DISTRIBUTED COOPERATIVE SYNCHRONIZATION CONTROL OF 2 ARTICULATED ROBOTS FOR INDUSTRY 4.0 APPLICATION

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UNIVERSITI SAINS MALAYSIA

2018

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by

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Thesis submitted in partial fulfilment of the requirements

for the degree of

Bachelor of Engineering (Mechatronic Engineering)

JUNE 2018

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and acknowledge to the contribution of those that help me a lot during my research work in order to make it successful.

First of all, I would like to express my deep gratitude to my project supervisor, Dr. Muhammad Nasiruddin bin Mahyuddin, for his guided, believe, patience and doing this project under his monitoring. I can proceed with my project with his help by giving me advices and task for completing this project step by step. I was able to learn on how to implement on what I had studied in real situation from his experience in robotic system and control system.

Moreover, I would like to thanks all the technical staff of Electrical and Electronics School, Universiti Sains Malaysia espeacially Mr. Aswadi bin Mohd Desa, Mr. Amir bin Hamid and Mr. Haslami Hazwan bin Hamzah whom always provide the laboratory facilities for me to carry out this project.

Lastly, I would like to appreciate my families and my friend for supporting me in conducting this project.

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LIST OF ABBREVIATIONS

CPS	Cyber-Physical System
PID	Proportional-integral-derivative
PD	Proportional-Derivative
CRE	Cooperative robot exploration
CPU	Central Processing Unit
ID	Identification Number
I/O	Input Output
D-H	Denavit Hartenberg
PM	Phase Margin
LED	Light-Emitting Diode
AMS1P	Arduino Mega Slave 1 Pin
AMS2P	Arduino Mega Slave 2 Pin
IC	Integrated Circuit
DC	Direct Current
IDE	Integrated Development Environment
OS	Operating System
3D	Three-Dimensional
T	Time constant

LIST OF SYMBOLS

f	Frequency
v_i	Input voltage
Θ°_0	Encoder reading
Φ	Phase
α_i	Angle in x-axis
a_i	Distance in x-axis
d_i	Distance in z-axis
θ_i	Angle in z-axis
$\boldsymbol{C}$	Cosine
$\mathbf{S}$	Sine
K	Dc Gain
D_C	Digital transfer function
G	Transfer function of the system
D_{lead}	Phase lead Digital Transfer Function
β	beta
w	w-domain
w_l	Lower break frequency
w_h	Higher break frequency
ϕ_{uncomp}	Uncompensated phase angle
ϕ_{PM}	Phase Margin angle
$\phi_{M_{comp}}$	Compensated phase angle
ω_{max}	New gain crossover frequency
$G_{OL(NEW)}$	System new transfer function
e	Error

PENGAGIHAN KERJASAMA PENYELARASAN KAWALAN 2 ROBOT ARTIKULASI UNTUK APLIKASI PERUSAHAAN 4.0

ABSTRAK

Projek ini membentangkan reka bentuk penyelarasan koperasi yang diedarkan antara unit induk dan unit hamba. Dalam projek ini, dua robot hamba dihubungkan melalui rangkaian yang mana isyarat kawalannya mungkin akan dikongsi bersama dan data mengenai setiap robot saling bertukar di antara mereka. Kerjasama dan saling menghubungkan bersama isyarat konsep dalam siri robot bertujuan untuk membawa semangat industri 4.0. Sistem ini mengandungi 3 bahagian iaitu reka bentuk kawalan, persekitaran perkakasan dan persekitaran perisian. Unit lengan induk akan bersambung dengan unit hamba dengan menggunakan mikrokontroler Arduino Mega 2560. Oleh kerana ini system pengagihan, 2 Arduino Mega 2560 digunakan sebagai otak yang berbeza untuk mengawal robot hamba. Ia juga digunakan untuk bekerjasama dengan MATLAB sebagai memberi semua arahan atau blok untuk mengawal penyegerakan antara tuan dan kedua-dua unit hamba berasal darinya. Ia menyasarkan untuk dilaksanakan di persekitaran koperasi, jarak jauh atau berbahaya. Untuk pencapai penyegerakan yang baik, kawalan fasa pimpinan digunakan untuk membolehkan lengan robot bergerak dalam gerakan yang tepat dengan cara yang sama antara interaksi unit dan maklum balas utama dan kedua-dua hamba robot tangan sebagai kesalahan kedudukan dikurangkan.Prestasi system yg terkawal diukur dengan mengunakan Kesilapan Mutlak Integral (IAE) untuk memerhatikan ketepatan penyegeraan.

DISTRIBUTED COOPERATIVE SYNCHRONIZATION CONTROL OF 2 ARTICULATED ROBOTS FOR INDUSTRY 4.0 APPLICATION

ABSTRACT

This project present on the design of distributed cooperative synchronization between master unit and slave unit. Within this project, two slave robot arms is connected over a network which the control signal of it will likely be share throughout and the data about every robot is exchange amongst them. Cooperation and interconnected of the shared signal concept in series of robot arms to aim for same goal bring the spirit of industry 4.0. The system contains 3 parts which are control design, hardware environment and software environment. The master arm unit will interface with both slave unit by using Arduino Mega 2560 microcontroller. As it is distributed system, 2 Arduino Mega 2560 is used as different brain to control the slave robot arms. It also used to cooperate with MATLAB as all the command or block diagram to control the synchronization between master and both slave units comes from it. It is target to be implement in cooperative, remote or hazardous surroundings. To achieve excellent synchronization, phase lead compensated control is used to let the robot arms to move in accurate motion in the same manner between the interaction of master feedback unit and both slave robot arms as the position error is reduced. The controlled system performance was measured by using Integral Absolute Error (IAE) to observe the synchronization accuracy.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter provides an introductory passage describing first the motivation of embarking distributed cooperative control of two articulated robot arms research. The research is sufficiently motivated to justify the significance of research in context of Industry 4.0. A problem statement is derived thereby onwards specifying the issues observed by other recent work that need to be addressed. This is then further converged to a set of objectives outlining the specific measurable outcomes that need to be accomplished. The research scope which highlights the limitation and the assumption drawn in the project is to be presented.

1.2 Motivation

A robotic arm is a typically programmable mechanical arm with similar task as human arm. However, a single robot arm is not as superior as the two or more robot arms when a cooperative task is to be commissioned. A cooperative task such as parts assembly require one robot arm to hold the part in place whilst the other robot arm will be functioning to secure or fix the other parts in place. A single robot arm will not be able to accomplish such task. However, therecomes the problem of controlling the two robot arms for a cooperative task. There are at times, the motion of the two robot arms need to be synchronised. This requires a cooperative control scheme which able to control both arms synchronously in the pursuit to achieve a cooperative task.

