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An optimal motion path planning control of a robotic manipulator based on the hybrid PI-sliding mode controller

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ABSTRACT

This paper proposes a hybrid proportional-integral (PI-sliding) mode controller to improve and adjust the point-to-point path planning of a three-link robotic arm with three degrees of freedom. The main objectives of the proposed control unit are to control the tracking process to reach the desired path handle the outgoing vibrations, and dampen them in the links of the robotic arm during its movement to ensure accuracy in completing the work. Seventh-degree polynomial paths represented the segments of locomotion connecting the first, middle, and last points at the combined space through predefined route points via minimal travel time. While not exceeding a predetermined maximum torque, without hitting any obstacle in the robot's workspace. The results showed that the proposed control design provides a robust control performance and fast response corresponding with conventional sliding mode controller (SMC) and PI controller. Then the outcomes provide the best results for the demanded mission according to the whished intakes with minimal error. The system equations are solved using the techniques available in MATLAB software then the results of the model are validated by the results of simulations.

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1. INTRODUCTION

One of the most common areas considered in the development of robot manipulator systems is the field of trajectory robot manipulator control. This is because robotic systems work most of the time in unknown and unstructured situations and uncertainty in modelling. Furthermore, the non-linear dynamic model obtained complex systems such that the errors are in the end-effector position. This has great harm, especially in the industrial field. In this work, the application of automation-based robot manipulators has introduced a new area of technology that leads to tangible development in the industrial automation processes. These applications have rapidly grown due to their ease of design and construction, high efficiency and flexibility during work. This paper addresses a significant field of robotic systems, namely the trajectory planning of the manipulator robotic. In the last decades, some classical methods have been chosen by researchers for trajectory planning [1], [2].

However, because of the development of automation operations and their needs, many challenging tasks that pose a hazard to worker safety can be handled. The performed applications are such complex welding and work in risky zones; because they contain radioactive materials or explosive materials working under challenging and changing conditions. On the other hand, the need for industrialists to improve their plants to increase production, minimize costs, and develop the quality of a product. Yet, the designers work on getting the best control processes for the robot manipulator path planning to ensure that locomotion is within the best working domain. That leads to a passable acceleration used with this manipulator closely associated with nonlinear dynamics as well as external perturbations, and to minimize the effect of the forces dynamic which in turn decreases the vibrations of the robotic arm and thus gives excellent working accuracy. Therefore, this made them use applications of evolutionary control algorithms to obtain optimal path planning based on evolutionary methods for an artificial manipulator system. Therefore designing robust, high-performance controllers for robot manipulators to reimburse for the uncertainty and sustain the tracking performance is a challenge and has attracted a lot of interest in robot manipulators processes and systems [3], [4].

The researchers considered that trajectory planning is very substantial to the process of the robotic arm and the prominent target of trajectory planning is the generation of a path planning from the beginning to the target review for the fully or partially automated process [3], [5]. Discussion and analysis of motion techniques are investigated to find the path joint space and path planning selection approaches such as kinematics techniques. In the control design of the robotic arm approach, many important research areas provide fundamental steps toward analysis and control. Some works which offer principal knowledge to the current research will uncover by [6]. Cannon and Schmitz [6] started the control test for the elastic manipulator end-effector by calculating the position of the point and employing that calculator as a main to apply torque to another termination (hinge) of the beam. Nevertheless, it has been deemed a linear dynamic model and sweeps the arm at the horizontal level, even if it is not affected by gravity. Zhang *et al.* [7] proposed robot manipulators, a novel control framework combining the amended extended high gain observer (EHGO) and non-discrete proportional integral derivative sliding mode controller (PID-SMC). The Lyapunov technique has suggested improving the efficiency of EHGO [8] by a proposed study of controlling robot manipulator systems based on a robust controller with entirely unexplored dynamics. Furthermore, the authors suggested a sliding method with integration strategy disorder observer (SI-ISMDOB) based on the sliding control SMC technique. Ahmad *et al.* [9] used a data-based PID classical controller for a supple combined robot affirmed based on the adaptive safe experiment dynamics (ASED). This algorithm is an improved category of the SED class, such that the revamped tuned variable is adjusted to adjust the change in the objective process.

