

**HARDWARE INTERFACE FOR A 3-DOF SURGICAL
ROBOT ARM AND A 6-DOF END EFFECTOR**

by

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ABSTRACT

HARDWARE INTERFACE FOR A 3-DOF SURGICAL ROBOT ARM AND A 6-DOF END EFFECTOR

Robotic surgery aims minimum soft tissue damage and minimum operator intervention by employing automated, precise electro mechanical devices. In this project the hardware components of a surgical robot are integrated for orthopedic surgery. For this purpose an existing robot arm prototype is modified to operate a surgical end-effector that is designed specifically for orthopedic surgery.

The electronic control system for both the arm and the end-effector are designed in this study. In addition motor drive circuits of the end-effector were designed. Control interface of both units, the arm and the end-effector were implemented in hardware and also in software.

While serially articulated robot arms are easy to handle, precision requirements of dynamically active robots in surgery are very demanding. To overcome the problem we integrated a serial robot arm with a parallel end-effector. The serial arm is responsible for handling the end-effector on the surgical site at a relatively static position. The end-effector on the other hand, applying a dynamically changing force while moving the surgical tool on the operation area. Parallel stewart platform is preferred for the end-effector design to increase the accuracy.

Therefore the design includes two system structures; a stewart platform 6-DOF as the end effector, and a 3-DOF serial robot arm to hold the end effector.

Keywords: Robotics, Robotic Surgery, Computer Assisted Surgery, Parallel Robots, Serial Robots, DOF, Stewart Platform.

ÖZET

3 SERBEST DERECELİ CERRAHİ ROBOT KOLU VE 6 SERBEST DERECELİ UÇ EFEKTÖR İÇİN DONANIM ARAYÜZÜ

Robotik cerrahi, otomatik ve hassas elektro-mekanik cihazlar kullanarak yumuşak dokulara en az zararla çalışmayı ve en az operatör müdahalesini amaçlar. Bu projede ortopedik cerrahi müdahalelerde kullanılmak üzere bir cerrahi robotun donanım gereksinimleri bir robot sistemine entegre edilmiştir. Bu amaçla ortopedik cerrahi için özel tasarlanan bir uç efektörü konumlandırmak ve kontrol etmek üzere var olan bir robot kolu üzerinde değişiklikler yapılmıştır.

Bu çalışmada robot koluna ve uç efektöre ait elektronik kontrol sistemi tasarlandı. Bununla birlikte uç efektör motorlarını sürmek için yeni bir donanım kartı da hazırlandı. Her iki sistemin kontrolü hem donanımsal hem de yazılımsal olarak gerçekleştirildi.

Seri robotları kontrol etmek çok kolay olsa da, cerrahide hareketli uygulamalarda hassas konumlama gereksinimi artmaktadır. Bu gereksinimi karşılamak üzere seri yapıdaki robot koluna paralel yapıda bir uç efektör eklendi. Seri yapıdaki robot uç efektörü cerrahi bölgede sabit bir pozisyonda tutmakla sorumluyken, uç efektör operasyon bölgesinde sürekli değişen kuvvetlerle cerrahi aleti istenen pozisyonda tutmakla sorumlu olacaktır. Hassasiyeti artırmak için paralel yapıdaki "stewart platformu" seçilmiştir.

Böylelikle bahsedilen sistem paralel ve seri iki sistemi içermektedir; stewart platformu 6 serbest dereceli uç efektör paralel sistemi, uç efektörü taşıyacak robot kolu da 3 serbest dereceli seri sistemi oluşturur.

Anahtar Sözcükler: Robotik, Robotik Cerrahi, Bilgisayar Yardımlı Cerrahi, Paralel Robotlar, Seri Robotlar, Serbestlik Derecesi, Stewart Platformu.

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LIST OF SYMBOLS

V	Voltage
R	Resistor
l_1	Length of Robot Arm Link 1
l_2	Length of Robot Arm Link 2
θ_i	Angle of i th joint
μs	micro seconds ms
κHz	kilo hertz kHz
\pm	Plus minus pm

LIST OF ABBREVIATIONS

DOF	Degree of Freedom
CAS	Computer Assisted Surgery
RS	Robotic Surgery
SP	Stewart Platform
PWM	Pulse Width Modulation
CT	Computer Tomography
MRI	Magnetic Resonance Imaging
3D	Three Dimensional
LCD	Liquid Crystal Display
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
RS	Register Select
RW	Read Write
LDAC	Load DAC
VREFH	Voltage Reference High
VREFL	Voltage Reference Low
MCU	Microcontroller Unit
VREFH	Voltage Reference High
AC	Alternative Current
PID	Proportional Integral Derivative

1. INTRODUCTION

Today both Computer Assisted Surgery (CAS) technologies and Robotic Surgery (RS) are in use and their role is getting more important in our life. With Emerging Technological and economic opportunities people can get own health protection and prevent diseases with early diagnosis, treatment, prevention measures and required necessary operations with less side effects and faster recovery time.

In this project, a surgical robot system is purposed to be implement for orthopedic surgery, with minimum soft tissue damage and a minimum of operator intervention. Figure 1.1 illustrates the system and operation. Orthopedic surgery is one of the most common operations in hospitals. Most bone-related orthopedic surgeries are performed to straighten bone deformities, to extend bone length or to remove bone regions affected by tumors and infections. Various orthopedic surgery robotic systems have been developed to perform orthopedic surgeries, which improve the precision and accuracy of the surgery. Some of these systems use serial manipulators and some parallel manipulators [1].

The early research and applications on robotic systems are in serial robot structures, but the poor precise of its positioning capabilities, parallel robot applications has brought to the fore, where the precise positioning is important. In this project our design includes both system structures; a "Stewart platform" will be used which is a 6-DOF parallel robot structure as an end effector and a 3-DOF serial robot arm will be used to hold the end effector. Figure 1.1 and Figure 2.1, shows the whole design.

1.1 Objective

In the project, we use serial and parallel robots to locate a medical tool on desired position. Both serial and parallel systems work independently. Serial robot arm is used to locate "Stewart Platform" on desired location. Then Stewart platform,

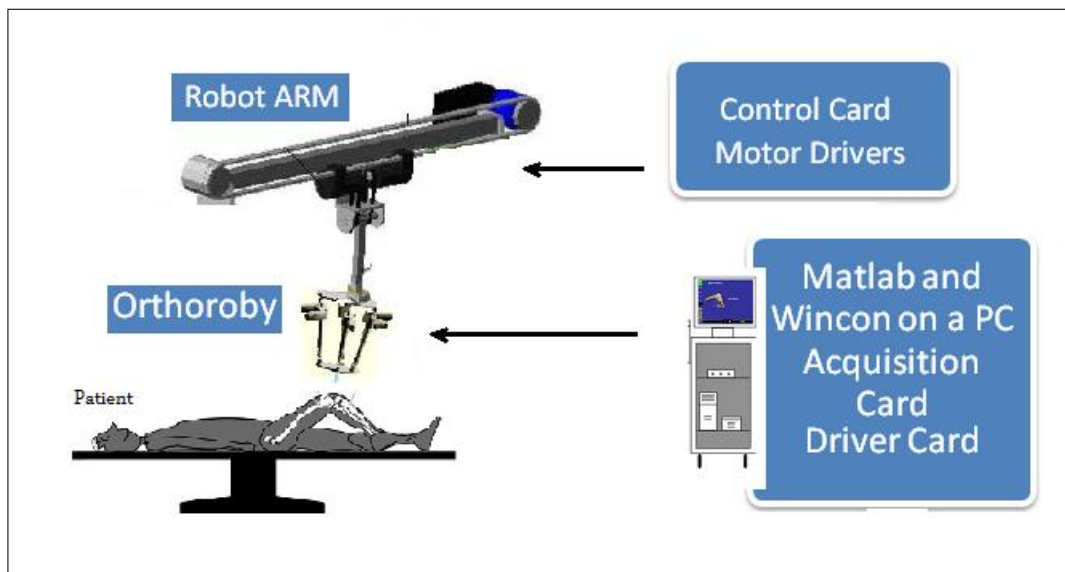


Figure 1.1 Desired Whole System.

parallel structure of the system is utilized to fine tune surgical tool, in other words tool can be exactly located to the desired position with precise movements of Stewart platform.

The main objective of this study is to design a hardware interface to control "robot arm" and hold the end effector at the desired position. For this purpose an electronic hardware card was implemented. Electronic card consist of user and system interfaces for inputs, outputs and feedback data that are controlled via a microcontroller. Also a motor driver card was implemented which can generate PWM pulses for driving linear actuators of Stewart platform. Block diagrams can be seen in Figures 3.3 and 4.3.

1.2 Background

1.2.1 Computer Assisted Surgery Technologies

In Computer Assisted Surgery (CAS) systems, three dimensional (3D) images can be obtained from patient's medical images like CT, MRI images or from other

medical imaging techniques after segmentation and registration processes. 3D images can be very useful before, during and after surgery. Background of this CAS systems is registration (surface matching) of the patient and medical tools, locating their position and real-time tracking of these tools in 3D.

CAS systems can be divided into three sections; Navigation systems, Augmented reality navigation systems, Virtual reality systems. Augmented reality navigation systems use special devices; such as, head mounted camera and display for locating surgeon's position and tracking his point of view. These systems than supply 3D images according to surgeon's point of view [2]. Virtual reality systems can give a chance to make surgical planning before and during surgery without any intervention.

Today Computer Assisted Surgery techniques are in use and they are still being developed with new advances. Image guided surgery, surgical navigation, 3D computer surgery techniques are now more useful in surgical planning and during surgery with important advantages than classical surgery techniques [2, 3]. Now it is possible that CAS systems with special equipments and software can detect medical tools ' positions in anatomical structure in real-time with less than 1mm error.

1.2.2 Robotic Surgery

- *Robotic Surgery*

Since the first usage of the word "robot" in 1921, robotic systems have been improved rapidly. Today Robotic systems perform more complex and hard works in different fields. Robots become widely used especially in manufacturing, assembly, and various areas in the industry. With the use of robotic systems for surgical operations a rapidly developing field was born under the name of "Robotic Surgery". Surgical robots work under the control of a computer that detects changes in environment with sensors and make a decision for desired action. Robotic systems in surgery give us to reduce healthy tissue damage, less pain, smaller scars, less hospital stay duration,

less blood loss, lower probability of infection, shorter recovery time. Bringing these benefits, Robotic Surgery can be mentioned as minimally invasive surgical methods. Today, robotic systems are often used in endoscopes gall bladder surgery, urological surgery, hysterectomy and minimally invasive gynecologic surgery, miyomektomi, gastroesophageal reflux and heartburn treatment [4, 5]. In these surgeries, the surgeon's finger movements can transmit very precise to robotic arm surgical wound can be reduced to one centimeter length

- *Parallel and Serial Robots*

In general, Robot systems imitate human behavior and abilities. Traditional industrial robots, consisting of series of linked bonds are the open loop mechanism. This structure is similar to the human arm and called a serial robots and have human arm's advantages and disadvantages [6].

This type of robot has a capability in a large volume of work with high maneuverability. In contrast, limitation of load-carrying capacity, stretching under heavy loads and vibration at high speed problems are the disadvantages of serial robots. Despite having a large volume of work precision, positioning capabilities are weak [7].

In recent years, high-precision, load carrying capacity, accuracy, rigidity and speed applications that require robots to be developed in parallel in the face and began to be used [8]. Parallel mechanisms, consist of two platforms; the base of the platform tied up to upper platform with at least two independent kinematic mechanisms that are connected with joints. These kinematic mechanisms which are tied up two platforms called legs (linear actuators). This type of kinematic chain of the most famous case was modified mechanism is developed by Stewart [6, 9].

1.3 Organization of The Thesis

The thesis includes 5 chapters with summarizing topics related to general explanations of the system, system design hardware and theoretical explanations of functional blocks of electronic design. This thesis emphasizes especially on electronic hardware and possible improvements on mechanical design and control algorithms mentioned in future works.

In the first chapter, an introduction is given about robotics, robotic surgery and CAS systems. These systems are widely in use and their role is getting more important in our life. I mentioned these concepts because they are relevant to each other and want to show differences between these systems.

Also in this chapter, Robotic surgery is explained with more details and examples that are being developed or in use. In addition, a briefly introduction is given about robotics and serial and parallel structures are explained.

