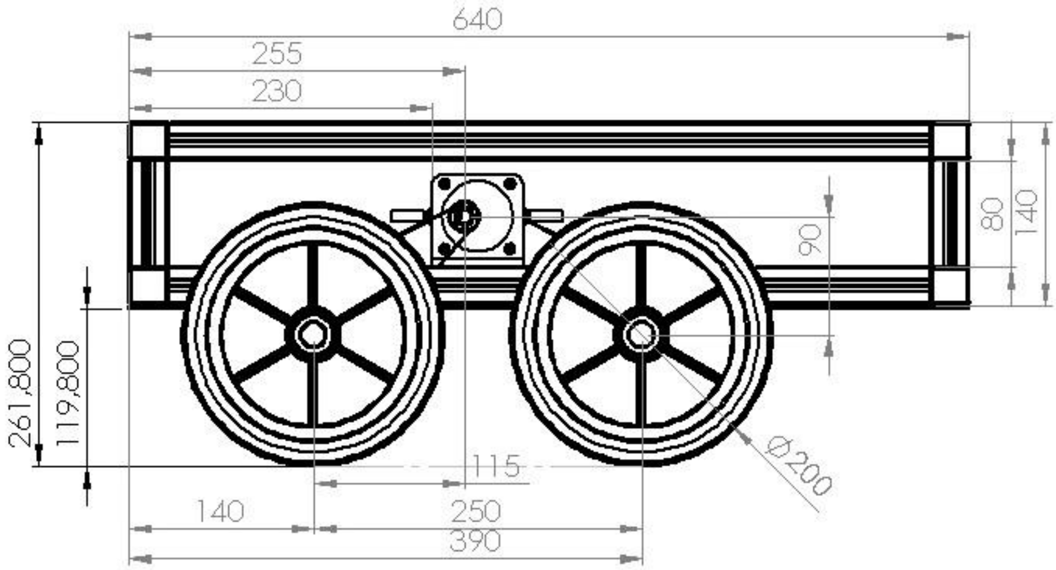


Figure 3.20 Side view of mobile platform

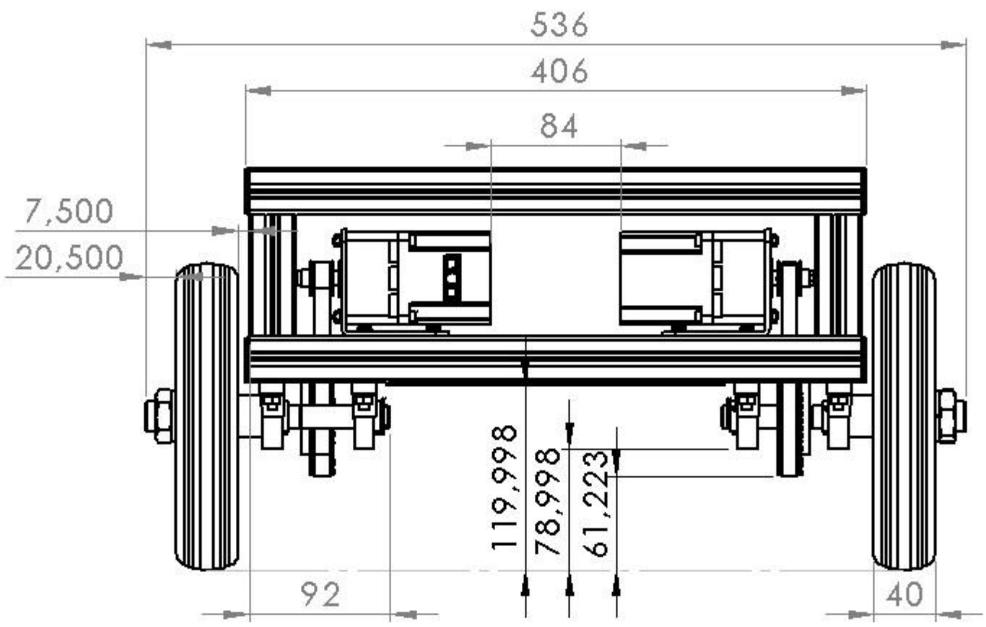


Figure 3.21 Front view of mobile platform

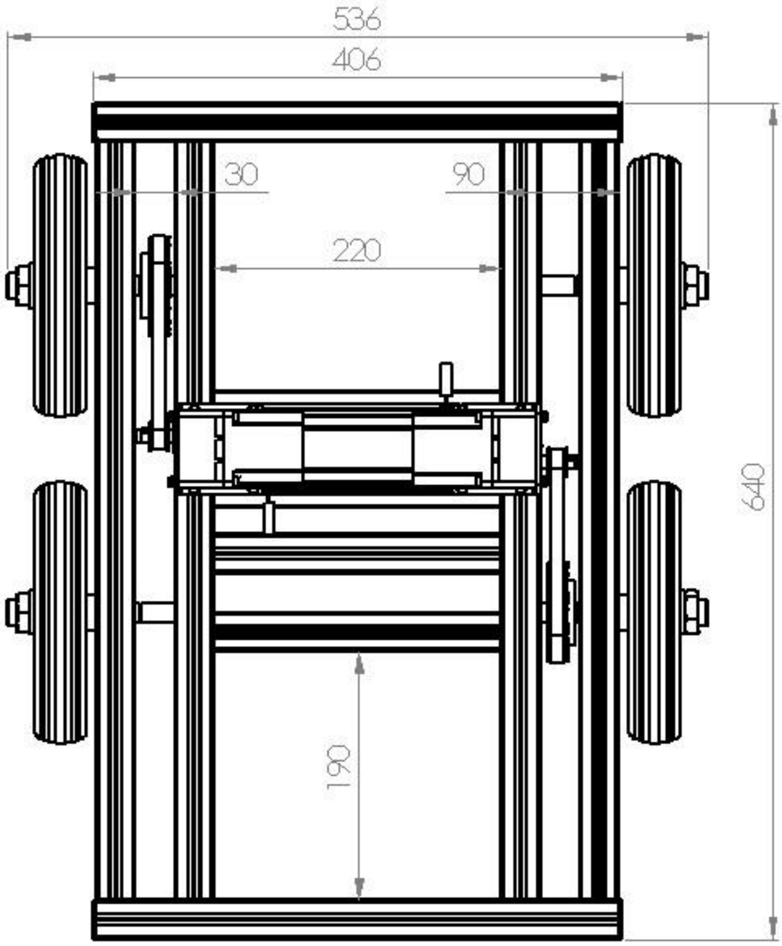


Figure 3.22 Top view of mobile platform

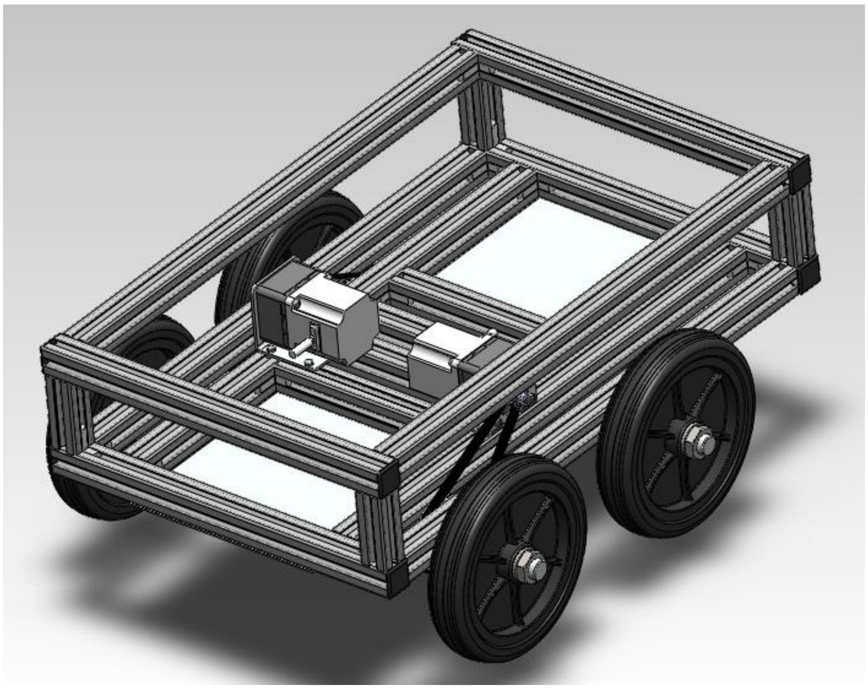


Figure 3.23 Isometric 3D view of mobile platform

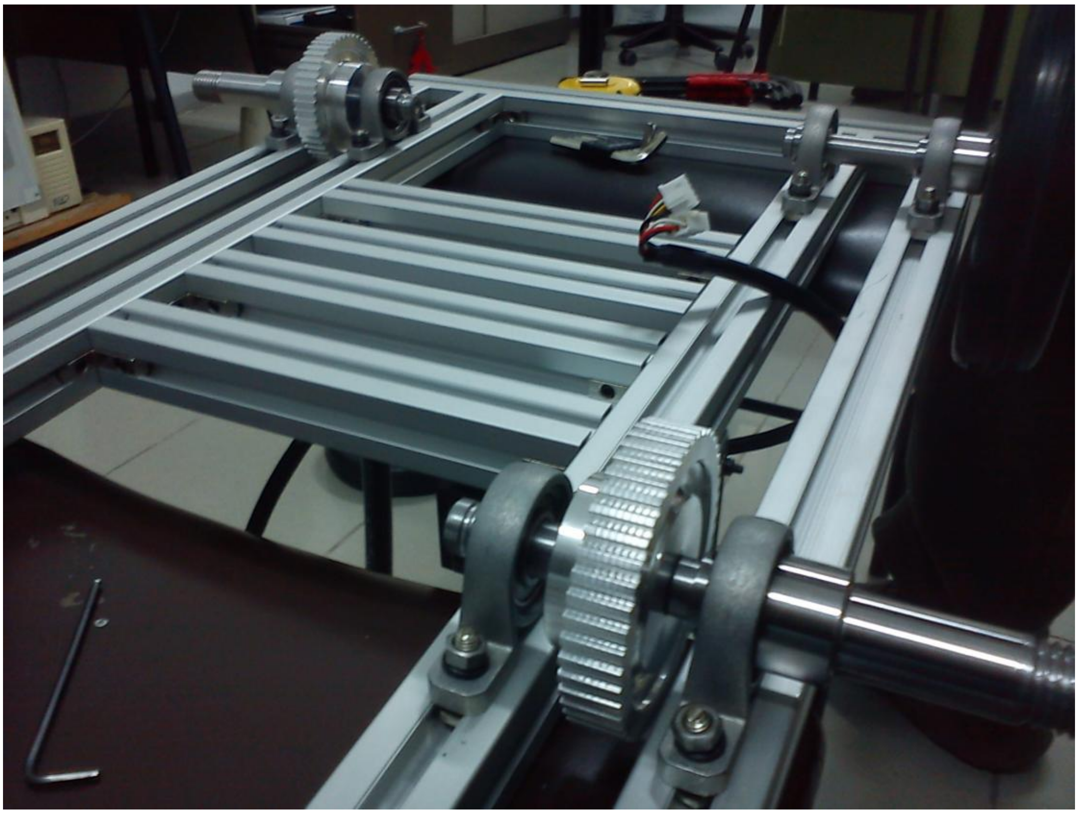


Figure 3.24 Mounting of shaft and bearing

Figure 3.25 First locomotion

Figure 3.26 Mobile platform after mounting of wheels and motors

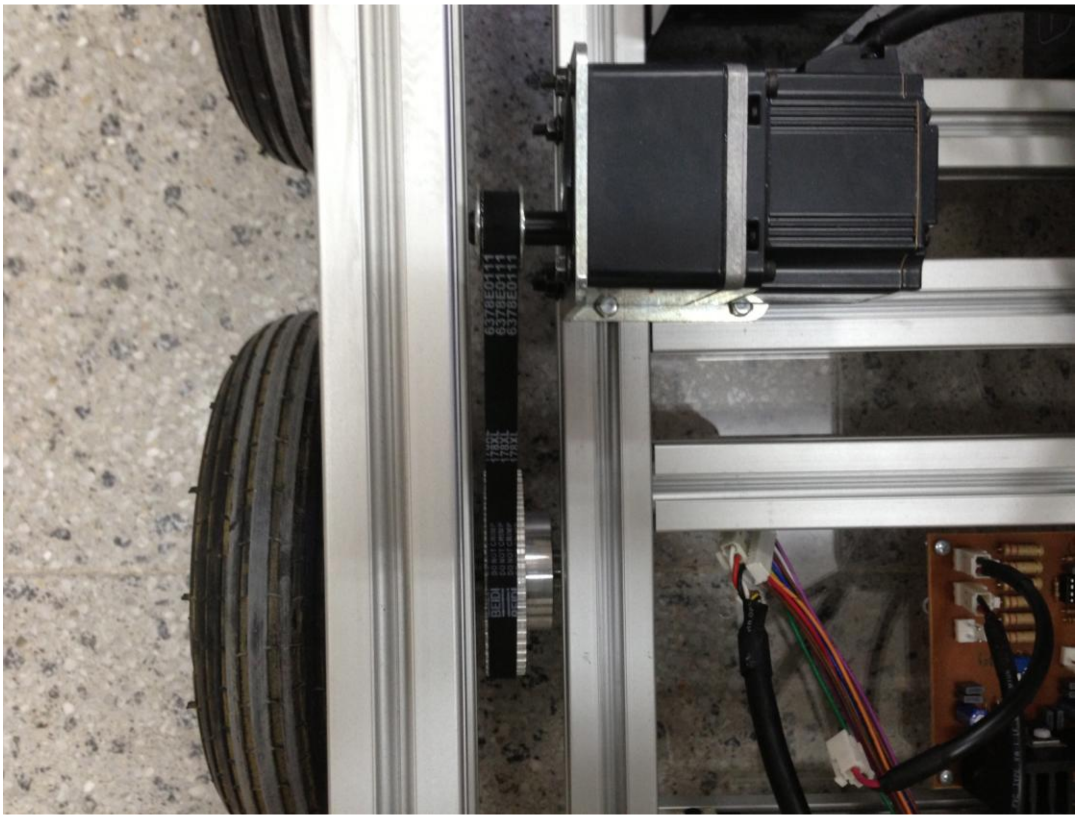


Figure 3.27 Pulleys-Belt-Motor on frame

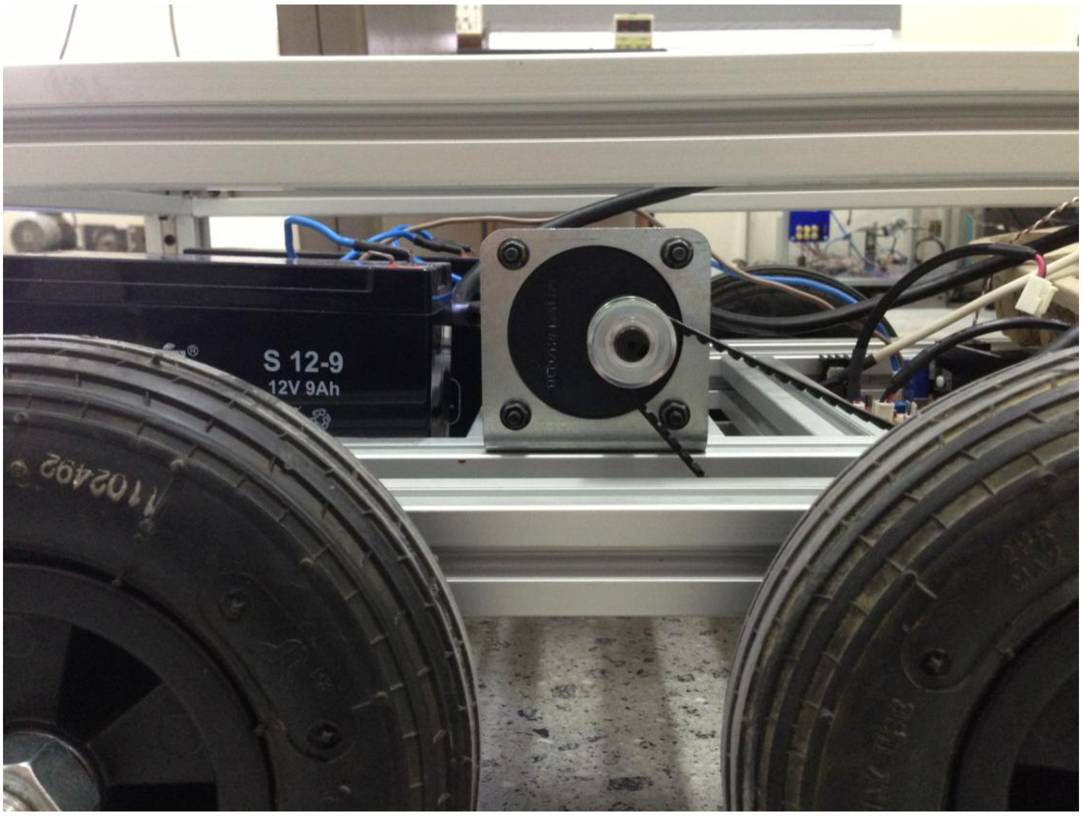


Figure 3.28 Side view of motor-belt connection

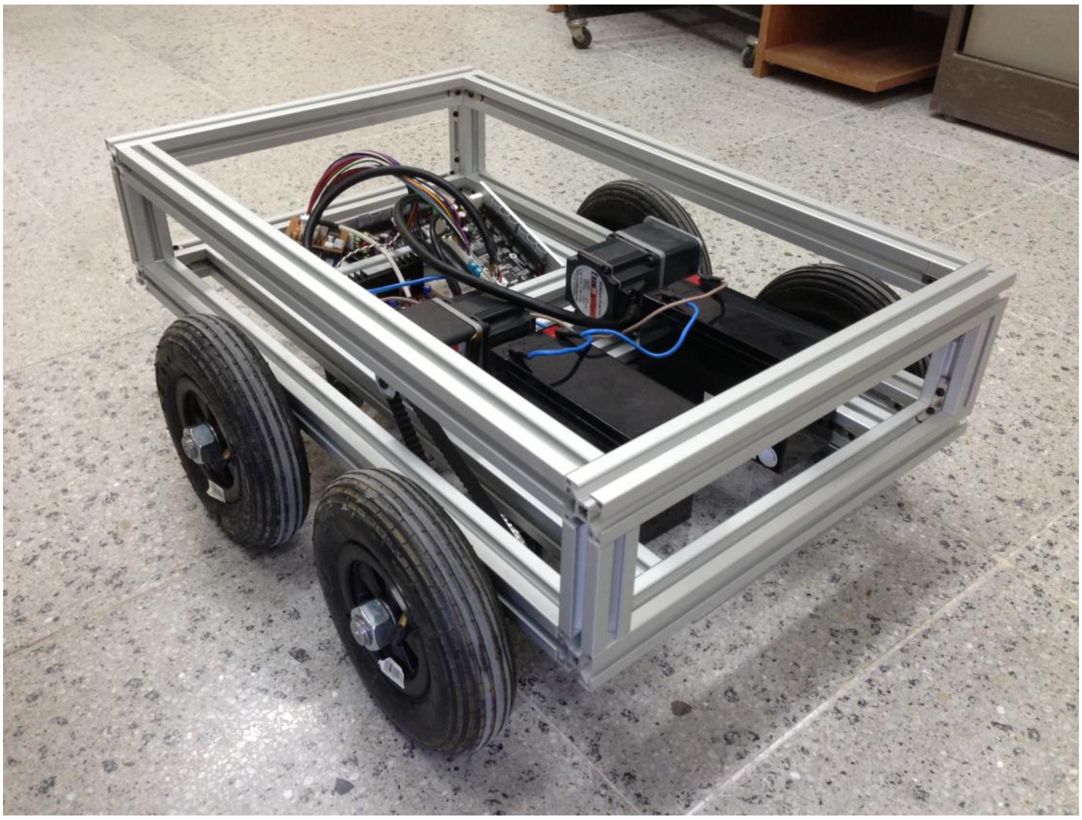


Figure 3.29 The mobile robot equipped with electronic hardware

3.1.4 Robot Manipulator

In this thesis, the robot manipulator, which was designed and produced for his master thesis by Tokel (Tokel, 2009), has been mounted on the mobile robot with my supervisor's suggestion and has been used to perform given tasks.

Tokel's robot manipulator, shown in Figure 3.30 and 3.31, can be summarized with these; it was originated from Lynxmotion 5 while designing, it has 6 pieces servos; two of servos used first joint is synchronous, it has 4 DOF and gripper as an end effector according to Denavit-Hertenberg method, its workspace is 400 mm and it has 200 g payload. It was made from Aluminum composite for decrease weight and vibrations based dynamic behavior (Tokel, 2009).

Figure 3.30 3D Robot manipulator (Tokel, 2009)

Figure 3.31 Used robot manipulator (Tokel, 2009)

Detailed information about the robot manipulator such as drawings, static torque analysis, montage, etc. can be obtained from Tokel's thesis.

3.1.5 Mobile Manipulator

The mobile manipulator which is one of the focuses of this study has been finished mechanically after Tokel's manipulator was mounted on the mobile platform, shown in Figure 3.32.

