Control of Polar Robot Manipulator Subjected to Harmonic Excitation Using Low Cost Controller

Mohamed H. Mabrouk and Ahmed Y. Abdel-Hamid

***Abstract*—Robot manipulators have been used for many years in several environments especially that prove hazardous or out of human reach. However, the operating conditions especially for the military applications may include unpredicted excitations that negatively affect the manipulators' performance. The objective of the research presented in this paper is to develop a model for a three degree-of-freedom polar robotic arm that can be employed on a disposal system platform. The forward and inverse kinematics equations of the robot arm have been developed, and then have been used to design a low cost control circuit to control the manipulator in normal operating conditions as well as in the presence of harmonic excitation. The manipulator links have been then designed with the aid of SOLIDWORKS®. Using the proposed links geometry and calculated torques' values for each robot joint, motors that can support the expected torques have been selected. The proposed models have been used to simulate the manipulator's behavior when it is subjected to excitations. Finally, a robot arm prototype has been implemented to test the proposed control technique to ensure a satisfactory response of the manipulator.**

***Index Terms*—disposal systems, proportional integrated control, line of sight (LOS) platforms, maritime units**

I. Introduction

ROBOT manipulators hve been useful over the years in many fields such as planet exploration, disposal systems, space missions, underwater discoveries, etc. For example, using manipulators in industries resulted in improving the product quality, increasing the productivity , decreasing the production costs, and releasing labor from working in hazaedous conditions. In spite of the the revolution of using robot manipulators in several fields that casue their rapid progression, it is still difficult to deal with the problem of robot's path-planning especially in complex environments [1], considering the fact that a robot manipulator end effector can reach a certain point in space depends mainly on the way of defining the position of that point precisely with respect to the manipulator's main frame.

When dealing with dynamic environments the problem becomes more difficult and the neediness for a real time target positioning technique is necessary. For the last few decades, many researchers have contributed in the field of target position determination within robot manipulator workspace [2-8] in diversity of fields such as material handling, painting, welding, inspection, assembly lines, space applications, and surgeries. These applications require accurate control of robots during maneuvers especially when applied to complex tasks [9].

Robot manipulators that work in hazardous or out of human reach environments may be exposed to unpredicted excitation disturbances that can affect their performance. However, most of those disturbances can be modeled in harmonic pattern as it is the basic pattern of disturbance noted by researchers [10]. For example, the drive which is widely used as a reducer in the spacecraft manipulator is of harmonic pattern due to the alternative thermal environment that makes manipulator to experience periodic heating and cooling in the sunlight and shadow region of the earth. That kind of disturbance may influence the dynamical properties and performance of the manipulator.

The key point in this paper is to develop a model for the standard polar manipulator, simulate its behaviour, then study the efficiency of a local PID controller in case of exposure to harmonic excitation function.

II. Mathematical Model of the Polar Manipulator

Actual robot manipulators employed in disposal systems platforms are advanced manipulators offering high precision and repeatability. It's common to have medium payload up to 20kg with repeatability up to 0.1 mm. Small manipulators can exhibit even better repeatability up to 0.01 mm. Those manipulators are basically composed of rigid links, connected in by joints and properly tooled with suitable for the job end-effector. An example of employing manipulators in disposal systems engineering platforms is shown in figue1.

Kinematic analysis of a robot manipulator is a fundamental tool that aids in its design and control since kinematic parameters are considered in specification planning, trajectory planning, and dynamic computations.

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Fig. 1. PEROCC, Pearson eng. route opening and clearing capability (courtesy of Pearson Engineering Ltd®)

Usually the inverse solution is more important since robot manipulators are usually actuated in terms of joint variables while objects to be manipulated are generally described in global coordinate system. The manipulator studied in this paper is a three-axis arm with two revolute joints and one prismatic joint is shown in figure 2.

