THE APPLICATION OF INTELLIGENT ACTIVE FORCE CONTROL OF A ROBOT MANIPULATOR IN SURFACE FINISHING PROCESSES

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ABSTRACT

In manufacturing, and industrial robot is often used to manipulate objects (work pieces) either in free or constrained environments. The latter is more critical since it involves significant interaction of forces between the robot's end-effector, object and its surrounding which can directly affect the performance (accuracy) of the robot. Typical robotic tasks include de-burring, machining, contour/profile tracking, welding assembly, polishing and pick-and-transfer operations. Thus, the study of robot force control is a potential area of research to address the problems as it seeks ways to counteract them effectively and robustly. The proposed research is aimed at investigating and analyzing the effects of changing various parameters including the different loading and operating conditions in a robotic control system. A rigorous simulation study was conducted particularly on the trajectory tracking performance of a two-link planar robot that is assumed to execute grinding and deburring processes. Active force control with intelligent elements was used in the study. The effectiveness of the proposed control scheme was verified and also compared with the conventional proportional –plus- derivative (PD) counterpart.

ABSTRAK

Dalam pembuatan, robot industri selalu digunakan untuk mengolah objek (bahan kerja) samada dalam keadaan sekeliling yang bebas atau terdapat kekangan. Keadaan menjadi lebih kritikal apabila melibatkan interaksi daya antara hujung robot dan sekelilingnya yang mana secara langsung boleh mempengaruhi prestasi (kecekapan) robot. Jenis tugasan-tugasan robot yang biasa adalah termasuk operasi menyahgerigis, pemesinan, penjejakan profil/lengkukan, kimpalan, pemasangan, penggosokan dan operasi ambil dan pindah. Dengan demikian, kajian kawalan daya robot merupakan satu bidang penyelidikan yang berpotensi bagi mengutarakan masalah sebagaimana mencari jalan untuk mengatasinya dengan secara berkesan dan lasak. Penyelidikan yang disyorkan adalah mensasarkan kepada menyelidik dan menganalisa kesan-kesan perubahan pelbagai parameter-parameter termasuklah perubahan bebanan dan keadaan operasi dalam sistem kawalan robot. Satu kajian simulasi secara mendalam telah dijalankan terutamanya terhadap penjejakan prestasi trajektori robot dua lengan mendatar yang diandaikan melakukan proses mencanai dan menggosok. Kawalan daya aktif (AFC) dengan elemen kecerdikan telah digunakan dalam kajian ini. Keberkesanan skema yang dicadangkan telah disahkan dan juga di bandingkan dengan kaedah konvensional yang setara iaitu terbitan berkadaran (PD)

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CHAPTER I

INTRODUCTION

1.1 Background

Most manufacturing tasks require mechanical interactions with the environment or with the object being manipulated. In other words, the tasks require the end-effector to follow a prescribed trajectory with the presence of the interactive forces. There are many industrial applications that involved such interaction such as in welding, process assembly, cutting, machining and surface finish operations. Robotic deburring is an example of such task.

As can be seen in Table 1.1 from [15], robotic deburring represents an example of the class of advance robot application problems in presence of constrained forces acting between the robot and the environment. Both conditions must be closely regulated in order to obtain satisfactory performance. A natural description of deburring task is in terms of burrs itself represents a significant fraction of the total volume of material to be removed from the edge. The contact force and tracking velocity must be changed in accordance with the variation in burr size to obtain uniform edge geometry

Table1.1: Robot application

- ***Available Robotic Technologies*:**
  No requirement for simultaneous robot motion and application of contact force
  - —Materials handling
  - —Paint spraying
  - —Water jet cutting
  - —Sealant application
  - —Spot welding
  - —Arc welding

- ***Developing Robotic Technologies*:**
  Simultaneous robot motion and application of force is required
  Contact forces $\gg$ process forces
  Well-defined and unchanging interaction geometry
  Force signals are interpretable in terms of position error
  - —Assembly
  - —Bolting
  - —Routing with templates
  - —Drilling with drill guides

- ***Needed Robotic Technologies*:**
  Process forces dominant
  Large dynamic force variations
  Large uncertainty in geometry and need for high precision
  Force signals are not interpretable without a detailed process model
  - —Precision deburring
  - —Off-hand machining

1.2 An Overview of Surface Finishing Processes

It is known that material surface finishing operations such as deburring, grinding, chamfering and other edge finishing operations can be responsible for 10~30 percent of all manufacturing cost [20]. Even with the present state of technology in manufacturing, problems of burr removal are still encountered by manufacturers.

This is mainly due to the fact that in most manufacturing plants' deburring is performed by human labor, which is highly labour intensive. Annual deburring costs alone are currently estimated at USD 3.9 billion nationwide. These cost include time required to finish a part at the bench, the cost of thorough inspection, possible subsequent rework, and sometimes rejection of the component. In a recent assessment in technology development, it was revealed that the problem of deburring and finishing ranked second in a list of 46 manufacturing problems [20]

Burrs are almost always generated during machining is performed. It is formally defined as an undesirable projection of material formed as a result of plastic flow from machining operation. The nature of the burrs may vary with the machining conditions, which may affect its uniformity, thickness and location consistency. Whereas small or regularly shaped parts may be effectively deburred using bulk deburring processes such as tumbling or vibratory deburring, the parts. This is typically done by Computer Integrated Manufacturing (CIM) and requires a significant amount of handwork.

There are potential advantages of using robots for edge finishing operation such as improved compatibility with existing machinery, particularly in the computer-integrated environment, higher quality and shorter throughput times. In the study, the surface finishing operations were treated as the 'disturbances' that need to be compensated through suitable force control scheme.

1.3 Problem statement

It is often difficult to develop accurate mathematical models [4]. There are inevitable uncertainties in their constructed models for a number of robotic applications. These uncertainties may be due to unknown or partially known parameters of the control systems and their environment as well as to the unpredicted but unavoidable disturbances. Therefore, the design of a robust controller that can take care of uncertainties of a system is a key issue to ensure the robust performance of robot in the presence of disturbance in many forms such as noise and external forces from manufacturing activities

Nevertheless, robot control has been an attractive field to many researchers to carry out their studies over the years. There are various robots of control methods that have been proposed ranging from a simple classical proportional plus derivative (PD) control to the more recent adaptive and intelligent methods. One such method is called the Active Force Control (AFC) scheme. The aim of this control method is to ensure that the system is stable and robust even in the present of known and unknown disturbances. The method bases its concept on using mainly the estimated or measured values of certain parameters to effect its compensating action. This method is proven to work practically on robotic system [8, 9].

In the study, the AFC method with intelligent mechanisms is applied to the trajectory control of a robot arm performing surface finishing operations regarded as the disturbances to the system. A number of operating and loading conditions with parametric changes is considered in the study to explore the robustness and effectiveness of the proposed scheme.

1.4 Research Objectives

The major objective of this research is to study the effectiveness of the robot control strategy applied to surface finishing processes subject to various loading and operating conditions with changes in the parameters.

1.5 Scope of Study

The focus of this study is on the modeling and simulation of the proposed robotic system. The mathematical models of the various components in the system are required and later transformed into 'computer' models. Simulation study is performed using MATLAB, SIMULINK and relevant toolboxes considering a number of loading and operating conditions with parametric changes. These effects are investigated and evaluated based on the trajectory tracking performance of the robot. The selected manufacturing processes are limited to two types of surface finishing operation namely grinding and deburring.

1.6 Expected Contribution of Study

The outcome of the study can provide an indication of the robustness of the proposed system that could be applied to a real manufacturing environment. It can also serve as a basis for future works both theoretically or experimentally.

1.7 Thesis Outline

This study is organized into six chapters, each of which is described as follows;

Chapter 1 discusses the objective, scope and importance of the study. It also presents an overview of the proposed works to be carried out

Chapter II relates the literature review related to the various robot control methods and surface finishing processes.

Chapter III describes the complete proposed system involving the modelling of robot arm (static, kinematic and dynamics), controller, and the surface finishing processes.

Chapter IV highlights the simulation study of the integrated models developed in Chapter III. A number of experiments were conducted considering various conditions, parameters and disturbances to verify and evaluate the control scheme.

Chapter V presents an analysis and discussion of the results obtained in the simulation work. A comparison was made considering a number of different control schemes.

Chapter VI summarizes the overall outcome of the study and also suggests works that can be carried in future.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

With the increasing demands on robot manipulator performance in manufacturing processes, there is a need to improve the manipulator control techniques for more robust and effective performance. In the process, two very significant obstacles are encountered [1];

1) Nonlinearity : the dynamic characteristics of general spatial manipulators that are highly nonlinearity function s of the position and velocities of the manipulator elements.
2) Uncertainty: often parameters of the robot manipulator are not known exactly.

Basically, this chapter will first review some control methods, which have been applied by other researchers. It covers various aspect of the control system of robot including the description of the main control technique, the intelligent mechanisms incorporated and also how they employed in performing manufacturing tasks.

2.2 Review of Past Study

2.2.1 General Robot Control

A broad class of the robot tasks requires an interaction force control between the manipulator and the environment. Robot control is a problem under extensive investigation. Robot manipulators are highly nonlinear and involve coupled dynamics. There are many nonlinear tracking control schemes that have been proposed. A well-known approach for the controller design is the model-based computed torque technique [2]. The computed torque methods are capable of providing excellent results for tracking performance if the complete dynamics of the robot are known. However, it is a well-known fact that no perfect dynamic model could be obtained for all robots.

Meanwhile, there are several constraints on the controller model-based computed torque technique. It yields a centralized controller with complexity of the same order as the robot model and is difficult to realize. Also, accurate estimate of the nonlinearities is required. Even many decentralized adaptive control schemes have been proposed but their application in practice is limited due to complex and expensive implementation. In view of this, Swarup and Gopal in [2] have investigated through a simulation study the effect of decentralized structure on the robustness of the trajectory tracking performance. They also proposed a simple compensation scheme using an error-data knowledge based to improve its performance. A linear tracking control scheme used consists of linear robot model, feedforward control, and feedback control.