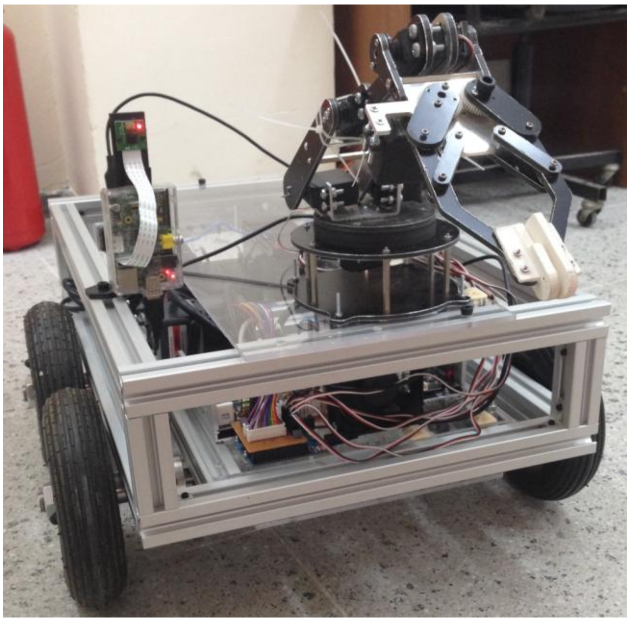


Figure 3.32 The mobile manipulator after mounting

Workspace of the mobile manipulator has been calculated from Solidworks design. Figure 3.33 shows 400 mm workspace boundary when all links of the manipulator are parallel each other and the gripper is positioned in effective hold point.

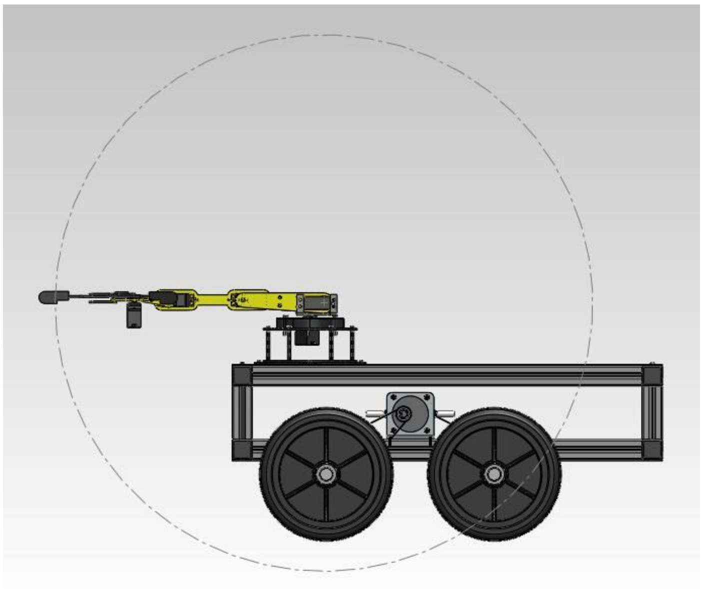


Figure 3.33 Workspace boundary

First joint of manipulator can move 180 degrees according to its base because the servo mounted related joint has 180 degrees motion capability so second joint should move after this plane of workspace. Workspace of second joint shown in Figure 3.34.

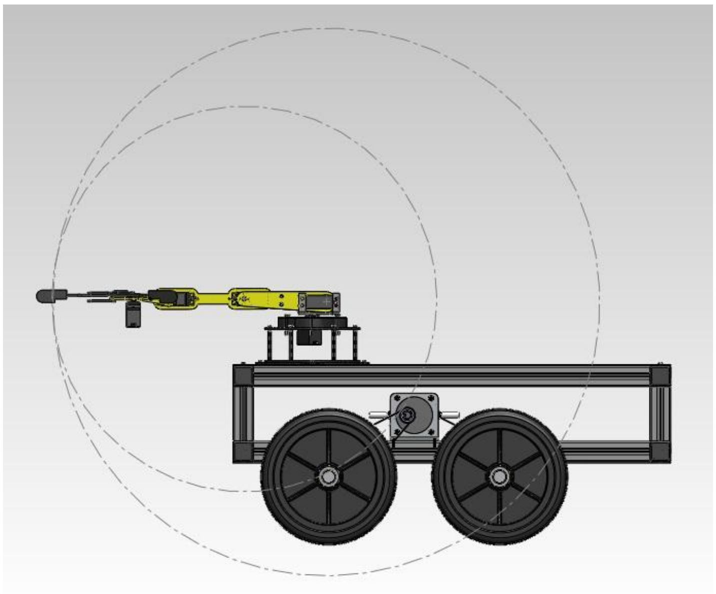


Figure 3.34 Workspace of second joint

The second joint can move until related link is limited from frame of mobile platform, seen in Figure 3.35

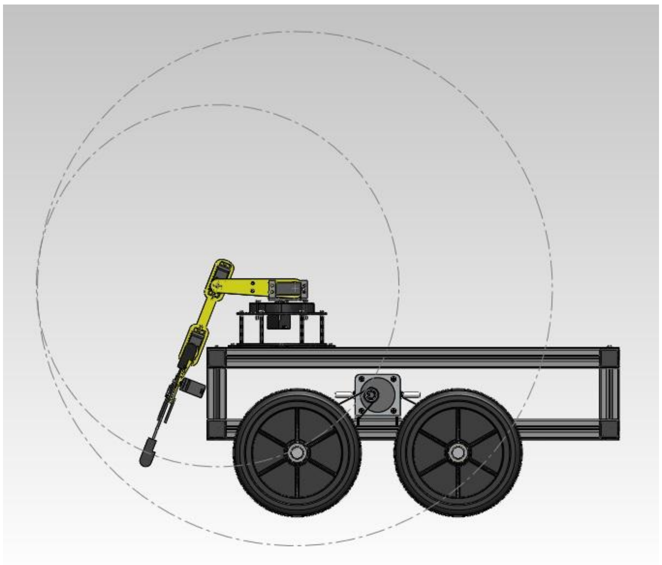


Figure 3.35 Limit of workspace

Same calculation, too, is performed for opposite direction needed for putting object with the gripper. And as a result, Figure 3.36 shows usable 3127.48 cm2 workspace.

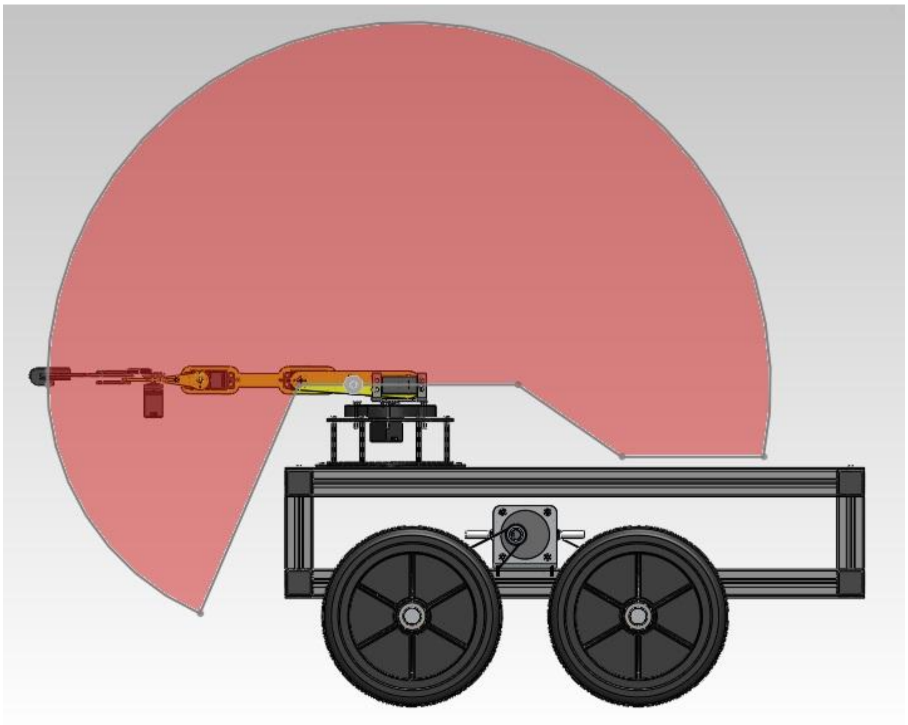


Figure 3.36 Effective workspace

Only 2D workspace is calculated because effective one is this for perform tasks. Workspace of other axis is ineffective because of size of mobile platform so 3D workspace is not needed in this study. Figure 3.37 shows dimensions of mobile manipulator with its workspace.

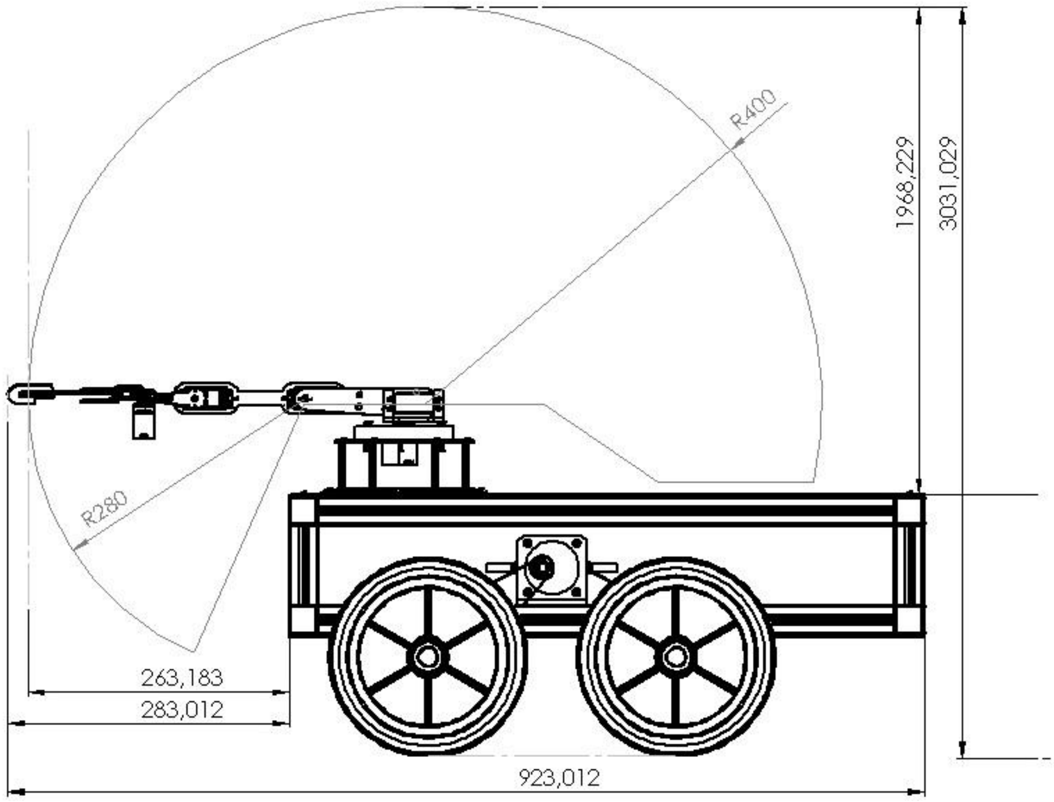


Figure 3.37 Dimension of the mobile manipulator

3.2 Electronic Hardware

Project objectives, control technique, communication method and Mechanic hardware especially motors and their requirements have formed electronic hardware structure. Primarily, needs have been determined for objectives and then required signals and their forms have been specified intended for needs. Thus, controller and required circuits structure have been determined for low level control.

