Cooperative Control of Dual Series Robots

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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UNIVERSITI TEKNOLOGI PETRONAS

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SITI AISYAH BTE OMAR

ABSTRACT

Development in manufacturing, automation, space and underwater exploration has shown vast number of robots being used where most of the existing robots are of coordinated control of a single arm only. Increasing demand for robots application, especially in manufacturing has opened a new challenge; dual arm robot cooperation. This challenge is to develop robots which can carry out greater task which could either be heavy in load or complex in working. The main objectives for this project are to study on the available techniques of cooperative control, to design a program based on the chosen technique, to integrate the program in the system of two existing robot arms handling one common load and to ensure precise tracking of a desired formation and simplicity in its design. The methods being used in this project are performing literature review, selection of cooperative control technique where three cooperative control techniques namely Master/Slave control, Centralized and Decentralized control are compared and implemented to the existing robots, as well as conducting experiment on the real system. Results from the experiment are analyzed and improvised to prove that cooperative control technique could be used for this study. Results from this study are in form of programming of the control system, ladder diagram showing inputs and outputs of the system utilized and calculation of error of relative coordinate of the two robots after experiment execution. In conclusion, master/slave technique has been selected to be most suitable for this study based on its accuracy and simplicity of its design. The objectives for this project have been achieved where no error above 1mm recorded which indicates accuracy and number of lines of programming are 21 lines for Master and 16 lines for Slave robot thus, proving its simplicity. However, improvement on the method used could be further studied to minimize number of lines, using other method or extension of this project where rotational motion could be studied.

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CHAPTER 1
INTRODUCTION

The purpose of this progress report is to explain in details on the research topic of Cooperative Control of Dual Series Robots, to report on the progress and finding completed and achieved as well as on the way forward of this research. Chapter 1 of this report will cover the background of study, problem statement, objectives and scope of study.

1.1 BACKGROUND OF STUDY

This project correlated with the study of various techniques in cooperative control namely Master/Slave, Centralized and Decentralized where one of the techniques is chosen and a controller (controlling device) is to be designed to ensure two (2) autonomous robots can cooperatively working together in handling one common load using only one controller.

Robotic is not a single area of technology but encompasses such diverse areas of technologies as mechanical, electrical and electronic systems [1]. Most industrial robots today are designed to replace human workers in unpleasant, hazardous or too precise jobs. The robots designs used are often patterned after human functions. Analyzing how humans use their arms, legs and other moving parts is helpful in developing moving parts for robots while the study of human brains; how human remember and interpret information helps in adapting artificial intelligence to be use in robots [1].

Various studies made on human challenges scientists and engineers to keep improving robots' functions and communication as in this project, cooperative communication between two robots are studied.

1.2 PROBLEM STATEMENT

Most of the existing robots applications in manufacturing are of coordinated control of a single arm working on one specific task and are independent of each other [1]. Even research work in the past has concerned only the position control of single manipulators. When we take a look at the actual human behavior of handling, we use two hands efficiently and skillfully, and are producing not only the simple quantitative effect that the use of two hands does twice of the work by one hand, but also the qualitative effect that it makes possible tasks which are impossible to execute with one hand[2]. Furthermore, these robots, although are efficiently working on their specifically designed task, are very expensive and can usually only do one type of work with limitation in load handling[1].

For example, in manufacturing floor where unpleasant, hazardous or too precise job is required, more robots are needed to perform the jobs where each robot; depending on the types and tasks specified, could cost from $10,000 up to a million per robot and could be more. Whenever the robot becomes malfunctioned, or failed to work, the cost to repair it, even the spare parts is very expensive. The robots may require specialized skill to repair and maintain them.

When a new batch of products are being run, new processes are going to take over the old procedures and thus, new robots have to be bought to replace the existing robots which may not be suitable for the new tasks due to the specific task designed. The specific designed task could be in terms of range of working rate, tools can be used with the robot and limitation in movements or workspace the robot could reach[3].

In cases where the load of production increases, the existing robot may encounter difficulty in handling the new loads as each robot is designed to work with limited load handling capabilities[2]. This situation may lead to the possibility to have to buy a new robot to handle the new loads.

Therefore, in order to reduce, if not solved the problems as stated above, an external controller is to be designed which integrate the collaboration between two robot arms to work cooperatively for applications beyond the capability of a single arm such as manipulation of massive and bulky objects and handling flexible payloads[3].

However, many technical issues have to be resolved before these systems can be fully utilized in the areas such as assembly automation and flexible manufacturing. Amongst the issues include the design of coordinated motion, stale and robust control, algorithms, programming methodologies and fast collision avoidance schemes[3].

1.3 OBJECTIVES

The objectives of the project are:

- To design a program using the Cooperative Control method
- To integrate the program in the system of two existing robot arms towards cooperatively working in handling one common load
- To ensure precise tracking of a desired formation configuration and simplicity in the design

Three (3) Cooperative Control techniques are going to be evaluated and one will be chosen to be applied in designing the controller which will give the optimum accuracy in position tracking with simplicity in its controller design.

Precise tracking is indicated by accuracy of movement between the two robots and is measured in terms of relative distance between the two end-effectors at the start of the experiment and at the end.

Simplicity of the design will be determined by the number of lines of programming work of the controller.