A different approach was taken by Gan Feng [3] to improve the trajectory tracking performance. A compensation scheme using an error data knowledge-based is developed. This scheme takes advantage of the computed torque method, and incorporates a compensating controller to achieve high tracking performance. The compensation controller is based on a Radial Basis Function (RBF) neural network, which is trained on-line to identify the robot modelling error. A main feature of the proposed scheme is that the resulting closed lop control system is guaranteed to be stable In addition, the neural network based correcting controller is an add-on device which can be added on many existing robot control systems. In this work, a simulation study is conducted to demonstrate the performance of algorithms where a simple two-degree of freedom manipulator was used in this simulation. From the simulation result, it was found that through RBF neural network and tracking error of the robot in joint space is greatly improved

Liou and Jamshidi [4] also introduced modified MRAC (Model Reference Adaptive Control) that the scheme can solve the robustness problems to different extents. One of the robust control schemes called variable structure control has been combined with MRAC can display remarkable transient behavior over conventional MRAC and maintains robustness with respect to the bounded disturbances, nonlinearities, plant variations, and unmodels dynamics. In addition, the proposed MRAC [1] achieved acceptable performance in some very difficult situation involving nonlinearity and/or time varying parameters during the robot manipulator operation. A stability robustness condition for the model reference computer torque control has been developed to quantify the stability robustness of the closed loop system. Simulation is performed by PUMA 560 Robot. The simulation results shows that the addition of the variable structure component in the control law improves the transient response (output error converge speed) drastically and is capable of rejecting the disturbance.

Kazerooni [5, 6, 7] presented a nonlinear approach for the stability analysis of robot manipulators in compliant maneuvers. For stability of the robot, there must be some initial compliancy either in the robot or in the environment. Stability of the environment and manipulator taken also as a whole has been investigated, and abound for stable manipulation has been derived. According to this stability condition, smaller sensitivity either in the robot or in environment leads to a narrower stability range. In the limit, when both robot and environment have zero sensitivity, stability cannot be guaranteed. The general stability condition has been extended to the particular case where the environment is very rigid comparison with the robot stiffness. This condition has been verified via simulation and experiment on the Minnesota direct drive robot.

Hewit and Musa also have explored the Active Force Control to obtain robustness and good stability in the presence of known and unknown disturbances [8, 9]. The major advantages of this control system is able to reduce/ compensate of erroneous of the tracking path through estimated measure values of particular parameter. On top of that it also reducing of mathematical complexity of the robot control. The incorporation of the intelligent mechanisms has been shown it greatly improved the performance of the system.

2.2.2 Robot Control in Manufacturing Process

F.Pfeiffer [10] demonstrated the problems connected with assembly processes performed by robots. Performing assembly process by robot system requires a combination of the dynamic and control of a robot. The key issue here is how this application adapts to the disturbances. During typical assembly tasks, the manipulator has changing contacts with the environment that include impact. The resulting interaction between assembly dynamics and robot dynamics can influence part surface quality and may lead to undesired effects such as jamming. The compliance control during interaction of tool with constraint surface is highlighted here. He also focuses more on problems of the dynamics than on the control aspect such of describing contact processes like impact and stick-slip. In other words, his work also estimates the maximum disturbance possible for the feasibility of automated assembly, using a simple PD controller

Shoham and Srivatsan [11] describe the rubbing process of the surface of a piano. The method is using non-linear robot, which is exerted forces to trace a complex contour. They also utilized micro (linear actuator for minor variations) and macro (large variations) manipulator's concept to improve response time. The ability of the system has been proven experimentally.

Whitney and Tung [12] describe grinding and finishing robot for cast iron stamping dies, which based on closed-loop force control system. Research was focus on the process modelling, advanced sensor technology, novel control and task planning schemes. By using Taguchi method to determine process parameter and the goal to improve quality, productivity through full automation and cost saving were achievable. However the successful implementation depends on the ability to model the grinding process and control the normal forces.

Meanwhile, Elbestawi [13, 14] describes the development of a high performance active end effectors for improving robot precision in deburring. The dynamic analysis is gained from combination of robot arm, end effectors, and deburring process dynamic the focus is on the fine motion control of the end effectors. The model orders and parameters are obtained directly from experimental measurements. The system goal is to control the chamfer depth with minimum surface roughness. The dynamics of both the process and disturbances are modeled explicitly. Several force control algorithms are evaluated such as Linear –Quadratic –Gaussian Control, Generalized Minimum-Variance Control, Extended Horizon Control and Extended PID Control. Simulation results are verified by real-time force control experiments. Performance comparisons are made based on the force variance and surface roughness. The unit was built and tested. The force control system, based on discrete time plant model, is developed off-line through computer simulation. The end effectors based deburring system is then tested in real time.

Kramer and Shim [15, 16] have carried-out their study on the development of a robotic deburring system which provides for simultaneous edge following and force control. The manipulator that called 'AdeptOne' has been interfaced with an instrumented remote center of compliance manipulator to provide a system which tracks an edge at a controlled force level that can be specified by the operator. It has been shown experimentally that, at a given tracking speed, the tangential component of the robot deburring force is proportional to the material removal rate (burr size), whereas the normal force remains relatively constant. If the cutting torque during assembly in process, a continuous monitoring of the tangential force would be possible

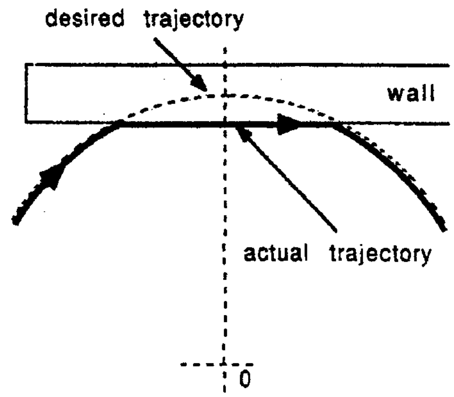


Figure 2.1:Robot trajectory-interaction with the environment

Figure 2.1 shows a view of experimental setup. In the figure 2.1 reinforced aluminum wall was mounted vertically in the robot workspace. The planar robot is actuated in horizontal maneuvering, and then the robot can have stable interaction with the environment.

Kazerooni [17, 18] tries to incorporate this technique into robotic deburring in two-dimensional planar parts with unknown geometry. Robotic deburring requires compliancy and stiffness in the robot directions tangent and normal to the part, respectively. Compliancy in the tangential direction allows robotic accommodation of tangential cutting forces, while stiffness in the normal direction impedes a robotic response to normal cutting forces. But to track the part contour, the robot requires compliancy in the normal direction. . In general these two problems are coupled however in his study, they are separated into a hardware problem and a control problem. A tracking mechanism has been designed and built which incorporates a roller bearing mounted on a force sensor at the robot endpoint. This force sensor is located directly below cutter and measures the contact forces, which are the input to the tracking controller. These contact forces are used not only to calculate the normal vector to the part surface, but also to set of forces (cutting forces generated by the cutter) to produce a stable metal removal process. This deburring control method guarantees compliancy and stiffness in the robot in response to the tangential and normal cutting forces, respectively. Experimental results are given to show the effectiveness of this method.

In manual deburring process, the burrs are often removed from part edges by chamfering. It is often required that the chamfer depth be within specific tolerances: a consistency, which is difficult to achieve manually. To successfully complete this constrained maneuver, the manipulator must develop compliant motion where the interaction force along the constrained direction is accommodated rather than resisted. Figure 2.2 illustrates model for damping processes, such as deburring 'burr removal' are characterized through velocity proportional forces under constrained motion. An essential component for successful automation of surface finishing process is appropriate control of the mechanical system to achieve required performance, such as specified surface finish to hold tolerances, precision contours, and tool-work piece.

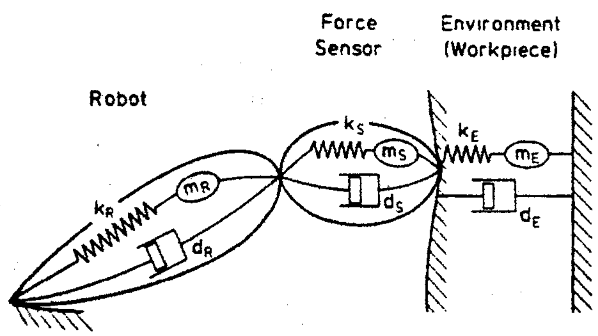


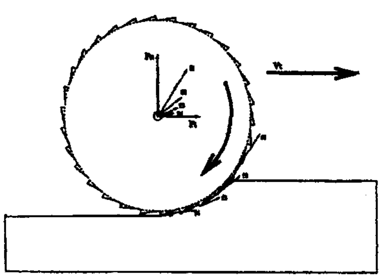
Figure 2.2: The model representation of an industrial robot under constrained motion [19].

Considerable research in the theory to design effective controller, requires knowledge in two factors;

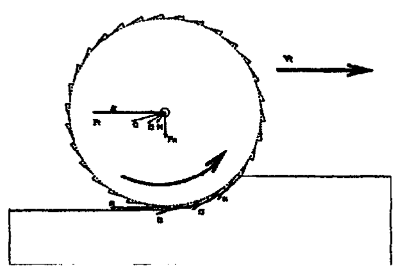
a) Accurate modeling of the mechanical system to model the behavior of the system interacting with the external environment during the process

b) Knowledge on process model, such as cutting force models and burrs models.

Experimentally, both factors were satisfied. Experimental result shows that by good knowledge will benefits to the particular work . For example in term of tool setup for surface finishing process, the direction of grinding tool will influence in the obtained result [20]. Comparing experimental results of mode 1 and mode 2 such in Figure 2.3 indicates that better surface finish can be obtained in mode 2.



a) Mode 1



b) Mode 2

Figure 2.3: Shows surface finishing mode. (a) mode 1 and, (b) mode 2.

Thomessen, Terje and Sannes [21] present a robot control system dedicated to grinding large Francis Turbines. The control system is based on an active force feedback system using a three- axes force sensor attached to the robot's end effectors. This system offers high flexibility and robustness against work piece positioning and grinding tool wear. Its provides control of the grinding process parameters ensuring high productivity in addition to good grinding performance and grinding tool economy. The system was experimentally tested on a MultiCraft 560 grinding robot.