Tang *et al.* [10] concentrated on the flexible link manipulators tracking control problem. Orderly, to lessen the effects of nonlinearities and doubts, the strategy of control design-based combination of sliding is suggested orderly. The phenomenon of swinging by common SMC is composited based including the saturation part in the suggested unit control [11]. This paper to optimize the trajectory planning based on the method of the seventh-degree polynomial that meets the characteristic of smoothness and allows the conditions to reach the desired position-based trajectory tracking control. Moreover, the hybrid PI-SMC is employed to overcome problems that encounter a manipulator trajectory during movement. Therefore, the sliding control approach is in demand in this work due to its robustness against disruptions. This control precept is relied on to compel by converging concerning the desired plane and then developing despite the disturbances and uncertainties. The plant has a specified collection of linkages between the inconstant system states. Nevertheless, the swinging sensation remains the major disadvantage of this control design. Dominate this concern, a hybrid PI-SMC is employed and experimented with in this work. The main structure of the comprehensive work is constructed by: i) introduction, ii) the manipulator dynamic model, iii) path planning approach based on seventh-degree polynomial, iv) hybrid PI-SMC, v) results and simulation, and vi) conclusion.

2. RESEARCH METHOD

2.1. The manipulator dynamic model

To design and test the suggestion controller for the robotic arm. The arm of the three-link planar robotic arm shown in Figure 1 is used as a prototype for testing the proposed control algorithm with trajectory planning. This robotic arm has three revolute joints that connect three links.

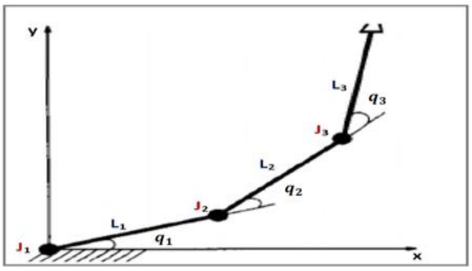


Figure 1. Three link robot robotic arm

Where:
L1, L2, and L3: length of first, second and third links respectively in robotic arm
q_1, q_2, and q_3: joints angle for the first, second, and third angles respectively in robotic arm
The equations of forward kinematic for 3-link robotic arm is:

$$x(t)=L_1 cosq_1 + L_2 cos\ (q_1+q_2) + L_3 cos\ (q_1+q_2+q_3) \tag{1}$$

$$y(t)=L_1 sinq_1 + L_2 sin\ (q_1+q_2) + L_3 sin(q_1+q_2+q_3) \tag{2}$$

Where:
$x(t)$: the X-axis domain for robotic arm
$y(t)$: the Y-axis domain for robotic arm

In (1) and (2) describe the end-effector coordinates of the robotic arm. They fully define the end-effector within the workspace's desirable orientation and position in need. The position are (1) and (2), where the robotic arm orientation end-effecter can be exemplification. The angle of rotation for the frame is linked to the effector terminus and is proportional to the fixed framing connected to the robot base. The direction of the final effector is related to the actual joint displacement as [12], [13]:

$$q_E=q_1+q_2+q_3 \tag{3}$$

2.2. Path planning approach based on seventh–degree polynomial

In this paper, the trajectories based on the seventh-degree polynomials had applied to determine the predefined path per joint of a 3-link robotic arm. Later it can be formulated as a problem of interpolation by using functions of the smooth parametric. For simplicity, they must be generated directly through trajectories $x_c(t)$ and $y_c(t)$.

In specific, suppose that in the initial time set t=0, robot starts from the initial state denoted by $(q_s, \dot{q_s})$=$(x_s, y_s, \alpha_s, \dot{x_s}, \dot{y_s}, \dot{\alpha_s})$ to achieve a target state $(q_g, \dot{q_g})$=$(x_g, y_g, \alpha_g, \dot{x_g}, \dot{y_g}, \dot{\alpha_g})$ at the time t=T, where $(x_s, y_s, \alpha_s,)$ is initial position of cartesian of the base of the last link, and (x_g, y_g, α_g) is a final initial position of cartesian of the base of final link. Where q is joint vector (radian); $\dot{q}$ is angular velocity (radian/sec); $\ddot{q}$ is angular acceleration (radian/sec^2).