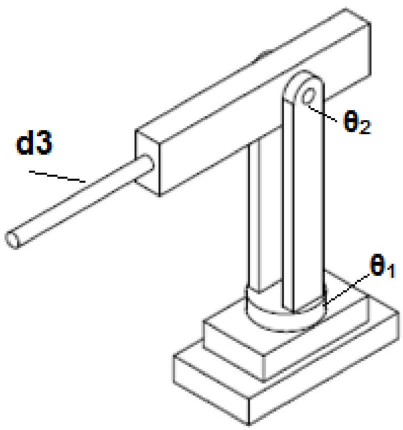

Fig. 2. Polar manipulator

A. *Kinematic Model*

The forward kinematic model is the mathematical model associated with calculating the position of the end effector in the universe frame using a series of matrix calculations that find the position of the end effector relative to each robotic joint. Once the forward kinematic equations for the manipulator are formulated, Matlab® routines can be written to implement these equations and plotted a three-dimensional picture of the manipulator for a specified set of joint angles.

The direct kinematic algorithm for the three DOF polar manipulator is represented in equations from Eq.(1) to Eq.(6) . Coordinate frames are assigned in accordance with the DH representation, as shown in figure 3.

where Z_0 points to joint 1 axis of rotation, Z_1 points to joint 2 axis of rotation, Z_2 points to joint 3 axis of translation, X1 is parallel to the common normal between joint 1 and joint 2, X_2 is parallel to the common normal between joint 2 and joint 3, and X_3 is parallel to X_2. The link parameters are established as shown in figure 3. While table I shows the manipulator links and joints variables.

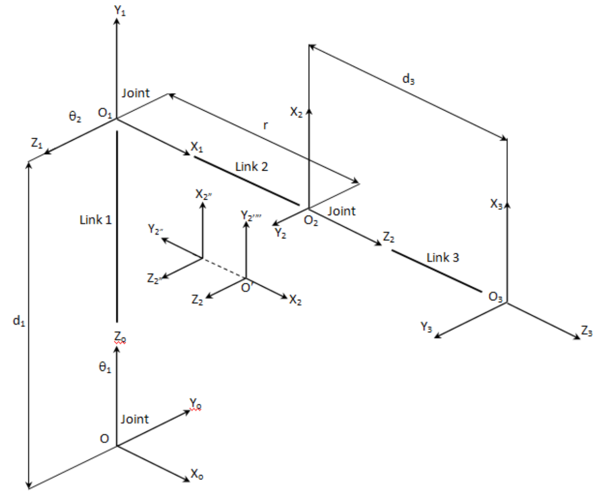

Fig. 3. Assignment of coordinate frames

TABLE I
MANIPULATOR KINEMATIC VARIABLES

Link	Variable	θ	α	L	d
link 1	θ_1	θ_1	90	0	d_1
link 2	θ_2	θ_2	90	l_2	0
		θ_2	0	r_2	0
link 3	d_3	d_3	0	0	d_3

Where $\alpha_2 = 90$ angle from Z_1 to Z_2 around X_2, θ_2 is the angle from X_1 to X_2 around Z_1, the joint 2 variable. dl is the distance between the origins of O_0 and O_1 along Z_0. $L_1 = 0$ since Z_0, Z_1 intersect $\alpha_1 = 90$ angle from Z_0 to Z_1 around X_1, θ_1 the angle from X_0 to X_1 around Z_0 , the joint 1variable. Therefore, the "A" matrix can be deduced as follows

$$A = \begin{bmatrix} c\theta & -s\theta\ c\alpha & s\theta\ s\alpha & 1\ c\theta \\ s\theta & c\theta\ c\alpha & -c\theta\ s\alpha & 1\ s\theta \\ 0 & s\alpha & c\alpha & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The kinematic transformation equation from link 1 to link 3 is as follows:

$$A1\ A2\ A3 = \begin{bmatrix} -c1s2 & s1 & c1c2 & (d3+r2)c1c2 \\ -s1s2 & -c1 & s1c2 & (d3+r2)s1c2 \\ c2 & 0 & s2 & (d3+r2)s2+d1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Solving for the end effector orientation angles (Ø Θ ψ), the transformation matrix and the general orientation matrix are used such that,

$$^{R}T_{H} = \begin{bmatrix} c\phi c\theta & c\phi s\theta s\psi - s\phi c\psi & c\phi s\theta c\psi + s\phi s\psi & P_x \\ s\phi c\theta & s\phi s\theta s\psi - c\phi c\psi & s\phi s\theta c\psi - s\phi s\psi & P_y \\ -s\theta & c\theta s\psi & c\theta c\psi & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Therefore,

$$Px = (d3 + r2)\ \cos\theta 2 \cos\theta 1 \tag{4}$$

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$$P_y = (d_3+r_2)\ \cos\theta_2\ \sin\theta_1 \quad (5)$$

$$P_z = (d_3+r_2)\ \sin\theta_2 + d_1 \quad (6)$$

B. *Inverse Kinematics*

The inverse kinematic equations give the joint angles that place the end effector in the goal position. These equations should be solved simultaneously to reach optimum path due to the possibility of multiple solutions and existence of singularities. In this paper, the inverse kinematic formulation used in [1] is adopted and a Matlab algorithm that solves the equations is then executed. The inputs to this algorithm are the geometry of the manipulator and the desired position of the end effector. The output is one or more sets of joint angles that would put the end effector into the desired position and orientation. To obtain Cartesian coordinates in terms of joint coordinates, the manipulator transformation matrix and the general transformation matrix are used such that,

$$\begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} = \begin{bmatrix} -(r2+d3)s1c2 & -(r2+d3)c1s2 & c1c2 \\ (r2+d3)c1c2 & -(r2+d3)s1s2 & s1c2 \\ 0 & (r2+d3)c2 & s2 \end{bmatrix} \begin{bmatrix} d\theta1 \\ d\theta2 \\ d\theta3 \end{bmatrix} \quad (7)$$

III. Modeling and Prototype Implementation of the Manipulator

SOLIDWORKS® simulation model is used to aid the design process for the three links manipulator prototype. Link 1 is a rotary base, Link 2 is an elevated shoulder, and Link 3 is a telescoping boom that moves in and out, the SOLIDWORKS® model developed is shown in figure 4.

The model is used as a designing aid for the implementation of a prototype that can be used to study the dynamic behaviour of the system as well as the control strategy. The links are made from aluminum alloy sheets in a way to ensure that the links cross sections can provide considerable flexibility in the lateral direction while maintaining sufficient stiffness in the vertical direction. The implemented prototype for the polar manipulator is shown in figure 5.

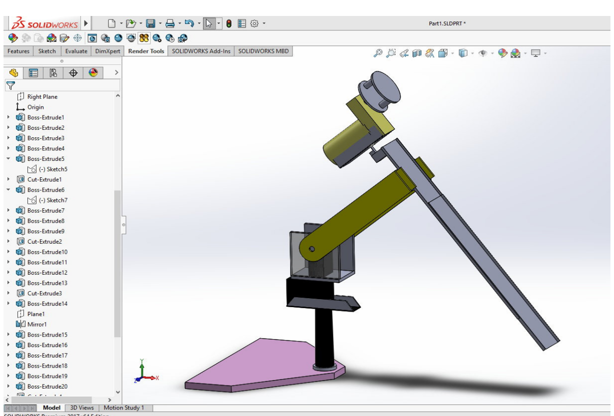

Fig. 4. (a) Modeling of the polar manipulator

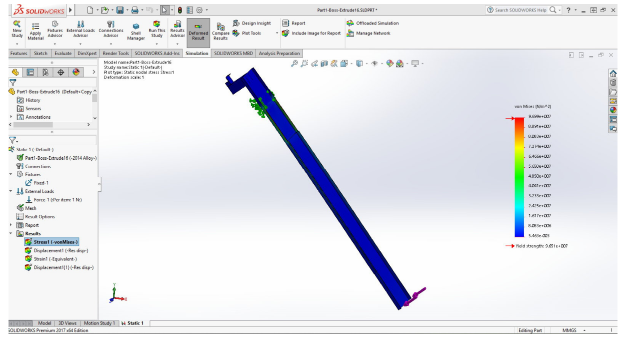

Fig. 4. (b) Links of the polar manipulator (stress analysis)