2.3 Conclusion

From the review, it can be deduced that the robot force control applied to manufacturing processes is an important area of study. It is more challenging and demanding compared to the robot's tasks in free space. Thus, a force control strategy using intelligent AFC method will be explored and investigated in the proposed study involving selected surface finishing operations.

CHAPTER III

THE PROPOSED SCHEME

3.1 Introduction

This chapter presents the development of the proposed scheme, i.e. the intelligent AFC method applied to selected manufacturing processes. Mathematical models related to the main components of the system were derived and explained. These components are;

1. Physical manipulator (robot arm) involving static and dynamic analysis
2. Controllers consist of AFC, iterative learning algorithm and neural network.
3. Disturbances in the form of surface finishing operations (grinding and deburring).

3.2 General configuration

In this study, the AFC method is used in conjunction with intelligent mechanisms (iterative learning algorithm and neural network) applied to the trajectory track control of two-link manipulator or robot arm. The arm is supposed to perform a specific manufacturing task. Figure 3.1 shows a block diagram representing the interlinking of the proposed control scheme.

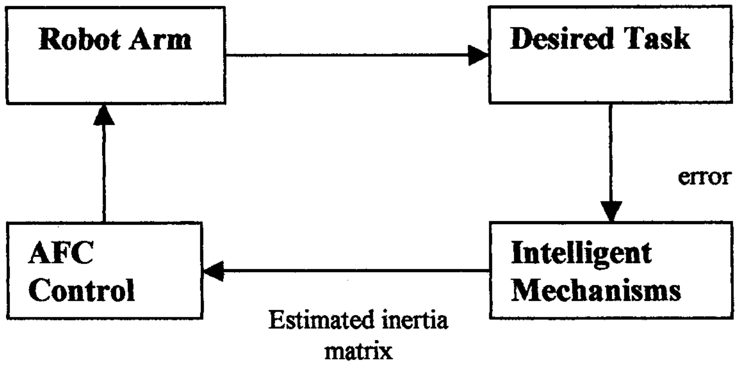


Figure 3.1 Interlinking of the proposed control scheme;

Three assumptions were made in the development of this algorithm;

1. The robot is rigid structure
2. Low speed of the robot arm
3. The gravitational terms is omitted because of the planar horizontal structure of the robot.

The manipulator considered here has two degrees of freedom with revolute frictionless joints whose links move on one horizontal plane.

3.3 Mathematical Model of Robot Arm

There are two forms of modeling which is essential in robot motion study. The model developed here are consists of static modeling and dynamic modeling considering the robot in the rest and motion conditions respectively.

3.3.1 Static Modelling

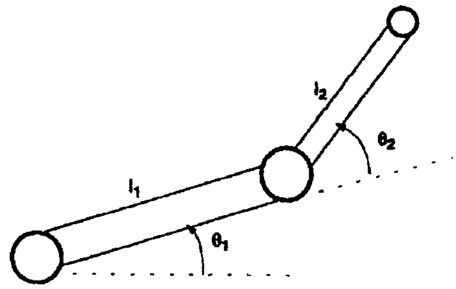


Figure 3.2: A representation of a two-link arm

Knowing the torques that act on the robot joint and also exerted the force at the end – effector is essential to ensure good robot control

Torque at 1st joint

$$\tau_1 = [\, L_1 \cos \theta_1 + L_2 \cos (\theta_1 + \theta_2)]Fy - [\, L_1 \sin \theta l + L_2 \sin (\theta_1 + \theta_2)]Fx \quad (3.1)$$

Torque at 2nd joint

$$\tau_2 = [L_2\, kos(\theta_1 + \theta_2)]Fy - [L_2 \sin (\theta_1 + \theta_2)]Fx \quad (3.2)$$

The components of generated force at the end-effector, F_x and F_y are

$$Fx = \frac{\tau_1 L_2 \cos(\theta_1 + \theta_2) - \tau_2 (L_1 \cos \theta_1 + L_2 \cos (\theta_1 + \theta_2)}{L_1 L_2 \sin\theta_2} \quad (3.3)$$

$$Fy = \frac{\tau_1 L_2 \sin(\theta_1 + \theta_2) - \tau_2 (L_1 \sin \theta_1 + L_2 \sin (\theta_1 + \theta_2)}{L_1 L_2 \sin\theta_2} \quad (3.4)$$

3.3.2 Dynamic Modelling

The general equation of motion for dynamic model [9] of a robot arm can be described as follows :

$$T_{q1} + T_{d1} = H_{11}\theta_{dd1} + H_{12}\theta_{dd2} - h\theta_{d2}^{2} - 2h\theta_{d1}\theta_{d2} \quad (3.5)$$

$$T_{q2} + T_{d2} = H_{22}\theta_{dd2} + H_{21}\theta_{dd1} - h\theta_{d1}^{2} \quad (3.6)$$

Where; $H_{11} = m_2 l_{c1}^2 + I_1 + m_2 (l_{c1}^2 + l_{c1}^2 + 2 l_1 l_{c2} \cos\theta_2) + I_2$

$H_{12} = H_{21} = m_2 l_1 l_{c2} \cos\theta_2 + m_2 l_{c2}^2 + I_2$

$H_{22} = m_2 l_{c2}^2 + I_2$

$h \quad = m_2 l_1 l_{c2} \sin\theta_2$

T_{d1} is disturbance torque at 1st joint

T_{d2} is disturbance torque at 2nd joint

Where; *m* is the vector of link masses

l is the vector of link lengths

I is the vector of mass moment inertias of the link

l_c is the vector of link lengths from the joint to the center of gravity of link

Since the arm movement is assumed in horizontal direction, the gravitational term of equation (3.5) and (3.6) are omitted.

3.3.3 Interrelationships Between Each Modelling.

From static modeling and dynamic modeling,

$$\tau_1 = T_{d1} \quad \text{and} \quad \tau_2 = T_{d2} \tag{3.7}$$

Known from deburring process modeling, disturbance torque

$$T_d = v(\theta) f_n + v'(\theta) f_t \tag{3.8}$$

where, $$F_x = f_t \quad \text{and} \quad F_y = f_n \tag{3.9}$$

The interrelationship of movement coordinate between static and deburring process modeling;

$$L_1 cos\theta_1 + L_1 cos(\theta_1 + \theta_2) = V(\theta)_1 \tag{3.10}$$

$$-L_1 sin\theta_1 + L_2 sin(\theta_1 + \theta_2) = V(\theta)_2 \tag{3.11}$$

$$L_2 cos(\theta_1 + \theta_2) = V'(\theta)_1 \tag{3.12}$$

$$-L_2 sin(\theta_1 + \theta_2) = V'(\theta)_2 \tag{3.13}$$

3.4 Robot Control Scheme

3.4.1 Intelligent Active Force Control

The benefit of AFC is ability to perform compensating action when subjected of disturbances and keep the system remain robust and stable condition. The fundamental of the AFC is accordance to Newton's second Law Motion [9]. For a rotating mass where the sum of all torques (*T*) acting on the body are the output of the mass moment inertia (*I*) multiplying the angular acceleration (α) of the body in the direction of the applied torque.i.e;

$$\Sigma T = I\,\alpha \qquad (3.14)$$

Therefore, for a robot system that having serial configuration,

$$T + T_d = [I\,(\theta)]\,\alpha \qquad (3.15)$$

Where, T is applied torque
T_d ia disturbance torque
$I\,(\theta)$ is mass moment of inertia of the robot
α is the angular acceleration of the robot arm

Figure 3.3 shows the AFC scheme is applied to a robot arm.

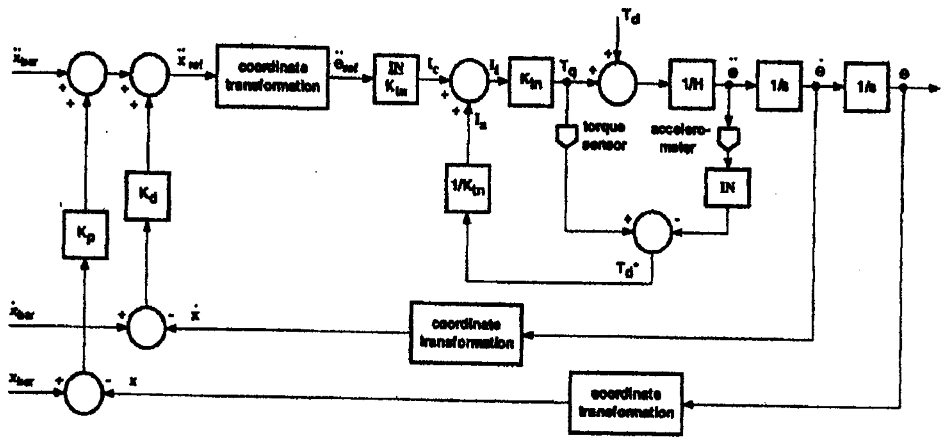


Figure 3.3: The AFC scheme applied to a robot arm

3.4.2 Iterative Learning Technique

Since the incorporation of two-control system will produce a better result, Iterative-learning algorithm is employed. As proposed earlier by Suguru Arimoto [9] that came up with several numbers of learning algorithms, it has shown that the track error effectively converges to zero with time.

Where

$$IN_{K+1} = IN_K + (\phi + \Gamma d/dt)\, TE_K \qquad (3.16)$$

IN_{K+1} is the next step value of estimated inertia matrix

IN_K is the current value of the estimated inertia matrix

TE_K is the current sum-squared positional track error,

$TE_K = \sqrt{(x_{bar} - x_k)^2}$

ϕ and Γ are learning parameters (constants)

Since a ' proportional constant and a derivative constant, the algorithm is described as a PD-type learning algorithms.

