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A SURVEY OF CONTROLLER DESIGN METHODS FOR A ROBOT MANIPULATOR IN HARSH ENVIRONMENTS

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ABSTRACT

The rate of deployment of robots in the industries is highly increasing day by day and many of these robots are located to work in harsh environments such as deep waters. The controller is a vital subsystem of the robot manipulator system that is designed to help the system achieve stability, good disturbance rejection and minimum tracking error. There are many research works carried out on the robot arm controller design. Majority of these works as reviewed, focused more on the performance of the robot arm in terms of rise time, settling time and overshoot, with little study on the robustness of the control system. This research work focuses on the survey on controller design methods for a robot manipulator that can perform optimally in harsh environments. Proportional-Integral-Derivative (PID) controller tuning methods such as the manual, Ziegler Nichols, software tool, fuzzy logic, Genetic Algorithm (GA), and the Artificial Neural Network (ANN) methods were reviewed. From the review, it was concluded that it is difficult to achieve optimal performance using manual and Zeigler Nichols methods. Fuzzy logic, GA and ANN methods can be used to achieve desired optimal performance but they lack the parameters to evaluate the disturbance rejection settling time which helps to determine how fast the system can cancel or reject disturbance in harsh environments. On the other hand, the software tool method using PID tuner can be used to achieve the desired performance and good disturbance rejection settling time which satisfies the goal of the design.

Keywords: Robot Manipulator, Controller, PID, Control System, Robustness.

INTRODUCTION

The position control system also known as robot manipulator is a control system that is capable of controlling the movement of a robot arm from one position to another accurately. The robot manipulator is a closed-loop control system with other subsystems namely: Direct Current (DC) motor, the position control plant, the feedback, and the controller. Most industrial processes are presently carried out by the position control system whereby the human operators can remotely monitor the progress of work, reprogram or disable the machine from a distance through a computer. Position control system has also taken over in the marine work by the use of Under Water Vehicles such as Remotely Operated Vehicle (ROV) used by most oil industries in their oil exploration works in the ocean and other deep waters. Most of these position control systems work under harsh conditions and experience varied workloads which can result to system failure (fault) if the control system does not cancel the effects of possible faults.

According to Farhan (2013), motion control is a sub-field of control engineering, in which the position or velocity of a given machine are controlled using some type of actuating device. Most used actuating devices in mechatronics applications are electric actuating machines such as DC motors. The movements of a robot manipulator are based on possible Degrees of Freedom (DOF) it is capable of completing. The DOF depends on the number of the actuators used to complete the different movements. In the five DOF (five functions) robot arm, each movement or DOF has a DC motor (Kumar and Raja, 2014) and a controller attached to it. A control system is said to be closed loop if the current output is taken into consideration and corrections are made based on feedback. The basic closed loop control subsystems are: reference input, controller, plant, measured output (actual output), transducer (or sensor) (Norman, 2011; Tarek et al).

Controller is a device which can sense information from linear or nonlinear system (e.g., robot manipulator) to improve the systems performance (Kurfess, 2005; Slotine et al, 1991; Ogata, 2009; Cheng et al, 2008). The main targets in designing control systems are stability, good disturbance rejection, and small tracking error (D'Azzo et al, 2003; Siciliano et al, 2008). The controller helps to achieve these design targets of the control system. Several industrial robot manipulators are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional- Integral-Derivative (PID) controller) (Farzin et al, 2012). According to Fallahi et al, (2011), the proportional-integral-derivative (PID) controller is widely used in many control applications because of its simplicity and effectiveness. The use of PID control has been a long history in the field of control engineering, the three controller gain parameters, proportional gain K_P, integral gain K_I, and derivative gain K_D, are usually fixed. The disadvantage of the fixed PID controller is poor capability of dealing with system uncertainty, i.e., parameter variations and external disturbance. To solve this problem the PID tuning method was introduced. Skogestad (2001) justified the use of PID controller by saying that hundreds, if not thousands, of papers have been written on tuning of PID controllers, and one must question the need for another one. The justification is that PID controller is by far the most widely used control algorithm in the process industry, and that improvements in tuning of PID controllers will have a significant practical impact. There are different types of PID tuning methods for designing controller for a control system. Youns et al, (2013) applied the Genetic Algorithm (GA) method to tune the PID gains and the control system performance was optimized but the method lacks the parameters to determine the disturbance rejection capability. Kumar and Raja (2014) employed the fuzzy logic method to tune the PID gains for controller design, from their results, the control system was optimized but the steady state error value was not zero and they did not determine the settling time of the step disturbance rejection. Muhammad (2013) used Artificial Neural Network (ANN) to design a controller for a position control system and the system produced desired performance but also lacked the parameters to study the exert robustness capability of the system.