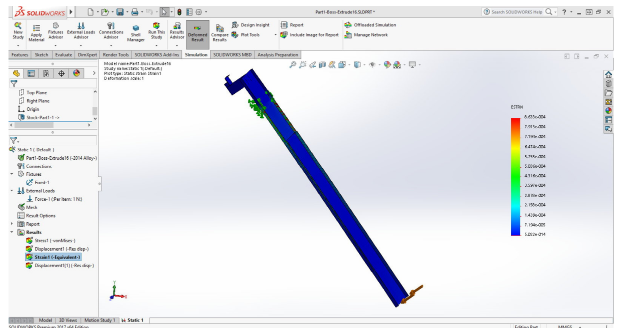

Fig. 4. (c) Links of the polar manipulator (strain analysis)
Fig. 4. SOLIDWORKS® model for the polar manipulator

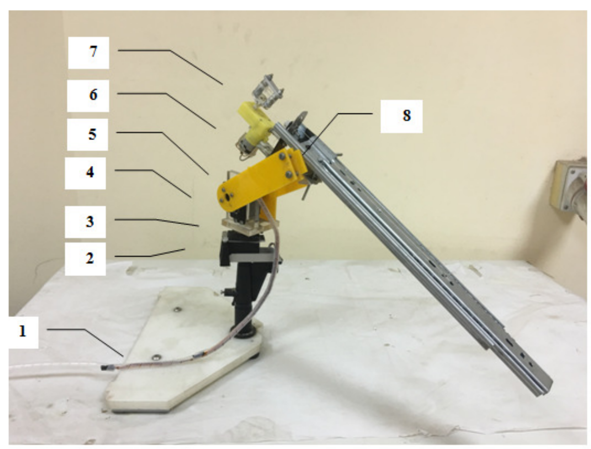

Fig.5.The implemented prototype for the manipulator

The prototype is constructed of acrylic fixed base (1), the base is designed to allow the arm to be fixed to a uniform work surface as well as to be attached to a slide base, resulting in an extended working range. A slewing servo motor (2) makes the manipulator upper structure to rotate with respect to the stationary base. The upper structure of the prototype is constructed of the acrylic rotating base (3) which is connected to servo motor (4) that actuates the 3 mm thickness acrylic link (5) to make it capable of rotation in a vertical plane perpendicular to the fixed base. Link (9) is constructed from two aluminum C shaped channels which are attached to each other in a way that allow relative translation sliding motion between them. The translation sliding motion of link (9) is controlled by a dc-geared motor (6) which rotates a pulley (7) that to control the slider wire rope. The end-effector position feedback signal is fed to

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arduino mega board using a linear potentiometer built in link (9).

IV. CONTROL PROBLEM DEFINITION AND SOLUTION STRATEGY

Robot path planning is one of the most important tasks in robotic, especially for robots that need to follow a particular path in hazardous environments [11-12]. The control problem of the manipulator can be defined as the determination and executing of the time sequence of the links movements including the determination of the forces or torques to be developed by the actuators to guarantee the accomplishing of the manipulator task. It is worth mentioning that the manipulator task may be affected by some internal and external factors coming from the manipulator construction and the environment, respectively. Environmental excitations can arise from inaccuracies due to workspace constraints, static friction in joints, mechanical compliance in linkages, electric noise in transducer signals, limitations in the precision of computation. The most important factor of interest in this paper is the external excitation that may occur in dynamic environments [13-15].