Here, we have

$$G(s)\ w(s) = 1 \tag{3.17}$$

i.e, $G(s) = K_{tn}$ and $W(s) = 1/K_{tn}$ where K_{tn} is the motor torque constant. The equation describing the disturbances is given as follows:

$$Td^* = IN\ \theta_{dd} - T_q \tag{3.18}$$

Where, Td^* is the estimate of all the disturbance torques

T_q is the applied control torque

IN is the estimated inertia matrix

θ_{dd} is the acceleration signal

Meanwhile, Figure 3.4 shows the complete AFCAIL scheme will be applied in the robot system

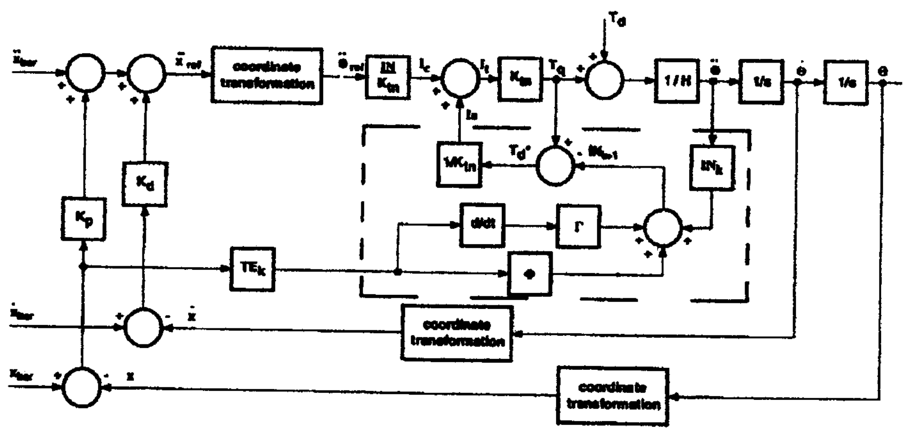


Figure 3.4: Active Force Control and Iterative Learning (AFCAIL) Scheme

3.4.3 Neural Network Technique

Another technique is used neural network algorithm to compute IN automatically and continuously. In complete term it is called Neural Network, which is embedded into Active Force Control ass shown in Figure 3.5. In other word it is called also AFCANN scheme. The scheme is capable to execute the non-linear mapping and approximation function. In order to ensure that the scheme is to be effective, the network need sufficiently trained.

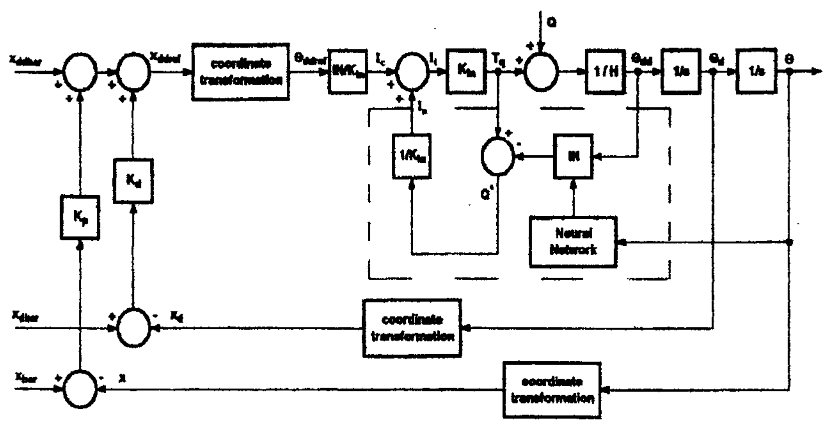


Figure 3.5 The AFCANN control scheme with neural network component embedded

In general the trained network is like a black box and then embedded in the AFC strategy with the joint angles and estimated inertia matrix (IN_1 and IN_2) acting as the active input values and the output value respectively. There are set of learning parameters needs to be applied in the neural network algorithm. Once this parameter is properly set, the inertia values will be produced are conveyed to the AFC loop able to activates the disturbance cancellation control process. A multiplayer feed forward neural network consists of 2-5-2 architecture, which is represents the number of neurons in the input, hidden and output layers [8].

The algorithm is expressed as follows;

$$\Delta W\,(i,j) = mc\ \Delta W\,(i,j) + (\,1\text{-}mc)\ lr\ d(i)\ p(j) \qquad (3.19)$$

where ; ΔW is the weight change matrix

lr is the learning rate

mc is the momentum constant

d is the delta vector (derivatives of error vector)

p is the current input vector

3.5 Surface Finishing Processes

3.5.1 Deburring Process Description

In general, typical automated surface finishing process commonly involves the following sequences [20]. The robot starts from the home position and moves freely for some time, makes contact with the workpiece, follows the workpiece contour while removing material and burrs from the surface, and leaves the surface returning to home position. In the case of robot deburring, the constrained surface is the surface of the work piece to be deburred. The contour is the tool path for the deburring tool, which specifies where material removal ought take place.

The kinetics of the deburring process and the robot must be taken into account as a basis of evaluating and increasing performance. A stable metal removal process requires a force control in the direction tangent to the part and a stiff trajectory control in the direction normal to the part [15]. Compliancy in the tangential direction leads to small cutting forces, while trajectory control in the normal direction prevents separation of the robot from the part. Force control for the robot in the normal direction is required for tracking the part contour in the presence of part fixturing errors and uncertainties in the part geometry. Fig 3.6 shows the procedure for determining end-effector orientation of the circular path and Figure 3.7 illustrates the deburring edge and the force components in tangential and normal direction.

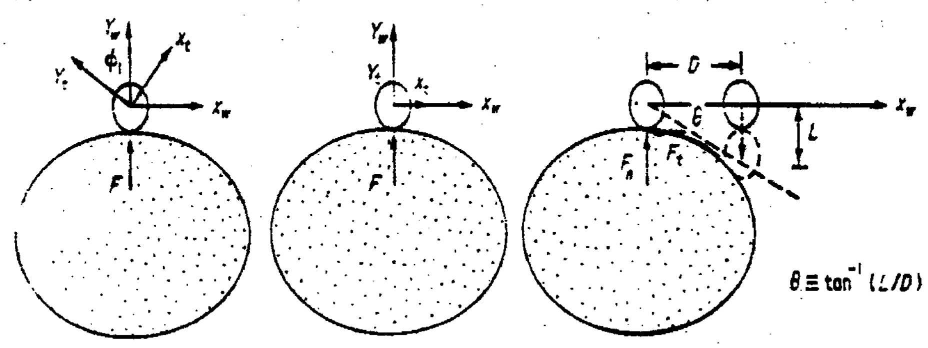


Figure 3.6: Procedure for determining end-effector orientation

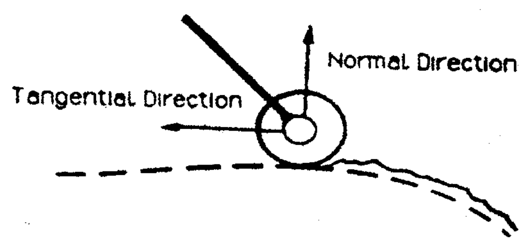


Figure 3.7: Deburring edge where normal and tangential direction is exerted on the deburring tool

3.5.2 Grinding Process Description

Grinding is a chip-removing process primary used to remove metal and burrs from machine parts to achieve the desired surface finish. In some cases grinding is also used for bulk removal of metal. Manual grinding often means hard and monotonous work and noisy environment. The workers have to use protective equipment. This, together with the fact that almost all manufactured products are directly or indirectly connected to grinding, leads to automation of the grinding process.

For the light grinding application [21], only small volume of metal per square unit is going to be removed from the workpiece surface. The main characteristic for these applications is that the grinding operation is done in one pass. For heavy grinding applications, the grinding operation is performed during several passes.

3.5.3 Process Modelling

A further important aspect is dealing with disturbance. During surface finishing tasks the manipulator has changing contacts with environment that include impacts. As seen in Figure 3.8, it clearly shows that the force acting on the deburring/grinding tool actually consists of two components which is in tangential direction, f_t and normal direction, f_n . From modeling point of view this means that the robot is subjected to changing geometric constraints that reduce its mobility. The resulting interaction between robot dynamic and deburring/grinding dynamics can influence part surface quality and may lead undesired effects.

In general term, the dynamic equation for dynamic condition is

$$T_q + T_d = H(\theta)\theta_{dd} + h(\theta, \theta_d) \quad (3.20)$$

where

$$T_d = v(\theta) f_n + v'(\theta) f_t \text{ (disturbance torque of model)} \quad (3.21)$$

$$f_t = \mu f_n \quad (3.22)$$

f_t is tangential force

f_n is normal force

μ is coefficient of friction between surface finishing tool and the workpiece

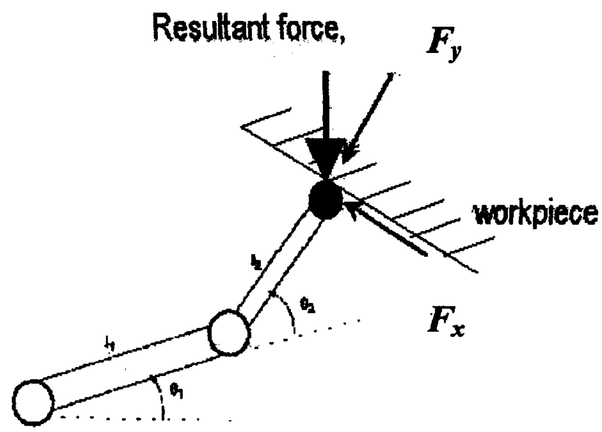


Figure 3.8 : Force acting on the deburring tool

3.6 Prescribed Path Trajectory

The task for this exercise is constraint surface which is straight low carbon steel firmly held by a vise. The desired complete task for the robot is move towards the constraint workpiece surface (DA), make contact with the surface (A), follow the surface while maintaining a desired normal contact force and perform the deburring operation with good cutting force (AB), and leave the surface (BC) and back to the starting point (CD).