The two articulated robot arms will be connected over a network by which control signals of the robot will be shared across and the information about each robot is exchanged among them. The shared control signals concept bring about the spirit of Industrial 4.0 by which series of robots are interconnected and co-operate with each other for common goal. The term Industry 4.0 hold the use of latest communication technologies and carrying through the cyber-physical systems in the manufacturing industry and has a great impact on corporation across technical innovations in production (Prinz et al., 2016). The production go with the flow may be modified where it will decrease manual operation at the same time as observing and controlling turns into extra dominant which lead the modified in job profile via making ready the workers with present day technology for example smart glasses (Prinz et al., 2016).

The Industry 4.0 pattern “promotes the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the Internet” (Sipsas et al., 2016). Revolution of industry always assist to a significant grow in productivity which uniquely depend within the development of brainwork and decision making processes (Schuh et al., 2014). It show that the future of manufacturing will be initiated “on the Internet and information technology based interactive platform, it integrates increasingly factors of production scientifically and becomes more networking, automated, intellectuality” (Cheng et al., 2016).

For the future of using internet of things technology and “equipment by means of technological hardware (including smart equipment, smart robotics, smart-auto manufacturing systems), smart software (high-speed computing, smart sensing, smart decision) and Cyber-physical system (simulation and analysis of CPS, virtual design & sorting), to further fulfill the objects of embodiment of CPS (Cyber-physical smart-auto production systems)” (Hsuen-Feng et al., 2016).

The task involved in carrying heavy object are major problem if only used one articulated robot arm. It maybe become unstable as the load increases and reached the maximum weight. As the robot arm increases, it will distribute the weight of the load equally to others robot arms and reduce the burden faces by each of the robot arms.

When the articulated robot arms move in synchronisation, it can increase the productivity in production side as the process become so much faster. Articulated robot arms can be reliable as they can work without taking rest and they do not feel emotionally where this can effect the work quality. Robotic arms also work more precise and accurate where this will improve in the quality of the product produse. For example, when we place 5 articulated robot arms in production line where they will pick up the material. So, in one time there are 5 material will be process synchronise where this speed up the process.

Proportional-Derivative controller(PD controller) is a feedback mechanism, in control loop commonly applied in industrial control system. It calculate the error as the difference between required set point and measured setpoint. PD controller applies a correction on value based on proportional and derivative action.

1.3 Problem Statement

The conventional built-in controller used in industrial robots or social robots often relies on the proportional controller or proportional-derivative controller. Such controllers are designed to work within the bounds of linear region which is locally stable. However, the scheme is susceptible to noise as PD controller may accentuate high frequency signal if the noise is present in the feedback signal. Proportional only controller may not satisfy the transient response specification (Franco, 2007). Moreover, in controlling two robots arms, a stable cooperative controller is required in order to perform cooperative task and both the transient and steady-state performance requirement can be fulfilled. . In industry, most of the controller are centralized which means that all the processes and resources in a single controller (INDUSTRY, 2018). Existing controller scheme and industry adopt centralized architecture. In case of changes in the system, the entire system need to be changed which is extremely time consuming (Garrehy, 2014). Most of the controller pre-coded is in proportional only controller (P). PD controller is not a proper design susceptible to instability due to inherent noise from the sensor. In centralized control, it is difficult to create a cooperative task by combining two robots or more as the complexity of the controller increases in proportion with the number of robots.

1.4 Objectives

- To design and implement a discrete phase-lead controller at an agent level to perform joint-based controller in master-slave concept.
- To develop distributed cooperative architecture based on the objective 1 for cooperative task of 2 robot arms.
- To validate a cooperative task which practically has impact to the industry and community.

1.5 Research Scope

In this project, the focus will be adding synchronization signal into the system of the articulated robot arms. It emphasized on the ability of synchronization to execute cooperative task like part assembly or final product inspection will give rise to the industry manufacturing systems. Whereas, for social robotics aspect, it can be used as service providers in which make people life easier. For example, serving elderly with tasks in daily life such as lifting heavy objects. For control algorithm part, phase lead controller will be implemented to the articulated robot arms to control the position of the robot arms. Torque feedback are not implemented because there is no current feedback. If there is current feedback we can correlate with torque which lead to dynamic composition. Right now it is pure position control of velocity control. Arduino Mega 2560 will be used as microcontroller to interface between articulated robot arms and MATLAB. To control the Arduino mega 2560 input and outputs from MATLAB, MATLAB® Support Package for Arduino® Hardware was employed to interactively communicate (The MathWorks, 2018a).

1.6 Thesis Structure

This progress report consist of five chapters. Every chapter describe and explain the chapter in detail. It will start with chapter 1 which is the introduction to give quick explanation on the project overview, motivation, problem statement, objectives and research scope.

Next chapter is the literature review of this project. It will improve on the understanding on the selected topics which are multi-robot system, cooperative of multiple robot arms, synchronization control, centralization and distributed control and PID with phase compensator.

Method used to carry off the project is shown in Chapter 3 which is the methodology. It give the detail on the how this project was carried out. First, the overall control design explained in flowchart to give easier way to understand the flow. Following by detail description of the control design, hardware environment and software environment.

Chapter 4 is the result and discussion of this project where it shows the result obtain from the hardware implementation of Phase lead controller with the articulated robot arms.

Chapter 5 concludes all the overall project and the future improvement of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will review research work from literature concerning the current development of the multi-robot system, cooperative control, and the benefits of having distributed control architecture over a centralized one. Section 2.2 describe on the multi robot system. Section 2.3 reviews on the cooperative of two robot arm. Section 2.4 explain about synchronization control. Section 2.5 compare centralization and distributed. Section 2.6 differentiate between PID and Phase-lead compensated. Lastly, section 2.7 is the summary of the chapter.

2.2 Multi-robot system working cooperatively

Over the last decade, control of multi-robot systems has an influential impact on the study of independent behaviors to be achieved by a collection of robots in both certain or uncertain environment condition (Sabattini et al., 2018), (Jeanpierre et al., 2017). Nonetheless, while the implementation of multi-robot systems increase complicated tasks, the intervention of the human can be useful (Sabattini et al., 2018). There are many potential application of multi-robot system namely, swarm robotics (Abdelaal et al., 2017), coordination control(Ding, 2017), transfer learning (Helwa and Schoellig, 2017), 3D multi-robot simulators (Noori et al., 2017), autonomous multi-robot (Renganathan and Summers, 2017) and mobile robots(Shan et al., 2016).