1.4 SCOPE OF STUDY

The project is basically involves study on cooperative control techniques and choose the best technique suit the problem arises; which is to coordinate the arm control over a common load. The chosen control technique will be modeled and implemented on the serial robot system. Therefore, the scopes of study for the project are:

1) Conduct literature review on Cooperative Control techniques and programming theory
2) Familiarization with serial robot system available in UTP
3) Implement the controller to the existing serial robots
3) Model and conduct experiment on the chosen Cooperative Control technique
5) Perform studies on results obtained from experiment conduct

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 COOPERATIVE CONTROL TECHNIQUES

Multiple robots grasping or handling a common object form a closed chain that is extremely nonlinear and coupled[4]. The control will become complex, constraints is imposed and the number of actuators exceed the system mobility. When dual or multiple robot system does a common task such as assembling, it receives constraints from the environment and, due to these constraints ability to control the object motion and constraint forces between environment and the object becomes vital. [5]

The difference between cooperative system and non-cooperative system or autonomous are as shown in **Table 1**:

Table 1 : Comparison between Cooperative and Autonomous System

Cooperative System	**Autonomous System**
• Collection of dynamical object which communicate and cooperate to achieve a common or shared objective[1]	• A system which is having own controller and is programmed to achieve the objective individually[1]
• Achieved through communication between robots	• Does not involve communication between robots

In general, there are three techniques could be used in cooperative control which are :

2.1.1 Master/Slave Control

Master/Slave control method is a method where one or a group of robot arms play the role of master, and the rest of the arms from the slave group are moving in conjunction with the master[5]. The main strength of the Master/Slave scheme is the simplicity of control of multi-robot system. The high-level controller specified only the behavior of the master. Other robots just track the master[6].

Master/slave mechanisms are in general, cost-effective, accurate and can be easily implemented[9]. However, when the master breaks down, the whole formation fails. There is also no feedback formation which means, when there is a lag of the slave behind the master by any reason such as perturbation in the environment occurs, this event does not affect the motion of the master[6].

Methods for controlling master/slave robots can be divided into two categories; unilateral control system and bilateral control system[7] where **Table 2** describes the differences and **Figure 1** illustrated the systems.

Table 2: Difference between Unilateral and Bilateral Control System

Unilateral Control	**Bilateral Control**
• No force-feedback available from the slave unit	• There is a force-feedback signal from the slave unit to the master control
• Simple controller and mechanism	• Controller and mechanism more complex than unilateral control
• Difficult in dexterous manipulation	• Dexterous manipulation is possible

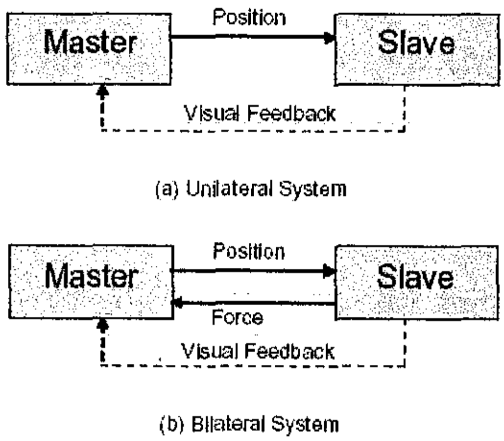

Figure 1 : Master/slave Control System

The serial communication is often done by interruption. The master unit indicates when the movement should start, and it does this by interrupting the slave operation so that it could be attended. The slaves do not make any kind of decisions, they just execute the commands[10].

2.1.2 Centralized Control

In a system containing more than one robot, centralized control refers to oversight of all the individual robots by a single controller[1]. Communication between the controller and the robots is usually done by wireless means such as radio, or flexible wire, and fiber optic. In a centrally controlled robotic system, the main computer plays the role of quasi-human operator. The individual units are completely and continuously dependent on the central controller, and cannot function if the communication link is severed[8].

Centralized control can best be implemented when the constraints and environments are known. This method also works well in settings where the task of each robot is independent of each other. Unfortunately, centralized method faced difficulties in coordinated tasks; tasks that require tight, continuous and coordination between the robot arms[11].

2.1.3 Decentralized Control

In **decentralized control**, each robot in the fleet is capable, to some extent, of making its own decisions and operating without instructions from other robots or from a central controller[8].

In a robotic system that employs uniformly distributed control, there is no main controller; each robot is fully autonomous, containing its own controller. Each unit is equal to all the others in significance[5]. In some systems, there is a main controller that oversees some of the operations of each unit in the fleet. This is known as partially distributed control. Another example of partially distributed control is a system in which each robot receives a set of instructions from a central controller, stores those instructions, and then carries them out independently of the central controller[12].

Robot autonomy might at first seems like a great assets; if a robot functions by itself, then when other parts of the system fails, the robot will keep working. However, in a system where many identical robots are used, autonomy is inefficient. It is better from an economic standpoint to put programs in one central computer that controls all the robots[8].

2.2 COMPARISON BETWEEN COOPERATIVE CONTROL TECHNIQUES

From the studies made above, in summary, the comparison of advantages and disadvantages of the three (3) cooperative control techniques namely Master/Slave, Centralized and Decentralized control are as stated in **Table 3**:

Table 3: Comparison between Cooperative Control Techniques

Master/Slave Control	Centralized Control	Decentralized Control
Advantages: • Cost-effective • Very accurate • Controller design is simple especially for slave unit • Easily implemented	• Only one main controller need to be designed • Effective when constraints in environment is known	• Larger task domains could be implemented • Greater efficiency • Greater fault-tolerance and robustness • Can operate even if communication link is severed • Each robot able to make own Decisions
Disadvantages : • Error in the master could add in error of operation when operation perform	• Cannot operate if communication link is severed • Robots are very dependent of one another	• Can be very costly to implement • Controller design is very complicated

After comparing the advantages and disadvantages of each technique in the cooperative control, it can be seen that decentralized control method gives the best solution to cooperative and coordinated tasks where each robot is having a controller of their own, and therefore, be able to make decisions and can still perform the required tasks even when the communication link between them are severed or interrupted. The field of decentralized control is being widely studied and has wider range of tasks could be implemented.

However, decentralized control is rather complicated and expensive for this study which involves two-robot arms which are independent of each other and the constraints are known. In other words, to ensure simplicity of the controller and cost-effective method to be implemented for this study, yet provide accurate results as of the measurement of relative position between the two robot arms manipulators, the Master/Slave control method is preferable. This method can be improve further by studying the error exhibits by both arms and take into account during the designing of the controller to ensure the error does not effect the accuracy and efficiency of the task.