It is necessary to combine to $(q_s, \dot{q_s})$ and $(q_g, \dot{q_g})$. A suitable boundary conditions for a novel case variables, i.e., x_c, y_c, and its derivatives over the third degree.
At time; t=0.

$$\begin{bmatrix} x_c\ (0) \\ \dot{x_c}\ (0) \\ \ddot{x_c}\ (0) \\ \dddot{x_c}\ (0) \end{bmatrix} = \begin{bmatrix} x_{cs} \\ \dot{x_{cs}} \\ \ddot{x_{cs}} \\ \dddot{x_{cs}} \end{bmatrix}, \begin{bmatrix} y_c\ (0) \\ \dot{y_c}\ (0) \\ \ddot{y_c}\ (0) \\ \dddot{y_c}\ (0) \end{bmatrix} = \begin{bmatrix} y_{cs} \\ \dot{y_{cs}} \\ \ddot{y_{cs}} \\ \dddot{y_{cs}} \end{bmatrix} \tag{4}$$

and at time t=T;

$$\begin{bmatrix} x_c\ (T) \\ \dot{x_c}\ (T) \\ \ddot{x_c}\ (T) \\ \dddot{x_c}\ (T) \end{bmatrix} = \begin{bmatrix} x_{cg} \\ \dot{x_{cg}} \\ \ddot{x_{cg}} \\ \dddot{x_{cg}} \end{bmatrix}, \begin{bmatrix} y_c\ (T) \\ \dot{y_c}\ (T) \\ \ddot{y_c}\ (T) \\ \dddot{y_c}\ (T) \end{bmatrix} = \begin{bmatrix} y_{cg} \\ \dot{y_{cg}} \\ \ddot{y_{cg}} \\ \dddot{y_{cg}} \end{bmatrix} \tag{5}$$

The direct solution to the interpolation problem is to construct paths like seventh-order polynomials for the output $yi(t)$ with normalized time: $\lambda = t/T$:

$$yi(t) = \sum_{j=0}^{7} a_j\, \lambda^j \tag{6}$$

Where i=1, 2, 3, ….
The projection for compactness in the outcome index i, the coefficients aj are clarified by:

$$a_{o\ =y_s T} \tag{7}$$

$$a_{1=\dot{y_s}T} \tag{8}$$

$$a_{2=\frac{1}{2}\ddot{y}_s} T^2 \quad (9)$$

$$a_{3=} \frac{1}{6}\ y_s^3\ T^3 \quad (10)$$

$$a_{4=} 35\ \left(y_g - \ y_g\right) - (30\ \dot{y}_s + 15\ \dot{y_g})\ T \quad (11)$$

$$a_{4=} 35\ \left(y_g - y_s\right) - (30\ \dot{y}_s + 15\ \dot{y_g})\ T - (5\ \ddot{y}_s - \frac{5}{2}\ddot{y}_g)T^2\ - (\frac{2}{3}\ y_s^3 + \frac{1}{6}\ y_g^3\ )T^3 \quad (12)$$

$$a_{5=}\ - 84\ \left(y_g - y_s\right) - (45\ \dot{y}_s + 39\ \dot{y_g})\ T + (10\ \ddot{y}_s -\ 7\ddot{y}_g)T^2 - (y_s^3 + \frac{1}{2}\ y_g^3\ )T^3 \quad (13)$$

$$a_{6=} 70\ \left(y_g - y_s\right) - (36\ \dot{y}_s + 34\ \dot{y_g})\ T - (\frac{15}{2}\ \ddot{y}_s - \frac{13}{2}\ \ddot{y}_g)T^2 - (\frac{2}{3}\ y_s^3 + \frac{1}{2}\ y_g^3\ )T^3 \quad (14)$$

$$a_{7=}\ - 20\ \left(y_g - y_s\right) + 10(\ \dot{y}_s +\ \dot{y_g})\ T + 2(\ \ddot{y}_s -\ \ddot{y}_g)T^2 + \frac{1}{6}\ (\ y_s^3 +\ y_g^3\ )T^3 \quad (15)$$

The state path of the robot and compensator is associated with the linear output path introduced in (6). This equation resolves the recommended issue and is gained by purely algebraic calculations. Furthermore, the open-loop signals which are aware of this path are [14], [15]:

$$vi(t) = \frac{1}{T^4}\ (\ 840\ a_7\lambda^3 + 360\ a_6\lambda^2 + 120\ a_5\lambda + 24\ a_4) \quad (16)$$

Where i=1, 2 ,3, ….