In swarm robotics, rather than depending on a single complex robot, a massive quantity of simple robot is used to carry out a task which has plenty of abilities in many application. One of the example is a multi-robot system which can be applied within the resource transportation assignment where simple robots perform shipping sources between two or more locations in a warehouse (Abdelaal et al., 2017). Control of multi-robots plays an extensive position in lots different practical responsibility but its coordination system normally has limited communication capability (Ding, 2017).

This systems provide extra benefits over single robot solutions but additionally enhance challenging design, control issues and also to set up in the real world because of the complexity involved (Florea and Buiu, 2017), (Noori et al., 2017). “This showed that while the system’s overall performance increases by adding more robots, the individual robot’s performance decreases” (Abdelaal et al., 2017).

The advantages using multiple robots instead of single robot as this enable some research group to extend their strategy to cooperative robot exploration(CRE) (Kim et al., 2017).

2.3 Cooperative control of multiple robot arms

Nowadays, cooperative robotics has been fast growing in lots of industrial fields around the world. The implementation of cooperative attracted growing in research network which allows new ways to do variety of application (Jaisumroum et al., 2017), (Wagner et al., 2016). It enables a group of robots to be carry out task that are impossible for a single robot (Wasik et al., 2017). Meantime, the changes from isolated robot operation to cooperative multiple robot make the complexity of the applied industrial robot station and the smart inter-connectivity grew to become harder (Schwung et al., 2017).

There are applications where it have been used in leader-follower robot configuration which the leading robot will define the trajectory to be followed by the rest of the robot (Shan et al., 2016). This can reduce the cost as only the leading robot needs to be prepared in full set of equipment (Shan et al., 2016). One of the place where the cooperative robot arms to be very useful is at hospital whereby patients transferring task can be accomplished by robot assistance. This substantially reduce work stress endured by the nurses (Mehrez et al., 2014).

In industry, cooperative robot system can offer high productivity, minimize labor cost, and completed risky or poisonous substances (Bai et al., 2015). As it is very risky for human to do task in this kind of environment as it can give side effect to the health of even can cause death. However, for the cooperative robot to do this assignment, the consideration has to make not only the motion and internal force but also need to look into the vibration control problem as both of it appear at same time (Bai et al., 2015).

With the advent of Industry 4.0, the use of cooperative robot arms bring a significant impact to the manufacturing ecosystem. A good example of robot arms working together in cooperation as amplified by Wagner (2016) high in this project one robot is holding a drawing plate and the other one holding drawing tools.

2.4 Synchronization control

Today, synchronization in robots arms is very important in many application. It allows the motion to be in synchrony which helps may application to be done in an easier way. The application of it may be seen at robot dancing (Yoshida et al., 2016), transfer learning (TF) (Helwa and Schoellig, 2017) and etc.

In some cases, the synchronization can be done by transfer learning. It will allows others robot to access the data stored by second or similar robot to enhance it personal behavior. This will reduce the computational burden of every robot as it can share the data generated among them. This will reduce the time required to teach any robot a new skills (Helwa and Schoellig, 2017).

In (Yoshida et al., 2016), the synchronization is done by connecting robot objects. When synchronization occur with each other, the connected robot object will change the circulate timeline as the host robot's. When the robot is connected together by the users, the two connected robot action is in synchronized but when it is disconnected the synchronization of robot stop.

Nonetheless, one of the example to synchronize the motions is teleoperation systems. It aim for local and remote control to synchronize the motion for example velocities and position. However, an important aspect of communication such as delay should be considered as this may lead to instability (Jing et al., 2016).

2.5 Centralized and Distributed Control

There are 2 types of control architecture namely centralized and distributed control. Assembly line contains a lot of different stages which make them an example that are familiar entities characterized by way of a modular structure. As assembly line contain a lot of different stages. It can be automated by one of the control technologies (Papenfort, 2005).

Within distributed control design, the module number and the quantity of the CPUs used depends on each other as each module has its' own dedicated controller (Papenfort, 2005). No central control to assign a task means that any robot within the system can find out and discover duties on their own (Zitouni and Maamri, 2016). This is an approach to interconnected subsystems where the design independent controller implemented as shown in Figure 2.1. To create a local controller, each joint of robot manipulator is considered as a subsystem (Jaisumroum et al., 2017).

To design distributed control system, the robot must be capable of distinguishing each other. This can be done by associating each robot with unique identification number (ID). To acquire the states and the IDs, there need to be communication exchange with each other (Wasik et al., 2017). In centralized control architecture, only one controller need to be dealt with all the task such as I/O connection (Papenfort, 2005). Only a single brain will work in to manage all the command in the system as shown in Figure 2.2. This centralized control architecture exposes the system vulnerability to total system failure in the event of breakdown or cyber-intrusion.

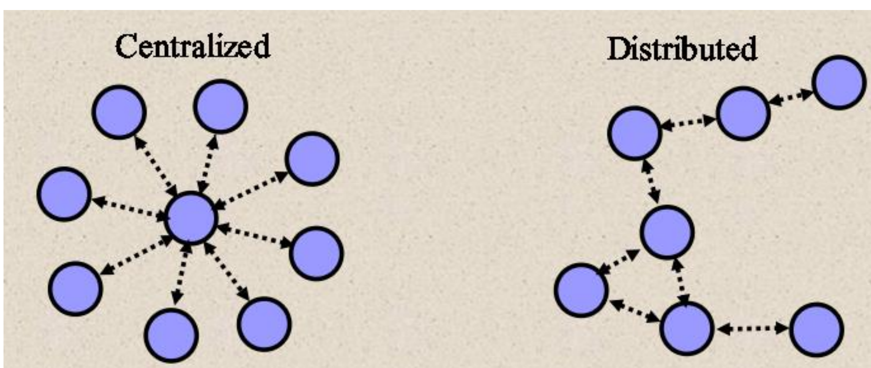

Figure 2.1: Architecture Model of Centralized and Distributed(Dias and Stentz, 2000)