When the manipulator is employed to work in such environments, the modeling problem is an extremely difficult task, since the system is quite complicated and largely uncertain. The approach adopted in this paper to study the problem is that used by researches which study the influence of the harmonic excitation pattern to reach feasible study of the problem along with reasonable problem difficulty. In this paper, the control strategy aims to apply a variable torque *T* in way that it equals 0 at some desired time *t*. Rather than calculating the absolute value of torque *T*, the proposed control strategy determines the change in torque ΔT which should be added to the initial torque. The determination of ΔT is achieved by a conventional PID feedback loop. The structure of the PID control system considered here is shown in figure 6. In practical terms, the actual value of the angle (θ_a) should be measured, while the desired value (θ_d) should be specified for the next time step and the controller then calculates ΔT and modify the actuator torque accordingly.

The study presented in this paper is directed to investigate the problem of the manipulator arm position control to achieve fast response and smooth settling to a commanded position using on-line computer control with the presence of environmental disturbance using a low cost controller. A typical manipulator signal flow chart and its functions is represented schematically in figure 7.

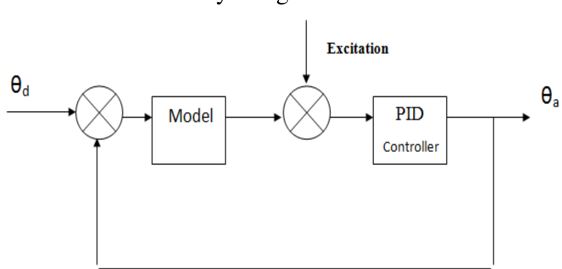

Fig. 6.Block diagram of the control system

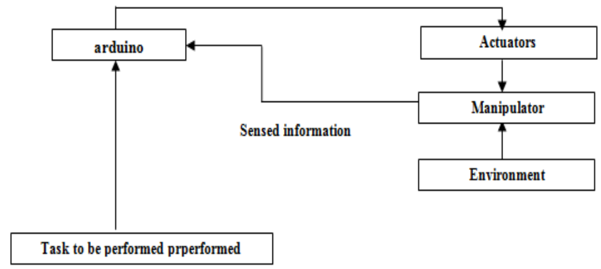

Fig. 7. Signal flow chart for the manipulator system

The overview of the experimental setup, in figure 7, shows that the sysatem consists of the manipulator arm, the actuators, arduino, and measuring sensors. A Matlab® function is used to record the position of the manipulator arm. The positional information is stored in the computer in one register, while the feedback information from the position sensor (a potentiometer is attached to the arm axis) about the actual position is sent to the computer through the A/D card and stored in another register. During the arm motion the, computer samples the two registers, and compare the data representing the reference position and the actual position.

The farther away from the desired position the arm is , the larger the error signal will be. As motion continues, the arm gets close to the programmed position and the error signal becomes smaller, and hence valve actuating signal decreases causing the cylinder to slow down. When this position is reached the arm actuator stops and signals the computer that the arm is in position. Other control laws which are more complex than the proportional control law can also be implemented. The control program can be tailored to give close to optimum response for the system by adding derivative and integral terms to control law.

The control program uses the correction control effort calculated from the following equation:

$$\Delta T(K) = K_{net} \{ K_P [\theta_d(k) - \theta_m(k)] + K_d [\theta_d(k) - \theta_m(k)] + Ki \int [\theta_d(k) - \theta_m(k)] dt \} \quad (8)$$

Where K_p is the proportional gain, K_d is the derivative gain, and K_i is the integral gain.

Considering the effect of an external load excitation on the performance of the position control system, the following excitation is assumed:

$$F_l = A_1 + A_2 \sin \omega t \quad (9)$$

Where; A1 & A2 are positive constants. This equation indicates that the load excitation is represented by the sum of the constant force and the sinusoidal force.