The second chapter explains the whole design generally with system components. In the third and fourth chapter, system components and connections between the functional parts of microcontroller are explained in detail. In the third chapter, information about robot arm design is given. Mechanical and electronic parts are explained under subtitles. Kinematics of the robot is also given. Same as chapter three, in chapter four information is given about end effector. End effector is chosen as a parallel structure robot named "Stewart platform". A general information is given about this structure and how it works.

The last Chapter makes brief comments about the design and gives ideas for future studies.

2. METHOD

In this study, it is aimed to design a robotic system for use in orthopedic surgery. The system includes parallel and serial system structures. A Stewart platform will be used which is a 6-DOF parallel robot structure as an end effector and a 3-DOF serial robot arm will be used to hold the end effector. It is shown in Figure 1.1.

Overall system consists of two systems; "Robot Arm" and "End Effector". As shown in Figure 2.2, both serial and parallel systems work independently. Robot Arm is controlled by a microcontroller with a electronic card, end effector is controlled by a PC with a real time software.

Robot arm, serial structure of the system, consists of 3 3-Phase AC servo motors with feedback capability, 3 motor driver units, limit switches and an electronic control card that can be driven with MSP430 Microcontroller is shown in Figure 2.4. Relation between block diagram of the robot arm and physical parts shown in Figure 3.2. End effector, parallel structure of the system, consists of 6 linear actuators that are made of DC motors with feedback capability, data acquisition card and an electronic driver card that can generate PWM pulses corresponding to analog outputs of acquisition card. Relation between block diagram of the end effector and physical parts are shown in Figure 4.2.

The robot arm which we use in our design was originally designed for painting applications on horizontal surface by moving the arm back and forth [10]. It was designed by Bridgestone Company with the name "Bridgestone Hybrid Robot Arm". It has AC servo motors and Rubber Actuators (Pneumatic Muscles) but in our design, Rubber Actuators are not used. Figure 2.3 shows old system components.

We use AC servo motors and motor driver units of this system for this study. To control the modified new system (Figure 2.4) an electronic control card is designed

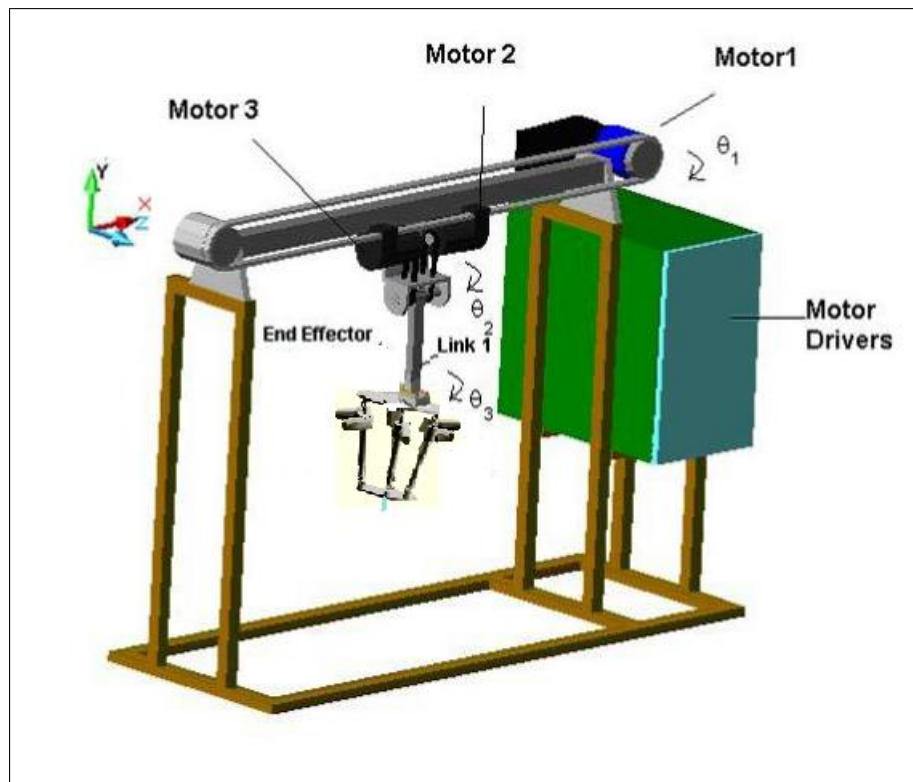


Figure 2.1 Robot Arm With End Effector.

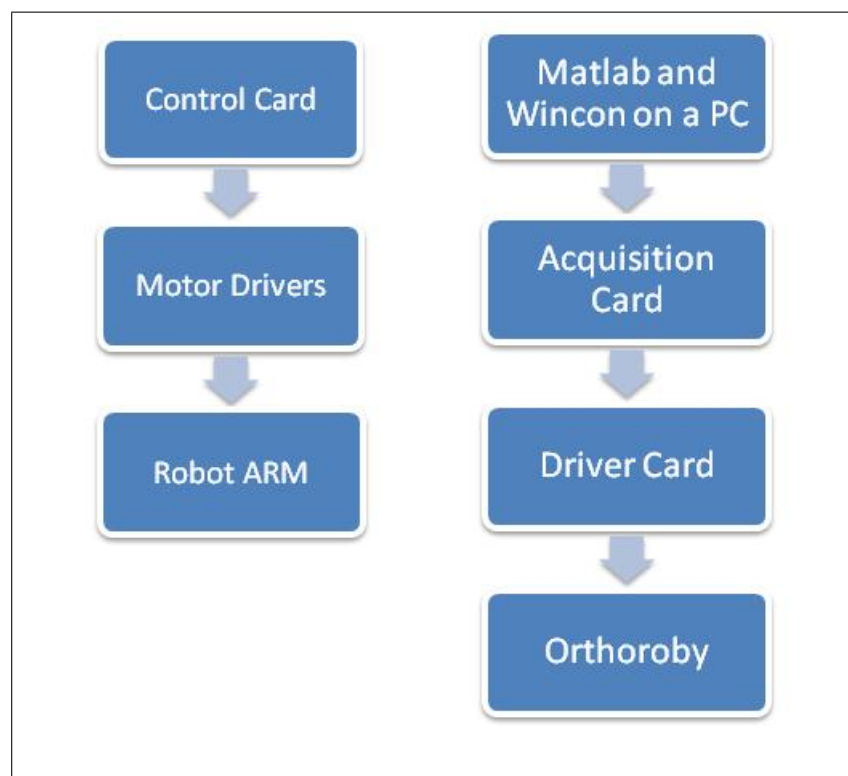


Figure 2.2 Block Diagrams of Both Systems.

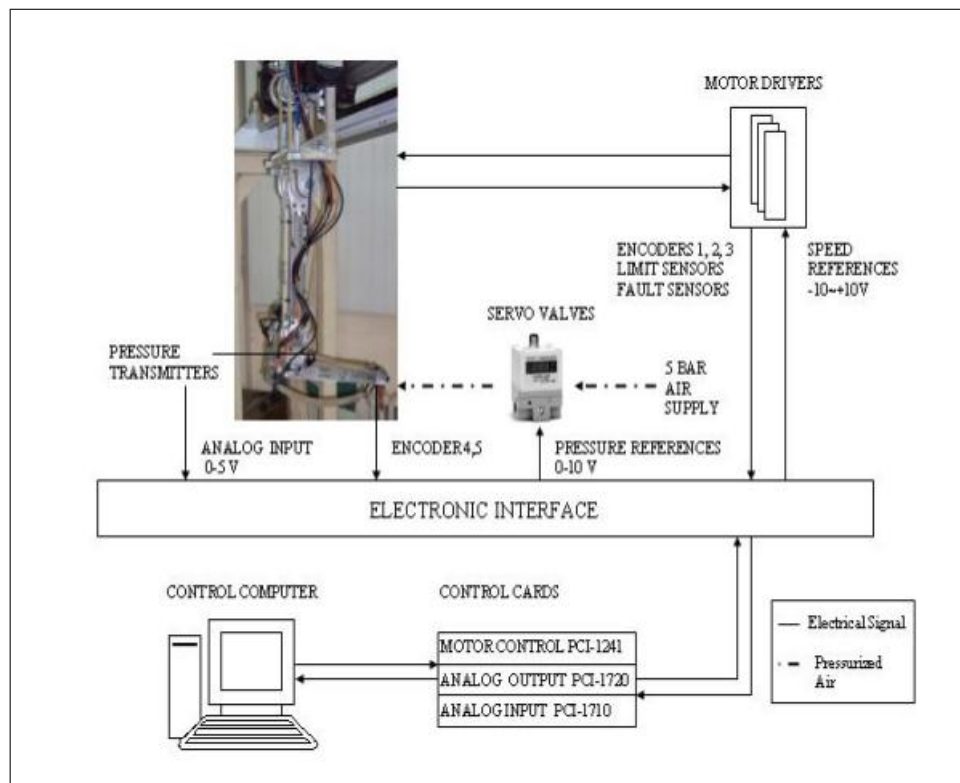


Figure 2.3 The Old System Architecture.

with MSP430FG439 Microcontroller instead of PCI cards. The control card has input-output user-interface units, input-output system-interface units for start and speed references and feedbacks.

The MSP430 is a microcontroller family from Texas Instruments. This family is designed for low cost, low power consumption embedded applications. The ultra-low-power MSP430x4xx devices offer 1.8V-3.6V operation, up to 120kB/ Flash/ ROM 8MIPS with FLL + SVS along with an integrated LCD controller for low power metering and medical applications. Several devices offer application-based peripherals to provide single-chip solutions for flow and electricity metering [11].

MSP430FG439 Microcontroller has 6 ports and each port is 8 bit which can be used as general input-output or for other peripheral functions. Pins are configured as input and output for related circuitry components. MSP430FG439 Microcontroller architecture can be seen in Figure 3.5. "IAR Embedded Workbench® for TI MSP430"

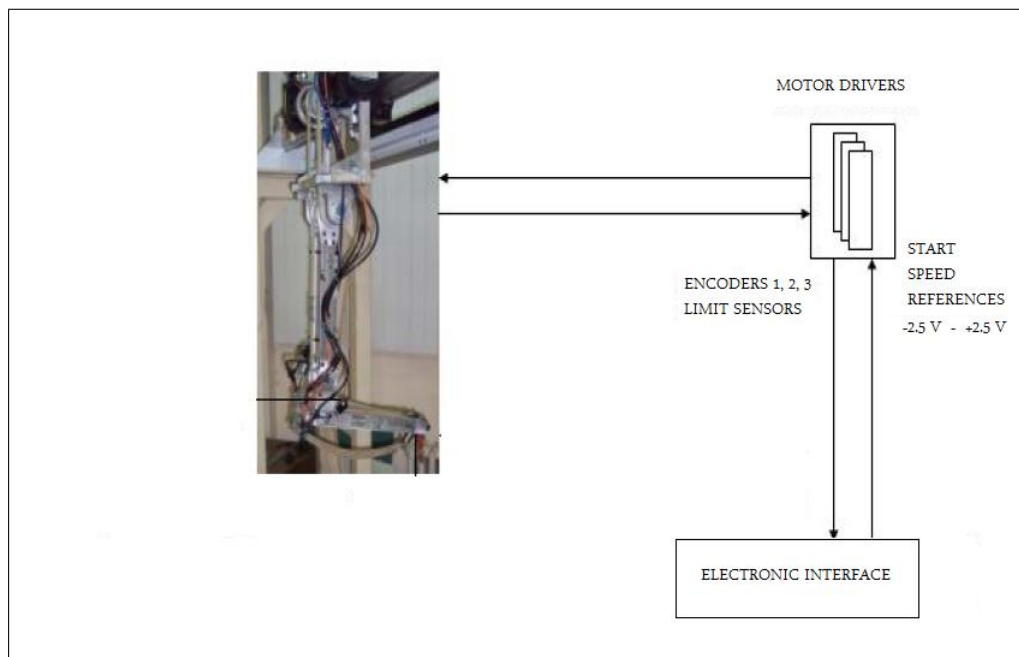


Figure 2.4 The New System.

is used to program the microcontroller. IAR Embedded Workbench with its optimizing C/C++ compiler provides extensive support for devices in MSP430 and MSP430X families and generates very compact and efficient code [12].

Stewart platform "Orthoroby" was designed in Yeditepe University, in Electric and Electronic Engineering department. It is shown in Figure 4.1. 6 Linear actuators are bonded base and upper platforms with spherical joints. Actuators are driven by a designed motor driver card and Stewart system is controlled by acquisition card via Matlab Simulink software programme. "Altium Designer" is used to design and print motor driver card.