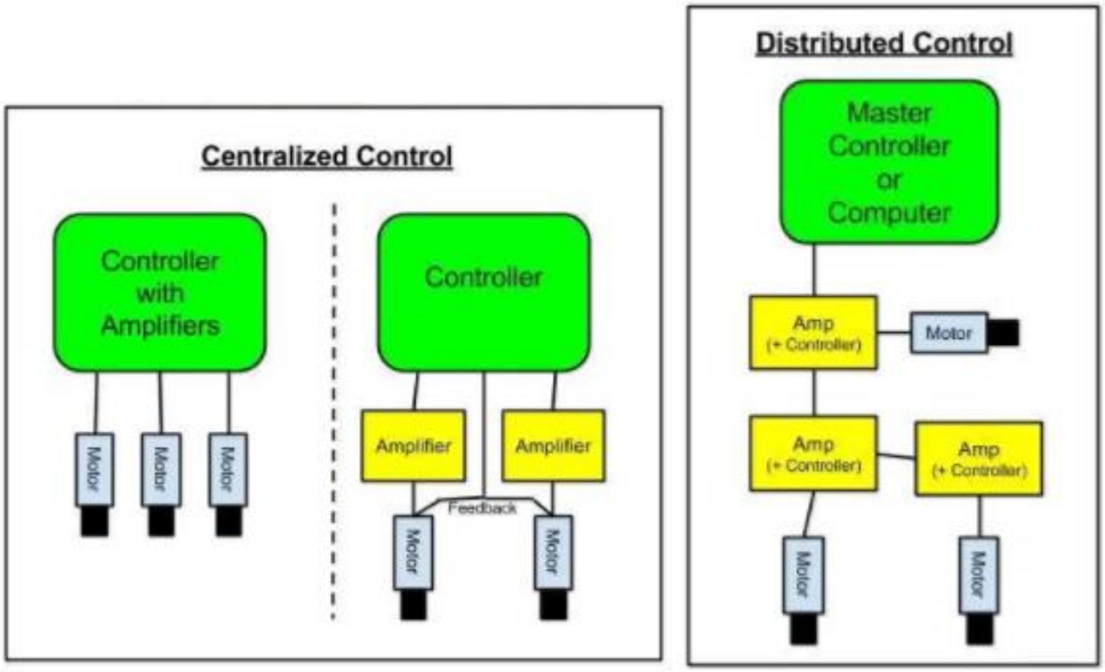

Figure 2.2 :Centralized and Distributed control (Kohanbash, 2014)

2.6 PID and Phase Lead Compensator

Proportional-integral-derivative (PID) controllers is one of the feedback control structures (Hsu et al., 2017). As it is understandable and quite powerful lead PID control to be broadly used. The appeal of PID controller is that it can be implemented intuitively without a deep understanding of control concept (Messner et al., 2017).

A compensated is an extra element that is fit right into a control system to compensate for lack of performance and "it is quite sophisticated in that it captures the history of the system (through integration) and anticipates the future behavior of the system (through differentiation)" (Hla Myo et al., 2008), (Messner et al., 2017). It is also "widely used because of their simple structure and substantial improvement to the transient performance" (Tavakoli and Safaei, 2017).Phase lead compensated can increase phase margin in requested frequency value to meet specification and also the gain of the open loop transfer function (Franco, 2007). It improves the speed of response or steadiness of the system (Messner et al., 2017).

The derivative action in PD controller makes the performance better in responding to signal change but at the expense of amplifying unwanted disturbance on the measured output. For this reason, the gain rolls off at high frequency in lead compensator. PD controller can create the same transfer function by coupling it with a low pass filter which the frequency of the zero is below the break frequency chosen (Franco, 2007).

In this project, cooperative controller for each subsystem will take the form of discrete phase-lead controller to control each robot-arm joint.

2.7 Summary

Based on the literature review, there are a lot of researcher that focus on finding the use of multi robot application, synchronization, cooperative, control architecture and control design to best meet their expectation. Multiple robot also been used in many application which most of them referring on synchronization motion between the multiple robot. Synchronization robot not only implemented in robot arm but also in other type of robot such as mobile robot and some of the researcher combine it with the artificial intelligent aspect. The nature of cooperative control is distributed. When implementing distributed control, not only hardware part is distributed but also with the software part. It used partial connection where controller exchange information with each other. Distributed control reduces the complexity of command and at the same time the structure of controller remain the same (modular). Phase lead will be the best option when dealing with robot arms as it shows improvement in the transient response and steady state accuracy.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will explain the complete methodology used to design distributed cooperative synchronization control of robot arms. Section 3.2 discusses the kinematics of the 2 robot arms used in the project where Denavit-Hartenberg convention is employed. Section 3.3 discuss the dynamic modelling of the robot arms used in the project. Section 3.4 discusses the controller design employed to control the robot arms for motion synchronization in joint-space. Section 3.5 shows hardware environment which included Arduino Mega 2560, master and slave robot arms, L293 motor driver and the electrical circuit connection. Section 3.6 describe on the software environment which include the design of using MATLAB, Arduino software and SOLIDWORKS. Section 3.7 discussed on control system performance. Section 3.8 is the summary of the chapter.

3.2 Robot Kinematic: Denavit-Hartenberg convention

Denavit Hartenberg convention or D-H convention is used to derive a kinematic configuration for the articulated robot arm. As shown in the Figure, classic robots is a set of bodies call links that are connected by joints which can be either rotational or translational.

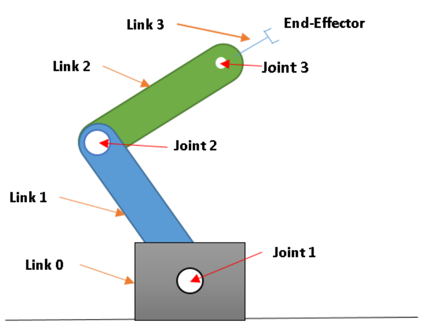

Figure 3.1: Serial Link Manipulator

Denavit-Hartenberg parameters are used to derive a kinematic representation describing the robot's configuration. This kinematic representation is defined by a homogenous transformation matrices. The D-H parameter shown in Table 3.1 and Figure 3.2 describes the revolute joint of the robotic arms.

Table 3.1: D-H parameter for Master and Slave robotic arms considering all joints

Joint i	α_i	a_i	d_i	θ_i
1	-90	0	d_1	θ_1
2	0	0	d_2	θ_2
3	0	a_1	0	θ_3
4	0	0	d_3	θ_4
5	0	a_2	0	θ_5
6	-90	0	0	θ_6