Table 4 : Lists of Early Works on Cooperative Control[10]

Control Strategy	Description
Leader-follower	Translation of single object
Leader-follower	Translation and rotation of single object
Stiffness or Compliance	Translation of single object
Stiffness or Compliance	Translation and rotation of single object
Impedance	Translation and rotation of single object
Hybrid position-force	Translation of single object internal loading
Hybrid position-force	Translation and rotation of single object internal loading
Hybrid twist-wrench	Translation of single object internal loading
Hybrid twist-wrench	Translation and rotation of single object internal loading
Hybrid twist-wrench	Translation of two objects internal loading
Hybrid twist-wrench	Translation and rotation of two objects internal loading

2.3 CONTROL OF FORMATION

Early work in dual-arm robot control features a master/slave architecture; whereby one arm moves under kinematics position control while the other follows the first, usually using force feedback and is therefore a special combination of position and force control. Another name for this type of control is leader-follower[6]. Generally, it is desirable to exert some form of control over the object being manipulated and the internal loading of object(s) being manipulated and thus share the task.

2.3.1 Position Control

In the control of master/slave formation, assumptions are made that each robot has the ability to measure the relative position adjacent to the master. Once the formation for the master is given, the slave motion is governed by local control laws based on the relative dynamics and relative position of the robots in formation[6].

We can assume that two hands grasp the object firmly and that two hands and the object are supposed to be one body, the position of a point on the object is determined by three (3) degrees of freedom of the master arm, Therefore the slave arm has to move completely following the motion of the object moved by the master arm, and cannot have degrees of freedom to the object.

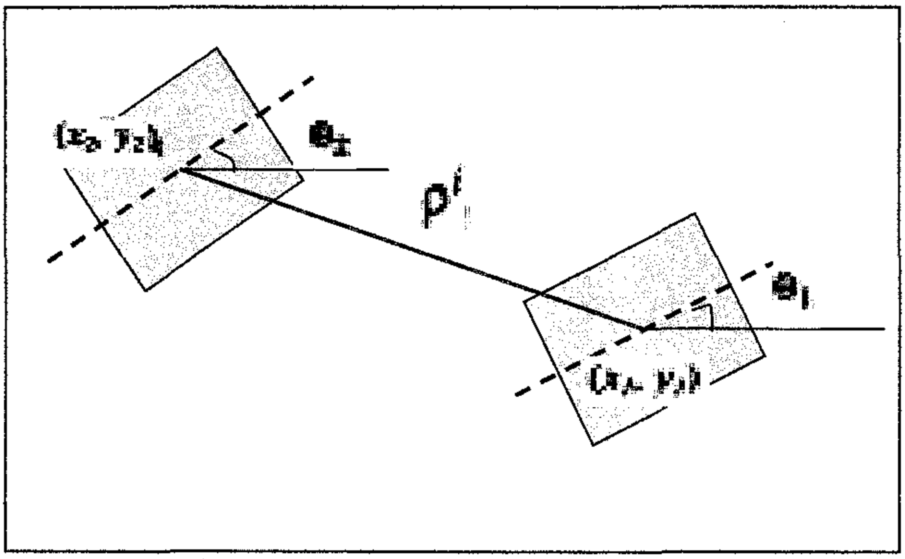

Figure 2: Notation for Formation Control

The scenario used in the feedback control of the formation is where the slave follows the master by controlling the relative distance and orientation[6] between the two are as illustrated in **Figure 2**. The relative dynamics equations used are as follows:

$$
\begin{aligned}
\dot{x}^i &= v^i \cos\theta^i \\
\dot{y}^i &= v^i \sin\theta^i \\
m^i \dot{v}^i &= F^i \\
\dot{\theta}^i &= \omega^i \\
J^i \dot{\omega}^i &= T^i, \qquad i = 0, \ldots, n-1
\end{aligned}
$$

where v_i, ω_i $(i = 1, 2)$ are the linear and angular velocities at the centre of each robot (m^i, J^i) are the mass and moment of inertia, and (F^i, T^i) are the control force and torque.

We are interested in the relative motion between the master (robot 1) and the slave (robot 2). Letting $\rho^i = \sqrt{(x^i - x^0)^2 + (y^i - y^0)^2}$, $\phi^i = \theta^i - \theta^0$ and denoting by ψ^i is the angle between the directions of master velocity and the line segment, ρ^i, the equation of relative dynamics becomes[6,8]:

$$
\begin{aligned}
\dot{\rho}^i &= v^i \cos(\psi^i + \phi^i) - v^0 \cos(\psi^i) \\
\dot{\psi}^i &= -\frac{1}{\rho^i} v^i \sin(\psi^i + \phi^i) + \omega^0 + \frac{1}{\rho^i} v^0 \sin(\psi^i) \\
m^i \dot{v}^i &= F^i \\
\dot{\phi}^i &= \omega^i - \omega^0 \\
J^i \dot{\omega}^i &= T^i, \qquad i = 1, \ldots, n-1.
\end{aligned}
$$

Combining and utilizing all the equations above, the relative position between the two robot arms with forces of action on a constraint object is known and thus, can be controlled. The relative position between the two robots, ρ^i is the main parameter to be maintained to ensure no collision between the robots, as well as to ensure the accuracy of the controller in maintaining specified relative position throughout the task performed.

2.3.2 Force Control

While the bulk of earlier work was based on position representation, cooperation of two manipulators requires interaction which is expressed in a force representation.

External forces and the interactive force between two arms can be obtained by the use of the wrist force sensor which is to be installed. Therefore, the control of motor torque of each joint is adopted instead of joint position control. The wrist force sensor is used in order to measure the interactive force between two arms.