A prescribde straight trajectory [20] is shown in Figure 3.9

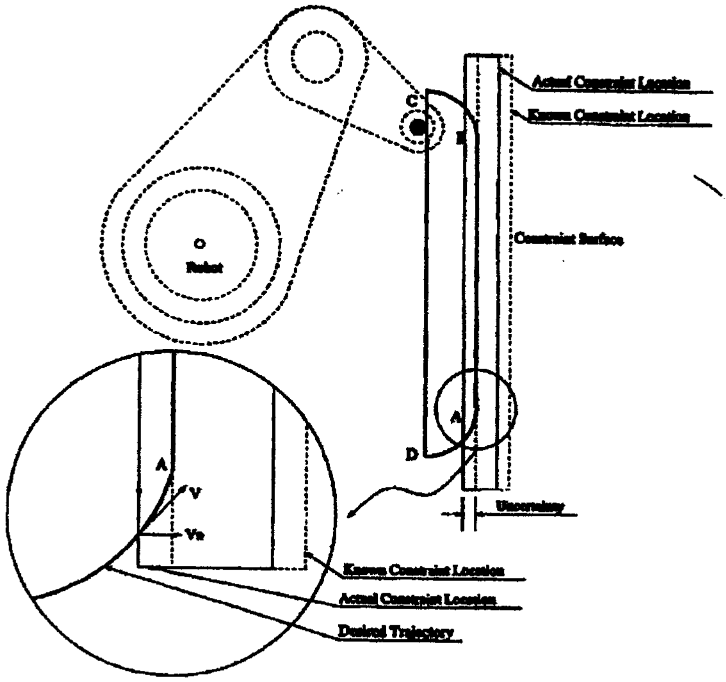


Figure 3.9; The deburring path in the straight line

3.7 Conclusion

All the main components that contributing to complete modelling of robot control system are clearly described. The necessary algorithms, assumptions and intelligent mechanisms were also presented. These are to ensure that simulation study can be carried out effectively.

CHAPTER IV

SIMULATION

4.1 Introduction

Simulations using the proposed control scheme will be conducted for both manufacturing process of grinding and deburring. The desired trajectory is a complete task containing straight line and parabolic curve motion. The AFCAIL and AFCANN control schemes are applied in this simulation. Both robot control schemes will be tested by applying different parametric changes, which gives different result.

For AFCAIL scheme, the parameters are controller derivatives and proportional gain (K_p and K_d), cutting velocity V_{cut}, estimated inertia matrix IN_1, IN_2 and external disturbance forces (grinding force and deburring force). Meanwhile, AFCANN scheme will be tested with learning rate *lr*, momentum constant *mc*, error goal *eg*, cutting velocity V_{cut}, and external disturbances.

4.2 Simulation Set Up

All schemes basically, are simulated using MATLAB and SIMULINK software packages. There are number of operating condition which is related to the physical robot arm, reference trajectory, intelligent algorithm, controller gains and simulation parameter should be considered in order to perform simulation work successfully. Figure 4.1 shows the schematic diagram representing the simulink model and proposed control scheme (Iterative Learning and Neural Network)

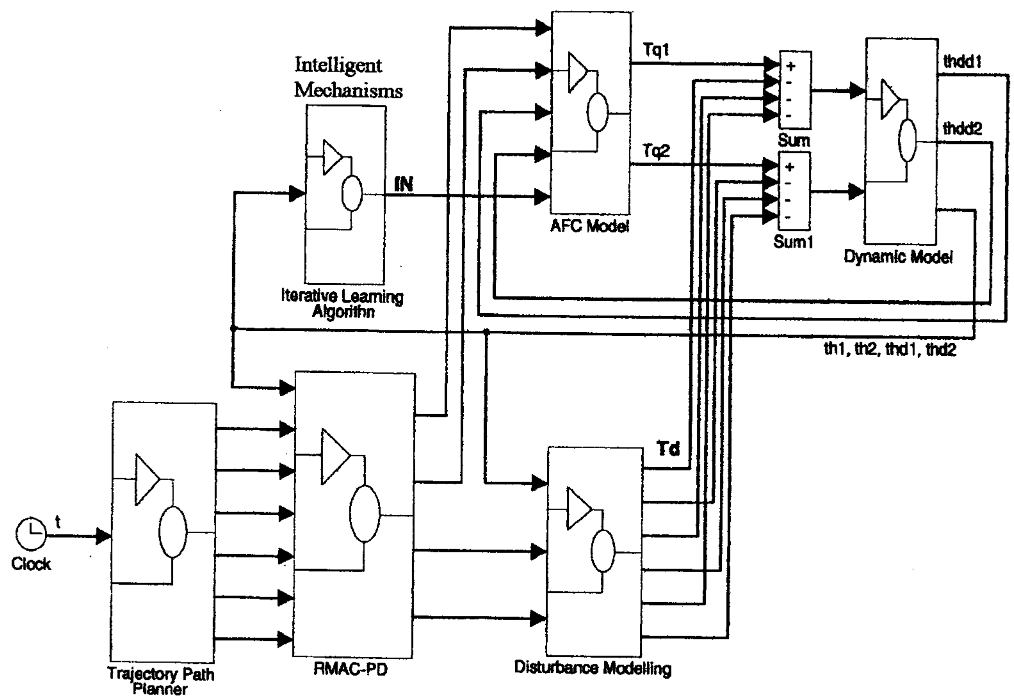


Figure 4.1 Simulink model of the proposed robot control scheme

4.2.1 Simulation Parameters

There are several important basic parameters, which are required to perform simulation process such as follows;

Robot parameters;

Link length: $l_1 = 0.25$m, $l_2 = 0.3236$m

Link mass; $m_1 = 0.3$kg, $m_2 = 0.25$kg

Motor mass: $mot_{11} = 1.3$ kg, $mot_{21} = 0.8$kg

Payload mass: $mot_{22}= 0.1$kg

Controller parameters:

Controller gain; K_p, K_d will be fined tuning

Motor torque constant: $K_{tn} = 0.263$ Nm/A

Base motor out torque(max): 245Nm

Elbow motor output torque (max): 40Nm

Iterative learning parameters:

Proportional term: $\Phi = 0.005$

Derivative term: $\Gamma = 0.0075$

Main simulation parameters:

Integration algorithm: Gear

Simulation time start, *tstart*: 0.0

Simulation time stop, *tstop* : Upon path trajectory

Minimum step size: 0.01

Maximum step size: 0.1

Other parameters:

Sampling time: 0.01s

Initial conditions: IN_1, IN_2 will be fined tuning

Endpoint tangential velocity: V_{cut} depends on path trajectory

4.2.2 Simulation Procedure

There are two stages in performing simulation process as follows;

1. Firstly, the parameter such as the controller gains, K_p and K_d, cutting velocity, V_{cut}, initial condition of estimated inertia matrix, IN_1, IN_2 and others mc, *lr,* eg of the control scheme will be adjusted to be satisfactorily tuned. Then, all the parameters value is fixed as initial setting condition.
2. Secondly, parametric changes are performed by choosing one of the above parameters followed by another parameters by applying external disturbances acting on the system

The method of the testing through parametric changes is based upon the load condition exerted on the robot control system such the following;

a. AFCAIL scheme for straight line trajectory.

- i. K_p =1500, 750, 300/s at zero load, 27N and 50N
- ii. K_d=700, 500, 250/s at zero load, 27N and 50N
- iii. IN_1= 0.5,0.1, 0.01 kgm2 at zero load, 27N and 50N
- iv. IN_2 = 0.1, 0.01 0.005 kgm2 at zero load, 27N and 50N
- v. V_{cut}= 1.0, 0.2, 0.03 m/s at zero load, 27N and 50N

b. AFCAIL for parabolic curve trajectory.

- i. K_p =50000, 5000, 750/s at zero load, 27N and 50N
- ii. K_d=500, 200, 150/s at zero load, 27N and 50N
- iii. IN_1= 0.5,0.1, 0.05 kgm2 at zero load, 27N and 50N
- vi. IN_2 = 0.5, 0.01 0.005 kgm2 at zero load, 27N and 50N
- iv. V_{cut} = 1.0, 0.2, 0.03 m/s at zero load, 27N and 50N

c. AFCANN for straight line trajectory.

i. K_p =1500, 750, 300/s at zero load, 27N and 50N

ii. K_d=700, 500, 250/s at zero load, 27N and 50N

iii. *lr*=0.56, 2.25, 9.0 at zero load, 27N and 50N

iv. *mc*= 0.375, 1.5, 6.0 at zero load, 27N and 50N

v. *eg* = 0.015, 0.06, 0.24 at zero load, 27N and 50N

vi. V_{cut} = 1.0, 0.2, 0.03 m/s at zero load, 27N and 50N

d. AFCANN scheme for parabolic curve trajectory.

i. K_p =50000, 5000, 750/s at zero load, 27N and 50N

ii. K_d=1000, 500, 300/s at zero load, 27N and 50N

iii. lr=0.56, 2.25, 9.0 at zero load, 27N and 50N

iv. *mc*= 0.75, 1.5, 6.0 at zero load, 27N and 50N

v. *eg* = 0.015, 0.06, 0.24 at zero load, 27N and 50N

vi. V_{cut} = 2.0, 1.0, 0.2 m/s at zero load, 27N and 50N

The results will be measured based on performance index through the trajectory track error. The trajectory error produced will reflect to the ability of AFC in term of make cancellation of error.

4.3 Deburring Process Parameter

In order to find the resultant force of deburring tool on the workpiece, the component of force in tangential and normal direction need to justify. Table 4.0 illustrates the value of coefficient of friction for different type of material. According to the study in [15], to remove burrs with width 1.14mm, it requires tangential force f_t, 25N

Thus, to find normal force, f_n

$$f_t = \mu f_n \tag{4.1}$$

The normal force, f_n = 25/0.6 = 42 N

Thus , the resultant force *Fr* that exerted on the deburring tool

$$f_r = \sqrt{(f_t^{\,2} + f_n^{\,2})}$$

$$f_r = \sqrt{(25^2 + 42^2)}$$

$$f_r = 48.88\ N$$

$$f_r \sim \mathbf{50\ N}$$

Table 4.1 : Coefficients of friction for different type of materials

Surfaces	Static coefficient	Kinetic
Steel on steel	0.7	0.6
Copper on steel	0.5	0.4
Glass on glass	0.9	0.4

Source ; W. Bolton- Engineering Science Book, Heinemann News, 1990

4.4 Grinding Process Parameter

For the purpose of study, the parameters were taken directly from the previous research in [20] where the desired normal force is f_n =15N and the grinding coefficient μ = 1.5. The tangential force, f_t can be obtained as

$$f_t = \mu f_n$$
$$f_t = 1.5 \times 15 = 22.5 \text{ N}$$

Thus, the resultant force f_r that exerted on the grinding wheel is

$$f_r = \sqrt{(f_t^2 + f_n^2)}$$
$$f_r = \sqrt{(22.5^2 + 15^2)}$$
$$f_r = \mathbf{27\ N}$$

4.5 The Prescribed Trajectory

There are two types of trajectories that will be carried out in this study. These became the reference trajectories in whichshould accurately track through the control strategy, given the end point tangential velocity. The trajectories are generated using time (t) dependent functions as mentioned in the following sections.