The next step has been determination of controller for high level control. Control technique, communication method and desired feature from system have formed to required controller for whole system controlling and it has been chosen. General block diagram of electronic hardware is shown Figure 3.38.

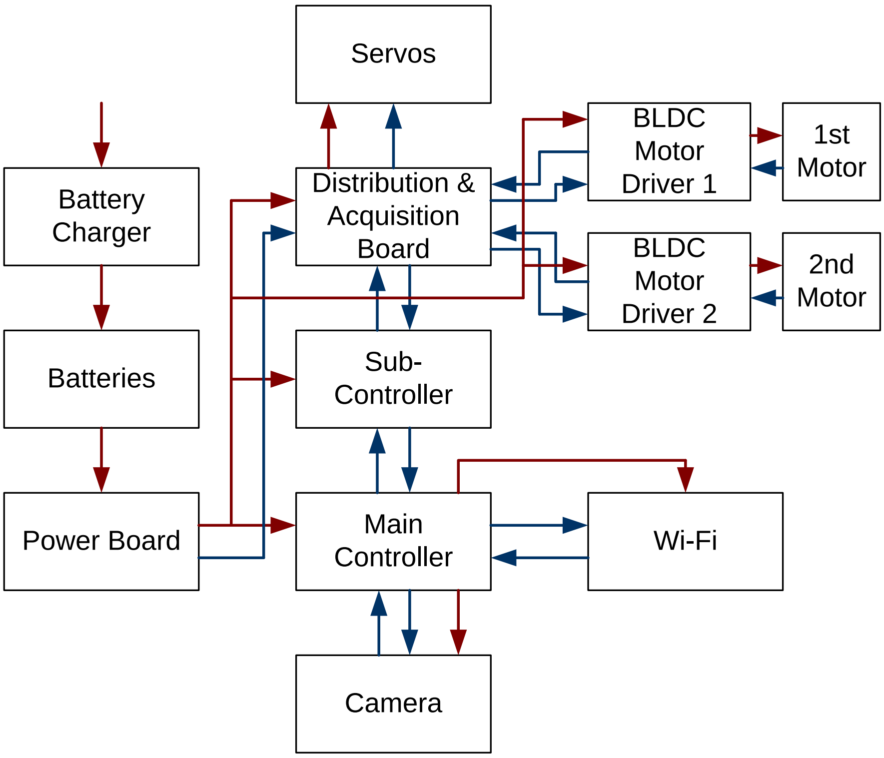


Figure 3.38 Block diagram of electronic hardware; red flow shows power, blue one shows signals

In this section, all elements of electronic hardware and all signal and power flows will be introduced exhaustively. Primarily, control section, drivers will be explained.

3.2.1 Main Controller

There are lots of control device, circuit, module, etc. for such system. One of them is Single Board Computer (SBC). SBC is a computer built on only one circuit board has microprocessor, memory, input-output ports. In today, SBC have been used extensively in robot research because of their cost-performance, dimension-performance and flexibility advantages.

In this study, SBC has been preferred because of required processing capacity of mobile manipulator implementation and above advantages. There are many SBCs in market such as PandaBoard (Pandaboard, n.d.), BeagleBone (Beagleboard, n.d.), Raspberry Pi (Raspberry pi, n.d.), etc.

Raspberry Pi is cheapest of all SBCs (Apc, 2012), shown in Figure 3.39 and 3.40. Raspberry Pi is a credit card sized SBC developed and released in February 2012 by Raspberry Pi Foundation and it is sold for US $35 by elemet14 and RS Components. (Wikipedia, n.d.)

Figure 3.39 Raspberry Pi (Wikipedia, n.d.)

Raspberry Pi can be summarized technically with these;

- Broadcom BCM2835 SoC as chip.
- 700 MHz ARM1176JZ-F CPU.
- 250 MHz Dual Core VideoCore IV GPU.
- 512MB SDRAM Memory.
- Onboard 10/100 Ethernet out.
- Onboard 2 USB outs.

- HDMI video output (PAL and NTSC).
- Audio output with 3.5mm jack and HDMI.
- Onboard Storage with SD, MMC, SDIO card slot.
- A CSI input connector for camera module.
- Low-level peripherals; 8xGPIO, UART, SPI, I2C, etc.
- 5V, 700 mA power consumption via MicroUSB or GPIO header.
- Linux based operating system.
- 8.6x5.4x1.7 cm dimensions.

As seen in above technical specifications, Raspberry Pi is comprehensive SBC according its price so this situation is an influential reason for using it in implementation. Also, this thesis includes camera application and Raspberry Pi has on board camera interface. Thus, camera interface can be used without decrease Universal Serial Bus (USB) port count. Another reason is that it has low-level peripherals as well. In this way, it can be expanded with new circuit boards like shields.

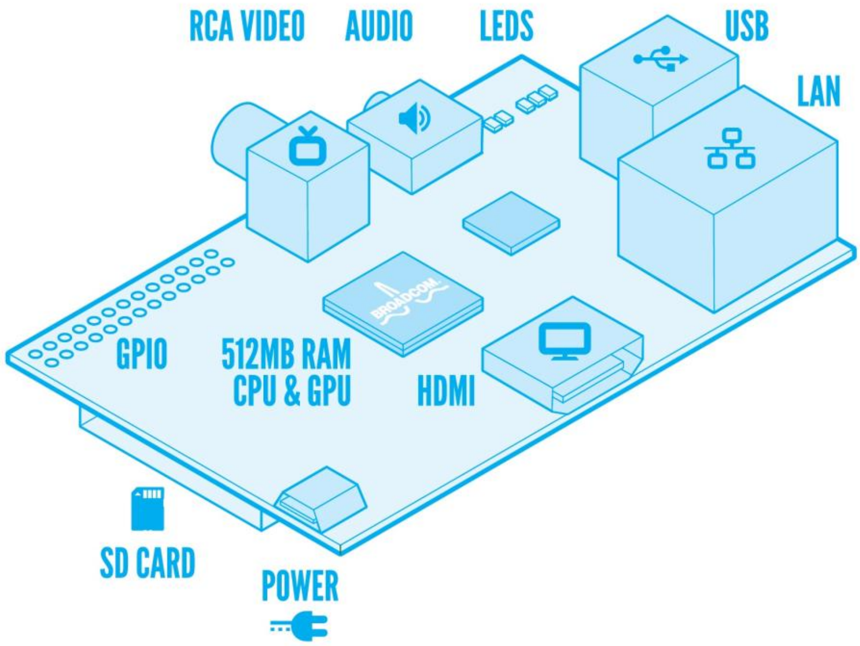


Figure 3.40 Raspberry Pi Model B (Raspberrypi, n.d)

Raspberry Pi is the heart of the whole system in this thesis. Linux based 32-bit Raspbian Opearating System (OS) was established on it and Raspberry Pi have been used as a web server for providing user interface with web pages. Thus, operator can send commands for performing tasks and can receive data and camera view from related task.

Communication process goes on over wireless internet connection thanks to USB Wi-Fi dongle. Second USB port connects sub-controller and Raspberry Pi each other in terms of communication. Raspberry Pi sends user commands to sub-controller for performing of low level control processes like motor control and receives feedback from sub-controller such as position, velocity, battary status, currents. Also, Raspberry Pi is received images from the camera mounted Camera Serial Interface (CSI) connector and provides video monitor in web pages for operator. 5 Vdc from power board supplies Raspberry Pi.

3.2.2 Camera Module

A camera module compatible with Raspberry Pi has been used in mobile manipulator for vision. The Camera module, shown in Figure 3.41, has been designed and manufactured especially to Raspberry Pi in order to connect it onto CSI connector on the Raspberry Pi. Thus, USBs on the board isn’t wasted with connecting USB camera. Another advantage of using CSI is that the CSI bus can carry extremely high data rates according to USB (elinux, n.d.).

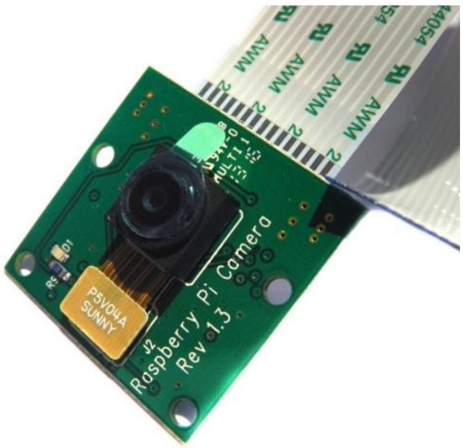


Figure 3.41 Raspberry Pi camera module (Modmypi, n.d.)

The Raspberry Pi camera module can be summarized technically with these; it has 5 Mega Pixel (MP) sensor in a fixed focus onboard module, camera can take 2592x1944 pixel static images and supports 1080p at 30 frames per second (fps), 720p at 60 fps and 640x480p at 60 or 90 fps video recording, 20x25x9 mm sizes, supported by latest version of Raspbian, it has 15 pin ribbon cable and Raspberry Pi CSI compatible socket.

3.2.3 Wi-Fi Dongle

A standard Wi-Fi dongle like seen in Figure 3.42 has been used for providing wireless internet connection of Raspberry Pi.

Figure 3.42 Wi-Fi Dongle (Modmypi, n.d.)

3.2.4 BLDC Motor Drivers

The BLDC Motors were already chosen according to system requirements. The BLDC motor drivers have been investigated dependently selected motor and electronic signals which are required drive technique of motors and necessary feedbacks about motors. Thus, BLDC driver with EXH630-30B number code have been chosen, seen in Figure 3.43.

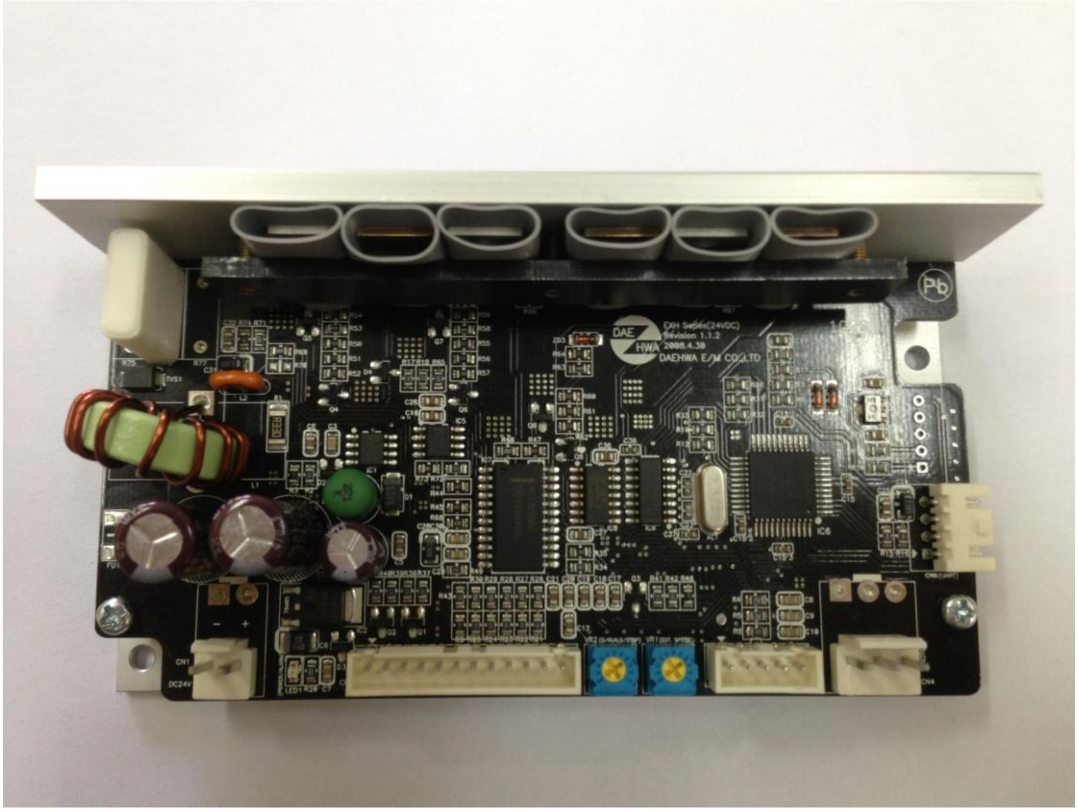


Figure 3.43 The BLDC motor driver

General specifications of chosen BLDC motor driver is shown in Figure 3.44. 24 Vdc supply voltage and 2.1A rated current is significant specifications for electronic hardware. Related specifications have been already taken into account for power board design.

Model	Combination Type	EXH630-30BK-□	EXH850-30BK-□	EXH91A-30BK-□
	Round Shaft Type	EXH630-30BS	EXH850-30BS	EXH91A-30BS
Rated Output Power	W(HP)	30(1/25)	50(1/15)	100(1/8)
Power Source	Voltage	24VDC±10%		
	Rated Input Current A	2.1	3.1	6.0
	Maximum Input Current A	3.5	5.0	9.0
Rated Torque	oz-in (N · m)	17(0.12)	28(0.20)	56(0.40)
Starting Torque	oz-in (N · m)	21(0.15)	34(0.24)	71(0.50)
Permissible Load Inertia J*	oz · in²(X10⁻⁴kg · m²)	9.8(1.8)	18.1(3.3)	31(5.6)
Maximum Speed	r/min	3000		
Rated Speed	r/min	3000		
Variable Speed Range	r/min	100~3000(30:1)		
Speed Regulation	Load	±1%Max.(0~rated torque, at rated speed)		
	Voltage	±1%Max.(Power supply voltage ±10%, at rated speed with no load)		
	Temperature	±1%Max.(32°F~122°F[0℃~+50℃] at rated speed with no load)		

Figure 3.44 General specification of driver (ExceM, p.23, n.d)

One of the important specifications of driver is torque control thanks to feedback of hall sensors in the motor. Thus, BLDC motor can supply same torque values for low speed and high speed driving. A starting and rated torque curves and regions according speed and current values are shown in Figure 3.45.

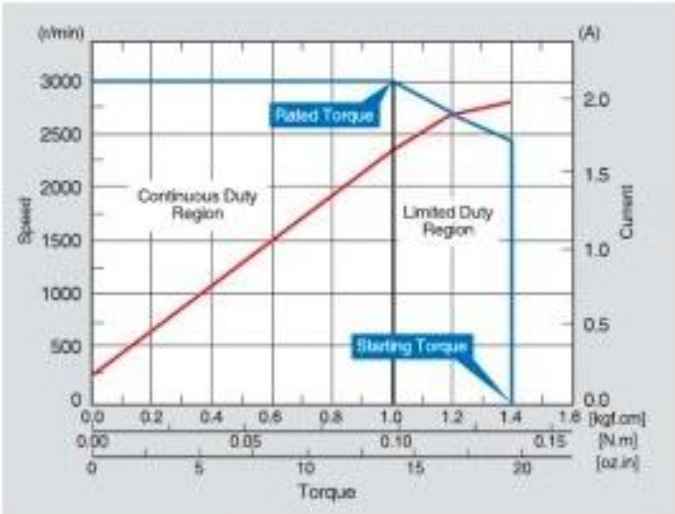


Figure 3.45 Torque graphic of the motor controlled driver (ExceM, p.21, n.d)

The BLDC motor driver has 12-pin control connector for digital system, 5-pin motor feedback connector and 3-pin motor output connector. Block presentation of pins is seen Figure 3.46.

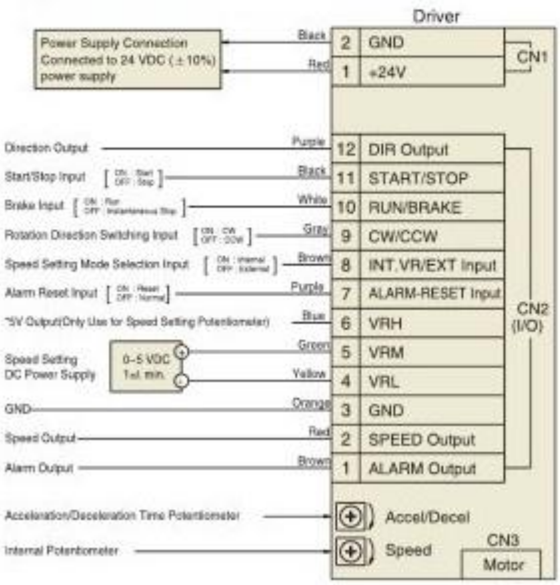


Figure 3.46 Block presentation of driver (ExceM, p.24, n.d)

There are 6 input pins, 3 output pins, one 5V pin and 2 GND pins in control connector seen as CN2 in Figure 3.46. Also, CN1 driver supply and CN3 motor connector is seen. The driver has internal speed and acceleration/deceleration setting potentiometer. Internal speed potentiometer wasn’t used for this study because speed of motors has been controlled by Pulse-Width Modulation (PWM) technique.