There are two basic tasks could be performed using the force control of formation involving cooperative robots; say handling a long bar which are parallel transfer and rotational transfer tasks.

2.3.2.1 Parallel Transfer

Parallel transfer means that the object is transferred maintaining the orientation of the two arms. Before considering parallel transfer tasks, the interaction of two arms should be considered. These two arms are supposed to work where one acts as a master arm and the other as a slave arm. The slave arm must be moved in cooperation with the master arm.

The slave arm is entirely force servoed and is free to move where necessary to follow the master arm. It applies forces to the object, if necessary. It exerts torques to cancel the interactive force from the other arm.

If the slave arm were only following forces resulting from motion of the other arm, there would be a lag in acceleration. For high performance, a feedforward term is included where slave arm knows what the master arm is doing.

2.3.2.2 Rotational Transfer

Rotational transfer means that two hands rotate the object around an arbitrary axis. One example of this task is the rotation of a large box or a long bar. If position control is applied to execute this task, the motion becomes awkward. But by using torque control for each joint to generate a force barrier to the direction of the rotation in both hands, the motion becomes very smooth.

2.4 KUKA ROBOT (KR 30-3)

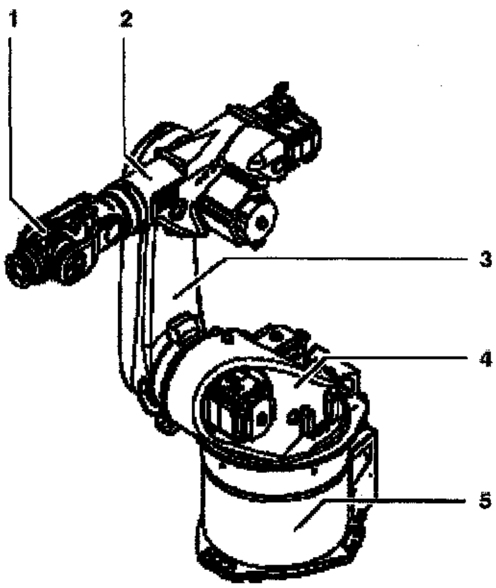

Figure 4(a) Principal Components of the robot

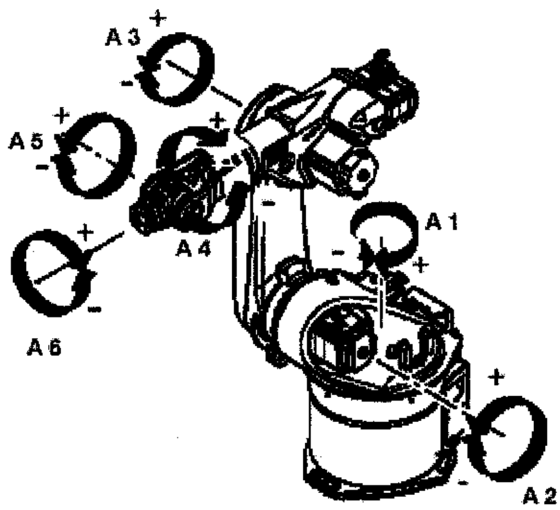

Figure 4(b) Rotational axes and directions of rotation in motion of the robot

KUKA KR 30-3 is the model of the robots going to be used in this study which are available in UTP. This robot, as shown in **Figure 4(a)** is a six (6) axis industrial robot which consists of :

(1) Wrist
(2) Arm
(3) Link Arm
(4) Rotating Column
(5) Base Frame
(6) End-Effector / Gripper

2.4.1 Manipulation and Control

In the analysis of spatial mechanism (manipulators), the location of links, joints and end-effector in 3-D space is continuously required. To describe position and orientation of a body in space, a frame is attached to the body. The position and orientation of this frame with respect to some reference coordinate frame, called base frame, mathematically describes the location of the body.

This coordinate reference as in **Figure 5** will be used as the input to the master robot for distance to move or the task specified while the distance moved by the slave robot will act as the output which measures the accuracy of movement and error (if any) of the formation. The distance moved by the slave will then be converted into relative position between the two robots which is required to be constant.

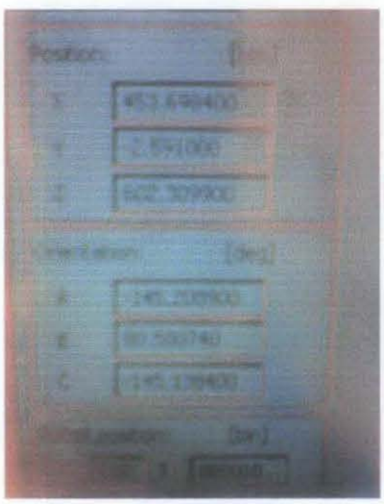

Figure 5: Coordinate of End-Effector in Reference to Base Frame

CHAPTER 3

METHODOLOGY / PROJECT WORK

The procedure for implementation of the project is illustrated in **Figure 6** below where the first semester of the project will cover until the control system modeling and design while the second semester will cover the implementation of the controller to the actual robots and analysis study of the results obtained from experiments.