The aim of designing a controller for robot manipulator that can operate optimally in harsh environments is good performance and robustness with zero steady state error and minimum disturbance rejection settling time. The goal of robust control system design is to retain assurances of system performance in spite of model inaccuracies and changes. A system is robust when the system has acceptable changes in performance due to model changes or inaccuracies (Dorf and Bishop, 2008). The disturbance rejection is used to test the robustness (Piltan et al, 2012) of a controller. Hence, a controller is robust when it can achieve zero steady state error, minimum disturbance rejection settling time and other desired performance for the control system. Robust control for robot manipulators is a typical control scheme to achieve good tracking performance in the presence of model uncertainties such as an unknown payload and unmodeled friction (Abdallah et al, 1991; Sage et al, 1999).

Many of the existing researches carried out on controller design for the robot arm focused more on the performance of the control system but discussed little or not on the robustness of the system. Secondly, none of the available research works studied or evaluated the disturbance rejection settling time which determines how fast the system can reject or cancel disturbances. Since some robots are assigned to work at extreme environmental conditions such as the ROVs which operate against ocean waves and the recently unveiled adult-size firefighting robot (Perlamo, 2015), there is need to study the controller design methods that can achieve good performance and robustness of the system in harsh environments.

ROBOT MANIPULATOR

The robot manipulator or position control system uses DC motor as its actuator as illustrated in figure 1. Direct Current (DC) motors are often used in various industrial applications where a wide range of responses are required to follow a predetermined trajectory of speed or position under variable load (Faramarzi & Sabahi, 2011). According to Farhan (2013), single joint robot arm system consists of three parts; arm, connected to actuator through gear train with gear ratio, n. The robot arm is not affected by gravity and rigid. The dynamic behaviors of the robot arm control system are given by the following equations (Phillips et al, 1996).

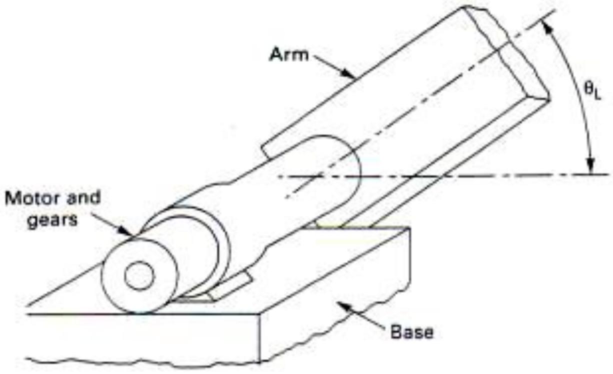

Figure 1: Single-Joint Robot Arm (Youns et al, 2013)

$$e_a = R_m i_a(t) + L_m \frac{di_a(t)}{dt} + e_m(t) \qquad \text{i}$$

$$e_m = K_m \frac{d\theta_m(t)}{dt} \qquad \text{ii}$$

$$T_m = K_T i_a(t) \qquad \text{iii}$$

$$T_m = J \frac{d^2\theta_m(t)}{dt^2} + B \frac{d\theta_m(t)}{dt} \qquad \text{iv}$$

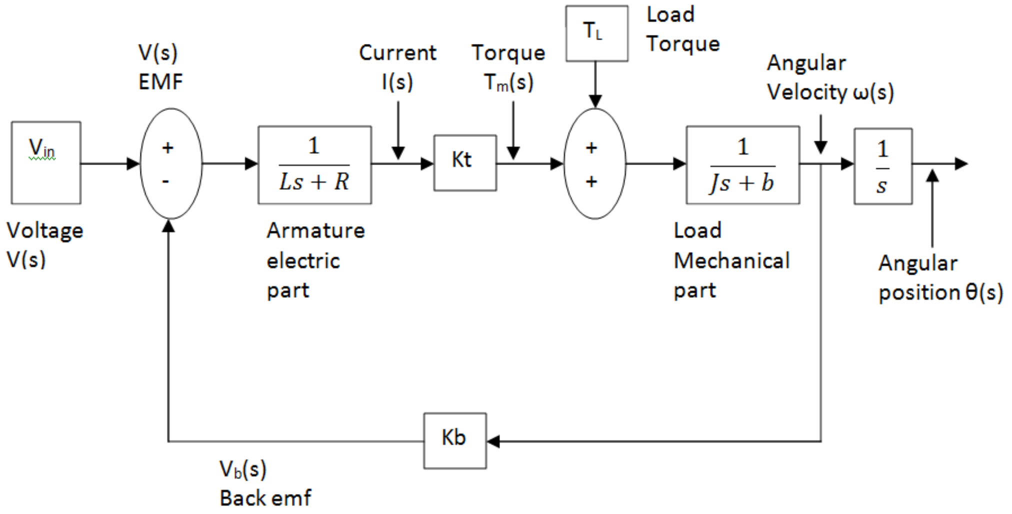

Figure 2: Position Control Plant model relating the input voltage to angular position