Overall system consists of two systems; "Robot Arm" and "End Effector". Whole System, Robot Arm and End Effector are shown in Figures 1.1, 2.4 and 4.1. In the following chapters and sections system components are explained in details.

2.1 Design Specifications

The objective of research and development in computer assisted surgery and robotics is to improve the surgical outcome in terms of accuracy and minimal invasiveness. Applications of robot-assisted orthopedic surgery currently under investigation include total hip and knee replacement, tunnel placement for reconstruction of knee ligaments, and trauma and spinal procedures. Several short-term studies demonstrate the feasibility of robotic applications in orthopedics, however, there are no published long-term data defining the efficacy of robot assisted orthopedic surgery [13]. Position accuracy in clinically used system is above 1mm. [14]. The on going research in this field aiming at improving the accuracy of these surgical robots.

There are several factors effecting the overall accuracy of a surgical robot. The most dominant of these are;

- Actuator response,
- Position sensor resolution,
- Control algorithm,
- Compliance of the articulated system,
- Elasticity of the material,
- Load and inertia on the robot arm

In this project, end effector is designed to hold drilling tool at desired position with 1mm position accuracy. The plates are connected by six linear actuators, which have a stroke length of 150 mm and each can take a load of up to 60 kg. The maximum force generated by each actuator can be as much as 600 N [1]. The mechanical design of the end-effector is the concern of an another on going project in which the accuracy is aimed to be less than 1 mm.

The robot arm is responsible for holding the end-effector on the surgical application site. The trajectory of the robot arm no strict speed requirements, thus making it possible to move the arm at a very slow speed with minimal acceleration. The resulting torque requirements are therefor within the capabilities of the robot arm. The most crucial demand on the robot arm is the position accuracy.

With upper and base platforms and six actuators end effector weight is 30kg. Robot arm has a capability of holding this end effector in a desired manner. Motors on the system can generate 954 N. These values are found from Equations 2.1 and 2.2.

$$power(kw) = \frac{torque(N.m) \times 2\pi \times rotationalspeed(rpm)}{60000}, \quad (2.1)$$

$$torque(N.m) = \frac{power(kW) \times 60000}{2\pi \times rotationalspeed(rpm)}. \quad (2.2)$$

For power= 0.1 kW and for low speeds rpm=1 for Motor1 and Motor2, Equation 2.2 becomes;

$$torque(N.m) = \frac{0.1 \times 60000}{2\pi \times 1} = 954Nm. \quad (2.3)$$

Three electric motors drive the 3-degree of freedom robot arm shown in Figure 1.1. The first joint, θ_1 , is a translate joint moving the robot arm along the x-axis. The next two joints, θ_2 and θ_3 are the rotary joints [10] (Figure 2.5).

It is possible to detect position in three axis with data which comes from quadrature encoders on each motors. Encoders send 1024 pulse per rotation. Number of pulses give position. Position accuracy for x-axis is 0.036 cm that can be calculated for r=6cm (diameter of gearwheel), from the Equation 2.5.

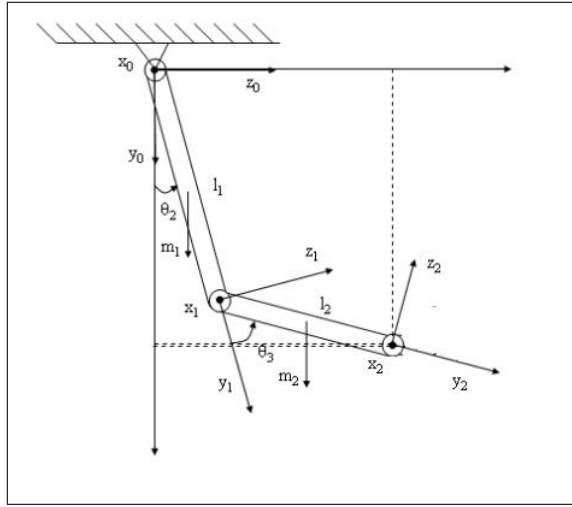


Figure 2.5 The Coordinates For Two Link Manipulator.

From Equation 2.4 encoder resolution is found 0.35° where;

$$\Delta\theta = \frac{360}{1024}, \quad (2.4)$$

$$\Delta X = 2\pi \times r \times \frac{\Delta\theta}{360}. \quad (2.5)$$

Position accuracy in y-axis and z-axis are same and dependent to each other. Maximum position error was calculated as 0.72 cm for both axis. When a maximum position error is calculated as 0.72 cm for y-axis, the error for z-axis is 0.01 cm. This error can be reduced to 0.30 cm by increasing encoder resolution. For better results and solutions, ways of increasing encoder resolution are mentioned in the last chapter.

$$y = l_1 \times \cos(\theta_2) + l_2 \times \cos(\theta_2 + \theta_3), \quad (2.6)$$

$$z = l_1 \times \sin(\theta_2) + l_2 \times \sin(\theta_2 + \theta_3). \quad (2.7)$$

Equations 2.6 and 2.7 give end effector coordinates with respect to θ_2 and θ_3 . Encoder resolutions are 0.35° for θ_2 and θ_3 . The position and position error on both axis can be calculated from these equations.

For operation, robot arm needs to move very slowly and stop at desired position. Then end effector moves very precisely for exact position. Navigation tools are planned to be used for further studies at this project and end effector will be able to tolerate position errors caused by robot arm.

3. ROBOT ARM

Robot Arm system, serial structure of the system, has three AC servo motors with their own driver units (Toshiba). Driver units of the system supply 3-phase AC power with appropriate voltage ranges for motors. Each driver unit has inputs and outputs for control the system. One of the inputs on each driver unit is used to enable each motor. One of the input is for speed reference to determine speed of motor rotation. Quadrature encoders on each motor supplies three channel feedback signal. By reading encoder signals, it is possible to detect direction of rotation and position. To activate motors and control the system for desired motion, speed references need to be set according to feedback data.

Motor driver cards on the system adjusts the motor speed with given speed reference inputs. In the manual it is said that speed reference inputs must be between -10 V , $+10\text{ V}$. We limited this range between -2.5 V , $+2.5\text{ V}$ since it is enough for our needs.

3.1 Mechanical Design

We used almost the same design of "Bridgestone Hybrid Robot Arm" system. We weren't interested in pneumatic parts of the system but we used its electronic parts such as AC servo motors, motor drivers, limit switches, emergency units and connections. Three 3-Phase AC servo motors with feedback capability, three motor driver units, limit switches were used for the project. Figure 3.1 shows *Robot Arm* system.

Figure 3.2 shows relation between block diagram of the robot arm and physical parts.



Figure 3.1 Robot Arm.

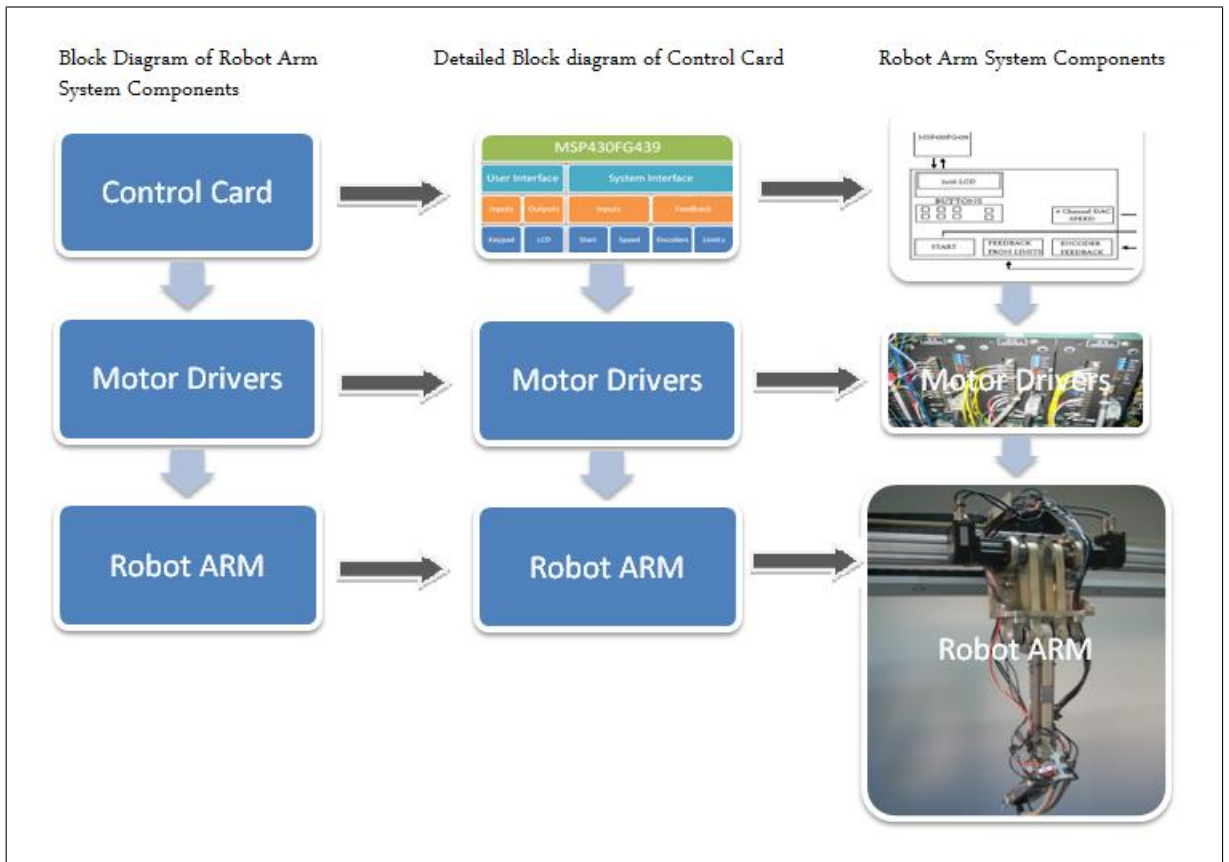


Figure 3.2 Block Diagram of The Robot Arm.

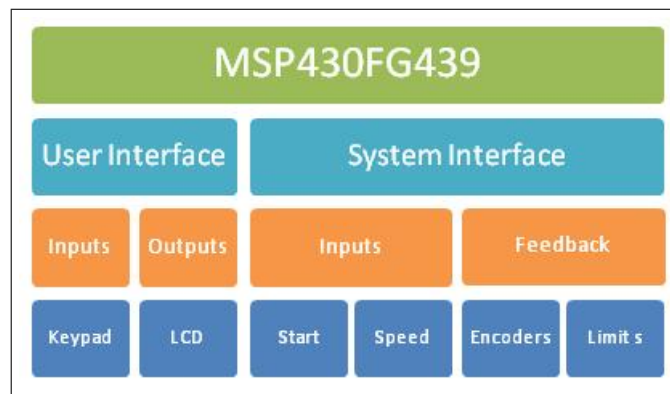


Figure 3.3 Block Diagram of The Control Card For Robot Arm.

3.2 Electronic Design

To drive the system, electronic circuitry was needed. The old system was designed to control via several PCI cards with so many connections. To make useful and simple control, MSP430FG439 Microcontroller was used in this study. For controlling Robot Arm position, inputs and outputs of the system are configured with necessary circuit adaptations. MSP430 Family and Units of the circuitry are explained in below titles. Figure 3.3 shows the block diagram of the electronic control card.

3.2.1 Hardware

Robot arm, consists of three 3-Phase AC servo motors (Toshiba) with feedback capability, three motor driver units (Toshiba RA Driver), limit switches and a electronic control card that can be driven with msp430 Microcontroller (Texas Instruments). Electronic card includes several units; keypad for user inputs, LCD units to see entered data and results, system start unit to enable motors on the system, speed reference units to control speed of the motor rotation, encoder unit and limit switches unit to get position data.