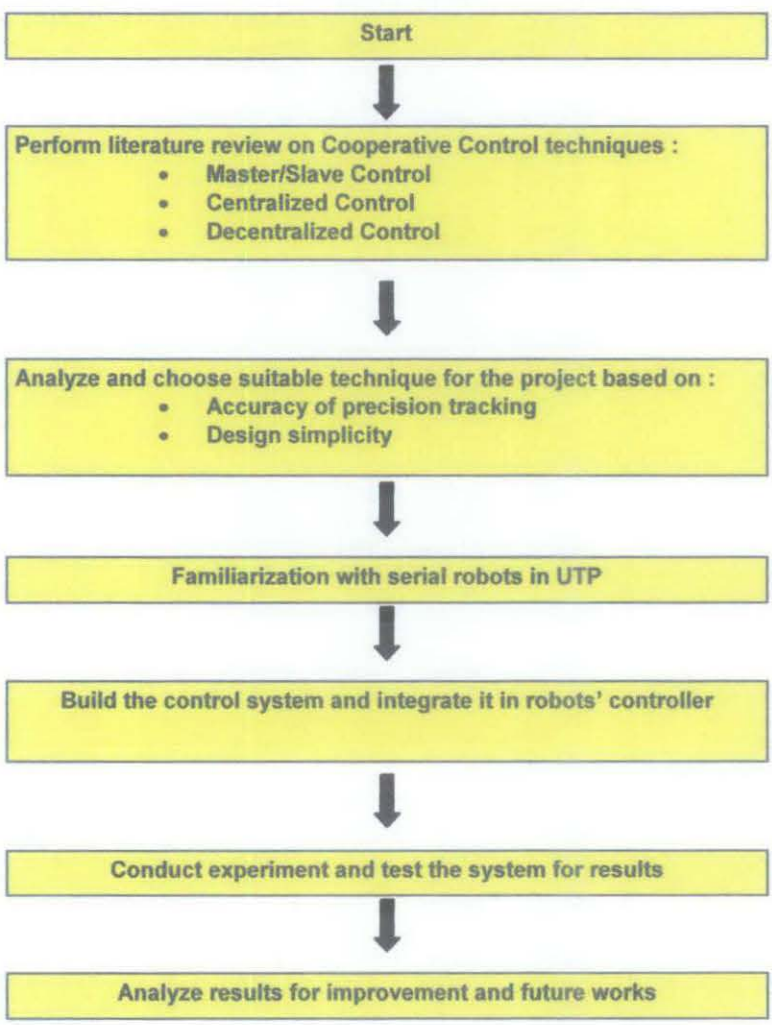

Figure 6 : Project Workflow Diagram

3.1 LITERATURE REVIEW AND RESEARCH

Literature review and research are done in the beginning of the project where sources of information are found using internet, journals, thesis and reference books on the related topics. The data gathered from the literature review are used as the guide for the project based on past works or related project done by experts and basic theory on the controller, dynamics and kinematics motion and positions needed to know to design the controller. This method is basically to understand the objective of the project and finding the need of this project.

3.2 STUDY AND ANALYZE OF COOPERATIVE CONTROL

The data gathered at the early stage of the project are now used as to study and analyze of the cooperative control techniques. There are basically three (3) primary techniques under cooperative control which are Master/Slave, Centralized and Decentralized Control. Each of the technique is studied and comparatively analyze on the suitability to be utilized in the project, the advantages and disadvantages of each control technique is compared especially based on the :

1) **Accuracy of the control** where relative distance (in millimeter or centimeter) of the two (2) arms robots are going to be measured before and after the experiment to ensure the position tracking of the slave robot as well as to determine the error produced from the design.

2) **Simplicity** of the controller design where number of lines of the programming should not exceed 100 lines as compared to previous works and research on the same topic.

The chosen technique, which is Master/Slave technique, is then being further studied on the specification needed in the design and based on the objective of the project. This method helps in detecting any constraints on the solution, criteria needed in the design, functions required of the design and parameters of the output required. Later, the mechanism and control formation may be determined which aids in modeling of controller program.

3.3 BUILD CONTOL SYSTEM OF PROGRAMMING

From various studies performed earlier, the dynamic equations, basic theory of control as well as the related research project information are customized and used to carefully model the controller. Modeling of the controller needs to take into consideration the integration between the controller designed with the existing robots' controller, the error may account during the task performance as well as the input and output required and will gain throughout the experiment later.

Steps in modeling the program are :

1) Identify and determine the sequence of processes and tasks involved

2) Optimize processes / tasks where necessary

3) Run simulation

Inputs supplied and outputs gained throughout the operations are :

1) All arm actuators can be commanded in terms of position, velocity, torque, and current.

2) End-effector loads are quantified by force/torque sensors mounted at the wrist locations.

3) Servo-control loops are embedded in the robot controller. From this control computer, the servo loop gains, control rates, control limitations (joint and velocity limits) may be reconfigured during operation.

4) The robots' controller is responsible in controlling the outer loops. Outer loops include:

- determining appropriate end-effector motions
- collecting and processing of information from the force sensors and manual controllers (operator input)

3.4 IMPLEMENT OF THE CONTROL SYSTEM TO SERIAL ROBOTS

This integration is an essential stage to ensure the input given by the controller designed can be interpreted by the robots controller and thus, carrying out the task as specified and also for the output from the robots controller to be translated back by the designed controller to ensure the parameters; relative distance (mm and cm) and force (N) can be measured to ensure the experiment successfulness.

3.5 ANALYSIS

Lastly, after the implementation and experiment has been performed, the results from both the simulation and actual implemented controller experiment are compared. This comparison is to analyze whether the experiment result is the same as predicted by simulation or varies by how much error. The analysis will then be concluded on the effectiveness and accuracy of the technique chosen, the comparison of results from simulation and experiment, error analysis and factors leading to errors if there are any and finally the recommendation on further improvement could be done to the controller specifically and also to this project.

3.6 GANNT CHART

The Gannt Chart for the first and second semester of the project is as included below as **Figure 7** and **Figure 8**.