Input pin status can be changed with logic voltage changing. All digital input pins have internal pull-ups that mean to have initial high logic level. Figure 3.49 shows a simple pin status and possibilities. For instance; if pin 11 and pin 10 is change as a low logic level and PWM is applied to pin 5, motor drives any direction. If pin 9 is change as a low logic level as well, motor direction changes. Pin 8 sets speed control method. It was set as a high logic level means external speed control usage. Thus, motor speed can be changed with PWM in this study.

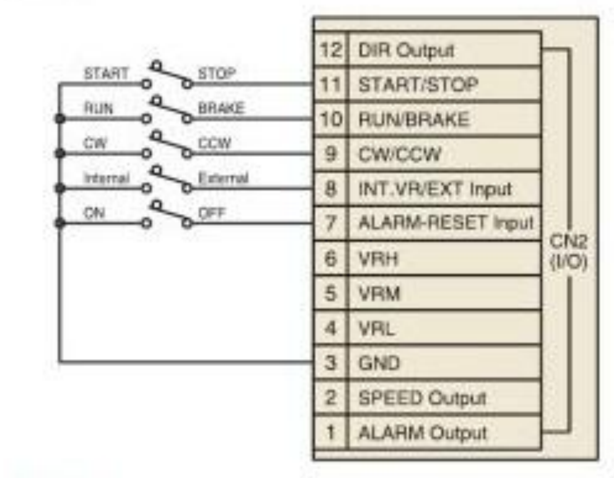


Figure 3.47 Digital pin status and possibilities (ExceM, p.24, n.d)

Output pin, which is seen in Figure 3.47 as 1st, 2nd and 12th pin, gives information about motor. All output pins are open collector so pull-up resistors were connected to signal route in distribution and acquisition board. First pin gives fault information about motor like motor not connected and second pin gives motor speed feedback with hall sensors in motor. 12th pin gives independently motor direction information.

Pin 3 and 4 are ground (GND); on the other hand, pin 6 is 5V source for different application like potentiometer speed control.

Speed output pin sends pulse signals at a rate of 36 pulses per rotation of the motor output shaft. Motor speed can be calculated with counting pulses in certain time interval. In this thesis, a 1:10 gear box has been used so speed output sends 360 pulses per rotation of gear box output shaft. Moreover, there is 1:4 reduction ratio in used pulley-belt system so this pulse value increases and it has been 1440 pulses per rotation. Also, speed output is significant for position calculation. Displacement of any wheel mounted motor shaft on any plane can be calculated as well.

The BLDC motor drivers in the system are supplied directly with 24 Vdc over the power board.

3.2.5 Servos

RC servo motors can be controlled with only PWM signal. Shaft position of servo can be adjusted with changing duty cycle of PWM generally between 1ms and 2ms. Servo motors have 3-wire flat cable, seen in Figure 3.48. Generally, white one is control signal wire, black one is GND wire and red one is positive supply wire.

Figure 3.48 Typically RC servo motor

Servo motor power supply is usually changeable in the range from 4.8 to 6 Vdc. For providing maximum torque, it is supplied with its absolute maximum voltage value.

In this thesis, there are 6 servos mounted on robot manipulator but two of them are synchronous for increasing torque of related joint. Thus, 5 PWM control signals and power supply for servos are needed. This requirement has been provided over a distribution and acquisition board.

3.2.6 Distribution and Acquisition Board

In electronic hardware of the mobile manipulator, there are lots of signals and different supply voltage. A circuit board, as a shield compatible with sub-controller Arduino Leonardo, has been designed for solving this complexity and providing connection to circuits with suitable connectors and jacks. Designed shield only tidies up required connection for sub-controller Arduino. In brief, any signal processing or signal generation isn't performed.

Primarily, used signals count was determined and then connector structure was chosen for cable connection to circuit. Needs are 2 pieces 12-pin connector for motor drivers, 6 pieces 3-pin connector for servo motors, a piece 4-pin connector for power board information, a piece 2-pin connector for sub-controller power supply and a piece 2-pin connector for power supply of servo motors. Besides, an extra 4-pin connector was considered for usart communication. Thus, distribution and acquisition shield has been designed and produced as compatible with pin structure and layout of Arduino platform, seen in Figure 3.49 and 3.50.

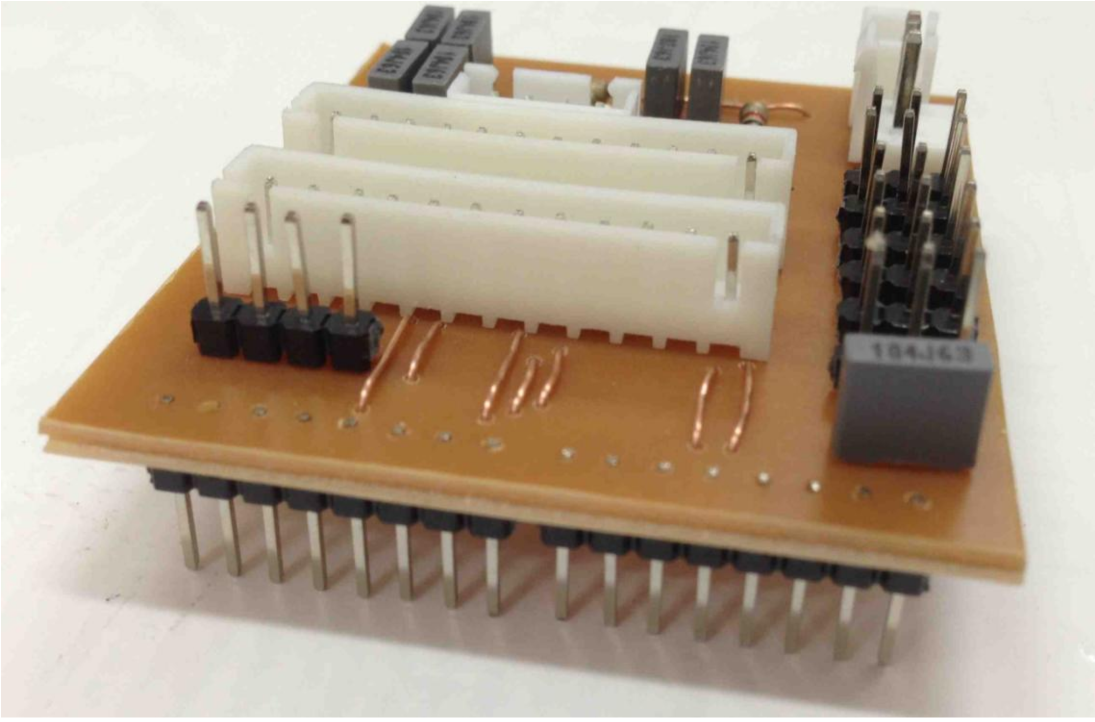


Figure 3.49 Distribution shield

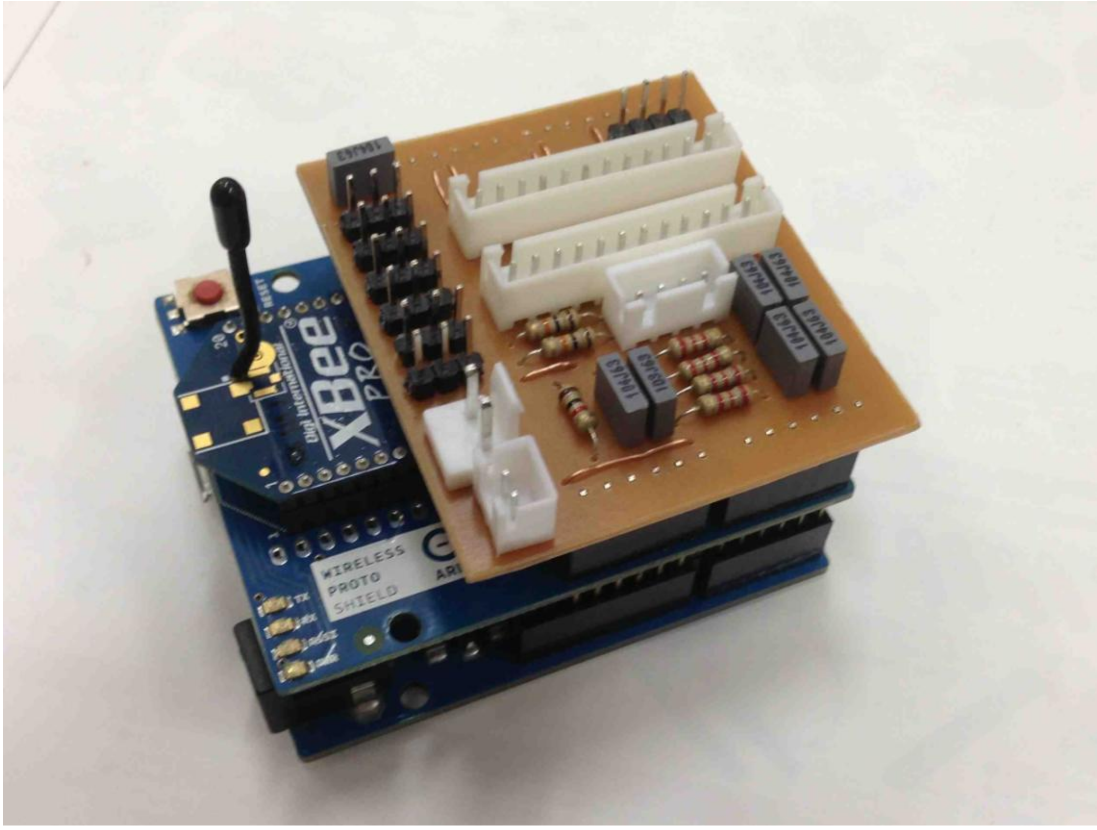


Figure 3.50 Designed shield with Arduino Leonardo, Xbee and its shield were used only for system development. In this thesis, it was not used.

In design stage, signals of shield headers plugged into Arduino headers have been attached importance to connect pins of the shield. Analog signals come from power board were connected to analog pins of Arduino in designed shield and low-pass filter was attached to analog signal route. Motor feedback signals were connected to interrupt pins of Arduino and motor drive signal PWMs were connected to PWM out pins. Schematic of designed shield is shown in Figure 3.53. Figure 3.51 shows servo motor connections and analog inputs and Figure 3.52 shows BLDC motor connections.

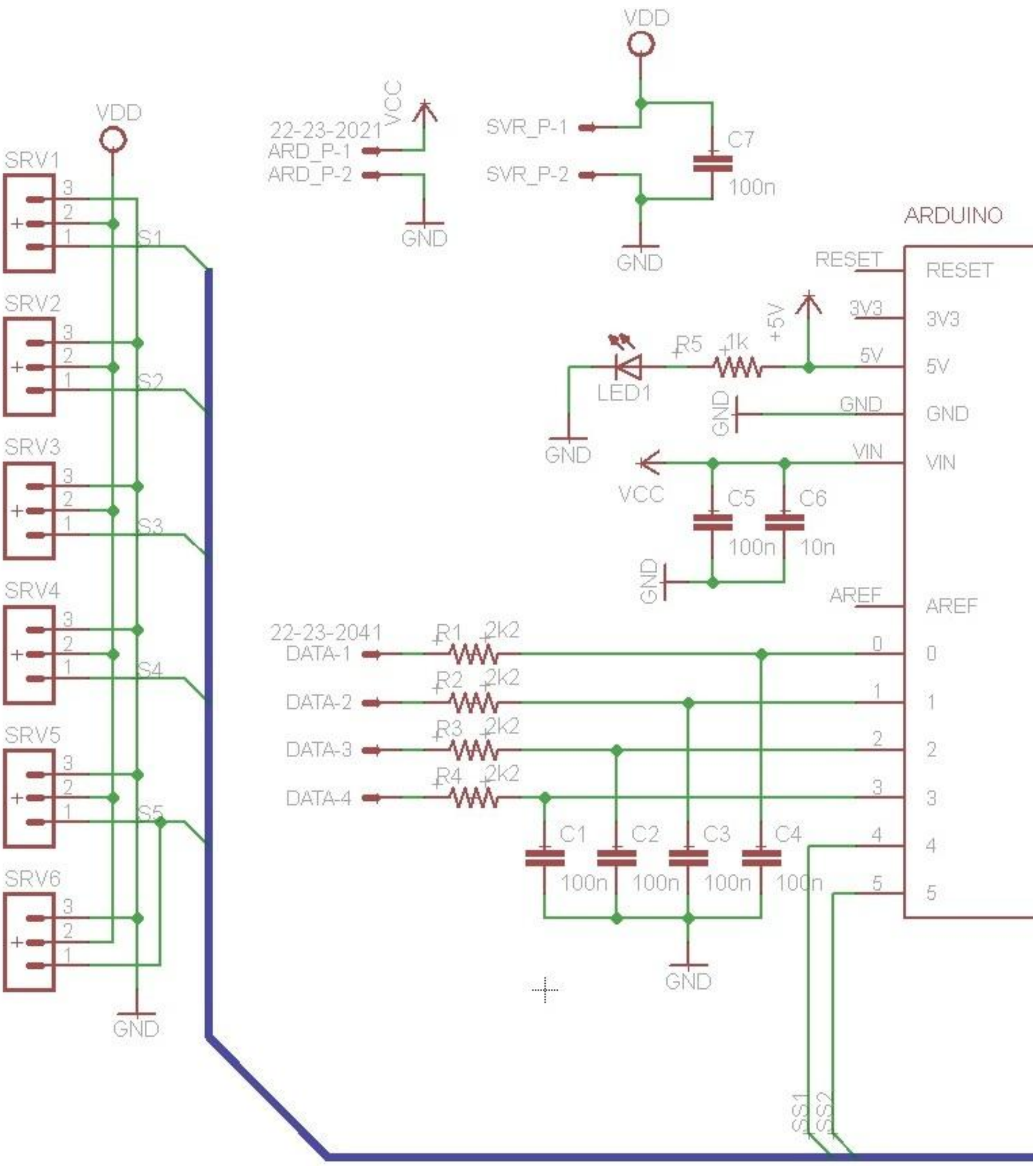


Figure 3.51 Servo motor connections on the shield

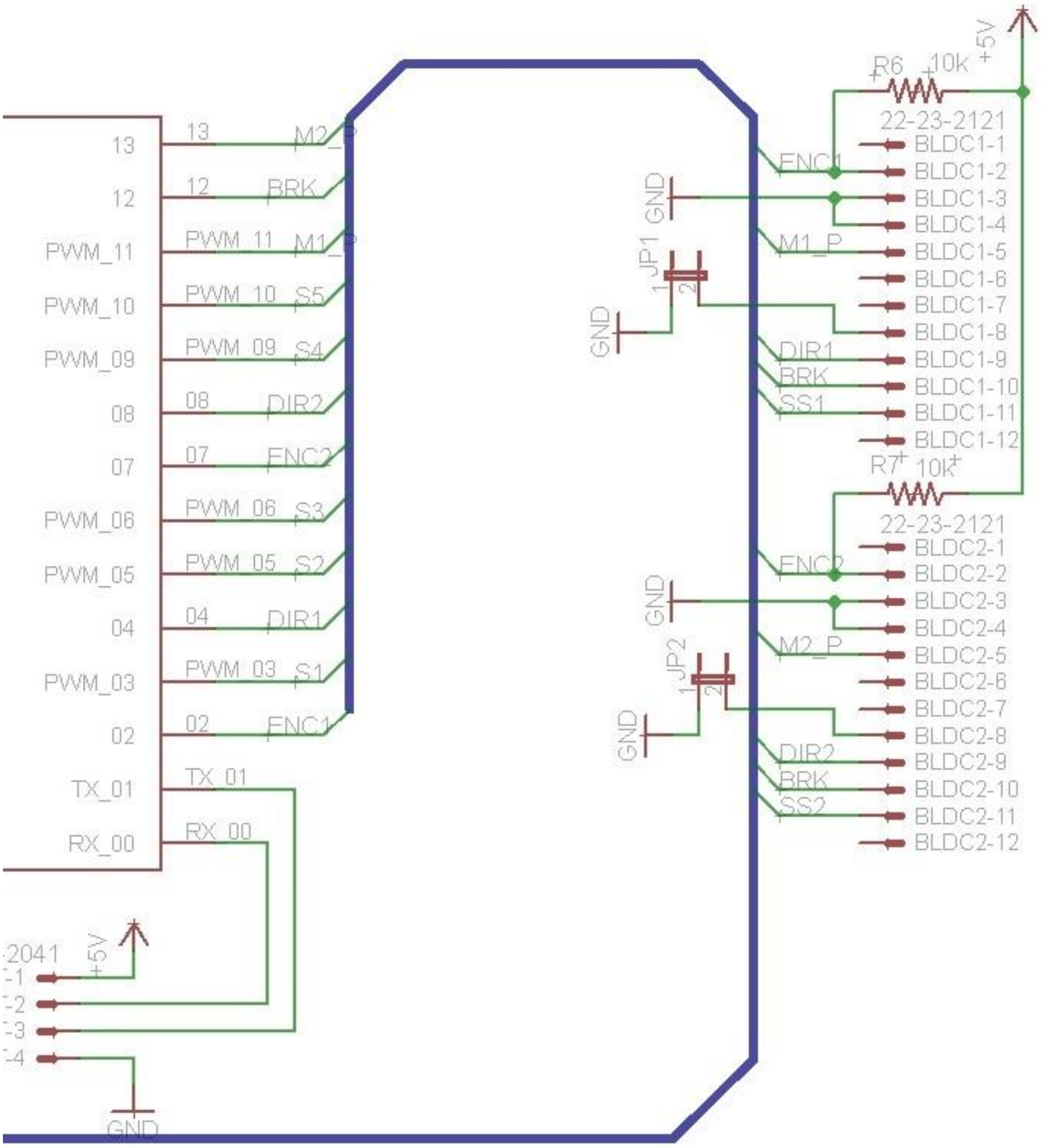


Figure 3.52 BLDC motor connections on the shield

Two different supply voltages are given to shield by the power board, seen in Figure 3.53. 12V is used to supply Arduino and adjustable in range from 4.8 to 6 V is used for supplying servo motors.