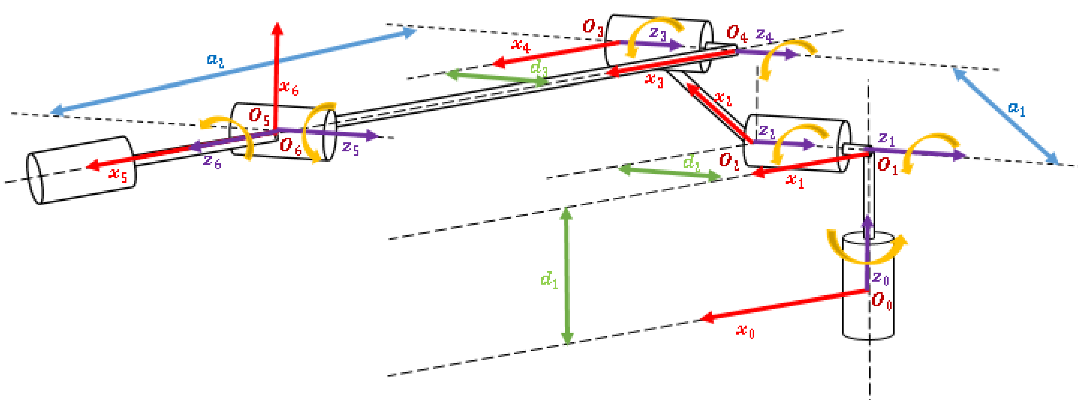

Figure 3.2: Revolute joint of the robotic arms

Transformation Matrix of Slave Robot (Mentor Robot)

$$\boldsymbol{{}^{0}T_3 = {}^{0}T_1\,{}^{1}T_2\,{}^{2}T_3}$$

$$\boldsymbol{{}^{0}T_3 = \begin{bmatrix} C_1C_2C_3 - C_1S_2S_3 & -C_1C_2C_3 - C_1S_2C_3 & -S_1 & C_1C_2C_3a_3 - C_1S_2S_3a_3 - S_1d_2 - S_1d_1 \\ S_1C_2C_3 - S_1S_2S_3 & S_1C_2S_3 - S_1S_2C_3 & C_1 & S_1C_2C_3a_3 - S_1S_2S_3a_3 + C_1d_2 - C_1d_1 \\ -S_2C_3 - C_2S_3 & S_2S_3 - C_2C_3 & 0 & -S_2C_3a_3 - C_2S_3a_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}}$$

3.3 Dynamic modelling of the robot arm system

For simplicity and due to the absence of current feedback signal in the current robotic system, the dynamic model and control can be achieved by assuming that the coupling between the robot links is minimal and insignificant. This is true under the condition that the commanded motion is steady and not too fast.

This assumption allows the robot arm dynamics to be modelled as input-output relationship (transfer function) relating position and voltage input. Therefore, individual joint-space joint position controller can be designed independently using frequency response approach. By using frequency response modelling, it feed the input of the system with sinusoidal input results in an output which also a sinusoid with different amplitude and phase but same frequency which describe the amplitude change and phase shift (The MathWorks, 2018c). A table need to be created to record the data from the experimental result which contain frequency, input voltage, potentiometer reading, magnitude and phase. From the collected data, uncompensated transfer function of each robot links can be obtained equation (3.0).

$$\frac{\theta_i}{V_i} = G_i(s) \tag{3.0}$$

3.4 Joint Space Control Design

3.4.1 Phase-lead compensator design

In this section, phase-lead compensated design procedure from(Mahyuddin, 2017) is referred through phase lead compensator design for each robot joint, it is required for cooperative synchronization of 2 robot arms to handle task. To proper design phase lead controller, bode plot is used to design for each joint. The basic close-loop block diagram as shown in Figure 3.3.

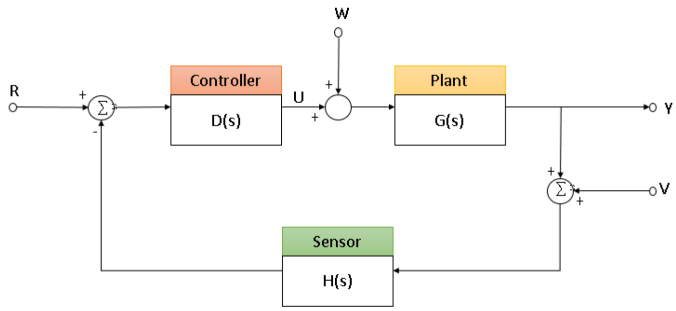

Figure 3.3: Basic close-loop block diagram (Franklin et al., 2010)

All the equation are from(Mahyuddin, 2017). The close-loop system with the introduction of compensation will have the characteristic equation (3.1)

$$1 + KD_C(s)G(s) = 0 \tag{3.1}$$

Phase-lead controller transfer function in w-domain will be in the form of equation (3.2).

$$D_{lead}(w) = \frac{1}{\beta}\left(\frac{w + w_l}{w + \frac{w_l}{\beta}}\right) = \left(K_\beta \frac{w + w_l}{w + w_h}\right), w_l \ll w_h \tag{3.2}$$

From the bode plot, uncompensated phase margin can be determined as shown in equation (3.3).

$$\phi_{uncomp} = \phi_{PM} \tag{3.3}$$

Additional phase contribution $\phi_{M_{lead}}$can be calculated using equation (3.4).

$$\phi_{M_{lead}} = \phi_{M_{comp}} - \phi_{M_{uncomp}} + \phi \tag{3.4}$$

Then, the value of β can be determined using equation (3.5).

$$\phi_{M_{lead}} = \sin^{-1}\left(\frac{1-\beta}{1+\beta}\right) \tag{3.5}$$

By substitute the value of β calculated, compensator's at the peak of the PM determine by equation (3.6).

$$|G_{lead}(j\omega_{max})| = \frac{1}{\sqrt{\beta}} \tag{3.6}$$

At the negative value of $|G_{lead}(j\omega_{max})|dB$, ω_{max} can be obtain. The value obtain will be used to calculate the value of ω_l then in calculating ω_h.

$$\omega_{max} = \frac{\omega_l}{\sqrt{\beta}} \tag{3.7}$$

$$\omega_l = \omega_{max}\sqrt{\beta} \tag{3.8}$$

$$\omega_h = \frac{\omega_l}{\beta} \tag{3.9}$$

All the parameter required can be substitute in equation (3.10) to form a phase-lead compensated transfer function. New transfer function obtain in equation (3.11).

$$D_{lead} = \frac{1}{\beta}\left(\frac{\omega + \omega_l}{\omega + \omega_h}\right) \tag{3.10}$$

$$G_{OL(NEW)} = D_{lead}(\omega)G_{uncomp}(\omega) \tag{3.11}$$

3.5 Hardware Environment

3.5.1 Arduino Mega 2560 (Hardware)

Arduino board is capable to read inputs for example from the potentiometer, encoder, sensor or button. It can also write the data by turning it to the output in the cases of activating motor or turning on an LED. The board (Figure 3.4) can be in any application demanded by the user through a set of instructions to the microcontroller on the board. In this project, Arduino will be used as an interface between master robot arm, slave robot arms and the MATLAB. For the implementation of the control system at the beginning, the Arduino Mega will be the controller to control the articulated robot arms by reading the position of the master robot arms and send the same reading to the slave robot arms to move into the same position. By mapping the position of each joint to the robotic arm through microcontroller, the synchronisation motion can be set. Figure 3.4 shows the Arduino Mega 2560 board.