In this section MSP430 Family and Units of the circuitry are explained in detail. Block diagram of the electronic hardware card with input output relations shown in

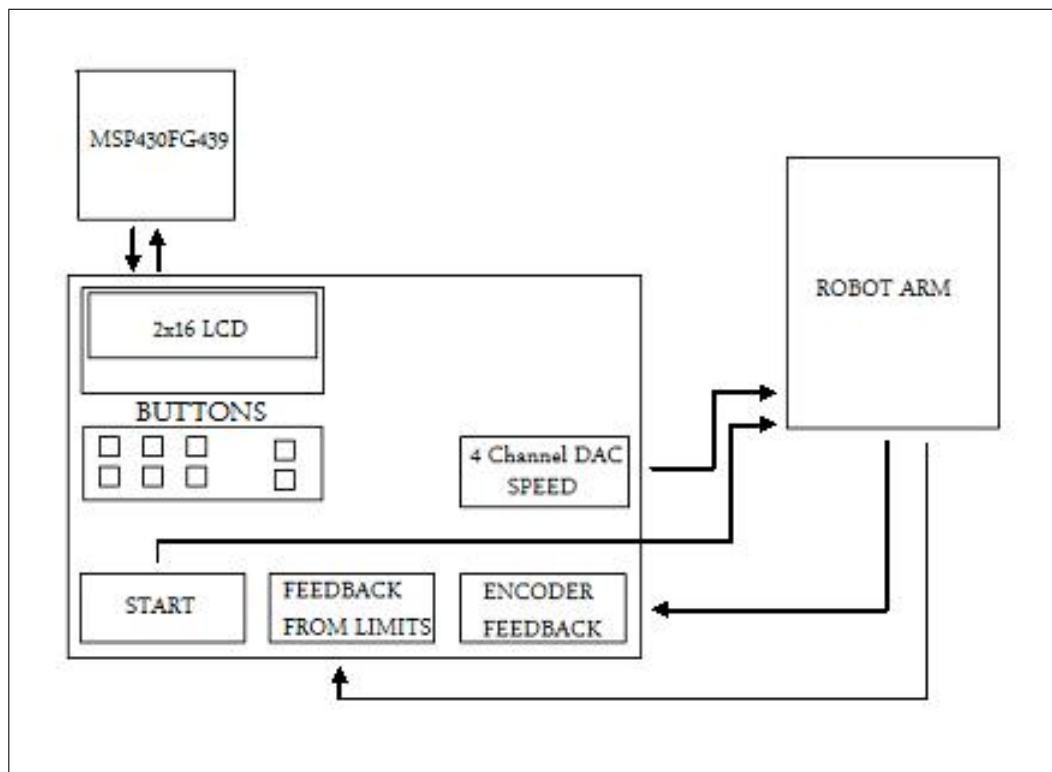


Figure 3.4 Electronic Control Card.

Figure 3.4.

- *MSP430 Family*

The Texas Instruments MSP430 family of ultralow power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 6 *ms*. MSP430 enables system designers to simultaneously interface to analog signals, sensors and digital components while maintaining unmatched low power [15]. Typical applications include utility metering, portable instrumentation, intelligent sensing, and consumer electronics. In this study MSP430FG439 is selected for the electronic control hardware for its functional

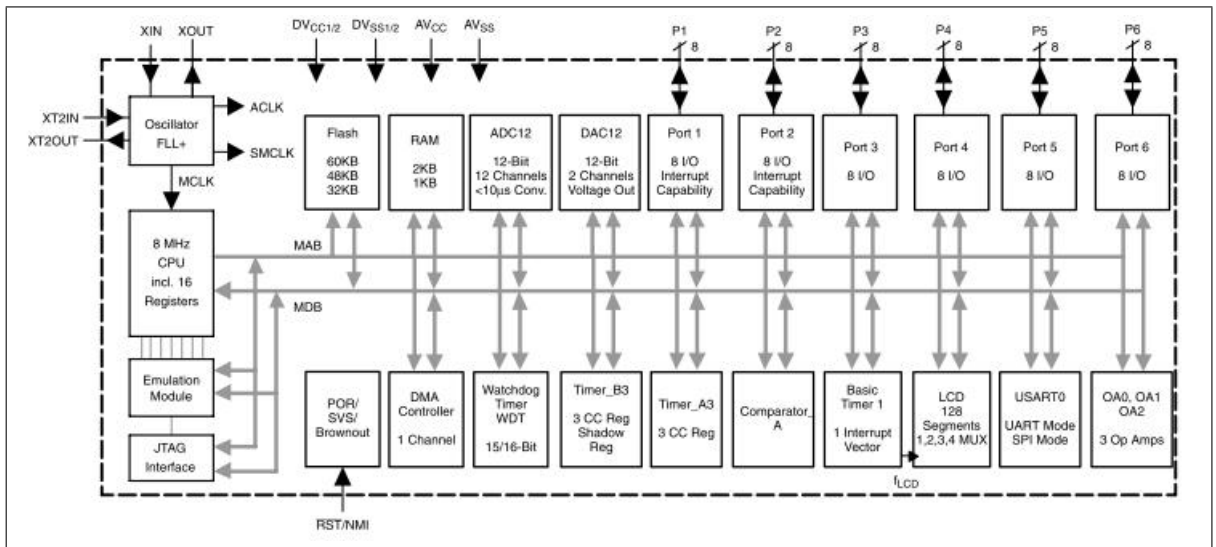


Figure 3.5 Architecture of MSP430FG439.

capabilities. The MSP430FG43x series are microcontroller configurations with two 16-bit timers, a high performance 12-bit A/D converter, dual 12-bit D/A converters, three configurable operational amplifiers, one universal synchronous/asynchronous communication interface (USART), DMA, 48 I/O pins, and a liquid crystal display (LCD) driver. Functional blocks can be seen in Figure 3.5.

Typical applications for this device include analog and digital sensor systems, digital motor control, remote controls, thermostats, digital timers, hand-held meters, etc. Each pin of the ports can be configured as input, output or a special function pin. Apart from these, port1 and port2 can be configured to accept interrupts from external components. All 6 ports of MSP430FG439 are used for the design with capabilities of I/O pins as inputs and outputs.

The MSP430 MCU clock system is designed specifically for battery-powered applications. Multiple oscillators are utilized to support event-driven burst activity. A low-frequency Auxiliary Clock (ACLK) is driven directly from a common 32- kHz watch crystal or the internal very low-power oscillator (VLO)-with no additional external components. The ACLK can be used for a background real-time clock self wake-up function. An integrated high-speed digitally controlled oscillator (DCO) can source

the master clock (MCLK) used by the CPU and submain clock (SMCLK) used by the high-speed peripherals.

- *Keypad*

For user inputs a keypad unit is designed with eight push buttons. Six of these buttons are adjusting X, Y, Z coordinates or θ_1 , θ_2 , θ_3 for desired position. Other buttons are used for selected functions and for enter input data and to pause or stop the system.

- *LCD*

LCD modul is designed to see the data entered by the user and the position of the robot arm. LCD modul is a standard 2x16 character LCD based on the HD44780 chip. This LCD can be driven in 8-bits mode, which requires in total 11 lines from your microcontroller. If we want (or need) to spare some lines for other purposes it is possible to drive the display in 4-bits mode, which requires seven lines. The only drawback using 4-bits is that commands and data have to be sent in two nibbles (4bit parts) to the display, which takes slightly more time.

The standard to communicate with HD44780 standard requires three control lines as well as either four or eight I/O lines for the data bus. The three control lines are referred as EN, RS, and RW.

The EN line is called "Enable." This control line is used to tell the LCD that you are sending it data. The RS line is the "Register Select" line. When RS is low (0), the data is to be treated as a command or special instruction (such as clear screen, position cursor, etc.). When RS is high (1), the data being sent is text data which should be displayed on the screen. The RW line is the "Read/Write" control line. When RW is low (0), the information on the data bus is being written to the LCD. When RW is high (1), the program is effectively querying (or reading) the LCD. LCD pin configuration can be seen in Table 3.1.

Table 3.1
LCD Pin Configuration.

LCD pins	Connections
Pin 1 (Vss)	Ground
Pin 2 (Vdd)	5V
Pin 3 (Vlc)	Ground
Pin 4 (RS)	MSP430 P6.4
Pin 5 (RW)	MSP430 P6.5
Pin 6 (E)	MSP430 P6.6
Pin 7 (DB0)	not connected
Pin 8 (DB1)	not connected
Pin 9 (DB2)	not connected
Pin 10 (DB3)	not connected
Pin 11 (DB4)	MSP430 P6.0
Pin 12 (DB5)	MSP430 P6.1
Pin 13 (DB6)	MSP430 P6.2
Pin 14 (DB7)	MSP430 P6.3
Pin 15 (Va)	3-5V
Pin 16 (Vc)	Ground

- *Start*

To enable Motors of "Robot Arm" Motor Drivers need a signal at 10 V voltage level. When you send this signal you can drive motors with given speed reference voltages. The designed circuit is simple that converts 3.3 V which of maximum output of the microcontroller to the 10 V voltage level with nmos transistors.

- *Speed*

Motor driver cards on the system adjusts the motor speed with given speed reference inputs. Speed reference inputs must be between - 10 V, + 10 V in the manual. But we limited this range between - 2.5 V, + 2.5 V that is enough for our needs. MSP430

is a mixed signal microcontroller and had a 2-channel DAC peripheral which can give analog signals in the range of 0, + 2.5 V. To supply - 2.5 V, + 2.5 V ranges opamp circuits integrated to system first, but this time only two motors could be driven. To over come this problem 12-bit 4-channel DAC7624 integrated circuit from Texas Instruments is used.

The DAC7624 is quad voltage output, 12-bit digital-to-analog converter (DAC). The architecture is a classic R-2R ladder configuration followed by an operational amplifier that serves as a buffer. It has its own R-2R ladder network and output op-amp, but all share the reference voltage inputs. The minimum voltage output ("zero-scale") and maximum voltage output ("full-scale") are set by the external voltage references (VREFL and VREFH, respectively). The digital input is a 12-bit parallel word and the DAC input registers offer a readback capability. The converter can be powered from a single +5 V supply or a dual ± 5 V supply. Device offers a reset function which immediately sets all DAC output voltages and DAC registers to mid-scale (DAC7624, code 800H). See Figure 3.6 for the basic operation of the DAC7624.

To provide analog output for desired values, the digital 12-bit input is supplied to output channels of DAC7624 are selected by microcontroller. When DAC7624 is configured as Midscale function as in Figure 3.6, selected channel becomes 0 V when digital 12-bit input is 0800h in hexadecimal format. Above of this value is converted as positive analog outputs for forward rotation with corresponding speeds. Below of this value is converted as negative analog outputs for backward rotation with corresponding speeds. Table 3.3 shows pin descriptions and connections of DAC7624. Table 3.2 shows 12-bit digital input and corresponding analog outputs.

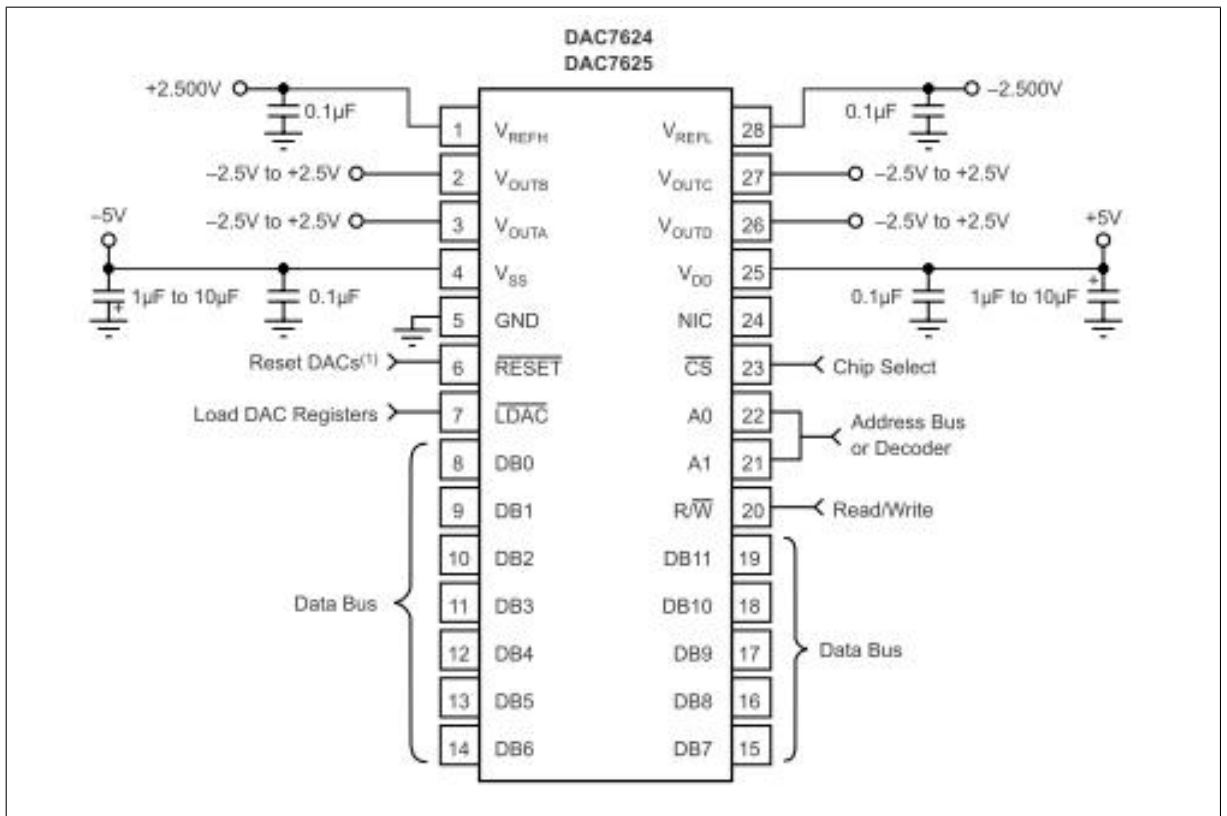


Figure 3.6 Wiring Diagram of DAC7624.