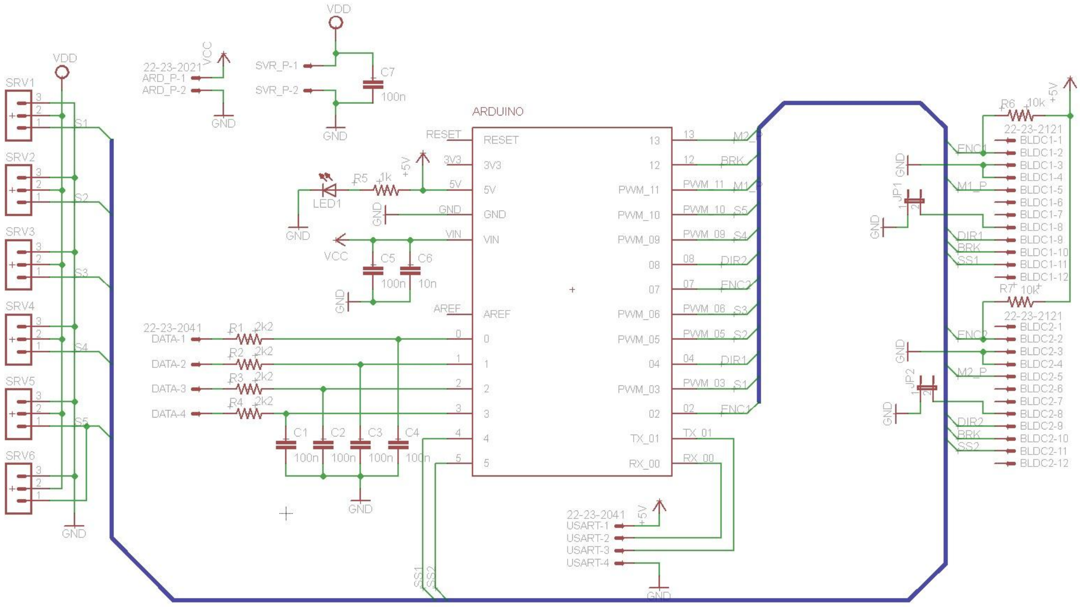


Figure 3.53 Schematic of designed shield

3.2.7 Sub-Controller

Arduino is an user-friendly in terms of hardware and software, open-source electronic development platform (Arduino, n.d.). Arduino platform can be expanded with shields. Shield is an electronic circuit board compatible with Arduino and it is mounted on Arduino platform. More Arduino platforms have same pin layout so lots of shields compatible with Arduino. Same pin layout provides an ease for software. Thus, Arduino platforms can be changed without any modification on software and hardware. User-friendly term comes from its C based programing languages, ready libraries, examples about more issues and its compiler. More significant disadvantage is its compiler doesn’t sport debug mode.

Arduino platform have been chosen to use for performing low level tasks of the mobile manipulator. Reasons of choosing Arduino is above usage advantages. Leonardo (Arduino, n.d.) have been prefer as a sub-controller with considering signal requirements. In this study, 7 PWM outputs are needed for control servo motors and BLDC motors. This is sufficient reason for choosing Leonardo because Leonardo has 7 PWM output. Also, Leonardo provides other pin requirements and necessary counts. Leonardo is shown in Figure 3.54.

Figure 3.54 Arduino Leonardo (Arduino, n.d.)

Arduino Leonardo can be summarized technically with these; it has ATmega32u4 microcontroller, its flash memory is 32 KB, it has 16 MHz clock speed, it has 20 digital input/output, 7 PWM channels, 12 analog input channels, its supply voltage is 7-12Vdc. It contains a micro USB, a power jack, an In-Circuit Serial Programming (ICSP) header and reset button.

Leonardo performs low level calculation, interpretation and control such as driving motors, reading feedbacks, etc. Signal connections in the system have been already shown in previous section on the designed shield. Leonardo generates and sends required signals over the shield mounted on Leonardo. In the same way, it collects signals from system. On the other hand, a communication between Raspberry Pi and Leonardo is ensured by USB. Its power can be supplied from shield or USB connection.

3.2.8 Batteries

There are two 12V 9Ah batteries in the system. They were connected as a serial. Thus, main voltage of the system is 24V for supplying all electronic hardware. The reason of using 24V supply voltage is the BLDC motor drivers can operate efficiently minimum 24V voltage level.

Battery capacity is determined high enough for performing tasks. In absolute maximum current ratings and continuous working condition, the batteries can be supply power during about 3 hours.

3.2.9 Power Board

There are normally different voltage levels depend on used electronic equipments in the system. Power board was need for provide this voltage levels and regulation of voltage. If voltage levels are want to summarize, there are 24V for BLDC motor drivers, 12V for Arduino, 4.8-6V for servo motors and 5V for Raspberry Pi. The power board, shown in Figure 3.55, has been designed and produced in order to supply all of these voltage levels.

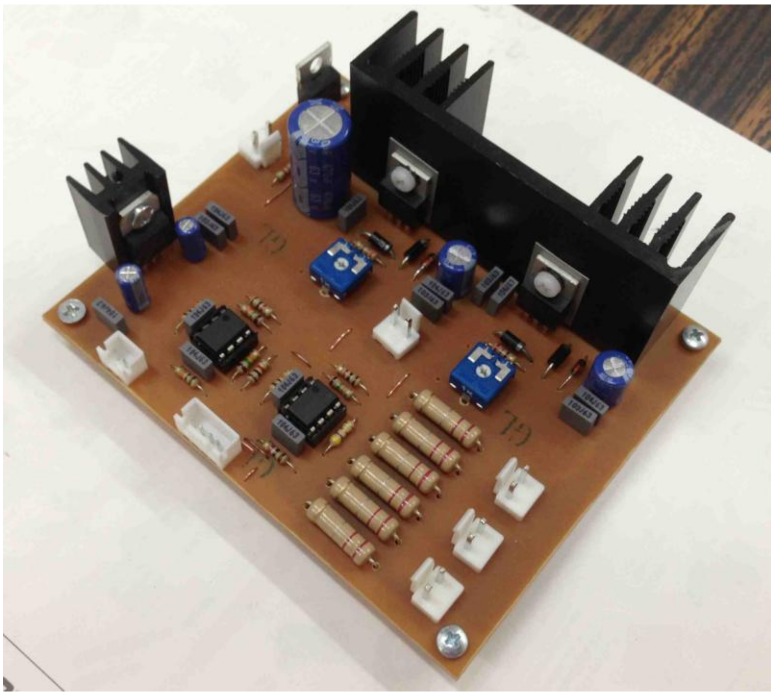


Figure 3.55 The power board

The power board has been improved to be able to carry maximum 5A so it has head sinks intended for this purpose. Also, the power board has adjustable voltage outputs for digital system and servo motors. It is useful especially servo motors for torque adjustment. Another significant spec is that it can be measure robot manipulator current and separately the BLDC motors currents. Also, it can be measure battery voltage level for providing battery status information. Thus, usable battery capacity can be estimated. Schematic of the power board seen separately in Figure 3.56, 3.57 and 3.68

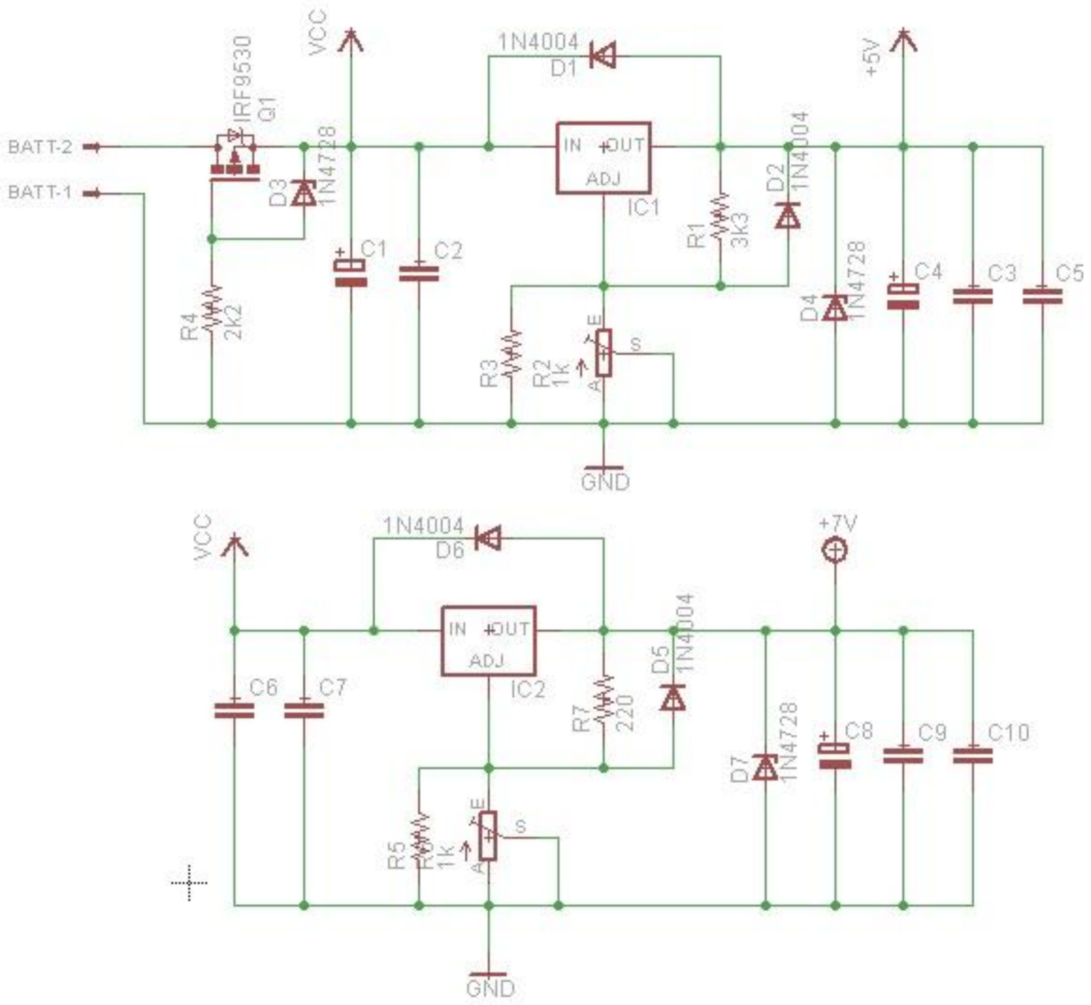


Figure 3.56 The power board schematic 1

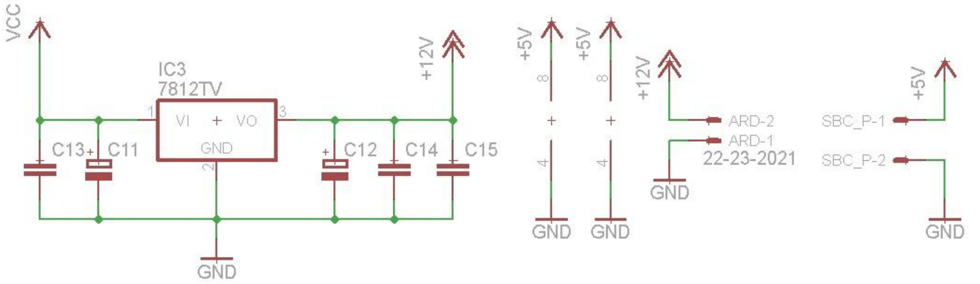


Figure 3.57 The power board schematic 2

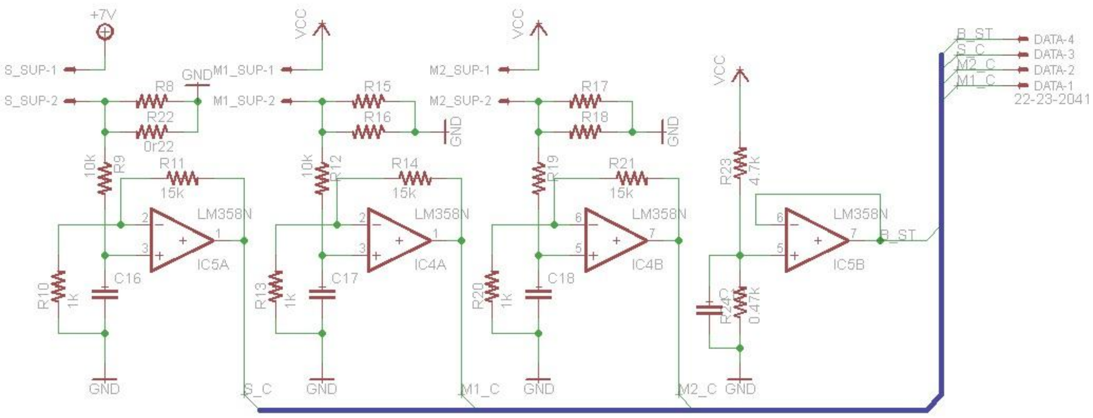


Figure 3.58 Currents and voltage measurement of the power board

3.2.10 Battery Charger

A battery charger module has been mounted in the mobile manipulator for charging battery without removing in the robot. It will be able to useful especially automatic charging as one of future works.

CHAPTER FOUR
SOFTWARE

In this implementation, software of the mobile manipulator can be separated two sections as a low level software in Arduino Leonardo for performing low level tasks and a high level software in Raspberry Pi for high level tasks.

4.1 Software in Arduino Leonardo

Software in Leonardo, as touched upon a bit in previous chapters, executes low level tasks in mobile manipulator like motor driving. Software of executing of similar task like previous example can be referred to low level software. Also embedded software can be used as synonym.

Code of Leonardo was written in compiler of Arduino. Code language of Arduino is C based but it isn't appropriate American National Standards Institute (ANSI). There are advantages and disadvantages of this situation. Codes written in Arduino complier aren't compatible with other ANSI C compiler. Thus, programmer depends only one complier. On the other hand, the compliers, which aren't compatible ANSI C, are developed for easing code language. In this way, programmers don't deal with register of microcontroller and study easily with different microcontroller. Arduino complier provides exactly this ease. Also, Arduino compiler has a lot of ready to use library. This factor eases workload as well.