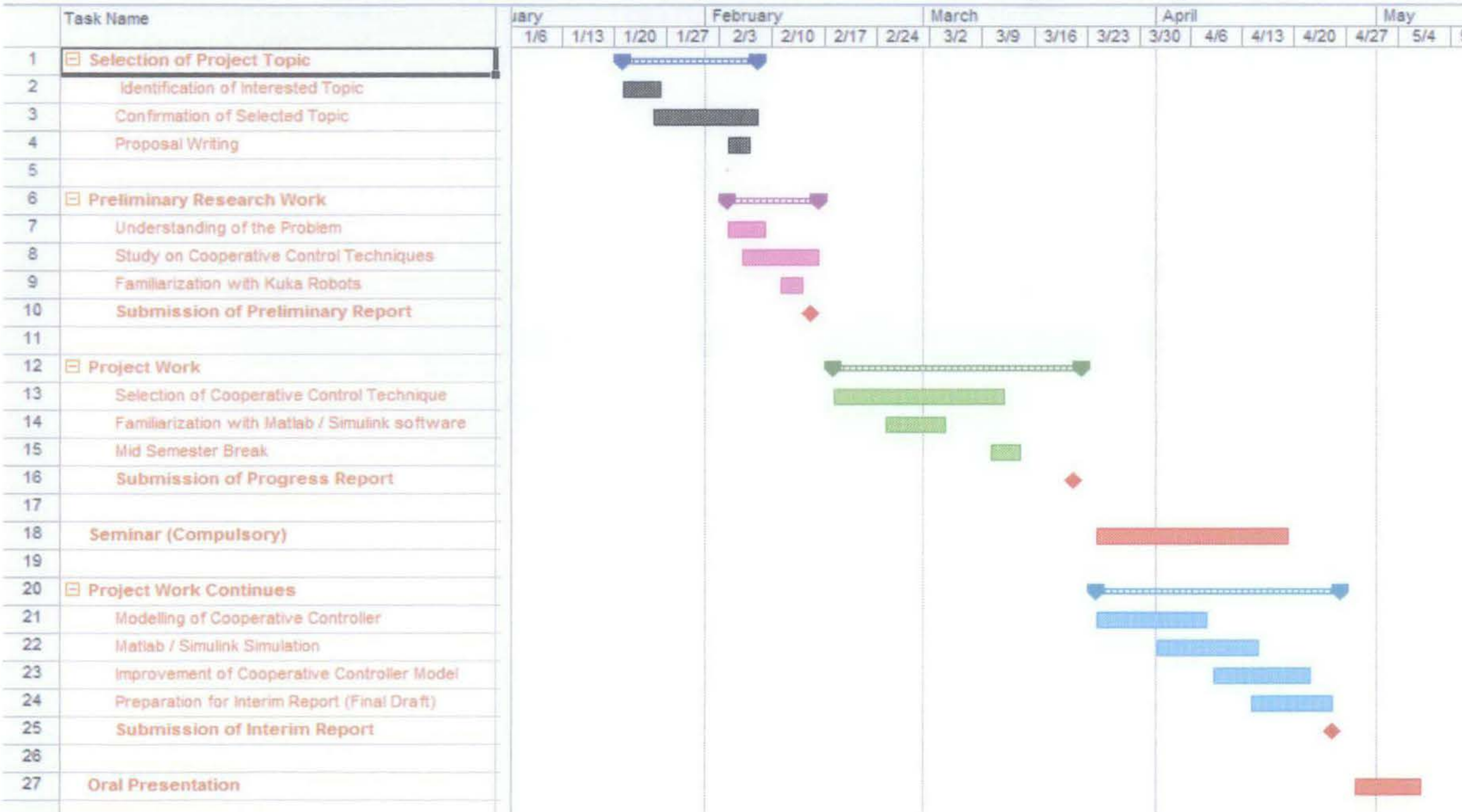

Figure 7 and 8 : Gantt Chart for 1st and 2nd Semester

CHAPTER 4
RESULT AND DISCUSSION

Figure 9 below is basic block diagram of the robot control system in which the controller will be integrated with during the implementation stage. Considering the robot control system, it can be seen that the robot act on the force sensor as the input and the output will be the linear motor or linear distance where the slave robot will received as input and followed the movement of the master.

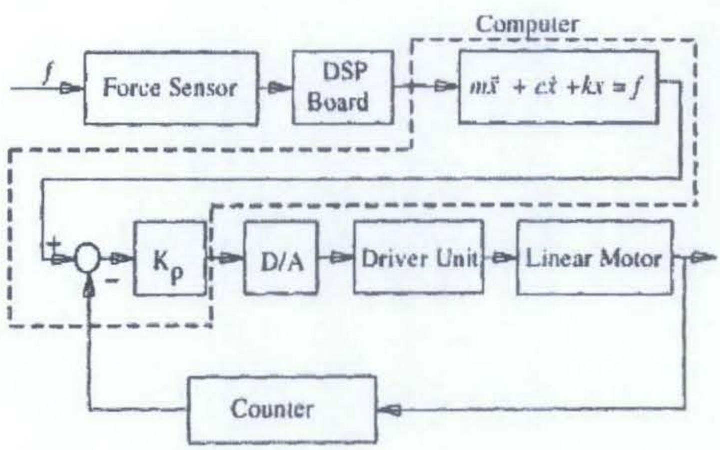

Figure 9: Block Diagram of the Robot Control System

Figure 10 indicates the experimental model of the system implemented during experiment. Basically there are four (4) external elements integrated together to assist in achieving the cooperative control aimed which can be seen as in the figure. From the figure, it is also can be seen that start and stop button, and proximity sensors are all connected to Master robot only, while stop button and strain gauge are connected to Slave robot.