Table 3.2
DAC7624 Outputs Corresponding To 12 Bit Hexadecimal Inputs

DAC7624 12 bit Digital Input	Analog Output
Hexadecimal	mV
0780h	-160
07A0h	-120
07C0h	-80
07E0h	-40
0800h	0-5
0820h	35-40
0840h	70-80
0860h	110-120
0880h	150-160

Table 3.3
DAC7624 Pin Configuration.

DAC 7624 pins	DESCRIPTION	Connections
pin 1 (VREFH)	Reference Input Voltage High.	2.5V
pin 2 (VOUTB)	DAC B Voltage Output.	Speed reference For motor1
pin 3 (VOUTA)	DAC A Voltage Output.	Speed reference For motor2
pin 4 (VSS)	Negative Analog Supply Voltage	-5V
pin 5 (GND)	Ground.	GND
pin 6 (RESET)	Reset Input.	P4.6
pin 7 (LDAC)	Load DAC Input.	P4.7
pin 8 (DB0)	Data Bit 0. Least significant bit	P3.0
pin 9 (DB1)	Data Bit 1	P3.1
pin 10 (DB2)	Data Bit 2	P3.2
pin 11 (DB3)	Data Bit 3	P3.3
pin 12 (DB4)	Data Bit 4	P3.4
pin 13 (DB5)	Data Bit 5	P3.5
pin 14 (DB6)	Data Bit 6	P3.6
pin 15 (DB7)	Data Bit 7	P3.7
pin 16 (DB8)	Data Bit 8	P4.0
pin 17 (DB9)	Data Bit 9	P4.1
pin 18 (DB10)	Data Bit 10	P4.2
pin 19 (DB11)	Data Bit 11. Most significant bit	P4.3
pin 20 (R/W)	Read/Write Control Input	
pin 21 (A1)	Register/DAC Select	P4.5
pin 22 (A0)	Register/DAC Select	P4.4
pin 23 (CS)	Chip Select Input.	GND
pin 24 (NIC)	Not Internally Connected.	Not connected
pin 25 (VDD)	Positive Analog Supply Voltage,	5V
pin 26 (VOUTD)	DAC D Voltage Output.	NC
pin 27 (VOUTC)	DAC C Voltage Output.	Speed reference For motor3
pin 28 (VREFL)	Reference Input Voltage Low.	-2.5V

- *Encoders*

A quadrature encoder input, also known as an incremental encoder and most often used in motor control, converts linear displacement into a pulse signal. By monitoring both the number of pulses and the relative phase of the two signals, you can track the position, direction of rotation, and speed of a motor or apparatus. In addition, a third channel, or index signal, can be used to reset the position counter.

There is 90° phase shift between A and B. It is possible to detect speed and direction of the rotation of motor by reading A and B channels. If A leads B, for example, the motor is rotating in a clockwise direction. If B leads A, then the motor is rotating in a counter-clockwise direction.

To get position of links existing encoders on motors were used for this project. AC servo motors are included internal encoders. Each encoder gives 3-channel signal; A, B and Z channels. A and B give 1024 pulses per rotation, Z gives one pulse per rotation. Pulse levels were measured as 4.4 Volts and with necessary circuit was added to detect signals by a microcontroller.

- *Limit Switches*

Table 3.4
Converted Values For Limit Switches

	Values	Converted Values	Value	Converted values
Evaluated as	"Open"	Logic "Low"	"Close"	Logic "High"
Limit Switch X	0 V	0 V	24 V	2.4 V
Limit Switch Y and Z	4.4 V	0.35 V	8.1 V	2.4 V

In the robot arm system links have physical limits. To keep system safety, limit switches were placed just before this physical limits of the system. Limit switches gives signal when a link comes to the limit position. Limit switches that are related to *motor1* is

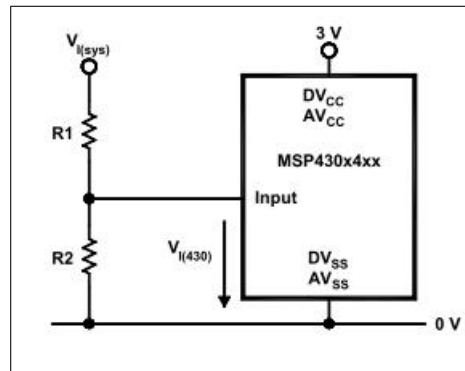


Figure 3.7 Voltage Divider Interface Circuit .

turned a $24V$ voltage level when it is reached limits otherwise the values are $0V$. Limit switches that are related to *motor2* and *motor3* are turned a $8V$ voltage level when it is reached limits otherwise the values are $4.4V$. To convert these voltage levels to the levels that microcontroller can understand if limit switches are "on" or "off" a basic voltage divider and a comparator circuit was implemented.

- *Interfacing MSP430 to System*

The modern MSP430s, the MSP430x4xx family, are available for the supply voltage range from 1.8 V to 3.6 V only. The interfacing of the $3.3V$ MSP430x4xx microcontroller families to circuits with a supply of 5 V or higher is necessary. Resistor-Divider Input Interfaces were used in this system with using $R = 1\text{Mohm}$ [16]. Figure 3.7 shows this interface.

- *Power Supply*

The system was designed for 3 phase- $200V$ AC power supply, which is 3 phase standard in Japan. In order to use it in Turkey, Delta-Delta type $380V$ AC-3 phase to $200V$ AC-3 phase transformer is used. Also 24 Volt power supply is used for the system. For Control card $\pm 5V$, $\pm 2.5V$ and $10V$ power supplies are used. Figure 3.8 shows wiring diagram of the power supply of the system.

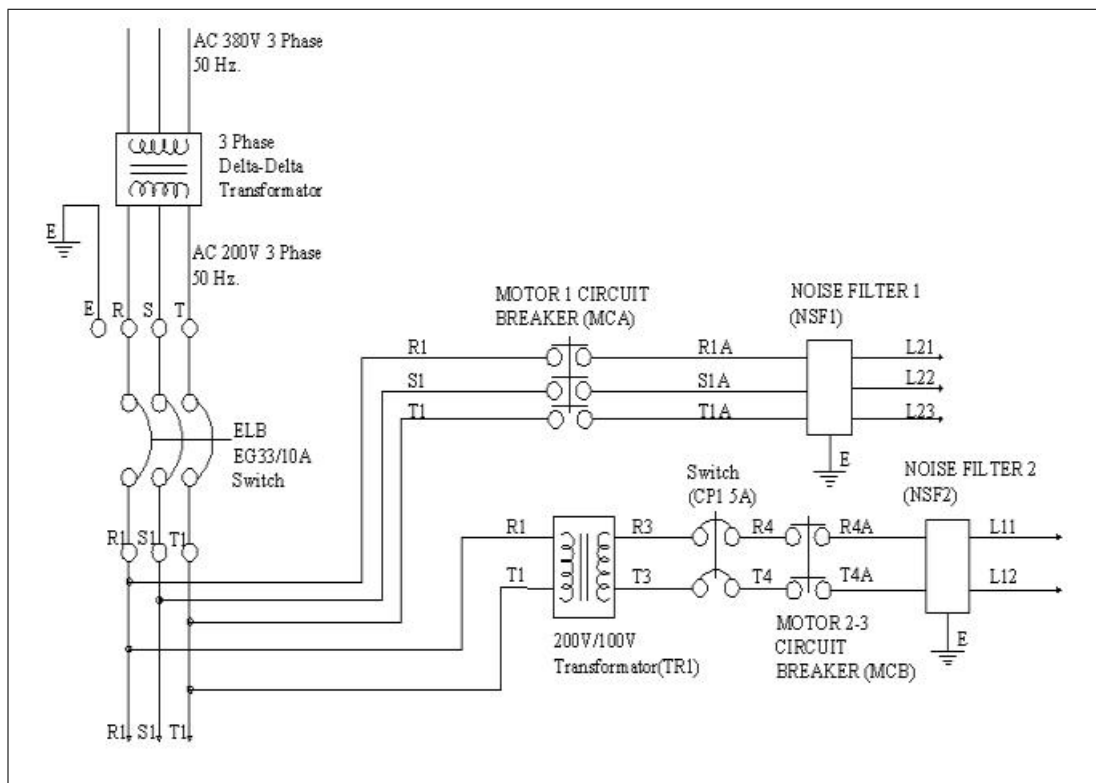


Figure 3.8 Wiring Diagram of Power Supplies of Robot Arm.

- *Emergency System*

The wiring diagram of the emergency system is shown in Figure 3.9. This emergency system, is controlled with current feedbacks. In addition, integrated emergency button gives us the chance for hard emergency.

- *Wiring Diagrams*

Wiring diagrams of motors are shown in Figures 3.10, 3.11

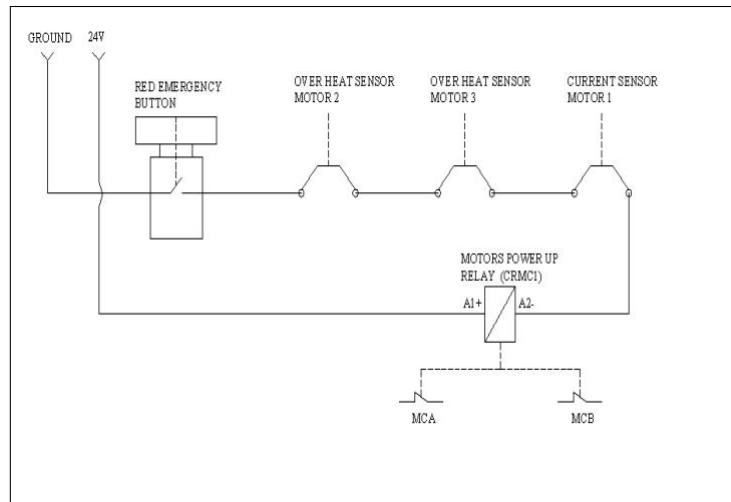


Figure 3.9 Wiring Diagram of The Emergency System.