Written Arduino code carries out following sub-tasks;

- Setting working parameters.
- Interpretation commands sent by Raspberry Pi.
- Choosing required sub-task.
- Generating required signal forms.
- Controlling BLDC motors.
- Driving servo motors.
- Executing required move direction.

- Reading system feedbacks
- Interpretation feedbacks and converting them to understandable values.
- Sending information to Raspberry Pi about sub-systems and sub-tasks

4.2 Software in Raspberry Pi

Raspberry Pi SBC executes high level tasks in the mobile manipulator such as providing user interface, monitorize video from camera, communication with internet and controlling sub-controller Arduino Leonardo.

Debian based 32-bit Raspbian free operating system has been established on the Raspberry Pi. Debian operating system is optimized for the Raspberry Pi hardware and Raspbian ensure over 35.000 packages for best performance of Raspberry Pi (Raspbian, n.d.)

Raspberry Pi has been used as web server on the mobile manipulator and OpNET web interface has been developed for being able to perform tasks, seen in Figure 4.1.

OpNET has been designed under Hyper Text Markup Language 5 (HTML5) and Cascading Style Sheets 3 (CSS3). In order to maintain responsible web design Gumby Framework (Gumbyframework, n.d.) was used as Software as a Service (SaaS). All the parameters are transmitted and received via Asynchronous JavaScript and XML (AJAX) technique. And for data interchange, JavaScript Notation (JSON) was chosen because of its human readable structure. JQuery (Jqery, n.d.) a multi-browser JavaScript library was used in order to display client side Graphical User Interface (GUI) and receive relevant commands.

On the server side, Lighttpd (Lighttpd, n.d.) has been used as web server. It is very lightweight and it has filtered of unnecessary modules. PHP web scripting language is used directly in order to read and write serial port of Raspberry Pi - Arduino Leonardo couple. MySQL, Relational Database Management System (RDBMS) is used in order to save sensor information for post process.

Live camera streaming is performed via open source video streaming package Motion (Lavrsen, n.d.) This program is gathering specified camera port and sends the image data though assigned port as Motion JPEG (MJPEG) standard. So it can also work non-Flash devices such as Apple iPhone, iPad, Google Android phones and tablet, etc.

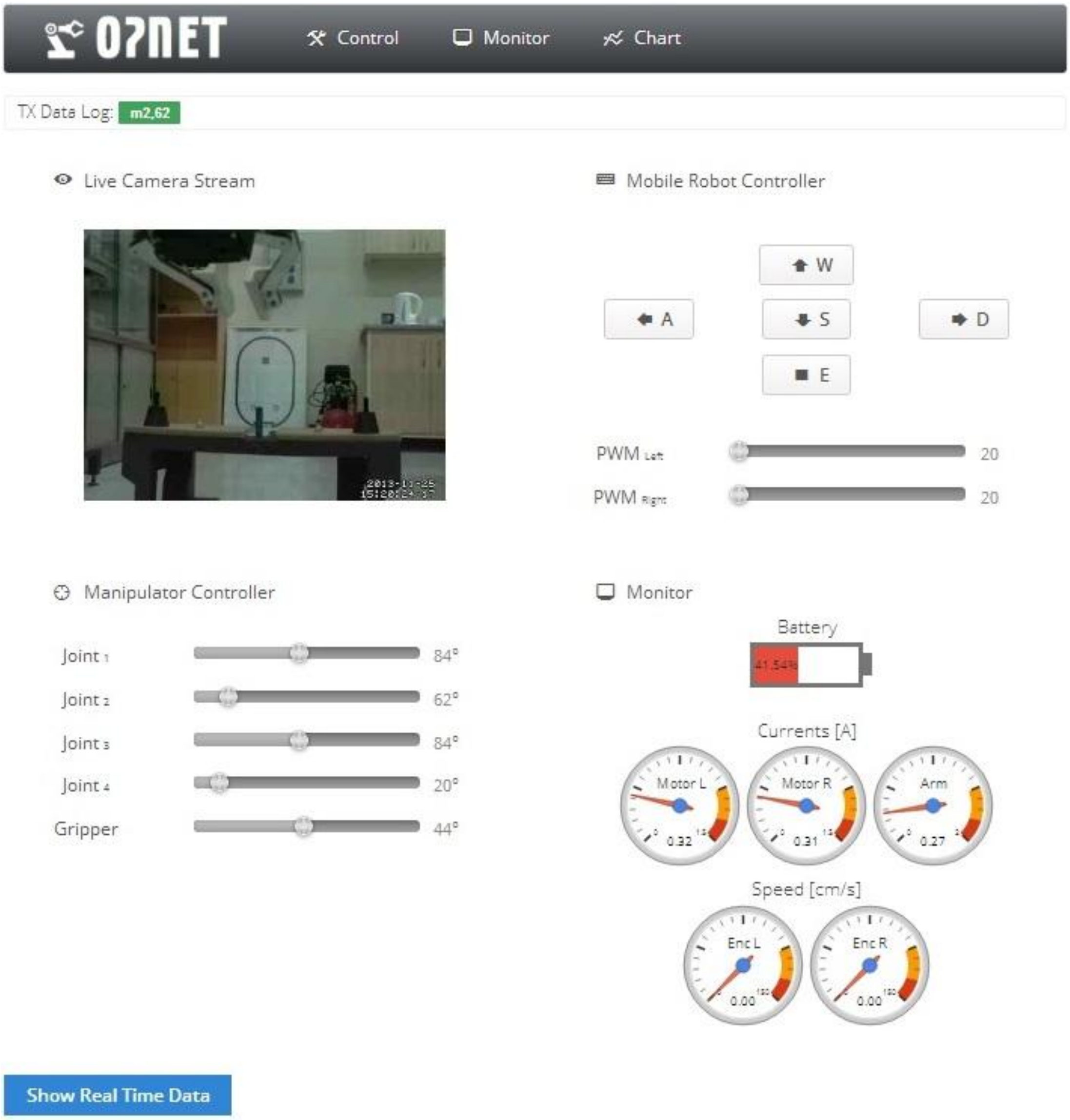


Figure 4.1 OpNET user interface

For monitoring purpose a real time chart with multi line is also plotted on the web interface with the help of D3.js, a JavaScript library for SVG driven graphics. This component is also flash independent so any mobile device can render graphs.

CHAPTER FIVE
IMPLEMENTATION

The mobile manipulator has been already designed. Its mechanic and electronic hardware have been produced completely and the mobile platform and the robot manipulator have been tested separately. And then, the robot manipulator has been mounted on mobile platform. And finally, all function of mobile manipulator has been tested and observed thoroughly by developed web based operator interface OpNET. Everything has been prepared to perform implementation scenario.

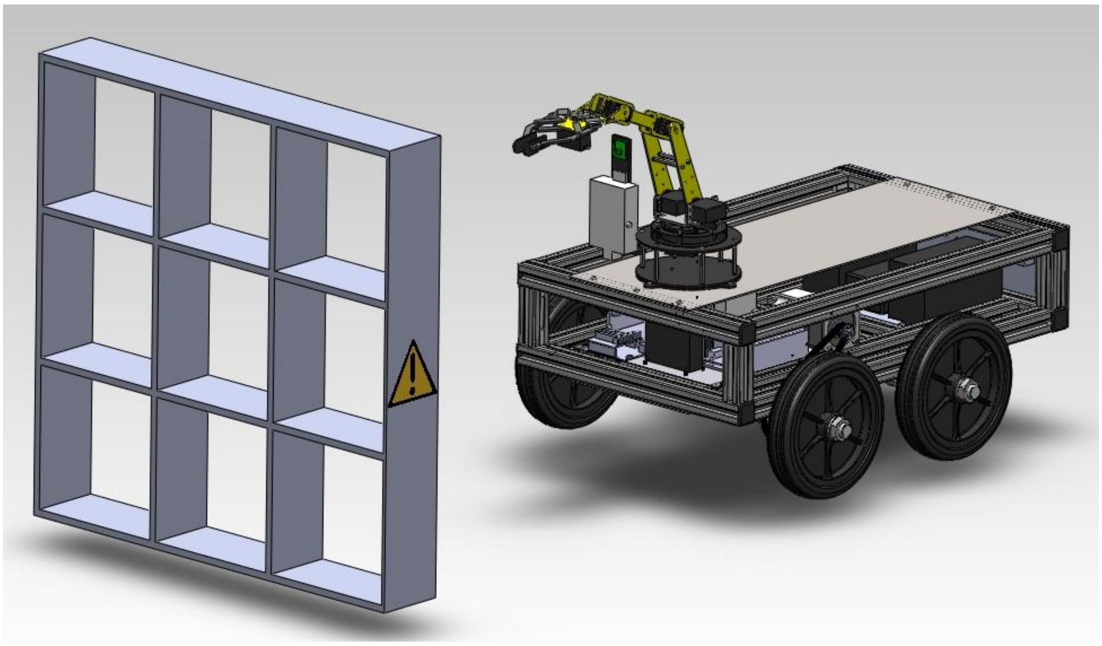


Figure 5.1 3D implementation scenario

The scenario is that various objects in shelf are carried another shelving in mini warehouse model with teleoperation technique over internet thanks to web based operator interfaces.

In the scope of this thesis, web based user interface has been designed for communication between operator and mobile manipulator over internet. Operator can send commands to the mobile manipulator and can see feedbacks from related tasks.

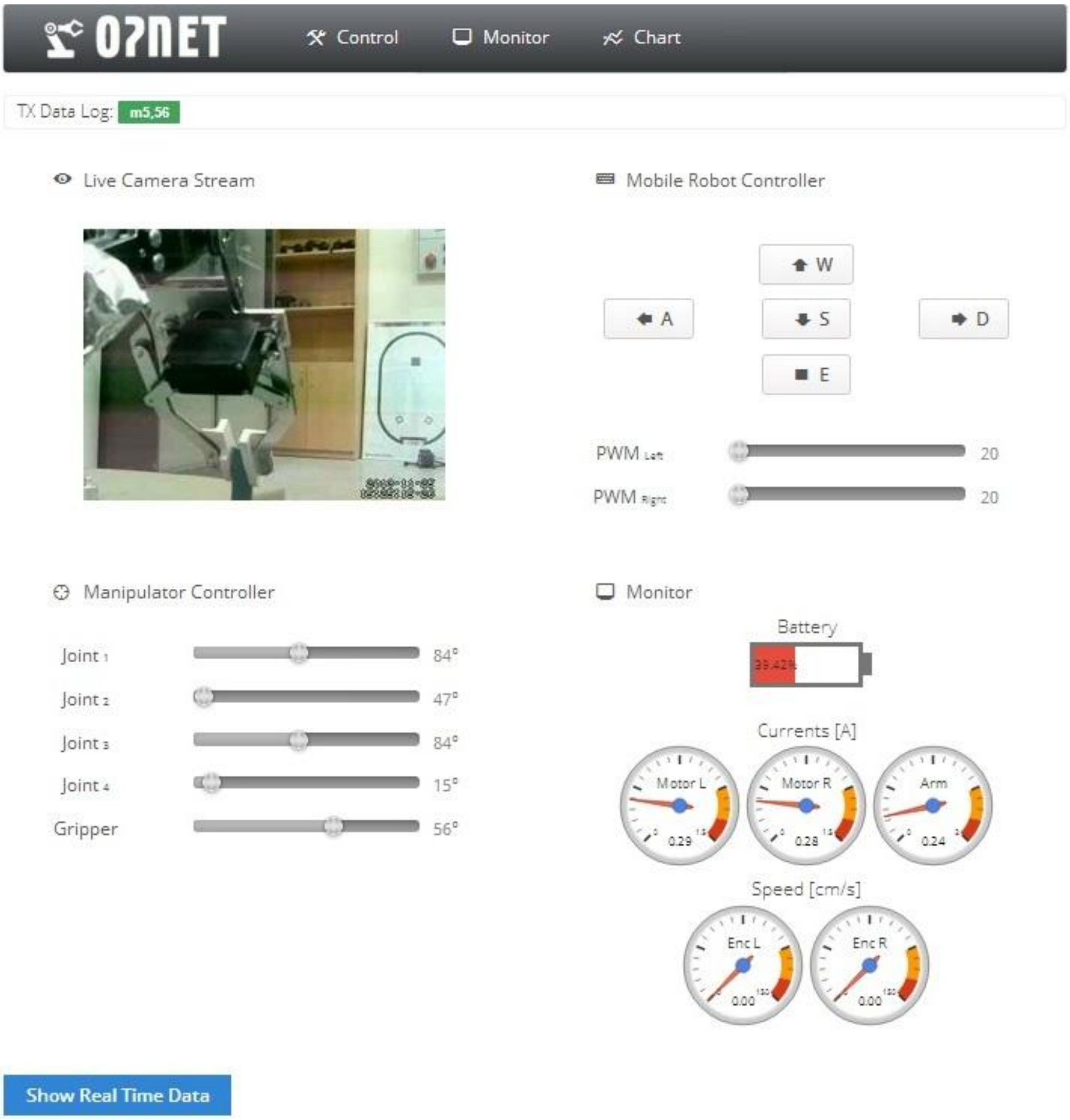


Figure 5.2 Real time sensor data and live camera stream

OpNET operator interface ensures 30 fps live stream and all the sensory information, shown in Figure 5.2. The sensory information Monitor placed onto right bottom corner, seen in Figure 5.2, gives battery status information, displacement, currents of right and left motor, current of robot manipulator and linear velocities of right and left wheel. The mobile manipulator base can be controlled in Mobile Robot Controller section placed on information monitor by keyboard or mouse click through OpNET. Also, motor PWMs can be adjusted separately in this section. Each joint angle of the robot manipulator and a gripper can be controlled in Manipulator Controller section placed onto left bottom corner in web page. Also, operator can watch real time data graphs from Show Real Time Data section.

Figure 5.3 Real time data graph

Determined implementation scenario has been performed successfully. Real time sensor information, real time data graph and live camera stream is shown in Figure 5.2 and 5.3 while the mobile manipulator was performing implementation scenario in different times. And also, Figure 5.4 shows Raspberry Pi and camera on mobile robot.