After simplification as illustrated in figures 2 assuming Load Torque, T_L is zero and taking the ratio of $\theta(s)/V_{in}(s)$ the transfer function becomes:

$$G_{position} = \frac{\theta(s)}{V_{in}(s)} = \frac{K_T}{JL_m s^3 + (R_m J + BL_m)s^2 + (K_T K_m + R_m B)s} \qquad \text{v}$$

Where;
R_m = armature- winding resistance in ohm
L_m = armature - winding inductance in Henry
i_a = armature - winding current in ampere
e_a = armature voltage in volt
K_m = back emf constant in volt / (rad/sec)
K_T = motor torque constant in N.m/A
J = moment of inertia of motor and robot arm in kg^2 m /rad
B = viscous - friction coefficient of motor and robot arm in N.m/rad /sec
θ = angular displacement of the motor shaft in rad
n = gear ratio N_1/N_2

The position control system is a closed-loop control system which utilizes an additional measure of the actual output to compare the actual output with the input (desired output) response as shown in figure 3. The H(s) is the feedback sensor gain. In this case the sensor is the potentiometer. The measure of the actual output is called the feedback signal. Feedback control system is a control system that tends to maintain a prescribed relationship of one system variable to another by comparing the functions of these variables and using the difference called error signal, as a measure of control. With an accurate sensor, the measured output is a good approximation of the actual output of the system.

The transfer function of the simple closed-loop control system is given as follows:

$$Tf = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)H(s)} \qquad \text{vi}$$

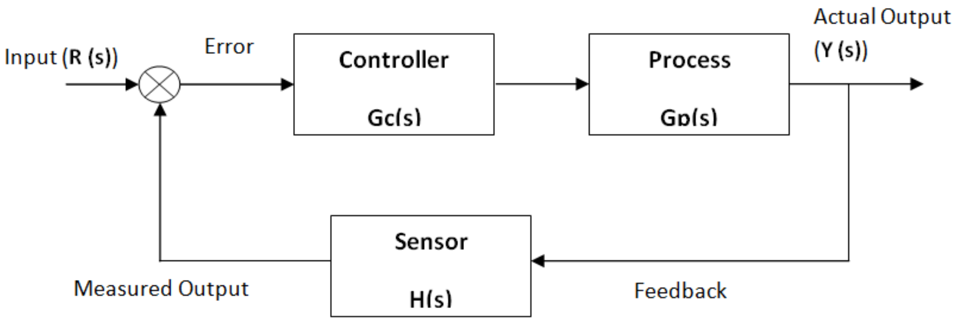

Figure 3: A block diagram of a closed-loop control system

CONTROLLER DESIGN

Many research attempts have come up with different controller design strategies such as the PID controller tuning, Artificial Neural Network (ANN) controller, sliding mode controller etc. The Proportional–integral–derivative (PID) controllers undoubtedly play an important role in process industries. More than 95% of the industrial controllers are of the PID type (Astrom and Hagglund, 2005). However, due to the inability of the fixed PID controller to handle uncertainties and produce optimal control performance, the PID tuning methods such as the manual, Ziegler Nichols, software and algorithmic methods were introduced to address the problem. PID controller is widely used in feedback control of industrial processes on the market in 1939 and has remained the most widely used controller in process control until today (Kambiz and Augustin, 2012). According to Muhammad (2013) PID control uses three mathematical control functions and applies them to input signals for desired outputs. Proportional value determines the response of the system towards current error. Integral value fastens the response introduced by proportional factor. However, increasing value of integral part makes the system to oscillate with overshoots. Derivative part reduces the overshoots introduced by integral part. However, increasing value of derivative control makes the response slow.

The PID controller gave rise to another three controllers which can be combined depending on the desired results namely, Proportional Controller (PC), Integral Controller (IC), Derivative Controller (DC). The role of a proportional depends on the present error, Integral (I) on the accumulation of past error and Derivative (D) on prediction of future error. Table 1 shows the effects of each controller gain K_P, K_I and K_D on the control system output response.