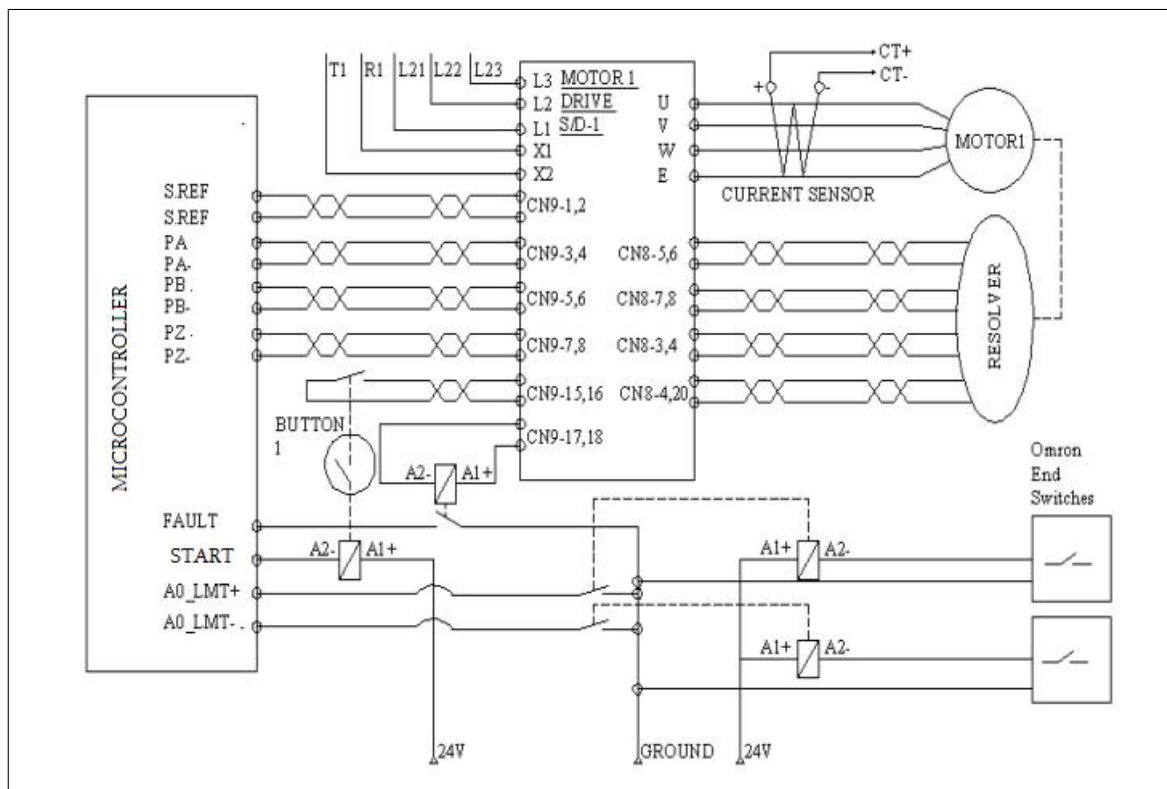


Figure 3.10 Wiring Diagram For Motor1.

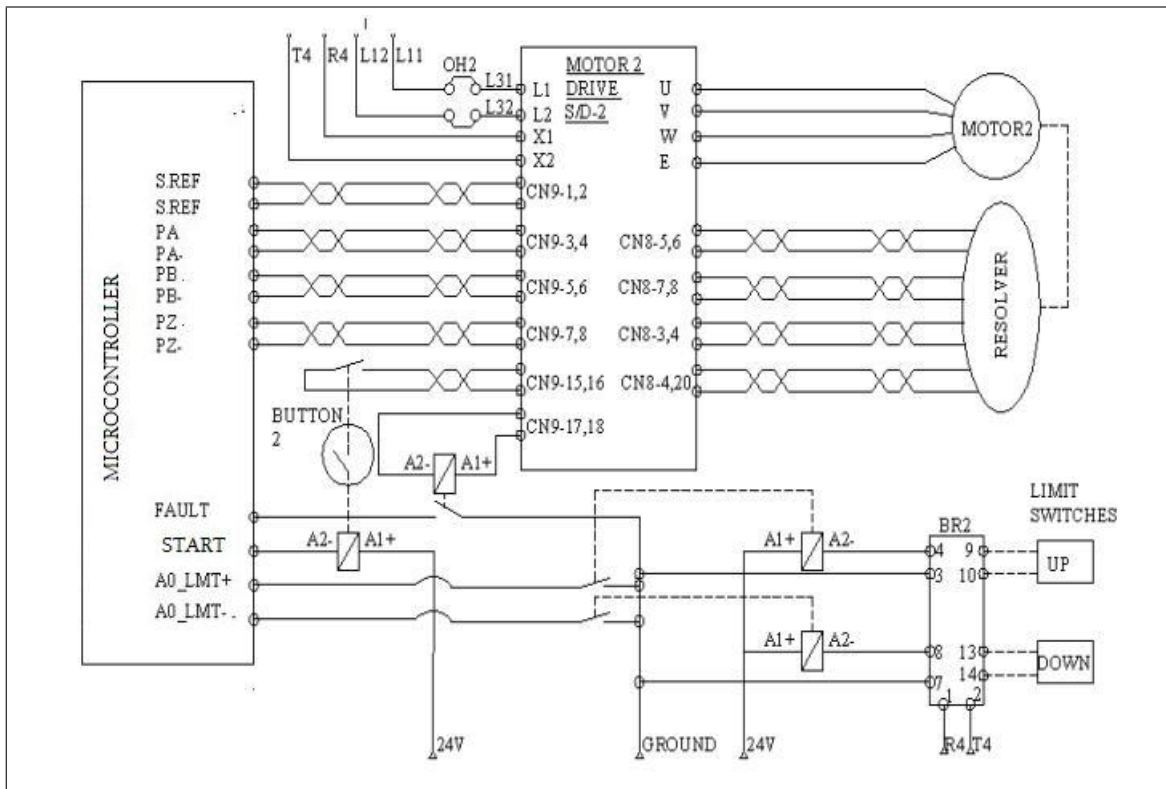


Figure 3.11 Wiring Diagrams For Motor2 and Motor3.

3.2.2 Software

- *Pin Configuration*

MSP430FG439 microcontroller has six ports and each port is 8-bit which can be used as general input-output or for other peripheral functions. Each pin of the ports can be configured as input, output or a special function pin. Port1 and port2 can be configured to accept interrupts from external components. All six ports of MSP430FG439 are used and pins are configured as input or output for related circuitry components. Port1 and port2 have interrupt capability. Port1 is configured for six encoder inputs. Port2 is configured input for limit switches. P1.6 and P1.7 are configured for enter and stop buttons with interrupt capability. Port3 and port4 are configured as output for DAC7624 to generate speed references. 12-bit is used for digital input data for DAC7624. P4.4 and P4.5 are used for output channel select pins, P4.6 and P4.7 are used for LDAC and Reset.

P5.0, P5.1, P6.7 are configured as output for enable the motors (start). P5.2-P5.6 are configured as input for keypad. P6.0-P6.6 is configured as output for LCD unit.

- *Functions*

In the software program, function blocks were written to control the Robot Arm with input output modules. LCD Function is one of the functions to see the entered modes and data and see the results on it. Buttons function is the function to enter data. Start, speed functions are to drive the system. Limits, encoders are functions for receiving feedback. Flowchart can be seen in Figure 3.12.

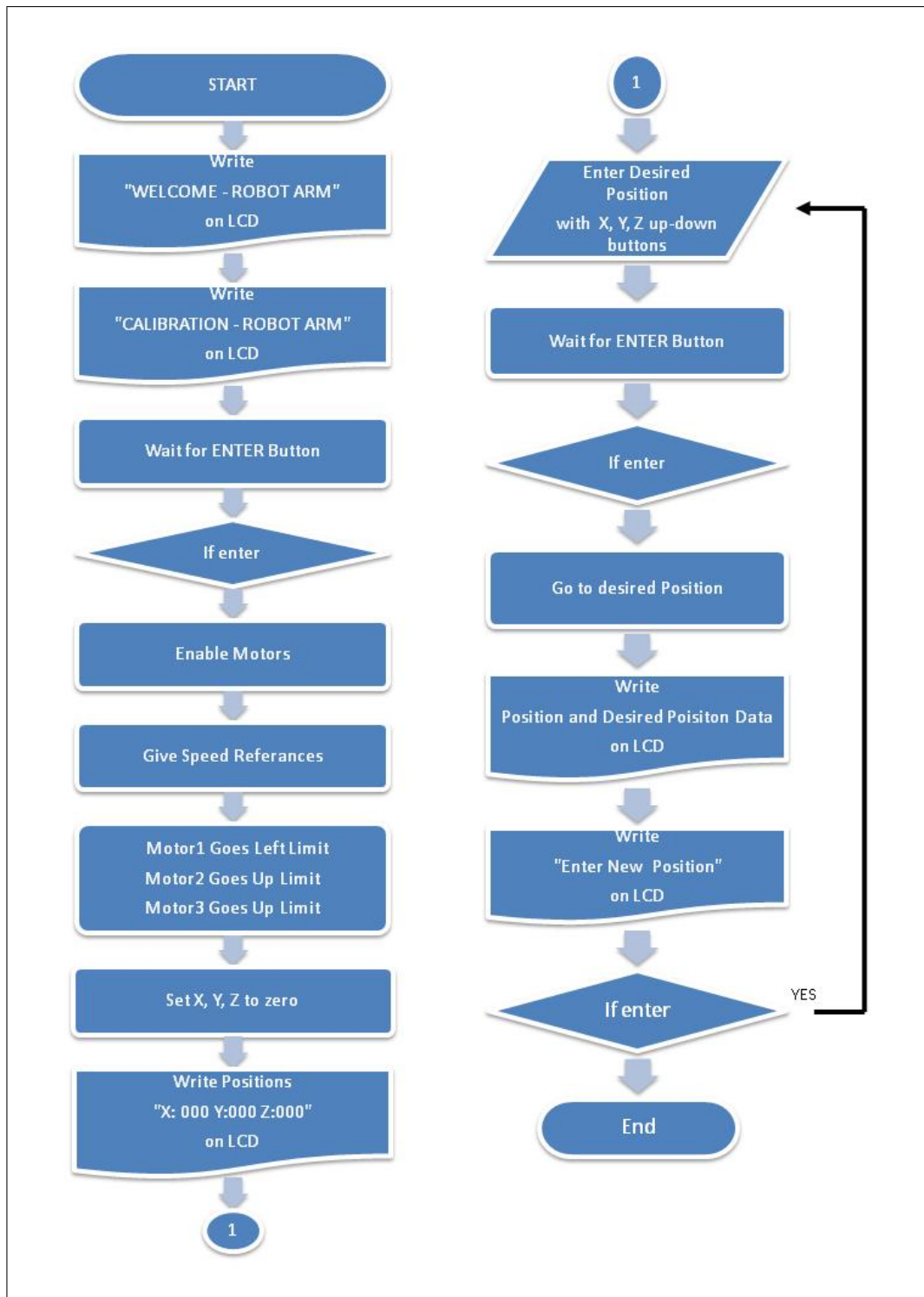


Figure 3.12 Flowchart of The Program.

3.3 Robot Kinematics

In order to manipulate an object in space, it is necessary to describe the end-effector position and orientation. The Robot Arm System corresponds to a two-link planar arm with an additional translate joint, θ_1 along the x-axis.

Inverse kinematics is concerned with determination of the displacements of the links and their time derivatives corresponding to a given position and orientation of the end effector. Forward kinematics is used to determine the position and orientation of the end effector and their time derivatives corresponding to given displacements of the links. Three electric motors drive the 3-degree of freedom robot arm shown in Figure 1.1. The first joint, θ_1 , is a translate joint moving the robot arm along the x-axis. The next two joints, θ_2 and θ_3 are the rotary joints [10].

Forward kinematics equations for position are ;

$$Px = 2\pi \times r \times \frac{\theta_1}{360}, \quad (3.1)$$

$$Py = l_1 \times \cos(\theta_2) + l_2 \times \cos(\theta_2 + \theta_3), \quad (3.2)$$

$$Pz = l_1 \times \sin(\theta_2) + l_2 \times \sin(\theta_2 + \theta_3). \quad (3.3)$$

Inverse kinematic equations are;

$$\theta_1 = x \times \frac{360}{2\pi \times r}, \quad (3.4)$$

$$\theta_2 = \arctan \frac{(-l_2 \sin(\theta_3)) \times y + ((l_1 + l_2) \times \cos(\theta_3)) \times z}{(l_2 \sin(\theta_3)) \times z + ((l_1 + l_2) \times \cos(\theta_3)) \times y}, \quad (3.5)$$

$$\theta_3 = \frac{(y^2 \times z^2) - (l_1^2 \times l_2^2)}{2 \times l_1 \times l_2}. \quad (3.6)$$

3.4 Control

To control Robot Arm system it is aimed to use proportional integral derivative controller (PID controller). A PID controller is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.

The PID controller has three separate parameters; the proportional, the integral and derivative values. These parameters can be adjusted by multiplying the error by constants. K_p , called the proportional gain, K_i , called the integral gain and K_d called derivative gain. By setting the right values to K_p , K_i and K_d one can achieved a good response for a system.

The proportional value determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element.

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input

error, and a less responsive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances.

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been corrected previously. The integral term (when added to the proportional term) accelerates the movement of the process towards setpoint and eliminates the residual steady-state error that occurs with a proportional only controller. However, since the integral term is responding to accumulated errors from the past, it can cause the present value to overshoot the setpoint value.