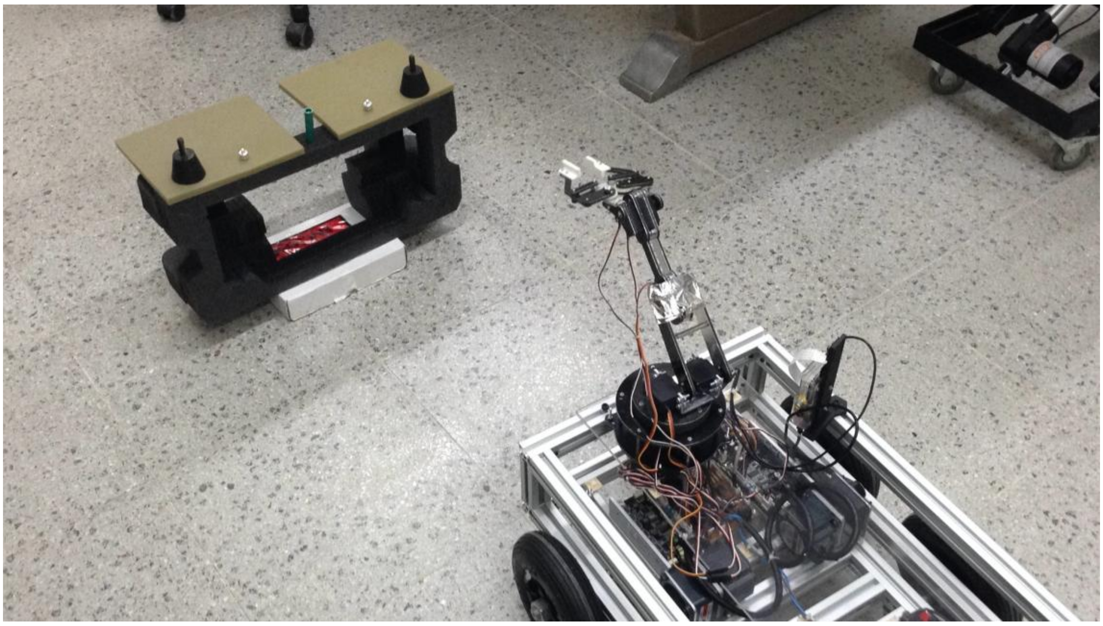


Figure 5.4 Implementation scenario

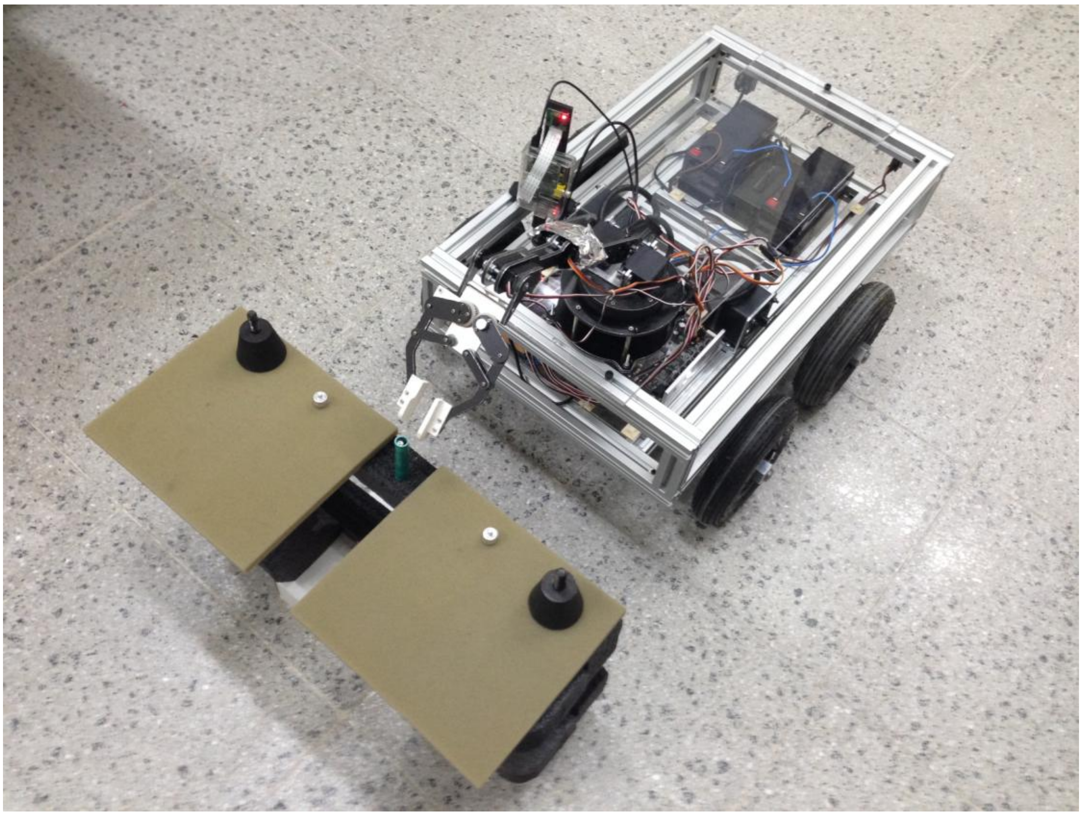


Figure 5.5 Moving to target object

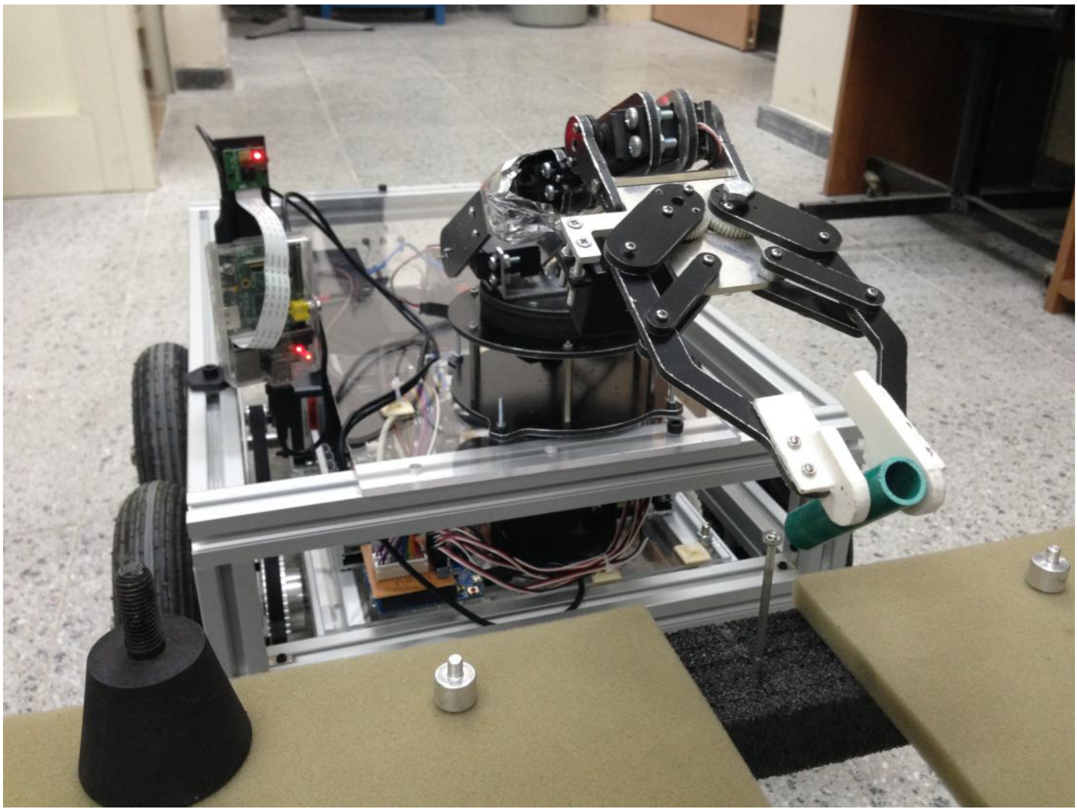


Figure 5.6 Gripping and extraction the object

CHAPTER SIX
CONCLUSION AND FUTURE WORKS

6.1 Conclusion

In this thesis, primarily mobile robots, mobile manipulators and their using area were presented. Teleoperation, one of the control methods for robotic system, was explained and research about mobile manipulator, internet teleoperation and reducing their problems were mentioned in literature review intended for objective of thesis. Structure of mobile robots was explained individually.

General mobile platform for mobile robot applications has been designed and produced. All elements of mechanic hardware of the mobile platform were explained individually and comprehensively and base electronic equipment in platform was introduced.

The robot manipulator was presented and it has been mounted on mobile platform for executing the aim of the study. However, specially designed electronic circuit boards and using electronic elements in electronic hardware of mobile manipulator were explained clearly.

The SBC was used as Linux based web server and main controller of the mobile manipulator. Finally, web based user interface was designed in order to providing communication between operator and the mobile manipulator and performing task over internet. In this scope, implementation scenario was developed. Determined implementation scenario was performed successfully and real time feedback data could be received from system.

In the scope of this thesis, the mobile manipulator, which is controllable over internet with web based user interface and can be used many robotic implementation, has been designed and produced elaborately.

6.2 Results

Internet teleoperation is one of the significant control methods without doubt. In today, more implementations have been developed with using internet teleoperation control structure. This thesis has been one of them as well. Researches about teleoperation still go on significantly because of developing existing control system and resolving problems.

In the scope of this thesis, successfully performing scenario with famous SBC Raspberry Pi in the mobile manipulator is one of the significant results for teleoperation system. The reason for this, Raspberry Pi has cost-performance, dimension-performance, easy usage and flexibility advantages. Also, developed web interface have flexible technological infrastructure, like explained in previous chapters, in order to provide dynamically interaction between user and the mobile manipulator. Therefore, this study has been an important example for other internet teleoperation studies.

There have been some problems in this study as every study. Communication delays influence this project as well. Delays are important problem for teleoperation. Lots of researches focus to figure out these delay problems. After this study, delay problems will be significant issue for future works.

Another problem is drive technique of the mobile platform. Diagonal differential drive was used for mobile platform. This technique sometimes causes slipping in rotation condition of platform. Also, weight balance of mobile platform is important factor for rotation smoothness. In this study, efficiency of diagonal differential drive can be observed sufficiently.

As a result, efficiently operating internet teleoperation system has been developed together web based operator interface OpNET in the scope of this thesis.

6.3 Future Works

In this thesis, mobile manipulator, internet teleoperation system and web interface have been already developed. There are two different way for future works; existing problems in system can be resolve or new specifications and new control systems can be developed in designed teleoperation system. Some of possible ways for future works are discussed below.

Delays occur naturally in teleoperation system because of its structure. Delays in the teleoperation system disrupt synchronization between command sending and executing task so it is complicated to control processes for operator. Delays can be decreased with using compensation methods.

Drive technique of mobile platform can be changed with normal differential drive; two independently driven wheels and one or two omnidirectional free wheels combination. Thus, rotation of mobile platform can be smoother and position accuracy can improve. Also, new robot manipulator can be designed or used for increasing maximum payload.

Web based user interface can be developed more with providing 3D workspace of the robot manipulator, local map and position information thanks to established indoor position system. These specifications can provide ease separately for using mobile platform and robot manipulator. Also, simulation mode can be developed for motion of the robot manipulator.

Indoor positioning system can be developed for position information and accuracy. Positioning system can provide semi-autonomous control of mobile manipulator against unexpected situation like connection rupture of internet and this can used delay compensation. Not for only semi-autonomous, it can be used fully autonomous control. Tasks can be executed with giving only shelf cell number over web interface.

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APPENDICES

A.1 Arduino Leonardo Code

```
// Definition of interrupt names
#include <avr/io.h>
// ISR interrupt service routine
#include <avr/interrupt.h>
#include <Servo.h>
#include <stdlib.h>

//System Timer
long previousMillis = 0;
long interval = 500;

//Pin Definition
Servo Servo1;
Servo Servo2;
Servo Servo3;
Servo Servo4;
Servo Servo5;

int m1_ss = A4;
int m2_ss = A5;
int m1_dir = 4;
int m2_dir = 8;
int m1_pwm = 11;
int m2_pwm = 13;
int enc1 = 2;
int enc2 = 7;
int brk = 12;

int battS = A3;
int armC = A2;
int m1C = A1;
int m2C = A0;

//Variables
int dc1 = 128, dc2 = 128;
int battV;
int armCV;
int m1CV, m2CV;
float batt;
float arm_current;
float m1_current, m2_current;
int m1_pulse, m2_pulse;
```

```
float w1_turn, w2_turn;
float w1_turn_prv, w2_turn_prv;
float w1_rpm, w2_rpm;
float w1_speed, w2_speed;
float w1_speed_prv, w2_speed_prv;
float w1_ms, w2_ms;
int a_second, timer_click=0;
int forward=0, backward=0, left=0, right=0, estop=0;

char inData[6];
char buffer[4]; //for servos
byte index = 0;
byte b_index = 0;
int receive_flag = 0;
int S1=80, S2=90, S3=90, S4=90, S5=90;
int buffer_int;


// Interrupt routines.
void ISR_Enc1()
{
  m1_pulse++;
}
void ISR_Enc2()
{
  m2_pulse++;
}

//Sub-routines
void timer (void);
void platform_control (void);
void voltage (void);
void currents (void);
void serial_out(void);
void speed_clc(void);
void data_receive(void);
void data_parsing(void);
void servo_write(void);

void setup()
{
  pinMode(m1_ss, OUTPUT);
  pinMode(m2_ss, OUTPUT);
  pinMode(m1_dir, OUTPUT);
  pinMode(m2_dir, OUTPUT);
  pinMode(m1_pwm, OUTPUT);
  pinMode(m2_pwm, OUTPUT);
  pinMode(brk, OUTPUT);
```

```
  digitalWrite(brk, LOW);

  // initialize serial:
  Serial.begin(9600);
  while (!Serial)
  {
    ; // wait for serial port to connect.
  }

  // initialize interrupts
  noInterrupts();                    // disable all interrupts
  attachInterrupt(1, ISR_Enc1, RISING);
  attachInterrupt(4, ISR_Enc2, RISING);
  interrupts();                      // enable all interrupts

  // initialize servos:
  Servo1.attach(9);
  Servo2.attach(10);
  Servo3.attach(6);
  Servo4.attach(5);
  Servo5.attach(3);
}

void loop ()
{
  timer();
  data_receive();
  data_parsing();
  platform_control();
  currents();
  voltage();
  serial_out();
  speed_clc();
  servo_write();
}

//Timer0 based system timer routine, Interval 500ms
void timer (void)
{
  unsigned long currentMillis = millis();

  if(currentMillis - previousMillis > interval)
  {
    previousMillis = currentMillis; // save the last time

    timer_click++;
    if (timer_click == 2) //two tick is one second
    {
```

```
      a_second=1;
      timer_click=0;
    }
    if(left != 1 && right != 1 && forward != 1 && backward != 1 )
    {
      digitalWrite(m1_ss, HIGH);
      digitalWrite(m2_ss, HIGH);
    }
  }
}

//Mobile platform control routine
void platform_control (void)
{
  if(left == 1) //a
  {
    digitalWrite(m1_ss, LOW);
    digitalWrite(m2_ss, LOW);
    digitalWrite(m1_dir, LOW);
    digitalWrite(m2_dir, LOW);
    analogWrite(m1_pwm, dc1);
    analogWrite(m2_pwm, dc2);
    left = 0;
  }
  if(right == 1) //d
  {
    digitalWrite(m1_ss, LOW);
    digitalWrite(m2_ss, LOW);
    digitalWrite(m1_dir, HIGH);
    digitalWrite(m2_dir, HIGH);
    analogWrite(m1_pwm, dc1);
    analogWrite(m2_pwm, dc2);
    right = 0;
  }
  if(forward == 1) //w
  {
    digitalWrite(m1_ss, LOW);
    digitalWrite(m2_ss, LOW);
    digitalWrite(m1_dir, HIGH);
    digitalWrite(m2_dir, LOW);
    analogWrite(m1_pwm, dc1);
    analogWrite(m2_pwm, dc2);
    forward = 0;
  }
  if(backward == 1) //s
  {
    digitalWrite(m1_ss, LOW);
    digitalWrite(m2_ss, LOW);
```

```
    digitalWrite(m1_dir, LOW);
    digitalWrite(m2_dir, HIGH);
    analogWrite(m1_pwm, dc1);
    analogWrite(m2_pwm, dc2);
    backward = 0;
  }
  if(estop == 1) //e
  {
    digitalWrite(m1_ss, HIGH);
    digitalWrite(m2_ss, HIGH);
    estop = 0;
  }
  delay(5);
}

//Current feedback routine
void currents (void)
{
  armCV = analogRead(armC);
  arm_current = (((float)armCV*5/1023)/16)/0.11;  //Amplified with 1k and 15k
  m1CV = analogRead(m1C);
  m1_current = (((float)m1CV*5/1023)/16)/0.11;
  m2CV = analogRead(m2C);
  m2_current = (((float)m2CV*5/1023)/16)/0.11;
}

// Empty Batt: 23.06, Full Batt: 28.2, Half Batt: 25V
// Batt voltage feedback routine
void voltage (void)
{
  battV = analogRead(battS);
  batt = ((float)battV*5/1023)*((4.7+0.47)/0.47);  //Divided with 4.7k and 0.47k
}

// Sensory out routine
void serial_out(void)
{
  if(a_second==1)
  {
    a_second=0;

    //Speed calculation according to system timer
    w1_rpm = (w1_turn - w1_turn_prv)*60;
    w2_rpm = (w2_turn - w2_turn_prv)*60;
    w1_turn_prv = w1_turn;
    w2_turn_prv = w2_turn;

    w1_ms = (w1_speed - w1_speed_prv);
```

```
    w2_ms = (w2_speed - w2_speed_prv);
    w1_speed_prv = w1_speed;
    w2_speed_prv = w2_speed;

    m1_pulse=0;
    m2_pulse=0;
    w1_turn_prv=0;
    w2_turn_prv=0;
    w1_speed_prv=0;
    w2_speed_prv=0;

    // String structure
    // # Batt ; M1C ; M2C ; ARMC ; ENC1 ; ENC2 #
    Serial.print("#");
    Serial.print(batt);
    Serial.print(";");
    Serial.print(m1_current);
    Serial.print(";");
    Serial.print(m2_current);
    Serial.print(";");
    Serial.print(arm_current);
    Serial.print(";");
    Serial.print(w1_ms);
    Serial.print(";");
    Serial.print(w2_ms);
    Serial.print("#");
    Serial.println();
  }
}

// Speed calculation routine
// 1/4 pulley ratio and 1/10 reduction ratio,
// Total wheel/motor ratio 1/40,
// Wheel diameter 200mm,
// 36 hall effect sensor pulses per motor rotate
// For wheel 36*40=1440 pulses per wheel rotate
void speed_clc (void)
{
  w1_turn = (float)m1_pulse/1440;
  w2_turn = (float)m2_pulse/1440;
  w1_speed = w1_turn*2*3.14*0.1;
  w2_speed = w2_turn*2*3.14*0.1;
}

// Command and data receive routine
void data_receive()
{
  while(Serial.available() > 0)
```

```
  {
    char aChar = Serial.read();
    if(aChar == '\n')       // End of string detected
    {
      index = 0;
      receive_flag = 1;
    }
    else
    {
      inData[index] = aChar;
      index++;
      inData[index] = '\0'; // Keep the string NULL
    }
  }
}

// Parsing routine of received string
void data_parsing()
{
  if(receive_flag == 1)
  {
    // Platform control commands
    if(inData[0] == 'w') forward = 1;
    if(inData[0] == 's') backward = 1;
    if(inData[0] == 'a') left = 1;
    if(inData[0] == 'd') right = 1;
    if(inData[0] == 'e') estop = 1;

    if(inData[0] == 'm')  // Servo value parsing
    {
      for(index=3; index<6; index++)
      {
        buffer[b_index] = inData[index];
        b_index++;
        buffer[b_index] = '\0';
      }
      index=0;
      b_index=0;

      buffer_int = atoi (buffer); //char to int conv

      switch (inData[1]) // write values related servo variables
      {
        case '1':
        S1 = buffer_int;
        break;
        case '2':
        S2 = buffer_int;
```

```
        break;
        case '3':
        S3 = buffer_int;
        break;
        case '4':
        S4 = buffer_int;
        break;
        case '5':
        S5 = buffer_int;
        break;
      }
    }

    if(inData[0] == 'p')  //Pwm value parsing
    {
      for(index=3; index<6; index++)
      {
        buffer[b_index] = inData[index];
        b_index++;
        buffer[b_index] = '\0';
      }
      index=0;
      b_index=0;
      buffer_int = atoi (buffer);
      switch (inData[1]) // write values to bldc motors
      {
        case '1':
        dc1 = buffer_int;
        break;
        case '2':
        dc2 = buffer_int;
        break;
      }
    }
    receive_flag = 0;
    inData[index] = NULL;
  }
}

// Servo value write routine
void servo_write(void)
{
  Servo1.write(S1);
  Servo2.write(S2);
  Servo3.write(S3);
  Servo4.write(S4);
  Servo5.write(S5);
}
```