4.5.1 Straight Line Trajectory

The straight line trajectory can be represented by

$$X_{bar\ 1} = 0.35 - V_{cut}\ t\ x\ t \tag{4.2}$$

$$X_{bar2} = 0.20 + V_{cut}\ x\ t \tag{4.3}$$

where X_{bar} is the vector of the desired end effector position in Cartesian space while V_{cut} is the endpoint tangential velocity.

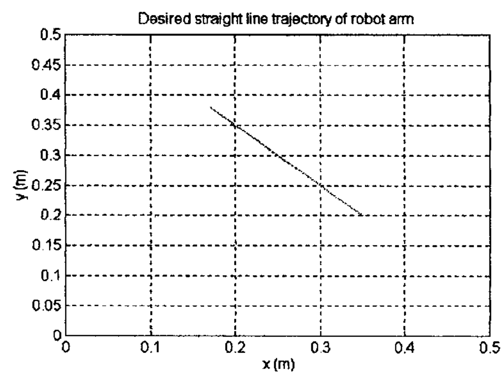


Figure 4.2: The desired straight line trajectory of the robot arm

4.5.2 Parabolic Curve Trajectory

The parametric representation of a parabolic curve as described in [18] is

$$X_{bar1} = 0.35\text{-}0.07(V_{cut}\ x\ t) \tag{4.4}$$

$$X_{bar2} = 0.20+[-0.09375(V_{cut}\ x\ t)^2]+0.1875(V_{cut}\ x\ t) \tag{4.5}$$

where X_{bar} is the vector of the desired end effector position in Cartesian space while V_{cut} is the endpoint tangential velocity. Fig 4.1 shows the desired parabolic curve trajectory

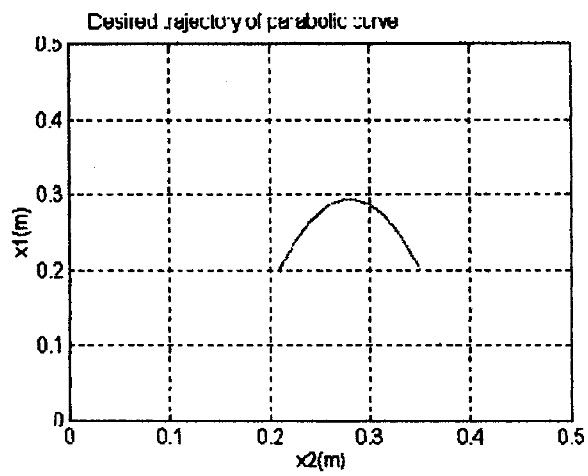


Figure 4.3: The desired parabolic curve trajectory of the robot arm

4.6 Conclusion

The essential parameters of simulation parameter, process parameter and trajectory, which involved in this simulation, are presented clearly. The resultant force is a guideline for estimating appropriates force disturbances to be applied on the system. Beside that this value is also important to measure the range of external disturbances

CHAPTER V

RESULTS AND DISCUSSION

5.0 Introduction

This chapter describes the outcomes from the simulation study. The results will be focused on the trajectory track performance. Since trajectory track error reflects to the robustness's performance, a comparative study will be carried out on the behaviour of each control strategy in the presence of disturbances.

5.1 Result Analysis

The performance of the proposed control schemes can be evaluated by considering the trajectory track performance of the arm under grinding and deburring force conditions. There are four categories of results, which are consisting of straight line and parabolic curve trajectories for AFCAIL scheme and AFCANN scheme respectively. Three types of disturbances (zero load, grinding force, 27 N, and deburring force 50N) are modelled. The details result can be referred to Appendix A, B, C and D. Firstly, simulation process is performed without load exerted on the system. Since the parameters are properly tuned, the following parameter's values as shown in Table 5.1

are selected as a setting conditions. For the next stage, the system is tested with different parameters value at each disturbance forces to gain the effects of the parametric changes on the system.

Table 5.1: The setting conditions of simulation parameter

Parameter	**Straight line trajectory**			**Parabolic curve trajectory**		
	PD control scheme	**AFCAIL scheme**	**AFCANN scheme**	**PD control scheme**	**AFCAIL scheme**	**AFCANN scheme**
V_{cut}	0.03 m/s	0.03 m/s	0.03m/s	1.0 m/s	1.0 m/s	1.0 m/s
K_{p1}	750	750	750	50,000	50,000	50,000
K_{p2}	750	750	750	50,000	50,000	50,000
K_{d1}	500	500	500	500	200	500
K_{d2}	500	500	500	500	200	500
IN_1	0.0kgm^2	0.1kgm^2	0.1kgm^2	0.0kgm^2	0.1kgm^2	0.1kgm^2
IN_2	0.0kgm^2	0.01kgm^2	0.01kgm^2	0.0kgm^2	0.01kgm^2	0.01kgm^2
t	6 seconds	6 seconds	5 seconds	2seconds	2 seconds	2 seconds
lr	-	-	2.25	-	-	2.25
mc	-	-	1.5	-	-	1.5
eg	-	-	0.06	-	-	0.06

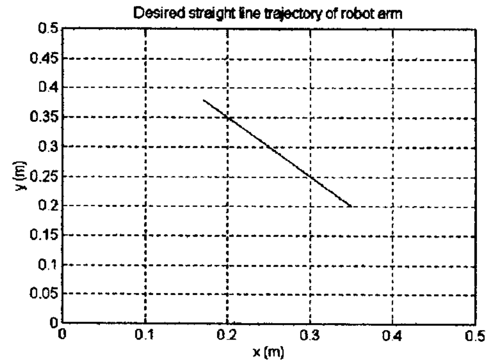
5.2 Trajectory Track Performance

The trajectory path of the robot arm consists of two types, which is straight line and parabolic curve. Nevertheless, a robot control system should always remain robust and stable in performance during tracking the desired trajectory even in the presence of any disturbances. In order to measure and assessing the robustness of the robot control system, the obtained results(Trajectory Track Error-TTE for each scheme) will be compared with PD type scheme, also called benchmark' of the result at the end of this discussion.

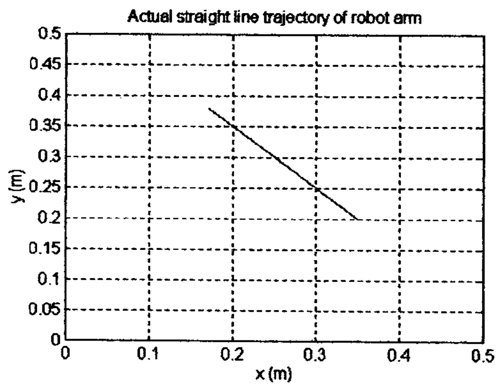
5.2.1 Straight Line Trajectory with AFCAIL Scheme

AFC strategy and Iterative Learning (AFCAIL scheme) offers great improvement in tracking of desired path trajectory. The effectiveness of the Iterative Learning control strategy is obvious at the initial stage where track error converges to zero. It means, this control technique is able to eliminate or make cancellation of any disturbances through compensating action. As seen in the Figure 5.1, the result shows that the arm is able to follow the desired trajectory satisfactorily in free condition.

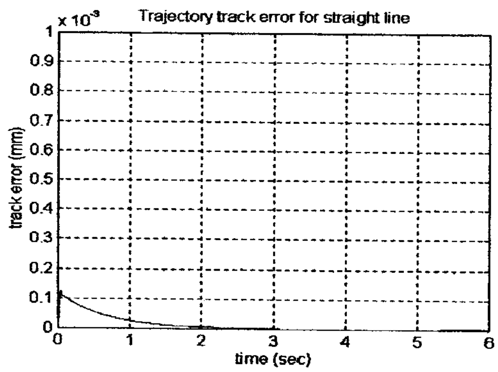
It be noted that in term of trajectory track performance , the system is stable and robust even in the presence of external disturbances such as grinding force and deburring force with load of 27N and 50N respectively as shown in Figure 5.2, Although, there is overshoot at the initial starting, it is found that there is no objection to robot arm to perform the task successfully.



a) Desired trajectory

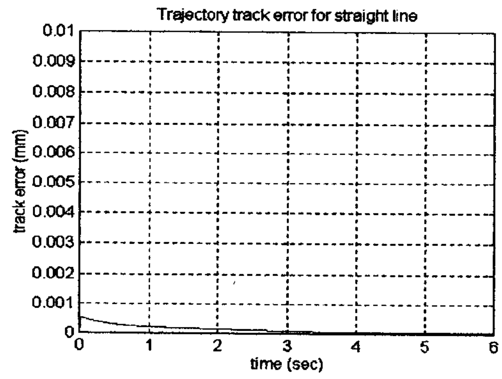


b) Actual trajectory

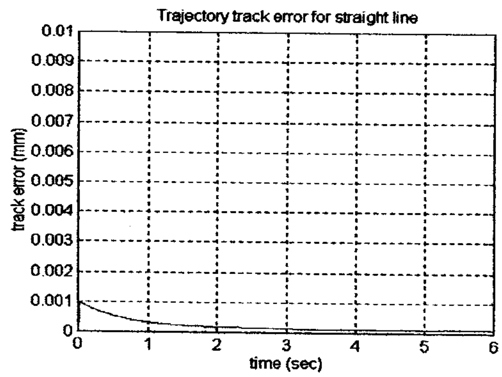


c) TTE

Figure 5.1: Graphs for straight line with zero load (AFCAIL scheme)



a) Grinding force, 27N



b) Deburring force, 50N

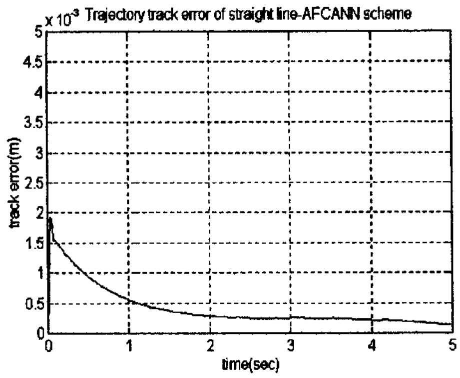
Figure 5.2: TTE for straight line with disturbance forces (AFCAIL scheme)