2.3. Design of the control systems

2.3.1. Sliding mode controller

The SMC design is one of the nonlinear and effective controllers [16]. The SMC has derived from variable structure control (VSC). The VSC is recognized based on a robust theoretical method in practical control engineering applications as a much clear form of nonlinear discontinuous control. The nonlinear dynamic system is changeable by applying a switching controller with a high frequency. This part aims to present the SMC approach that provides an efficient method to solve the chattering behavior. The first action to clarify the criterion SMC is to specify a sliding surface of time-varying S(t); this is stable and linear. The S(t) in this work selected the effect on the tracking error term:

$$S(t) =\ \lambda\ e(t) + e\ \dot{(t)} \quad (17)$$

A positive robustly constant is λ, the derivative time of tracking error e(t). The purpose control action is based on dampening the vibration value to zero, consequently, $q_f(t)$ and $\dot{q_f}(t)$ was utilized rather than $e(t)$ and $\dot{e}(t)$ respectively, then (18) becomes:

$$S(t) =\ \lambda\ q_f(t) + \dot{q}_f\ \dot{(t)} \quad (18)$$

The sliding mode method implies that the path case arrives on the surface of the sliding path trajectory of the system $S(e,\dot{e}) = 0$ and remains on it while sliding back origin (0,0), model uncertainties, disturbances and unmodeled frequencies [17]. To maintain the $S(e,\dot{e}) = 0$ at zero, the controller has developed to tolerate the following sliding state (Lyapunov function) [18]:

$$V{=}\frac{1}{2}\ S(t)^T\ \ S(T) \geq 0 \quad (19)$$

The time derivation evolves $\dot{V} = \dot{S}\ S$ and the control input uf is selected such that:

$$\dot{S}(t)\ S(t) \leq -\ \eta|S(t)| \quad (20)$$

Where η is a positive constant that warranty the trajectory system that touches the surface sliding at a precise interval time. Essentially, (19) states the squared distance to a surface, as calculated by reducing along all

trajectories of systems. Thus, (20) provides sufficient access status such as trace error will be asymptotically converged to zero [19], [20].
In respect satisfy this requirement, choose the control law (21):

$$u_{f} = -K_s \, sog\ (S) \tag{21}$$

Then, the sliding gain is KS > 0, and sgn(S) is a sign (or signum) function, which is described by:

$$Sog(S)=\begin{cases} -1 & if \;\; S < 0 \\ 0 & if \;\; S = 0 \\ 1 & if \;\; S > 0 \end{cases} \tag{22}$$

As mentioned before, employing a sign function often causes a chattering problem. The proposed combination of proportional integral (PI) for the sliding controller on the border layer is in a zone of the signum part [21]. The continuity of the control unit can compel the state variables to extend the sliding plane and obtain heightened implementation by following the saturated relative integral parts of this (23) found by [22]:

$$\rho pi(\sigma_{PI}) = \begin{cases} 1 & if \;\; \sigma_{PI} < 0 \\ \sigma_{PI} + K_I \int_{t_{io}}^{t_i} \sigma_{PI} & if \;\; -1 < \sigma_{PI} \le 1, \\ -1 & if \;\; \sigma_{PI} > -1 \end{cases} \tag{23}$$

Where: $\sigma_{PI} = \frac{S}{\Phi}$
$K_I > 0$ is the integral gain, and the starting duration when the states included in the border layer *B(t)* are defined [16], [17];

$$B(t)=\{e, |S(e,t)| \le \Phi\}, \Phi > 0 \tag{24}$$

where $|S(x,t)|$ is the space between the process state (e) and sliding surface (S), and Φ is mean by the thicknessof the boundary layer. If $|\sigma_{PI}| \ge 1$, the integral form is in (23). It will reconstruct to nil to qualify for the state to join the frontier layer see Figure 2. If $|\sigma_{PI}| \ge 1$, the integral form is in (23). Then suppose the gains of the chosen integration (KI) are large enough:

$$\begin{aligned} \dot{\sigma}_{PI} + K_I \, \sigma_{PI} > 0 \qquad for\ all \qquad \sigma_{PI} > 0 \\ \dot{\sigma}_{PIi} + K_I \, \sigma_{PI} < 0 \qquad for\ all \qquad \sigma_{PI} < 0 \end{aligned} \tag{25}$$