A.2 Serial Write and Read PHP Code Snippet in Raspberry Pi

```
http://<opnet_ip>/write.php?send=<command>
```

```php
<?php
if(isset($_GET['send']) && $_GET['send'] != "" && strlen($_GET['send']) > 0) {
	$fp = fopen("/dev/ttyACM0", "c+");
	if(!$fp) die("Port Error !");

	stream_set_blocking($fp,1);
	fwrite($fp, $_GET['send'] . "\n");
	echo $_GET['send'];
	fclose($fp);
}
?>
```

```php
<?php
$timeout = microtime(true) + 2; // timeout is 2s
$fp = fopen("/dev/ttyACM0", "c+");  // for Linux dev/ttyACM0
if(!$fp) die("Port Error !");

stream_set_blocking($fp,0);
do{
    $c=fgetc($fp);
    if($c === false){
        usleep(50000);
        continue;
    }
    $line.=$c;
} while($c!="\n" && microtime(true) < $timeout);

echo $line;

fclose($fp);
?>
```

A.3 String Parsing PHP Code Snippet in Raspberry Pi

http://<opnet_ip>/read.php

```
var arrRead = html.replace(/(\r\n|\n|\r|#)/g,'').split(';'); // RegEx for trimming
if(arrRead.length == 6) {
        // # Batt ; M1C ; M2C ; ARMC ; ENC1 ; ENC2 #

        gauges["ml"].redraw(parseFloat(arrRead[1]));
        gauges["mr"].redraw(parseFloat(arrRead[2]));
        gauges["arm"].redraw(parseFloat(arrRead[3]));
        gauges["enc1"].redraw(parseFloat(arrRead[4]));
        gauges["enc2"].redraw(parseFloat(arrRead[5]));
        var level = parseFloat(arrRead[0]);
```

A.4 Important Telnet Commands

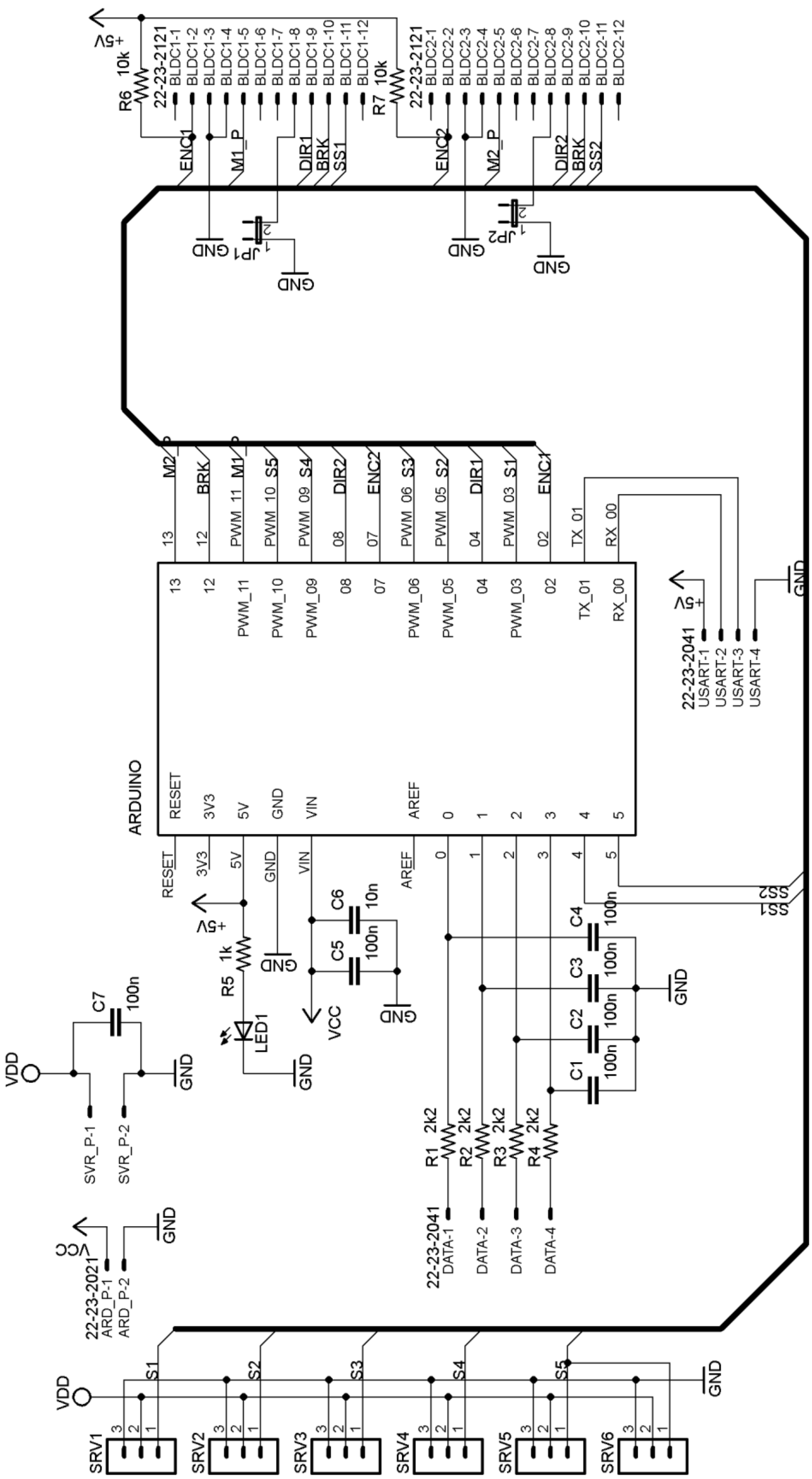
Login info;

User name: pi

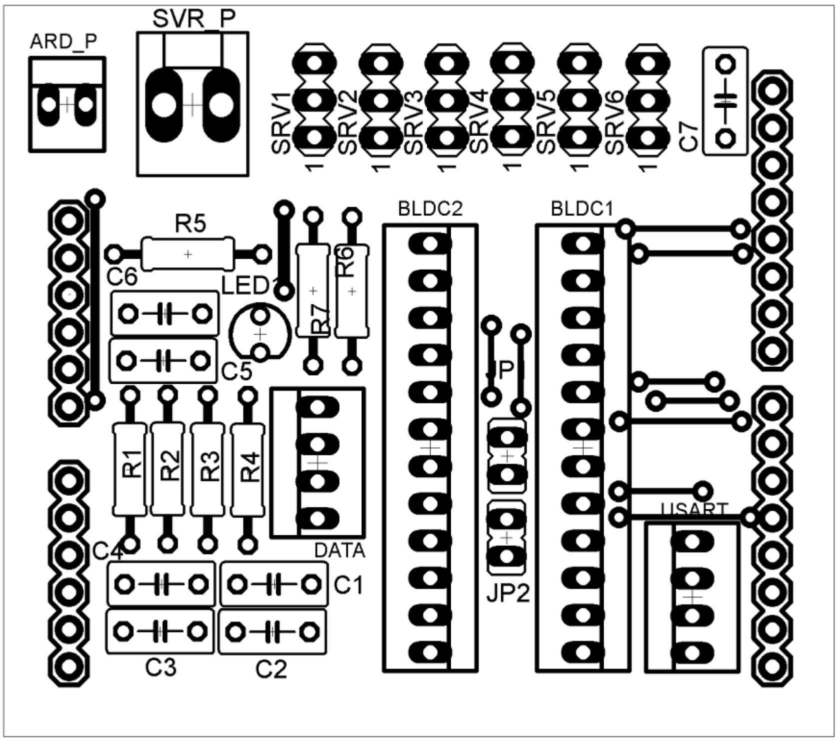
Password: opnet

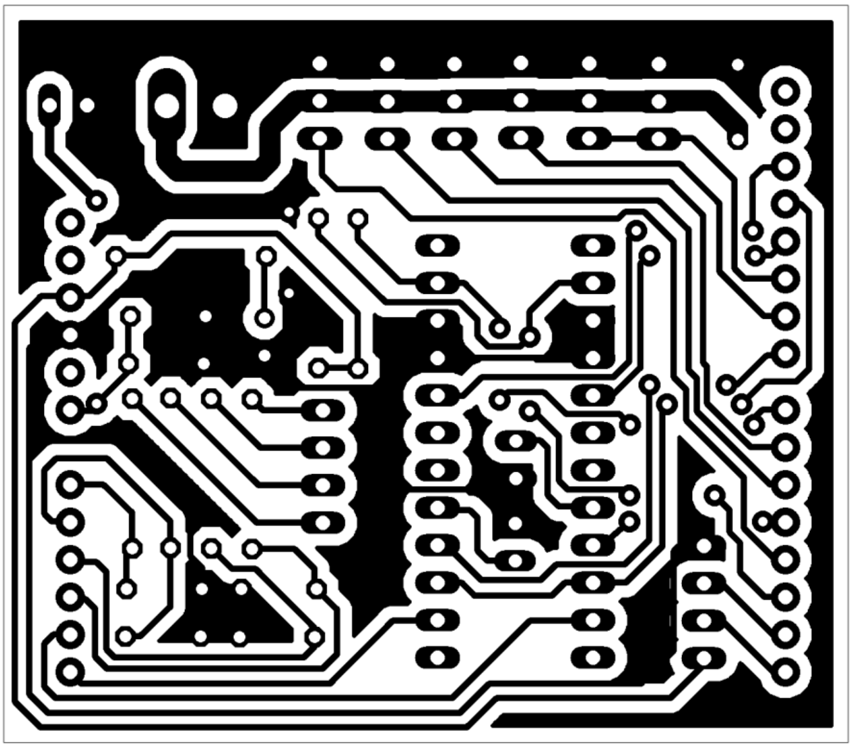
Run camera;	./motion –n –c motion.conf &
Shutdown web server;	sudo shutdown –h now
Restart raspberry Pi;	sudo reboot
Device list;	ls –l /dev or ls /dev
Read related port command;	cat /dev/ttyACM0
Authorization;	chmod atrw /dev/ttyACM0

B.1 Distribution Shield Schematic

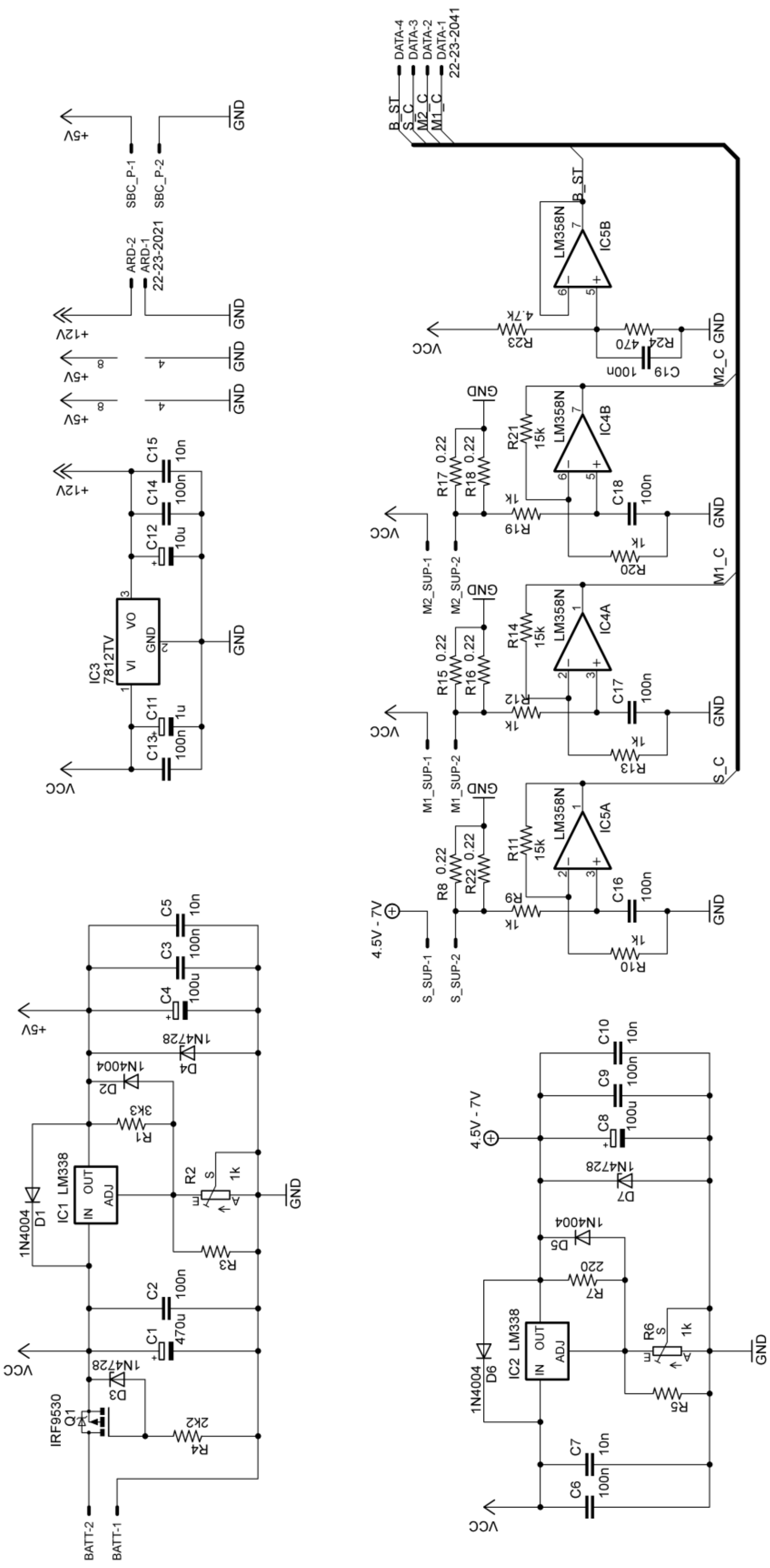


B.2 Distribution Shield PCB Top and Bottom View





B.3 Power Board Schematic



B.4 Power Board PCB Top and Bottom View