Figure 8 shows the simulation results for the step input responses using different amplitudes (0.5, 2, and 4 radians) without excitation. While a series of step inputs with same different amplitudes are applied to the system, the simulation results for the step input responses are shown in figure 9.

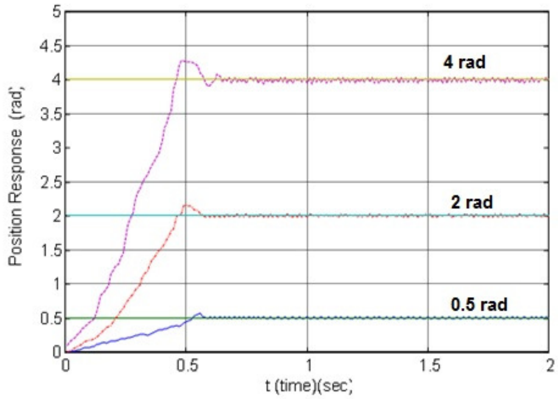

Fig. 8. Input responses of the load without excitation using different amplitudes (0.5, 2, and 4 radians)

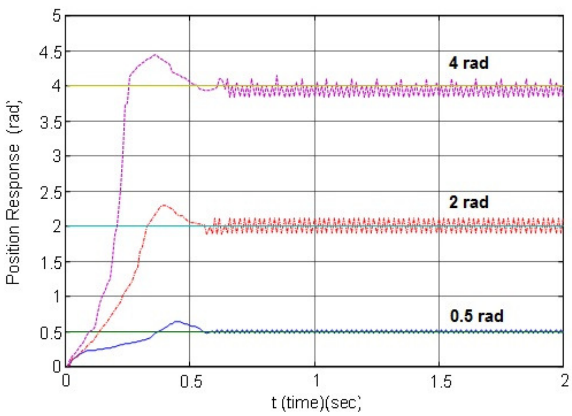

Fig. 9. Input responses of the load with excitation using different amplitudes (0.5, 2, and 4 radians)

V. FUTURE WORK

A possible application of the manipulator is to employ it with a line of sight (LOS) stabilization platform in a maritime unit [16]. The proposed application has been implemented in the lab and under further study especially for the control problem definition and the proposed solution strategy. The manipulator has been attached to a uniform work surface in a reconnaissance boat through a stabilizer platform, as shown in figure 10. However, this application is out of the paper scope and is considered as future work.

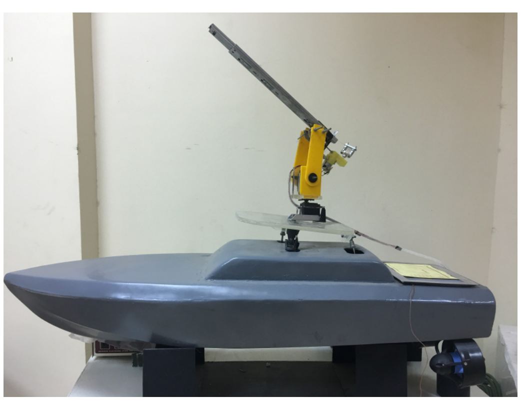

Fig. 10. The implemented prototype manipulator attached to a boat

VI. CONCLUSION

Non-linear model of coupled differential equations of motion for the three degrees of freedom polar robot manipulator case study is developed. The problem is simplified by convenient choice of coordinate frames. A one to one scale prototype of the manipulator has been implemented. SOLIDWORKS® simulation model has been used to aid in the design of the three links manipulator prototype. To examine the proposed simple low cost control methodology, two types of forcing functions are applied to the system. First a different amplitudes step inputs without excitation are applied, then different amplitudes step with excitation of different frequencies are applied. Numerical results using MATLAB® functions with and without excitation show stable and balanced behaviour of the manipulator as well as acceptable response.

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