Inequalities (23) imply that $|\rho_{PI}|$ increases for all $|\sigma_{PI}| > 0$, and $|\rho_{PI}|$ decreases for all $|\sigma_{PI}| < 0$ [22]. Figure 3 illustrates the Simulink model for the conventional sliding controller and robotic manipulator with unity feedback.

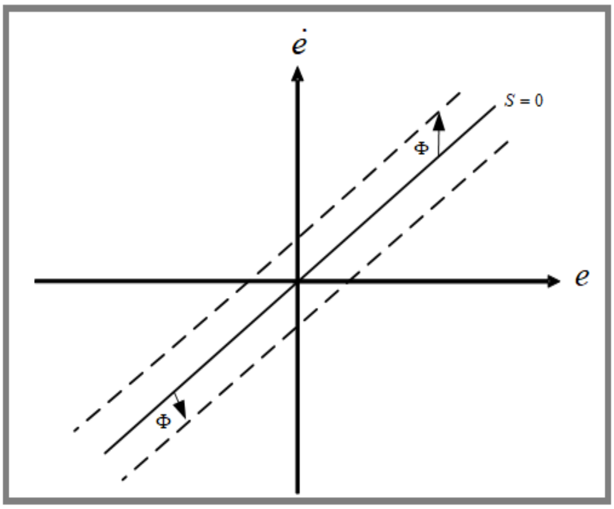


Figure 2. The boundary layer and sliding surface

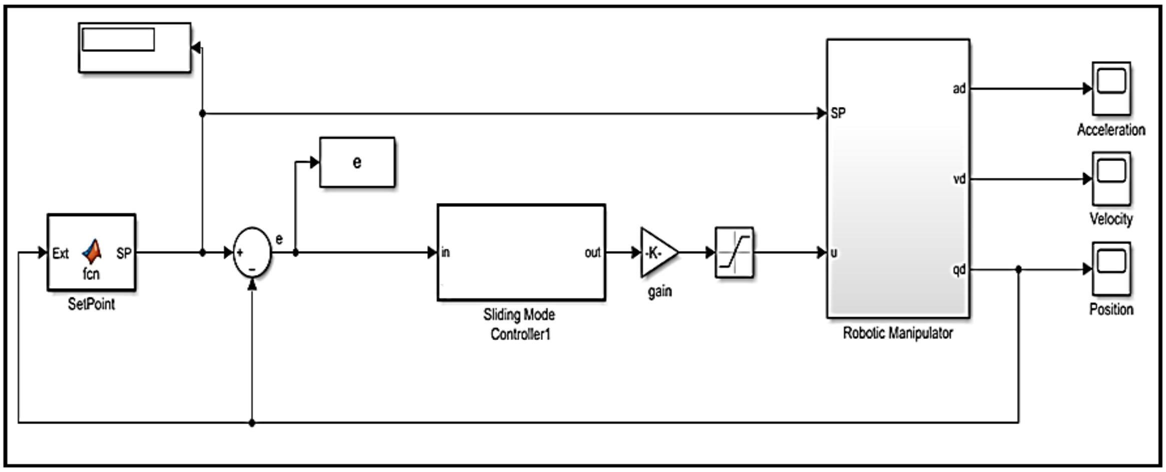


Figure 3. The Simulink paradigm of the ordinary sliding mode control

2.3.2. PI-controller

The controller PID unit remains a commonly used control unit due to its multiple known benefits [2]. However, the influence of the derivative coefficient in PID unit control is not preferred employing in some operations because of the noise caused by this coefficient in the control operations. Consequently, proportional integrated controllers are mainly favoured to be utilised instead of PID controllers. The PI controller has two parameters required to calculate to supply satisfactory outcomes in common control techniques proportional (P) and integrated (I) parameters determined by the Ziegler and Nichols approach [20], [23].