The rate of change of the process error is calculated by determining the slope of the error over time (its first derivative with respect to time) and multiplying this rate of change by the derivative gain K_d . The derivative term slows the rate of change of the controller output and this effect is most noticeable close to the controller setpoint. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, differentiation of a signal amplifies noise and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large.

The PID parameters used in the calculation must be tuned according to the nature of the system. Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. In this study only P controller is used, but system can be tuned by a PID control algorithm with software adaptations easily. Proportional control is the easiest feedback control to implement, and simple proportional control is probably the most common kind of control loop. A proportional controller is just the error signal multiplied by a constant and fed out to the drive.

4. END EFFECTOR

End effector, parallel structure of the system, is developed considering the well known parallel robot Stewart platform and named "Orthoroby" [1]. Figure 4.1 shows "Orthoroby" robotic system. Stewart platform has a moving platform connected to the base platform by linear actuators called legs. Each leg is connected to the moving platform and the base platform by spherical joints, universal joints and revolute joints (Figure 4.5).

End effector, consists of six linear actuators that made of DC motors with feedback capability, data acquisition card and an electronic driver card that can generate PWM pulses corresponding to analog outputs of acquisition card. Linear actuators CARE33H (SKF) which have a stroke length of 150 mm and each can take a load up to 60 kg. Q8 is a 8-channel acquisition card from Quanser Inc. The Q8 is equipped with eight analog outputs and eight analog inputs, with software programmable voltage ranges, eight quadrature encoder inputs and 32 lines of individually programmable digital I/O. Electronic driver card is designed for interfacing Q8 to linear actuators. Analog outputs of Q8 is converted to PWM pulses with this driver card. Figure 4.2 shows relation between block diagram of the orthoroby and physical parts.

Orthoroby with its control units shown in Figure 4.4.

4.1 Mechanical Design

The actuators are connected to the base and to the moving platform by spherical joints. The spherical joint connectors are manufactured with pivot angle 40° (Figure 4.5). A cutting tool is implemented in the middle of the upper platform of the parallel robot, as a surgical tool that the height of the tool can be adjusted. The "Dremel 400 Series Digital" (Dremel Inc) is selected with its flexible shaft unit. Its unique digital display, allows you to work more precisely on several materials that may require



Figure 4.1 Stewart System.

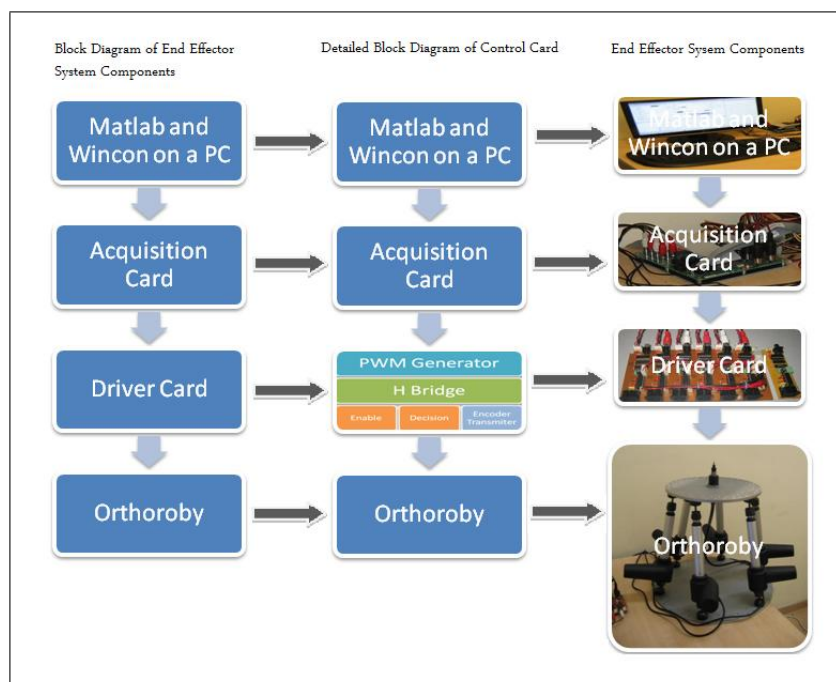


Figure 4.2 Block Diagram of The End Effector.

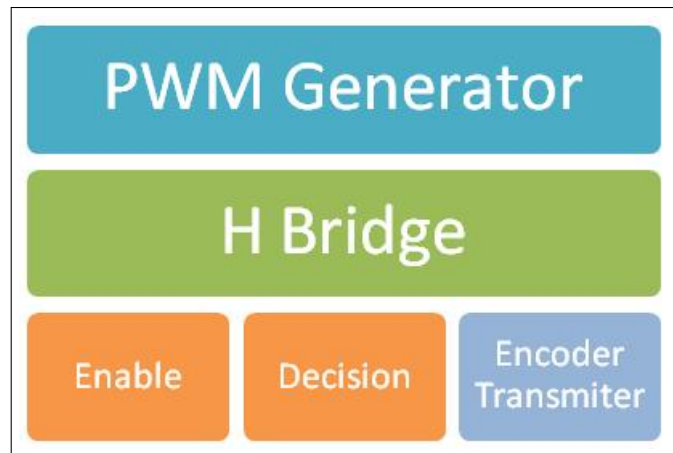


Figure 4.3 Block Diagram of The Control Card For End Effector.

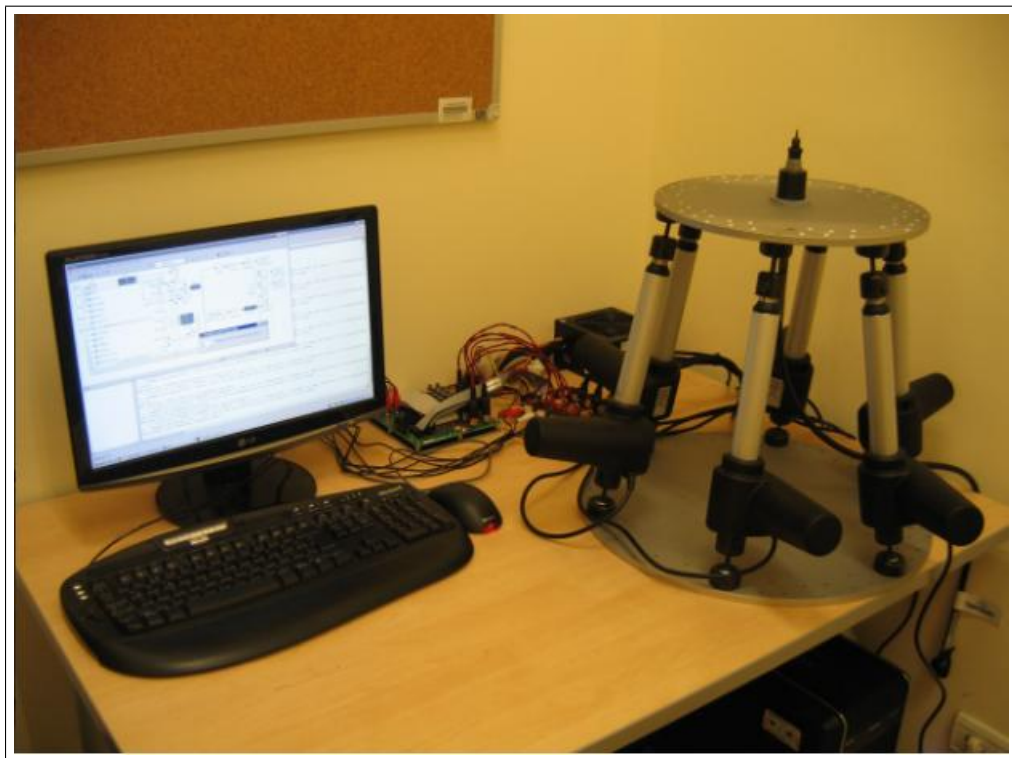


Figure 4.4 Stewart System.

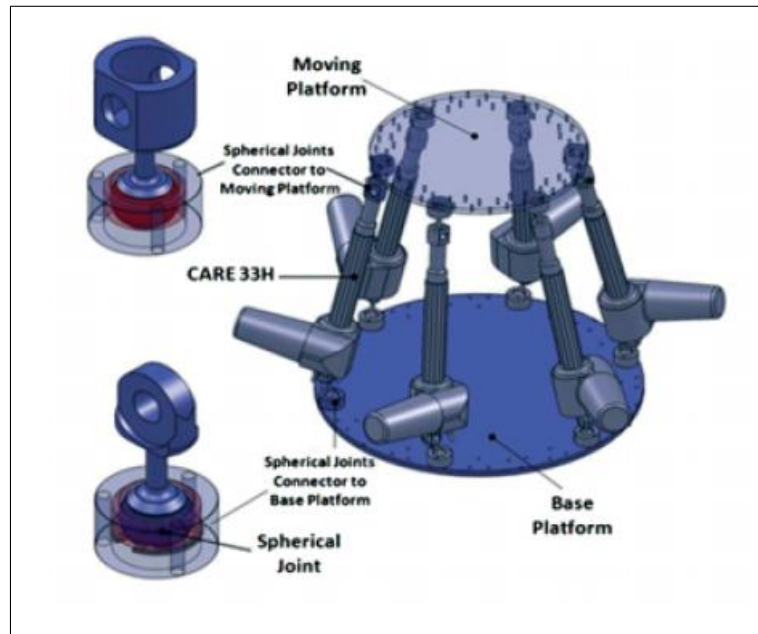


Figure 4.5 The Model of Stewart Platform.

different high or low speed settings and its flexible shaft unit allows you to transfer rotation of the drilling motor with minimum effects. (Figure 4.1). For details of mechanical design more information can be found in [1].

4.2 Electronic Design

For driving the DC motors(actuators) there is one driver card that we designed, which includes PWM generator and H-bridge amplifier. It is a simple design that there are three inputs one for speed, one for direction and one for enabling the H-Bridge. Encoder data from actuators is transmitted to the acquisition card via this control card (Figure 4.8).

The OrthoRoby is controlled via a PC with the MatLab Real Time Workshop Toolbox from Mathworks, and WinCon from Quanser Inc. All data input and outputs are handled by the Quanser Q8 board. The joint angles of the robot are acquired using encoders of CARE33H with a sampling time of 0.001 seconds from a Quanser Q8 card. The torque output to the OrthoRoby is given with the same card with the

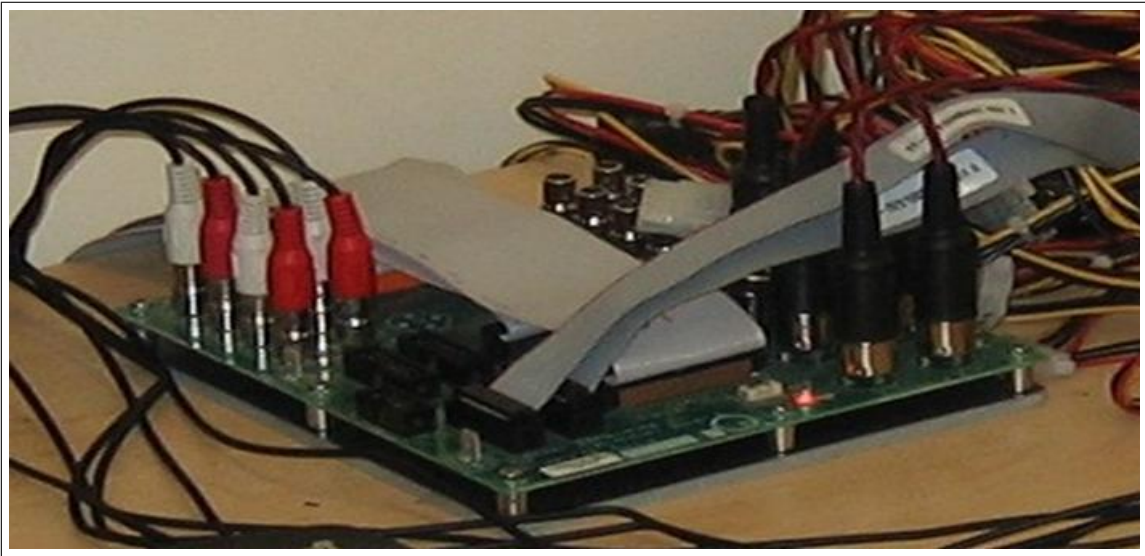


Figure 4.6 Q8 Acquisition Card.

same sampling time. A control card is developed to drive DC motors (actuators) of OrthoRoby (Figure 4.8). Position feedback of the actuators is received from internal encoders of actuators, which is transmitted to the Quanser Q8 (Figure 4.6) board via this control card. A power supply is used to provide 5 V and 12 V to the control card.