Table 1: PID controller in a closed-loop system (Kambiz and Augustin, 2012)

Parameters	**Rise Time**	**Overshoot**	**Settling Time**	**Steady State Error**
K_P	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	decrease Significantly
K_D	Minor decrease	Minor decrease	Minor decrease	No effect in theory

The proportional term is given by:

$$P = K_P.error(t) \qquad \text{vii}$$

The integral term is given by:

$$I = K_I \int_0^t error(t)dt \qquad \text{viii}$$

The derivative term is given by:

$$D = K_D \frac{derror(t)}{dt} \qquad \text{ix}$$

The PID controller mathematical function becomes:

$$G = K_P\left(1 + \frac{1+T_I.T_D.S^2}{T_I.S}\right) = K_P\left(1 + \frac{1}{T_i s} + T_D s\right) \qquad \text{x}$$

where K_P is the proportional gain, T_I is the integral time constant, T_D is the derivative time constant, $K_I = K_P / T_I$ is the integral gain and $K_D = K_P/T_D$ is the derivative gain. Figure 4 illustrates the PID three term functions. The transfer function of the PID controller is given as:

$$G(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{S} + K_D s = \frac{K_D S^2 + K_P S + K_I}{S} \qquad \text{xi}$$

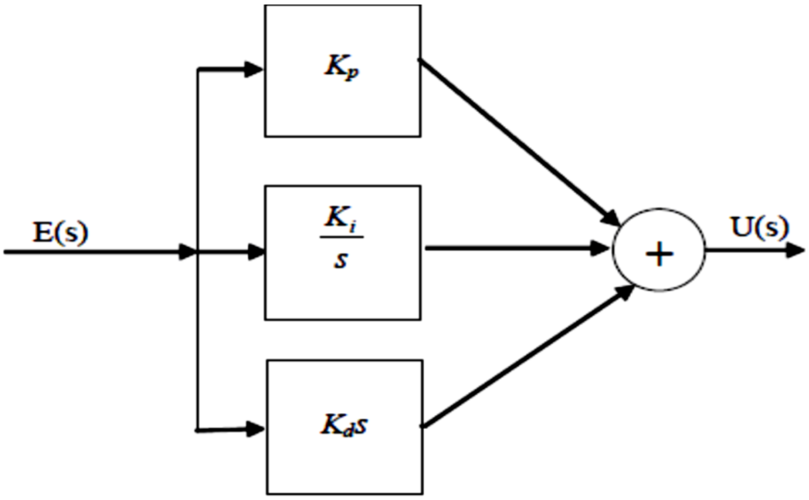

Figure 4: Parallel Form of the PID Compensator (Kambiz and Augustin, 2012).

REVIEW RESULTS

The control system performs poor in characteristics and even it becomes unstable, if improper values of the controller tuning constants are used. So it becomes necessary to tune the controller parameters to achieve good control performance with the proper choice of tuning constants. Controller tuning involves the selection of the values of K_P, K_I and K_D (Youns et al, 2013). Table 2 presents the summary of five tuning methods for a PID controller with their respective advantages and disadvantages (Barbosa et al, 2003; Barbosa et al, 2004).

Table 2: Summary of five tuning methods

Methods	**Advantages**	**Disadvantages**
Manual	Online method No math expression	Requires experienced personnel
Ziegler-Nichols	Online method Proven method	Some trial and error, process upset and very aggressive

		tuning
Cohen-Coon	Good process models	Offline method Some math Good only for first order processes
Software tools	Online or offline method, consistent tuning, Support Non-Steady State tuning	Some cost and training involved
Algorithmic	Online or offline method, Consistent tuning, Support Non-Steady State tuning, Very precise	Very slow Complex

Manual or Traditional Method: This method involves choosing the P-I-D controller gains and varying the gain values at each trial for a good result output. The method can be implemented using MATLAB codes on an m.file or SIMULINK. The method does not allow flexibility in varying the PID controller gains to produce the desired output. Therefore, this method does not support robust controller design. Farhan (2013) used the manual method with the m.file in the controller design for robot arm position control system, and from his results the method did not give the desired results.