The algorithm of a PI controller contains two parameters: proportional and integral values. These values have based on the analysis of present error e(t), integration of past errors and the prediction of future errors and then their summation constitutes the controller output. If u(t) has defined as the controller output and r(t) has specified as the controller input, then the final form of PI controller output is [24], [25]:

$$u(t) = K_p\,.\,e(t) + K_I \int_0^t e(t)dt \tag{26}$$

Where Kp is proportional gain and Ki is integral gain and e is the error.

Tuning the values of proportional gain and integral gain for the conventional controller has been done by Ziegler–Nichol's method. Figure 4 reveals the Simulink of the conventional-PI controller and robotic manipulator with the unity feedback [26].

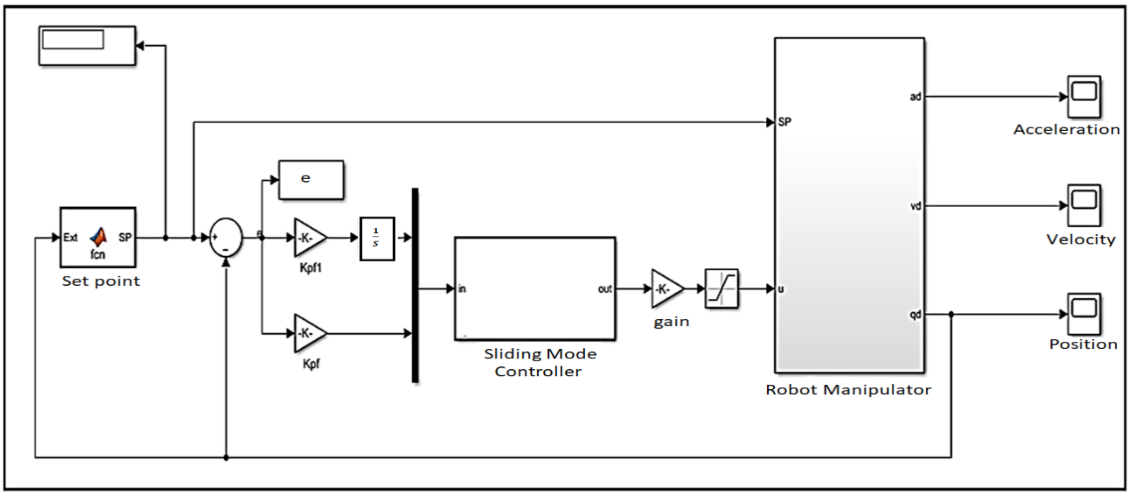


Figure 4. The Simulink diagram of an ordinary PI controller with robot model

2.3.3. Hybrid PI-SMC

Figure 5 clarifies the Simulink design of the proposed controller, which is called a hybrid PI-SMC and robotic manipulator with unity feedback. Where in the parameters of PI controller is designed to complete the SMC design as shown in above figure. Design of the proposed controller for robotic manipulator with unity feedback and this design of system ensures good stability for system with unity feedback.