5.2.2 Straight Line Trajectory with AFCANN Scheme

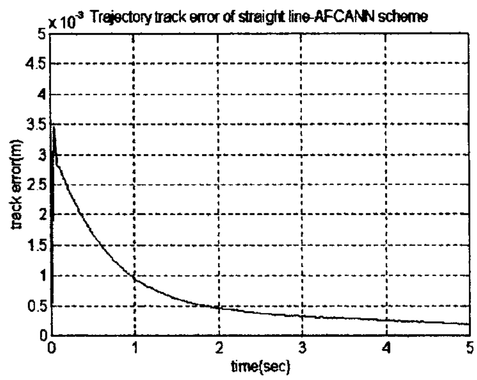
Meanwhile, for AFCANN scheme, there are some additional parameters involved in this task such as learning rate *lr*, momentum constant *mc*, and error goal *eg*, instead of other basic parameters. This scheme has proven which is able to reduce the trajectory track error. However the scheme will be more effective by providing more training on the system. The training constituting the pair of data by means the joint angles being the input while the inertia matrix becomes the output. The more training is performed, the more accurate of desired path is produced. Figure 5.3 exhibits the actual and desired trajectory of robot arm and also the track error behavior during the simulation process. The track error for both conditions whenever different load is acting on the system exhibits slightly higher than free load condition but then it reduced to the smaller value as shown in Figure 5.4

5.2.3 Parabolic Curve Trajectory with AFCAIL Scheme

This kind of trajectory is requiring holistic tuning in order to get appropriate parameter values at the optimum performance. Then, the system is tested similar with the previous method. Basically the parameter such as proportional and derivative gain, K_p and K_d are having major influences in the tracking of the desired parabolic curve path compared to the rest parameters are not much contribute to it. It be noted that the approximation of both K_{p1} and K_{p2} value require up to 50000/s in order to replicate the desired trajectory and it inevitably. In this task, AFCAIL scheme demonstrates the ability to follow the desired path; it is considered stable and robust. It can be seen in the Fig. 5.5 and 5.6 where overshoot error at the initial starting of trajectory tracking, the error only 0.6mm at zero load, 0.8 at load 27N and followed by 1.0mm at load 50N.

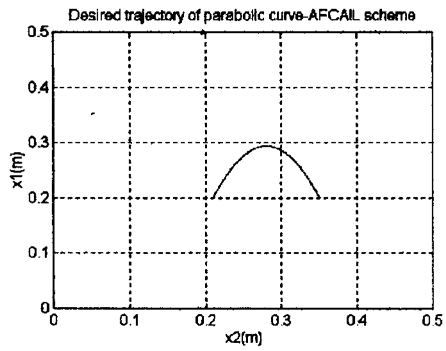


a) Grinding force, 27N

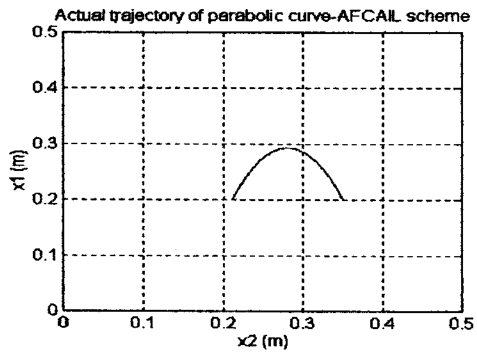


b) Deburring force, 50N

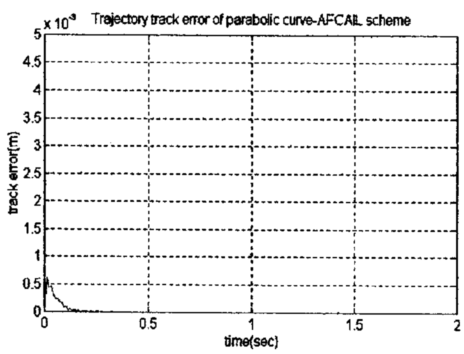
Figure 5.4: TTE for straight line with disturbance forces (AFCANN scheme)



a) Desired trajectory

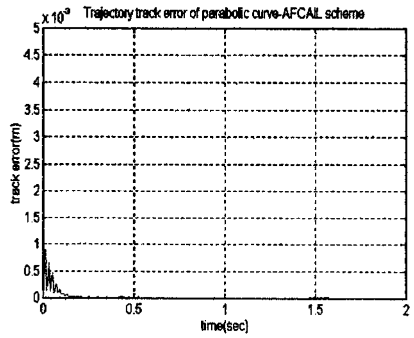


b) Actual trajectory

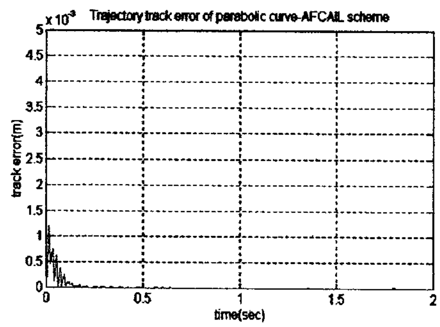


c) TTE

Figure 5.5: Graphs for parabolic curve with zero load (AFCAIL scheme)



a) Grinding force, 27N



b) Deburring force,50N

Figure 5.6: TTE for parabolic curve with disturbance forces (AFCAIL scheme)

5.2.4 Parabolic Curve Trajectory with AFCANN Scheme

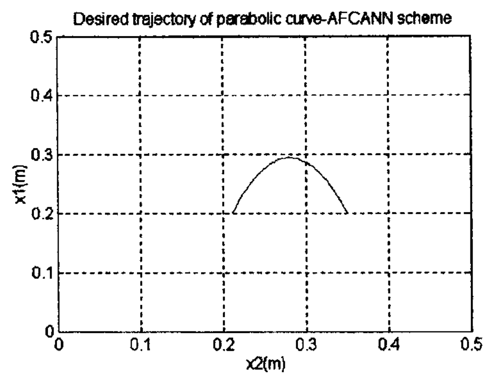
It has to be noted that the approach is similar to the AFCAIL scheme where main parameters such as K_p and K_d give great influences on the track error.
One difference is that in this case the value of K_d =200/s while AFCAIL scheme used K_d=500/s. After trial and error, its found that there is no much effect of other parameters like learning rate *lr*, error goal *eg*, and momentum constant *mc* on the track error.

Since all parameters have to be properly tuned, the track error shows improvement. By referring to Figure 5.7 and 5.8 eventhough there is overshoot track error at the initial phase, about 0.8mm at zero load, 1.0mm at 27 N and 1.5mm at 50N respectively, but it gradually decreased. This condition shows that this scheme have a fast response characteristic on any disturbances

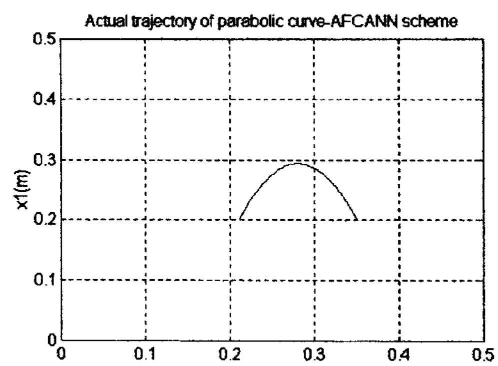
5.3 Comparative Study between AFC Based Scheme and PD Control Scheme.

The distinction between the each robot control strategy can be verified through observation onto the following graphs. As shown in Figure 5.9 and Figure 5.10,the track error for both trajectories (straight-line and parabolic curve) exhibits inconsistent condition at the initial phase but latter it gradually reduced as the time increases. This demonstrates that AFC based scheme through AFCAIL and AFCANN are able to absorb the presence of disturbances through compensating action.

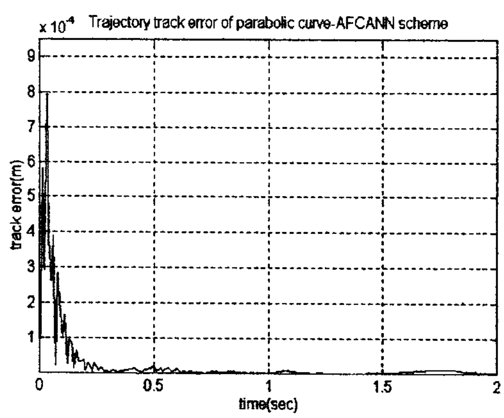
In contrast, it differs to PD control scheme, where the graph of track error is increases with time. Since the magnitude of track error become larger, error compensation become more critical in obtaining the stable condition. This shows the draw back of PD control scheme in accommodating the disturbances.



a) Desired trajectory

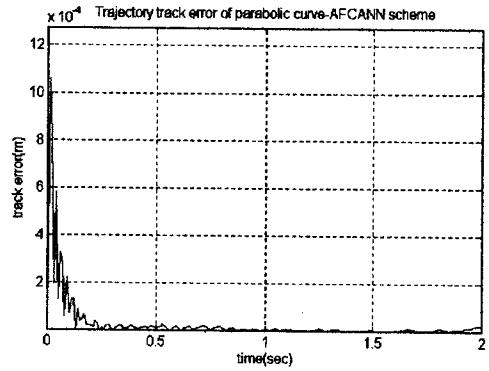


b) Actual trajectory

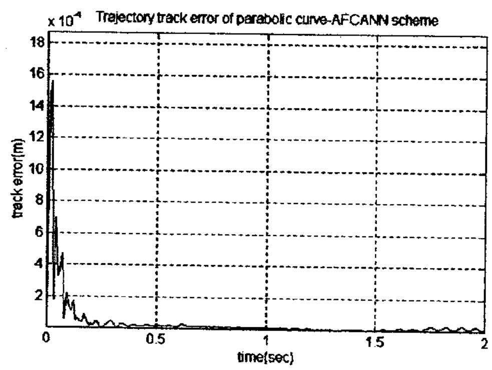


c) TTE

Figure 5.7: Graphs for parabolic curve with zero load (AFCANN scheme)