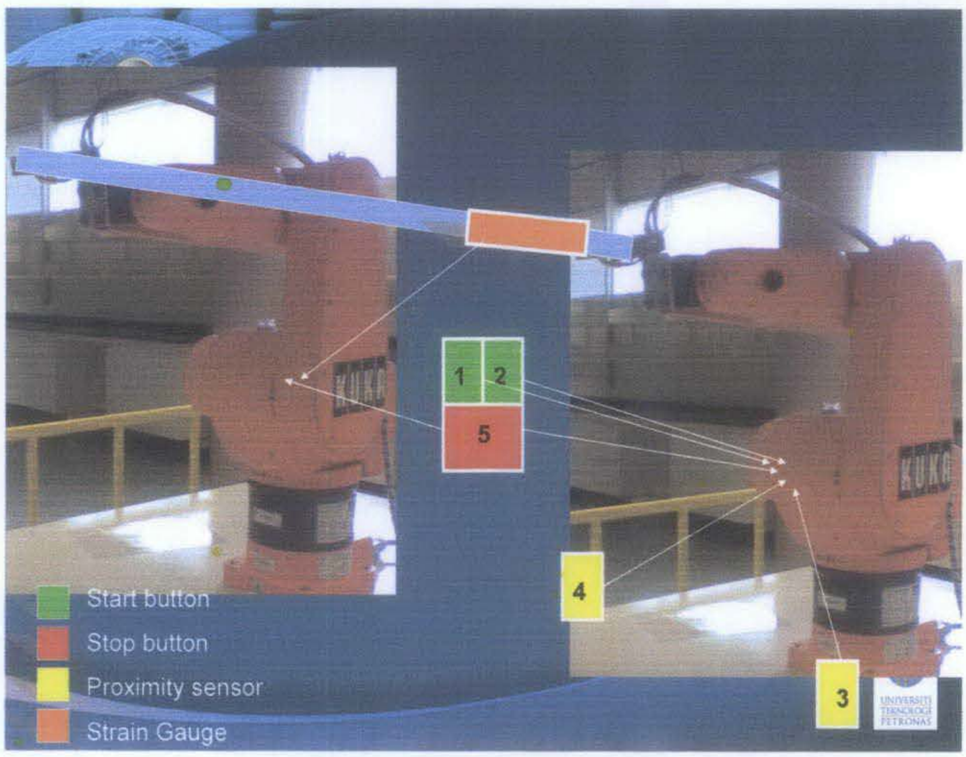

Figure 10 : Experimental Model of Cooperative Control

Strain gauge in this configuration is used to assist in Slave robot to detect changes in forces onto the load (bar) and move in feedback from this force changes, to achieve the initial force set before the experiment started.

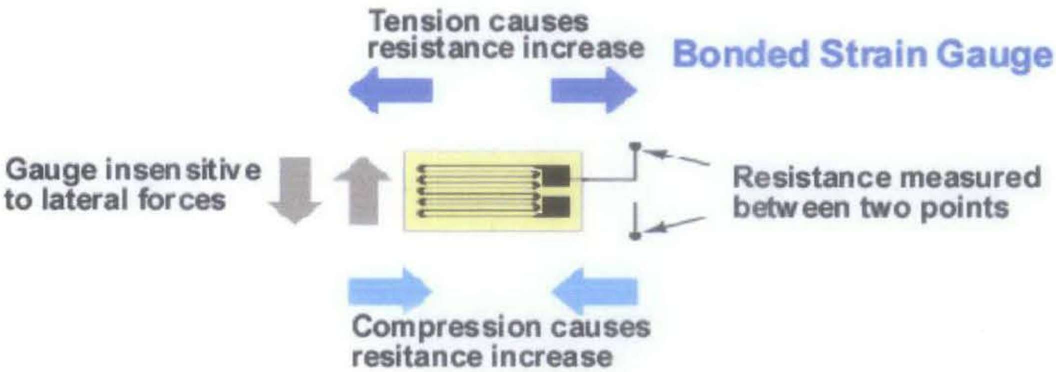

Figure 11: Mechanism on how strain gauge can be used to detect force differences

The key mechanism which works this control system is the integration of a strain gauge onto the load and connected to the slave as an input. **Figure 11** shows how strain gauge works where it gives input to Slave robot whenever there is a change in forces which is whenever the Master robot moves. Thus, Slave robot will move to ensure the force to be back as in the initial and therefore, execute movement as the same distance as Master.

The resulted programming for both Master and Slave robots are as shown by **Figure 12** and **Figure 13** below :

```
Master's Program :
INI
PTP HOME Vel 100% DEFAULT
PTP P1 Vel 100% BASE[0]              // Initial position//
WHILE $IN[5]==FALSE
//Input 5 is a stop button to terminate the program//
WAIT FOR [($IN[1]==TRUE) OR ($IN[2]==TRUE)]
//Input 1 is a start button indicates command for robot movement to the right//
//Input 2 is a start button indicates command for robot movement to the left//

IF $IN[1]==TRUE THEN
WHILE $IN[3]==FALSE
//Proximity sensor placed to stop motion when true//
PTP P2 Vel 100% BASE[0] //Robot moves to the right//
END WHILE
WAIT 3 SEC     //Waiting for Slave to copy movement//
PTP P3 Vel 100% BASE[0] //Back to initial position P1//
END IF

IF $IN[2]==TRUE THEN
WHILE $IN[4]==FALSE
PTP P4 Vel 100% BASE[0]    //Robot moves to the left//
END WHILE
WAIT 3 SEC
PTP P5 Vel 100% BASE[0] //Back to initial position P1//
END IF

END WHILE
PTP HOME Vel 100% DEFAULT
```

Figure 12 : Master's Program

```
Slave's Program :
INI
PTP HOME Vel 100% DEFAULT
PTP P1 Vel 100% BASE[0]             //Initial position//
WHILE $IN[5]==FALSE
//Input 5 is a stop button to terminate the program//

IF $IN[1]==FALSE THEN
//Input 1 false indicates changes in stress on strain gauge//
//Strain gauge is in compression//

REPEAT
PTP P2 Vel 100% BASE[0]//Robot moves to the right//
UNTIL $IN[1]==TRUE
END IF

IF $IN[2]==FALSE THEN
//Input 2 false indicates changes in stress on strain gauge//
//Strain gauge is in tension//

REPEAT
PTP P3 Vel 100% BASE[0]//Robot moves to the right//
UNTIL $IN[2]==TRUE

END IF

END WHILE
PTP HOME Vel 100% DEFAULT
```

Figure 13 : Slave's Program

The first simulation is of translation movement for the Master/Slave control strategy and was performed first in two axis (parallel transfer). The goal is to maintain constant forces on the held object. The slave moves toward the master if the force is above a specified threshold and away if below a specified threshold. The thresholds are specified for each axis.