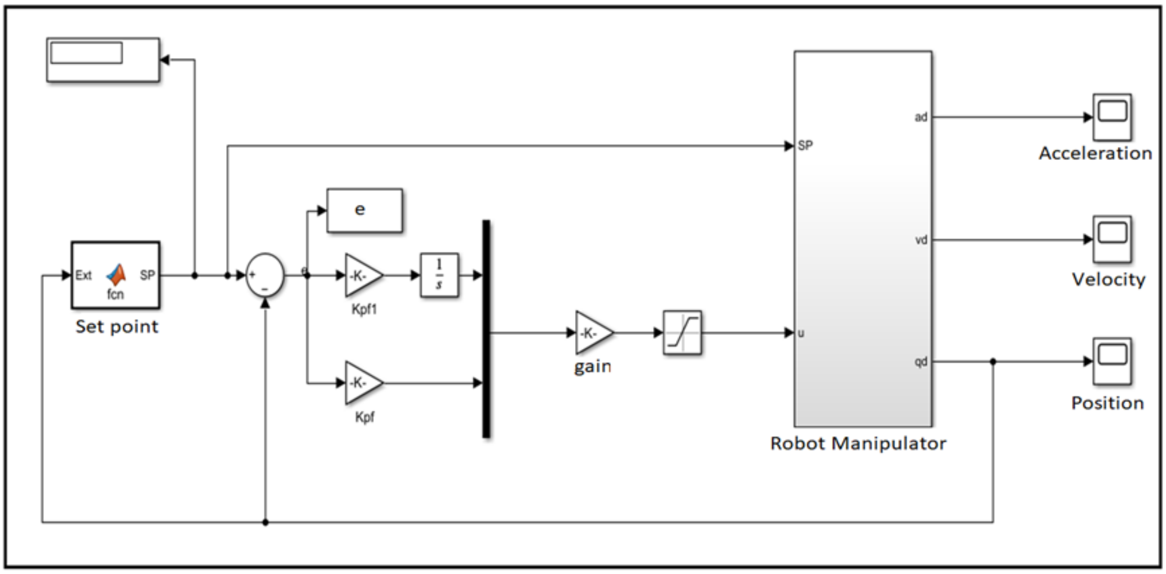


Figure 5. Simulink model of hybrid PI-SMC

3. RESULTS AND ANALYSIS

The desired path planning and joint movements are needed to achieve the trajectory planning task. Matlab code is employed to build up the dynamic model. The proposed model is the three-link manipulator and as clarified in Table 1. The simulation results given is to demonstrate the effect of the controller systems on links in tasks of trajectory planning.

Table 1. The input parameters of link (1) for a trajectory of the manipulator robot

Variable	Trajectory input parameters	Value of parameters
L1	The link length no. 1	L1=1 m
M1	Mass of link no. 1	M1=2 kg
q	Joint vector	30^o (radian)
$\dot{q}_o$	Initial angular velocity	0 (radian/sec)
$\ddot{q}_o$	Initial angular acceleration	0 (radian/sec^2)

The tracking performance simulation was tested using the PI hybrid slip mode controller to solve the differential equation of the system and compare these outcomes with the results of traditional sliding mode and PI control systems. Figure 6 shows the reference trajectory for the particular results like 6(a) positions, 6(b) angular velocity, and 6(c) angular acceleration. These upshots had calculated for the first link and joint, which parameters are provided in Table 1.

Figure 7 illustrates the considered trajectory performance regarding the various results such that the 7(a) positions, 7(b) angular velocity, and 7(c) angular acceleration, (the derivatives of the joint) are obtained for the second link and joint. Despite this, its parameters are displayed in Table 2 by using the PI hybrid slip mode controller to resolve the differential equation of the system and compare these outcomes with the results of the established sliding approach and PI controller.