4.2.1 Electronic Control Card

A control card is developed to drive the DC motors (actuators) of the OrthoRoby (Figure 4.8). The board included six sets of pulse width modulation (PWM) generators, an H-bridge amplifier and a decision-making circuit. For each set there were three inputs: (a) one for speed; (b) one for direction; and (c) one for enabling the H-bridge. Direction input assigned the direction of the linear actuator and enable input activated the H-bridge IC (L6205N). These were digital inputs connected to the digital input/output of the Quanser Q8 board. The third input assigned the velocity of the actuator, which was an analogue input. This input is analog and changes between 1-3 volts. To control the velocity of actuator with one input pin it was used a PWM generator IC on the control board. PWM generator converts a DC voltage into series of pulses, such that the pulse duration is directly proportion to the value of the DC voltage. PWM range can be adjusted from 0-100%, PWM frequency is adjusted to

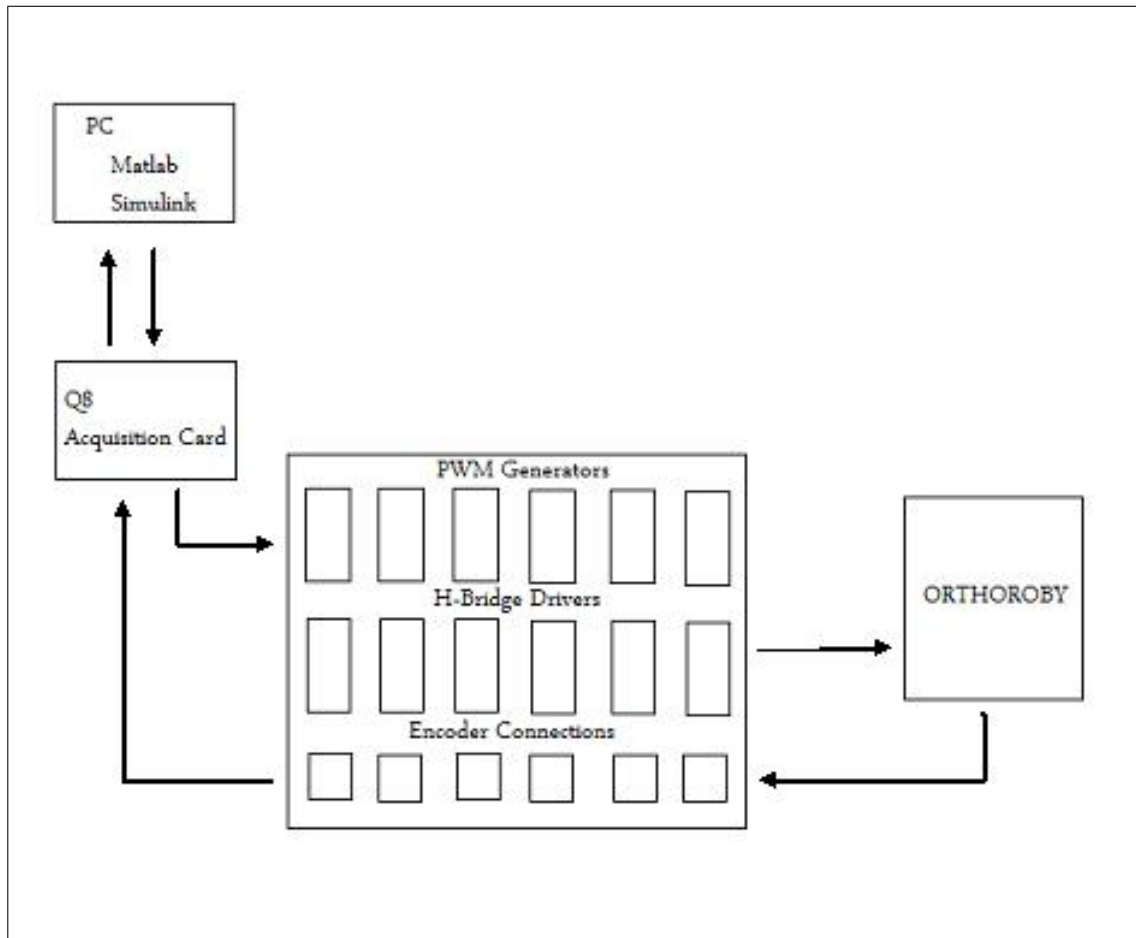


Figure 4.7 Block Diagram of Driver Card For Linear Actuators.

40 kHz. The signal from the PWM circuit was connected to the H-bridge to drive one motor with a high current (7 A). Logic gates (74H08,74H04) were used for the decision-making module to control the direction of the actuators. Position feedback of the actuators was received from the internal encoders of the actuators and transmitted to the Quanser Q8 board via this control card. A power supply was used to provide 5 V and 12 V to the control card [1]. Block diagrams shown in Figure 4.7.

4.3 Robot Kinematics

It is essential to solve the kinematics of a robotic system to achieve a closed-loop control of it. Inverse kinematics is concerned with determination of the displacements of the six links and their time derivatives corresponding to a given position and orientation

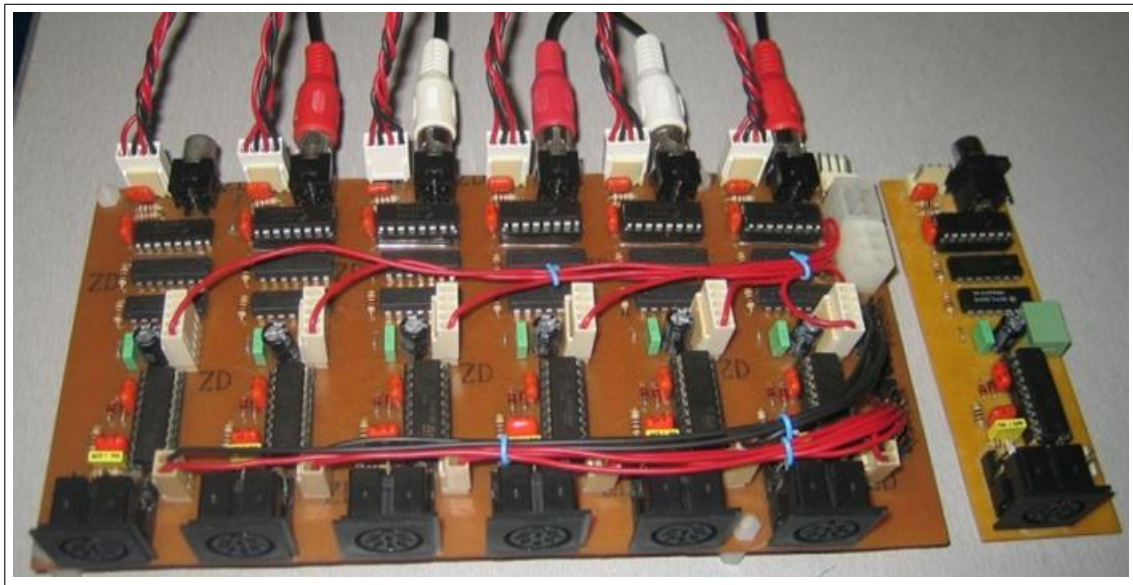


Figure 4.8 Electronic Driver Card For Linear Actuators.

of the moving platform. Forward kinematics is used to determine the position and orientation of a moving platform and their time derivatives corresponding to given leg lengths [17].

4.4 Control

Two position controllers namely "computed torque controller" and "disturbance observer based position controller" are implemented in Simulink and their performances are compared in terms of tracking accuracy and disturbance rejection to those that can be found in literature ([17]). In practice in order to control the movement of the parallel robot, a computed-torque control method is used. If the model of the robotic system is accurate, then the computed torque controller produces good control performance. Details can be found in the research conducted by Barkana ([1]).

5. CONCLUSION AND FUTURE WORK

It is intended to devise a hardware interface to control "robot arm" and hold the end effector at the desired position. For this purpose an electronic hardware card was implemented. Also a motor driver card devised which can generate PWM pulses for drive linear actuators of Stewart platform. Implementing a surgical robot system for orthopedic surgery, with minimum soft tissue damage and a minimum of operator intervention is the motivation of this study.

The OrthoRoby parallel structure robot have been developed and implemented which was planned to be used in bone-cutting operations. An intelligent control architecture has been developed for the OrthoRoby system to enable bone-cutting operations in a safe and desired manner [1, 17]. Because of the need to hold and locate "Orthoroby" just near the patient, "Orthoroby" was planned to implement to a serial robotic structure "Robot Arm".

An Electronic hardware card has been designed and implemented to Robot Arm as a control unit for this study. Robot Arm controlled with a firmware on a microcontroller successfully. System modules on electronic hardware card almost works properly. But there will be a need to reconfigure encoder feedback. It is possible to read encoder data four times better with different methods. It is also possible that different control algorithms can be implemented. Further more a serial communication can be added instead of LCD and button modules to system to control robot arm and orthoroby together via matlab simulink program.

Position accuracy for robot arm can be reduced by reducing encoder resolution. Also there is a way to get position of the links with 3-axis accelerometers to make better results for positioning. Error can be totally tolerated if a navigation system would be implemented to system.

REFERENCES

1. Barkana, D. E., “Design and implementation of a control architecture for robot-assisted orthopaedic surgery,” *International Journal Med Robotics Comput Assist Surg*, Vol. 6, pp. 42–56, November 2009.
2. Taylor, R. H., and L. Joskowicz, “Computer-integrated surgery and medical robotics,” *1st Edition, M. Kutz editor, Standard Handbook of Biomedical Engineering and Design, McGraw-Hill Professional*, pp. 325–353., 2002.
3. Splecht, C. R., L. A. Fuhrmann, and W. Rainer, “Aras - augmented reality aided surgery system description,” *Augmented Reality in Computer Aided Surgery (ARCS)*, 2003. VRVis Research Center, Austria.
4. Engel, D., J. Raczowsky, and H. Worn, “A safe robot system for craniofacial surgery,” *IEEE International Conference on Robotics and Automation*, pp. 2020–2024, May 2001.
5. Grace, K. W., J. E. Colgate, M. R. Gluksberg, and J. H. Chun, “Six degree of freedom micromanipulator for ophthalmic surgery,” *IEEE International Conference on Robotics and Automation*, pp. 630–635, 1993.
6. Ünsal, A., “Farklı yapıdaki stewart platform mekanizmalarının düz ve ters kinematik analizi,” Master’s thesis, Istanbul, Turkey, 2007.
7. Merlet, J. P., *Les Robots Paralleles*, Paris: Hermes, 1997.
8. Güneri, B., A. S. Sarıgül, and H. Karagülle, “Joint position-workspace-actuator force relationships on a stewart platform,” *13. Ulusal Makina Teorisi Sempozyumu*, pp. 395–403, Haz 2007.
9. Dasgupta, B., and T. S. Mruthyunjaya, “The stewart platform manipulator: a review,” *Mechanism and Machine Theory*, no. 35 (2000) 15-40, 1998.
10. Erdemir, E., “Design and optimization of a fuzzy-neural hybrid controller structure for a rubbertuator robot using genetic algorithms,” Master’s thesis, Bogazici University, Istanbul, Turkey, 2006.
11. “Msp430 ultra-low-power microcontroller platform,” tech. rep., Texas Instruments, Dallas, Texas 75243, USA, 2009. Technical Documentation.
12. “Integrated development environment and optimizing c/c++ compiler for msp430,” tech. rep., IAR Systems, Foster City, CA 94404, USA, 2009.
13. Adili, A., “Robot-assisted orthopedic surgery,” *Surgical Innovation*, Vol. 11, no. 2, pp. 89–98, 2004.
14. Brandt, A. G., A. Zimolong, and et al., “Crigos: A compact robot for image-guided orthopedic surgery,” *IEEE Transactions On Information Technology In Biomedicine*, Vol. 3, December 1999.
15. “Msp430x4xx family users guide,” tech. rep., Texas Instruments, Dallas, Texas 75243, USA, 2009. Technical Documentation.
16. “Interfacing the 3-v msp430 to 5-v circuits,” tech. rep., Texas Instruments, Dallas, Texas 75243, USA, October 2002. Application Report.

17. Ayvalı, E., "Parallel robotic system for orthopedic surgery." Graduate Thesis, Yeditepe University, 2009.