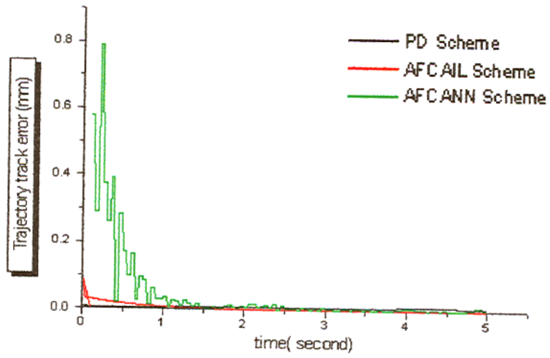


a) Grinding force,27N

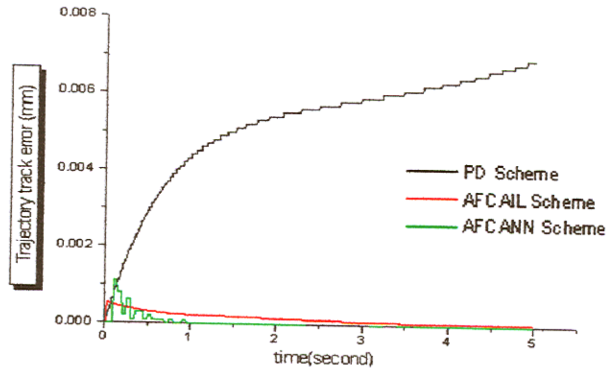


b) Deburring force, 50N

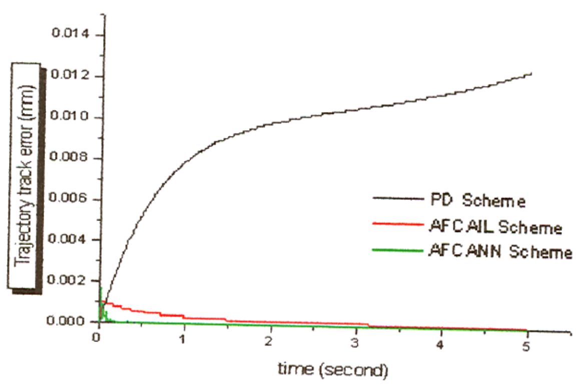
Figure 5.8: TTE for parabolic curve with disturbance forces for AFCANN scheme



a) Zero load

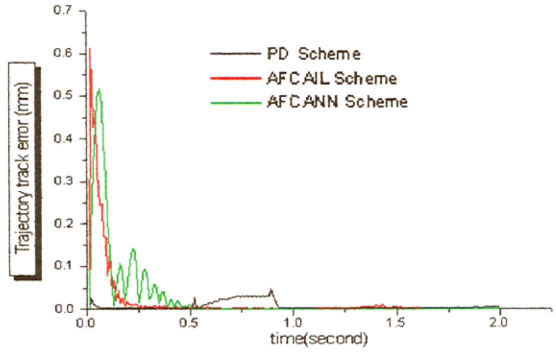


b) Grinding force, 27N

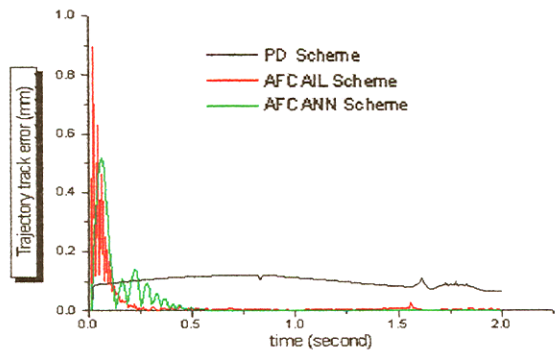


c) Deburring force, 50N

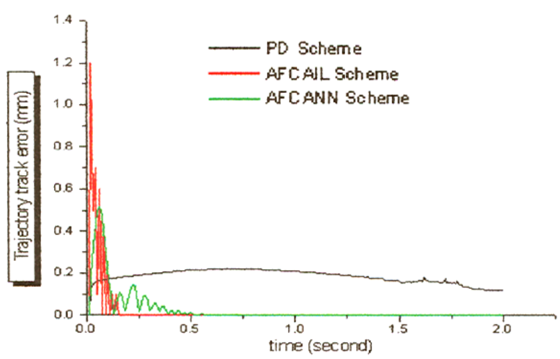
Figure 5.9: Various conditions of track error for straight line trajectory of each control strategy



a) Zero load



b) Grinding force, 27N



c) Deburring force, 50N

Figure 5.10: Various conditions of track error for parabolic curve trajectory of each control strategy

5.4 The Effect of Disturbance Forces and Parameter Variation.

Essentially, the function and the effects of all parameter should be explored explicitly. At the same time this is also as a guideline to improve the robot control performance.Furthermore, by performing parametric changes on the system, the behavior of the system can be verified. Appendix A, B,C and D clearly shows the behavior of robot control system. Here, the effects of disturbance forces and parameter variation on the system for AFCAIL and AFCANN scheme are as follows;

a. Proportional and derivative gain, K_p and K_d

It's a major influence in the error growth during robot arm tracking of the path. The higher of K_p, the tracking error at the initial phase is increased. Its can be seen whenever load is applied to the system. This is also similar to the parameter of K_d.

b. Cutting velocity, V_{cut}

The higher the speed of V_{cut}, the more error will occur. The appropriate value must be identified to minimize the error.

c. Initial condition, IN_1 and IN_2.

Basically, for AFCAIL scheme IN_1 must be greater than IN_2. Appropriate value must be approximate by trial and error such as in this task where IN_1 and IN_2 are 0.1 and 0.01kgm^2 respectively.

d. error goal *eg*, learning rate *lr*, and momentum constant *mc*

Generally, there is not much effect to the system. In other word, these parameters are not too critical but cannot be omitted.

e. Disturbance forces

The higher of force exerted to the system, the track errors is increased but it reduced instantly by compensating action characteristic.

5.5 The Trajectory Track Error

The surface finishing processes forces applied to the system have indeed a great influence on the tracking performance of the robot arm. The deviation between the actual and desired trajectory can be evaluated through observing of the track errors generated by the schemes. In general, the trend of error shows that it tends converging to zero with time whenever load is exerted to the system. But, the increasing of load of disturbances for each trajectories has different effects on the average track errors. It is proven as shown in the Table 5.2. Basically, the average track error obtained from both AFC based control schemes with disturbances is found to be higher than those without disturbances

However, from overall observation, even AFCAIL scheme is better than AFCANN scheme, both AFC schemes had indicated impressive results as shown in Table 5.3. For example, through AFCAIL scheme, it produces the lowest average track error; 0.001mm, 0.07mm and 0.14mm at different load conditions for straight line trajectory and 0.004mm, 0.005, and 0.008mm for parabolic curve. All of these represents 85.7%, 98.8% and 98.6% of reduction percentage of ATE for straight line and 42.9%, 95.0% and 94.4% for parabolic curve respectively.

Beside that, through AFCANN, this scheme also states low track errors; 0.007mm, 0.12mm and 0.20mm which represents 0%, 97.9% and 98.0% for straight line, while 0.007mm, 0.008mm, 0.010mm which represents 0%, 92% and 94.4% for parabolic curve. All of these values are compared with the benchmark control scheme – PD type control scheme. In other words, AFCAIL and AFCANN scheme shows great improvement in eliminating of error occurs during trajectory tracking task. Thus, we can say that AFC through AFCAIL and AFCANN schemes have proved that they are more stable and robust at any disturbance conditions.

Table 5.2 ; The Average Track Error for the AFCAIL, AFCANN and PD control schemes

Disturbance	Average Track Error, ATE (mm)					
	Straight line			Parabolic curve		
	AFCAIL	AFCANN	PD	AFCAIL	AFCANN	PD
Zero load	0.001	0.007	0.007	0.004	0.007	0.007
Grinding force, 27 N	0.07	0.12	5.6	0.005	0.008	0.10
Deburring force, 50 N	0.14	0.20	10.2	0.008	0.010	0.18

Table 5.3 ; The reduction percentage of Average Track Error

Disturbance	Reduction of Average Track Error (%)			
	Straight line		Parabolic curve	
	AFCAIL	AFCANN	AFCAIL	AFCANN
Zero load	85.7	0.0	42.9	0.0
Grinding force, 27 N	98.8	97.9	95.0	92.0
Deburring force, 50 N	98.6	98.0	95.6	94.4

5.6 Conclusion

Techniques for investigating the robustness of AFC strategy has been presented. An analysis on the results from different loading and parametric changes showed that the proposed control scheme was not only verified, but also has been compared with the convensional method PD counterpart. The overall performance clearly shows that the capability of AFC based scheme through AFCAIL and AFCANN scheme on accommodating the disturbances has been proven.

CHAPTER VI

CONCLUSION

6.1 Conclusion

In general, the objectives of this study have been achieved. This study is an effort to simulate the real manufacturing processes by employing Active Force Control strategy. The approach of such robot control system is applied into surface finishing processes to explore the capabilities of the system performance whether it is adaptable and applicable at any conditions of environments.

Referring to the simulation results, it exhibits significant improvement. The trajectory track errors obtained are reasonably small showing the excellent capabilities of AFCAIL and AFCANN scheme to accommodate all the disturbances. Thus, simulation results show much improved performance of the proposed control strategy-AFC for both grinding and deburring operations in terms of robustness of the system itself.

6.2 Suggestions for Future Works

This type of control strategy is beneficial if it can be applied widely in industrial application or manufacturing processes sector. It demonstrates great results in such manufacturing processes. Furthermore, the robustness of the performance can be tested and verified effectively. However, for future work, there are several criterions should be considered in order to gain excellent result as proposed bellows;

a. To conduct experimental work as well as simulation study for a comparative purposes.

b. To perform various trajectories such as complicated shapes in order to obtain excellent results.

c. To focus on heavy manufacturing processes activities especially those involving high load of disturbances. This will prove that the AFC is applicable for any job or tasks.

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