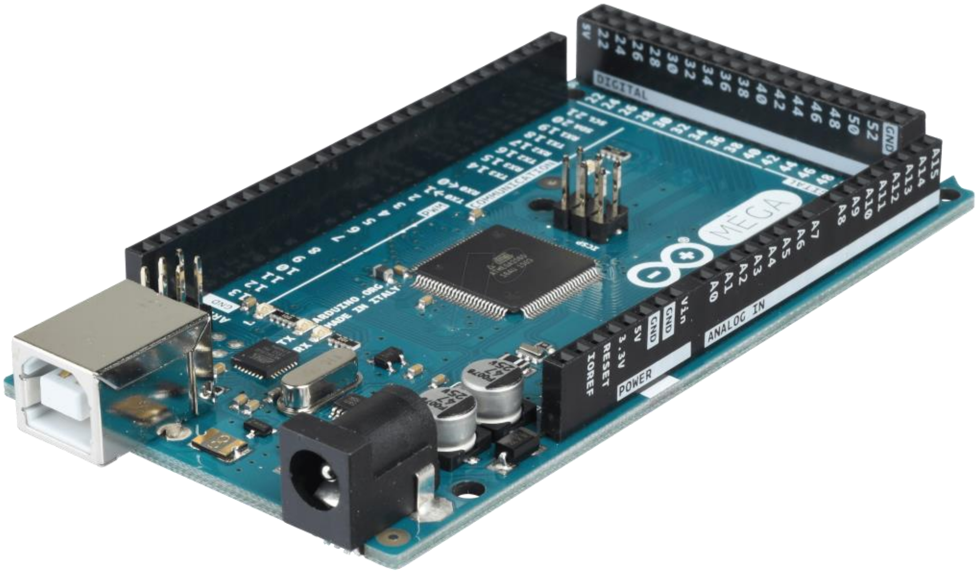

Figure 3.4: Arduino Mega 2560

3.5.2 Master and Slave Robot Arms

The mechanical part of the master and slave robot arms require some connections before it can be used. Both master and slave arms contain potentiometer to act as position sensor. Figure 3.5 and 3.6 present master and slave robot arms unit respectively. The connection configuration for the master and both slave unit has been shown in Table 3.2, Table 3.3 and Table 3.4.

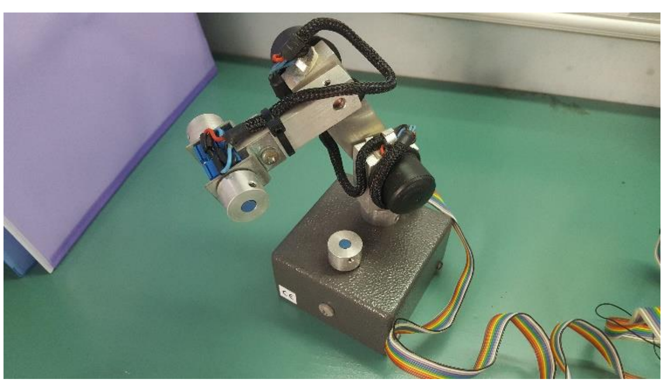

Figure 3.5: Master arm

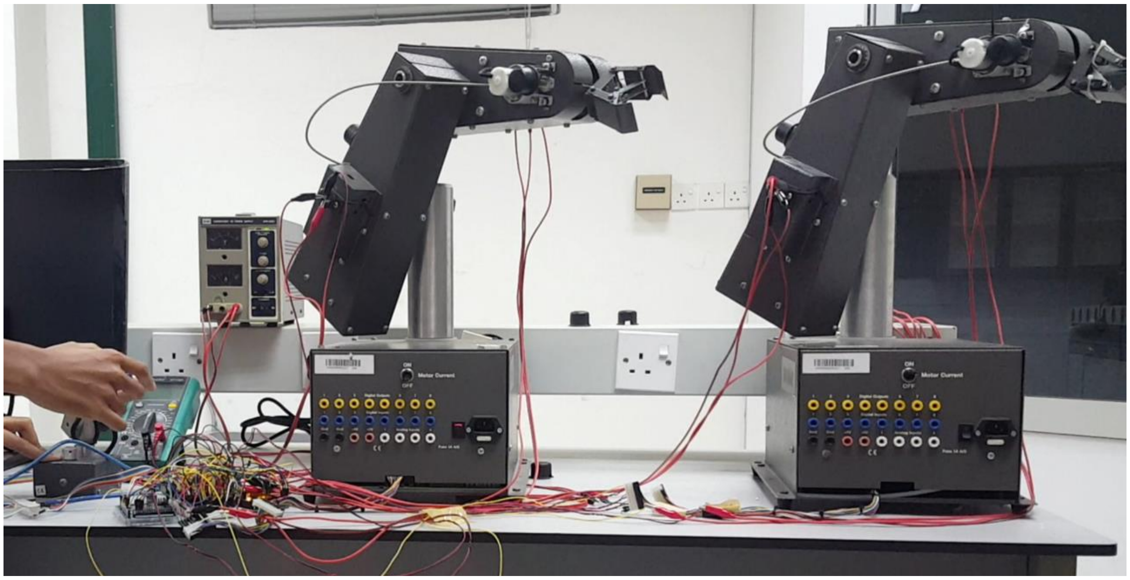

Figure 3.6: Slave robot arm (Mentor Robot)

Table 3.2: Pin identification of Master Feedback Unit

Color	Identification	Description	Arduino Mega Slave 1 Pin (AMS1P)
Black	5V	Used	5V
White	5V	Not Used	
Grey	Position Sensor (Joint 5)	Not Used	
Purple	Position Sensor (Joint 4 Right Side)	Not Used	
Blue	Position Sensor (Join 4 Left Side)	Not Used	
Green	Position Sensor (Joint 3)	Used	A3 (AMS1P)
Yellow	Position Sensor (Joint 2)	Used	A2 (AMS1P)
Orange	Position Sensor (Joint 1)	Used	A1 (AMS1P)
Red	Ground	Not Used	
Brown	Ground	Used	GND

Table 3.3: Configuration of 1st slave wire color

Joint	Color	Arduino Mega Slave 1 Pin (AMS1P) Arduino Mega Slave 2 Pin (AMS2P) L293D
Motor 1 (1st Slave)	Purple	6 L293D(1st)
	Grey	3 L293D(1st)
	White	A7(AMS1P) and A7(AMS2P)
Motor 2 (1st Slave)	Green	6 L293D(2nd)
	Yellow	3 L293D(2nd)
	Blue	A8(AMS1P) and A8(AMS2P)
Motor 3 (1st Slave)	Red	6 L293D(3rd)
	Brown	3 L293D(3rd)
	Orange	A9(AMS1P) and A9(AMS2P)