For the experiment purposes, a translational bar / string is going to be connected between the end-effectors of the two manipulators and the experiment consists of maintaining a constant force along a single axis (as specified by the force thresholds).

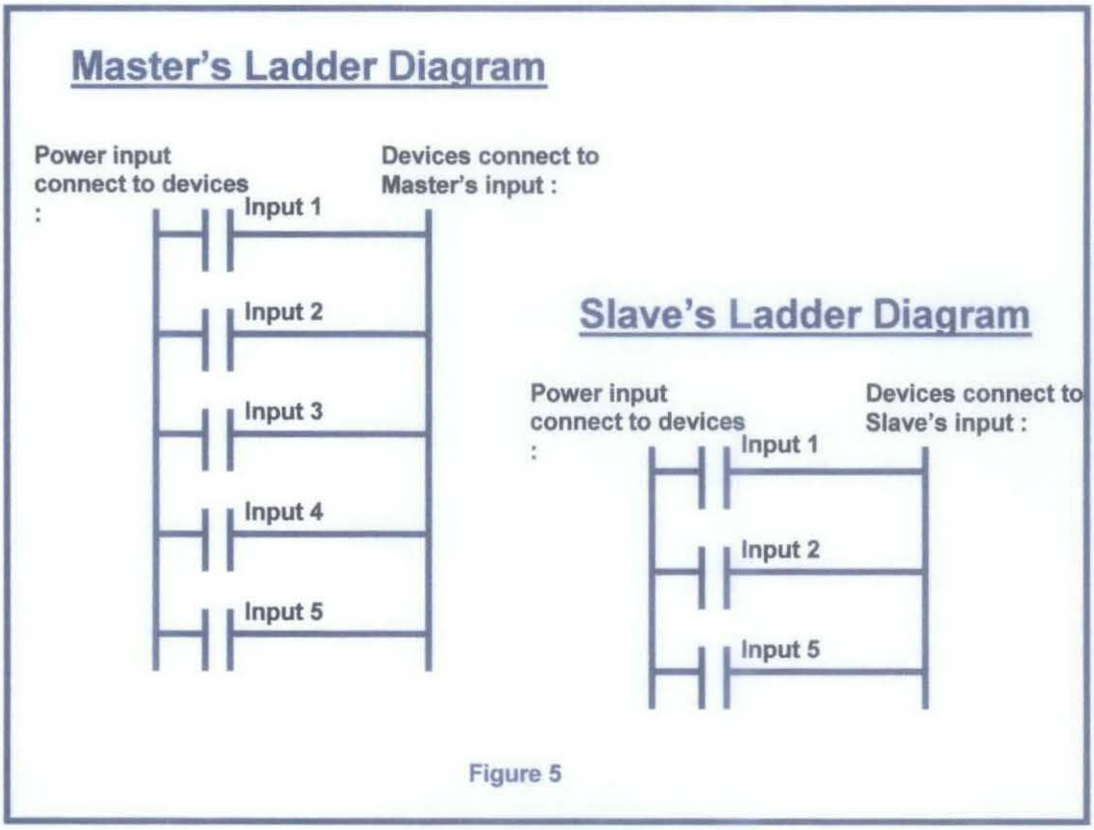

Figure 14 : Ladder Diagram indicates Inputs and Outputs of Robots

Figure 14 shows the ladder diagram for both Master and Slave robots. These ladder diagrams indicate the input and output for both of the robots which ensure the experiment utilization.

There are a total of five (5) inputs connected to Master's robot which are start and stop buttons as well as proximity sensors. Inputs connected to Slave robot are stop button and inputs from strain gauge.

Calculations :

Movement (mm) = End position – Initial position

(taken from robot's internal measuring tool indicating position of end-effector from robot's base)

Error (mm) = Master movement – Slave movement

From the experiment conducted, the above calculations are conducted to evaluate the precision tracking of the slave robot together with the error contains from the experiment. Five (5) runs of experiment have been conducted and the resulting movement and error are as shown below :

Table 5 : Experiment Results

Exp. No.	Master Movement (mm)	Slave Movement (mm)	Error (mm)
1	332.45	332.31	0.14
2	314.23	315.03	-0.8
3	289.86	289.12	0.74
4	320.39	320.28	0.11
5	303.24	302.76	0.48

CHAPTER 5
CONCLUSION

As a conclusion, although constructing the control program for Cooperative Control of Dual Series Robots is said to be complex with the dynamic parameters of the object often vary, many research has proven that it is possible to accomplish it using the three strategies of cooperative control namely master/slave control, centralized control and decentralized control.

Comparison between the three strategies has been made and focuses on their accuracy and simplicity method in which Master/Slave method is chosen.

Based from the theory and literature review studied, a model of two-dimensional (2-D) control for the series robots or translational transfer has been modeled and programmed.

The objectives for this project have been achieved where a program utilizing Master / Slave control method has been done and integrated in the system of two series robots.

Experiment has been conducted on translational motion of the robot and results shown that :

- *High accuracy* as no error above 1mm recorded
- *Simplicity of design* as the number of line of program are 21 for Master and only 16 for Slave program; which does not exceed 100 lines

CHAPTER 6
RECOMMENDATION

From the results shown, although the objectives of this project has been achieved, further improvement could be done where :

- Number of lines of the program could be reduced further by using other method of control or by using another sensor or approach towards conducting the experiment
- The experiment could be further conducted using rotational motion of robots
- Another technique of formation motion, Position Control could be implemented and tested for comparison

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