Zeigler-Nichols Method: The Ziegler–Nichols tuning method is a heuristic method of tuning a PID controller. It was proposed by John G. Ziegler and Nichols in the 1940's. It is performed by setting I (integral) and D (derivative) gains to zero. The P (proportional) gain, K_p is then increased (from zero) until it reaches the ultimate gain Ku, at which the output of the control loop oscillates with a constant amplitude. K_u and the oscillation period T_u are used to set the P, I, and D gains depending on the type of controller used (Barbosa et al, 2004; Maiti et al, 2008). Youns et al (2013) used Ziegler-Nichols tuning method to design a controller for robot arm. From their result, the rise time was about 0.2 sec, Maximum overshoot of the system was approximately 23.9 % and settling time as about 2 sec (Ogata, 2003). They concluded that the system was not tuned to its optimum since it did not meet the desired performance.

Genetic Algorithm Method: Genetic Algorithm (GA) is a stochastic algorithm based on principles of natural selection and genetics. It is a global search method that mimics the process of natural evolution. The implementation of the genetic algorithms tuning procedure starts with the definition of the chromosome representation. The chromosome is formed by three values that correspond to the three gains to be adjusted in order to achieve a satisfactory behavior. The gains K_P, K_I and K_D are real numbers and characterize the individual to be evaluated (Varsek et al, 1993). In the GA method used by Youns et al (2013), the step response under PID controller was better in terms of minimizing the max overshoot to 5.58 %, the rise time to 0.2614 sec and the settling time to 0.7564 sec compared with the Ziegler Nichols method. However, this work lacked the parameters to study the disturbance rejection of the control system therefore; it did not determine the robustness of the controller to handle uncertainties.

Software Tool Method: This method uses PID tuner in SIMULINK that allows a designer to adjust the response time which automatically tunes the values of the PID controller gains to generate the desired step responses which can be used to study the behavior of the control system. The PID tuner evaluates the performance and robustness parameters such as rise time, settling time, overshoot, peak, gain margin, phase margin and steady state error. It also generates the disturbance rejection response where the disturbance rejection settling time is studied. Farhan (2013) employed the SIMULINK PID tuner and from his results, the PID tuner achieved desired performance. But his work did not study step disturbance rejection settling time to determine how fast the controller can reject disturbances.

Fuzzy Logic Control Method: Fuzzy Logic Control (FLC) is a nonlinear mapping of an input data vectors into a scalar output (the vector output case decomposes into a collection of independent multi-input/single output systems). The richness of Fuzzy Logic (FL) is that there are enormous numbers of possibilities that lead to lots of different mappings (Mendel, 1995). FLC has four main components: the fuzzifier, knowledge base, inference mechanism and defuzzifier (Sreenatha and Makarand, 2002). Based on membership functions and fuzzy logic, the fuzzifier converts a crisp input signal to fuzzified signals. The knowledge base houses rule base and the data base. The inference mechanism fires relevant control rules and then decides what the input to the plant should be. Finally the defuzzification process converts the fuzzy output into crisp control signal. Kumar and Raja (2014) applied FLC method and from their results, the fuzzy logic control achieved better performance for tuning the PID gains than conventional tuning methods in terms of eliminating overshoot, rise time and steady state error. However, this design method did not achieve a zero steady state error for the disturbance rejection. Secondly, it did not evaluate the disturbance rejection settling time.

Artificial Neural Network: This is a computational model inspired by the natural neurons in human brain. The complexity of real neurons is highly abstracted when modeling artificial neurons. These basically consist of inputs (like synapses), which are multiplied by weights (strength of the respective signals), and then computed by a mathematical function which determines the *activation* of the neuron. Another function (which may be the identity) computes the output of the artificial neuron. ANNs combine artificial neurons in order to process information. An algorithm such as the back-propagation can be employed to adjust the weights of the ANN automatically in order to obtain the desired output from the network. This process of adjusting the weights is called learning or training. Muhammad (2013) used the ANN to design a controller for robot arm and from his results; the method achieved desired performance in terms of settling time and overshoot. However, the method lacks the parameters to study the disturbance rejection to determine precisely the robustness of the system. Secondly, from the review the ANN controller design method is a complex approach which may require extra technical training and would be difficult to implement.

CONCLUSIONS

A survey of controller design methods for robot manipulator was carried out in this work. From the review, all the research works carried out on the controller design for robot arm mostly focused on the performance of the control system with little study on the robustness of the system. None of the works reviewed studied the disturbance rejection settling time. The disturbance rejection settling time shows how fast the system can cancel faults or disturbances; therefore it is a vital parameter to determine actually the robustness of the control system against harsh environments. The PID tuner can be used to achieve the desired performance optimization and can also be used to study the disturbance rejection settling time. Since the focus of the controller design for robot manipulator in harsh environment is good performance and robustness therefore, the software tool PID tuner becomes the right choice to be adopted.

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