Table 3.4: Configuration of 2st slave wire color

Joint	Color	Arduino Mega Slave 1 Pin (AMS1P) Arduino Mega Slave 2 Pin (AMS2P) L293D
Motor 1 (2nd Slave)	Purple	14 L293D(1st)
	Grey	10 L293D(1st)
	White	A10(AMS1P) and A10(AMS2P)
Motor 2 (2nd Slave)	Green	10 L293D(2nd)
	Yellow	14 L293D(2nd)
	Blue	A11(AMS1P) and A11(AMS2P)
Motor 3 (2nd Slave)	Red	10 L293D(3rd)
	Brown	14 L293D(3rd)
	Orange	A12(AMS1P) and A12(AMS2P)

3.5.3 L293D Motor Driver

Throughout this project, L293D motor driver integrated circuit (IC) is used (Kushagra, 2012). As it is a dual H-bridge motor driver, it can control the motor direction which are clockwise and anticlockwise (Choudhary, 2012). L293D act as current amplifiers as they provide a higher-current signal since originally they take a low-current signal. To drive the motor, higher current signal is used. It can control 2 DC motors simultaneously. The detail on this IC shown in Figure 3.7 and Table 3.5.

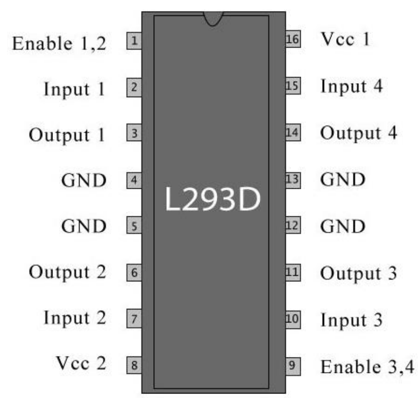

Figure 3.7: L293D Pin Diagram

Table 3.5: L293 Pin Description

Pin No	Function	Name
1	Enable pin for Motor 1; active high	Enable 1,2
2	Input 1 for Motor 1	Input 1
3	Output 1 for Motor 1	Output 1
4	Ground (0V)	Ground
5	Ground (0V)	Ground
6	Output 2 for Motor 1	Output 2
7	Input 2 for Motor 1	Input 2
8	Supply voltage for Motors; 9-12V (up to 36V)	Vcc_2
9	Enable pin for Motor 2; active high	Enable 3,4
10	Input 1 for Motor 1	Input 3
11	Output 1 for Motor 1	Output 3
12	Ground (0V)	Ground
13	Ground (0V)	Ground
14	Output 2 for Motor 1	Output 4
15	Input2 for Motor 1	Input 4
16	Supply voltage; 5V (up to 36V)	Vcc_1

3.5.4 Electrical Circuit Connection

Figure shows the centralize breadboard (Figure3.8) connection for testing the functionality of the circuit and the hardware component. Next, in Figure 3.9, it will show the connection of distributed breadboard which will be implemented phase lead compensated design. There are both breadboard connections to give the understanding by looking into the connection on the differences between centralize and distributed control. Figure will be used as the connection because it has distributed the controller that means it runs the command at the same time for both microcontroller where the cooperation is involve. It is like 2 brain working with each other.

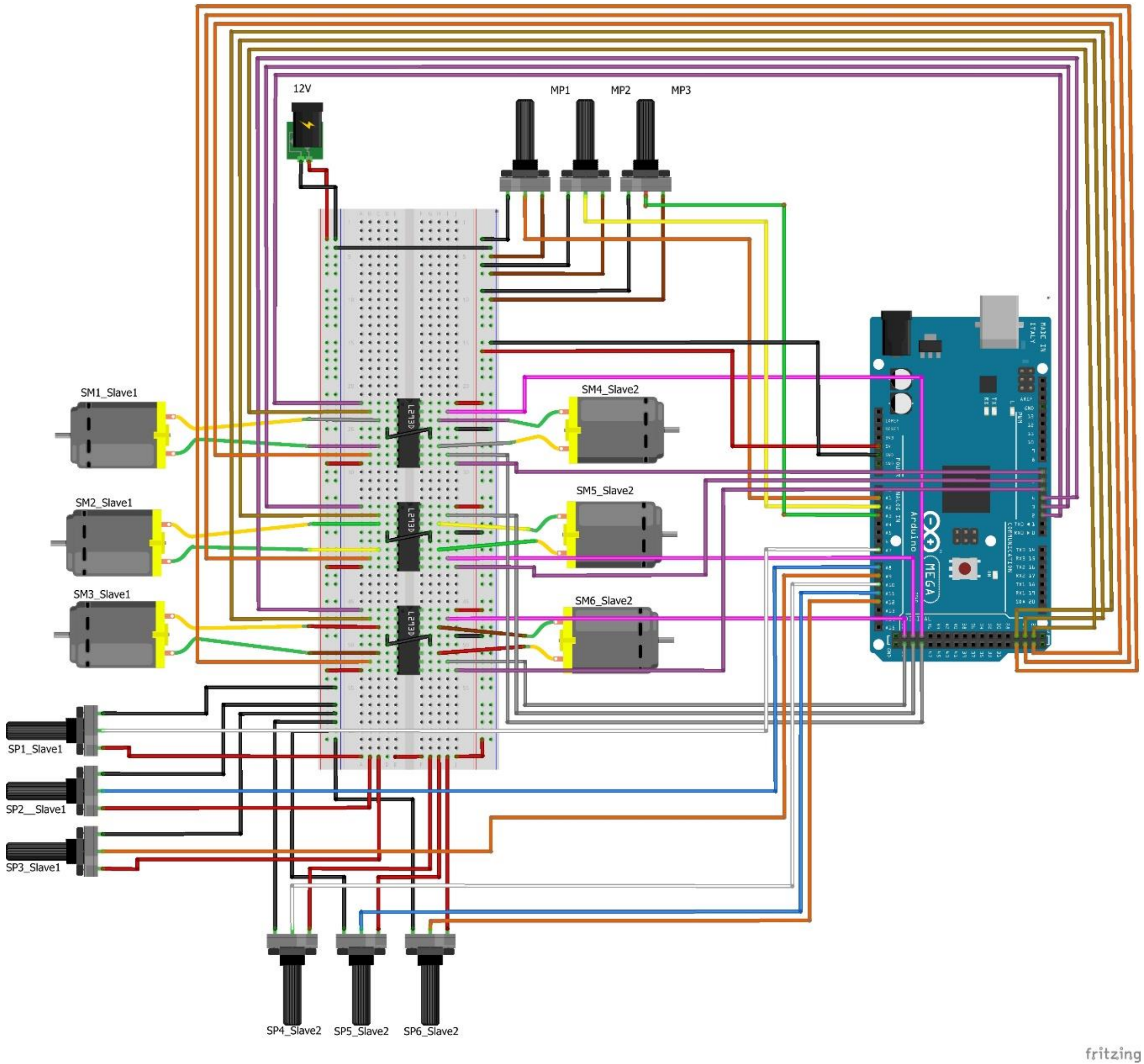

Figure 3.8: Centralize breadboard connection.

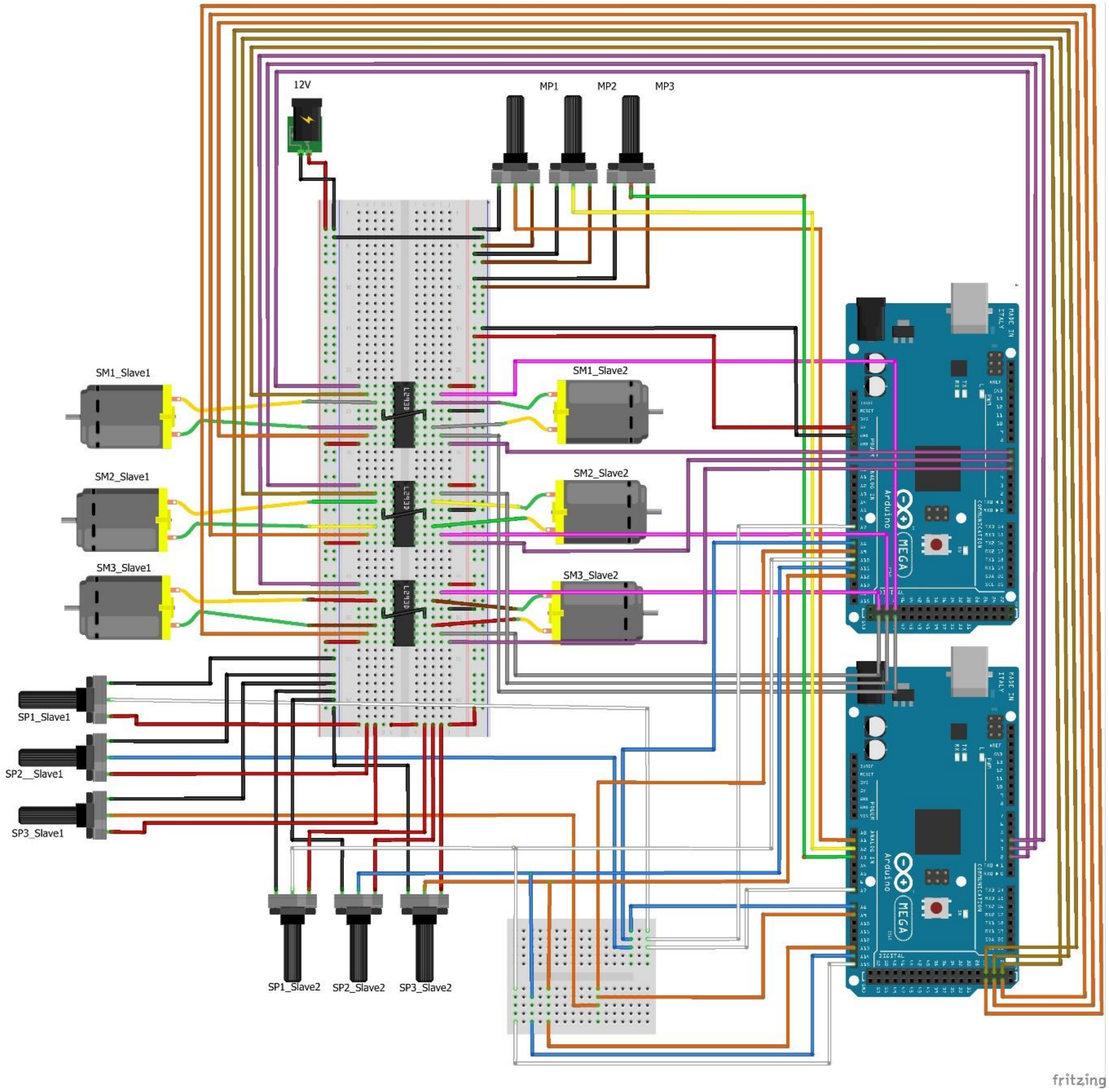

Figure 3.9: Distributed breadboard connection

3.6 Software Environment

3.6.1 MATLAB

MATLAB® Support Package for Arduino® Hardware as shown in Figure 3.10 allows MATLAB to control Arduino outputs and inputs. It will make interactively communication between Arduino and MATLAB. This add-ons enables MATLAB to acquire analog and digital sensor data from the Arduino Board and other functions (The MathWorks, 2018a). Moreover, users can use block diagrams and high level programming to build Arduino projects. MATLAB is easier than C/C++ as it is a high level interpreted language and the users can see the result from the I/O instruction immediately without compiling. So, it can easily analyze and visualize the data collected from the Arduino (The MathWorks, 2018b).

Figure 3.10: Arduino with MATLAB (The MathWorks, 2018b).

To allow the users develop algorithms in Simulink as in Figure 3.11, a block-diagram environment and run them standalone, Simulink support package for Arduino can be installed. Figure shows the Simulink support package for Arduino(The MathWorks, 2018b).

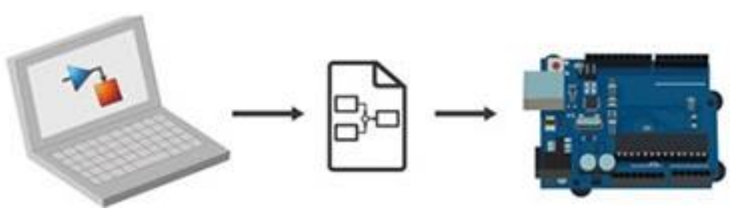

Figure 3.11: Simulink support package for Arduino (The MathWorks, 2018b)

In this project, MATLAB will be used to process the inputs from the position sensors and implement the Phase-Lead design in the application. After going through design block-diagram, write the outputs into the analog of the Arduino to adjust the error of the slave robot arms. All of the phase-lead algorithm calculated in MATLAB. It is used to do the calculation