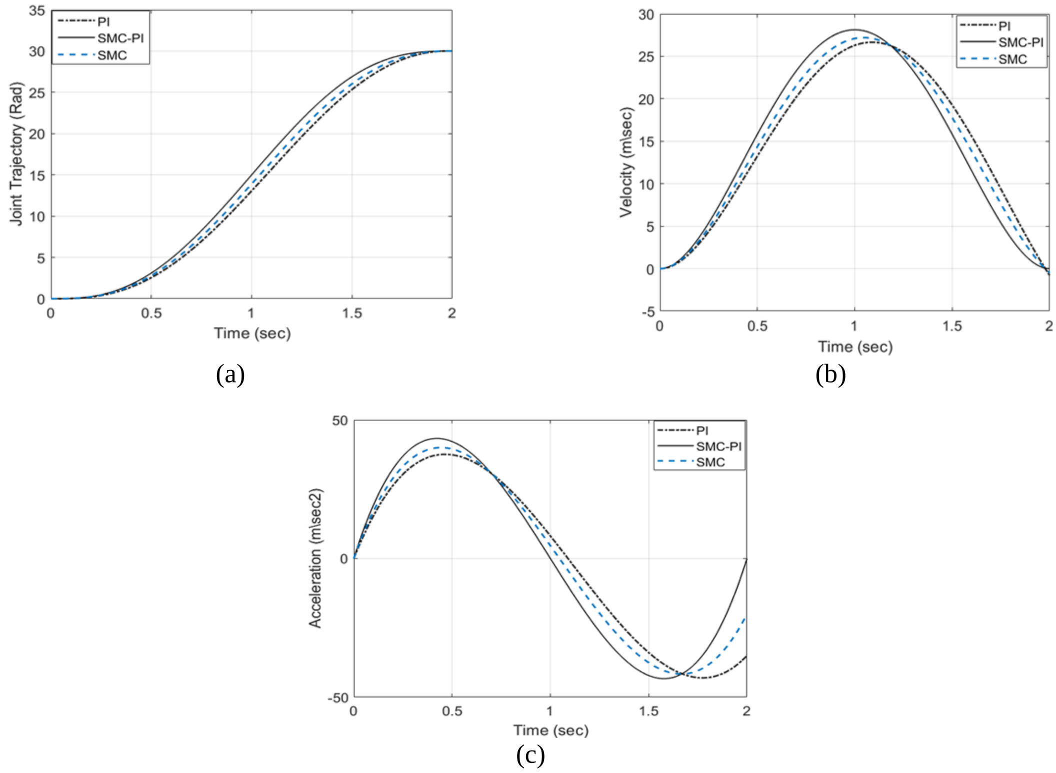


Figure 6. The comparison of tracking performance for hybrid PI-SMC with conventional (PI and sliding mode) controllers for (a) joint variables versus time, (b) joint velocity versus time, and (c) joint acceleration versus time for the first link

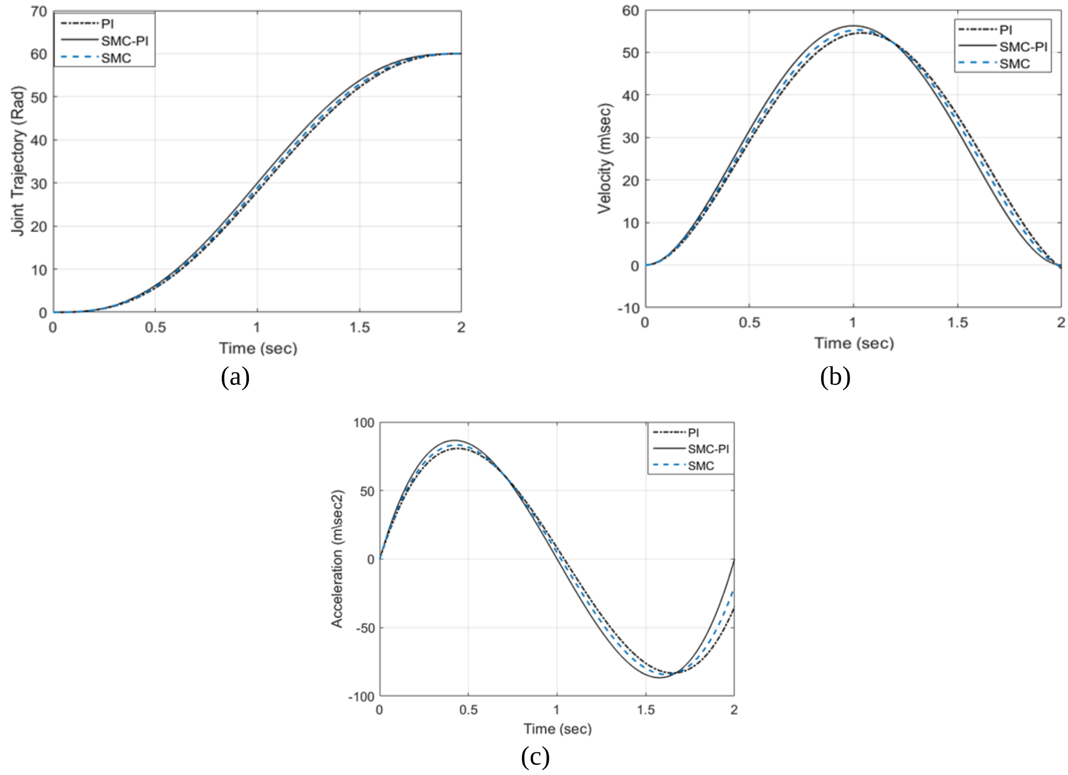
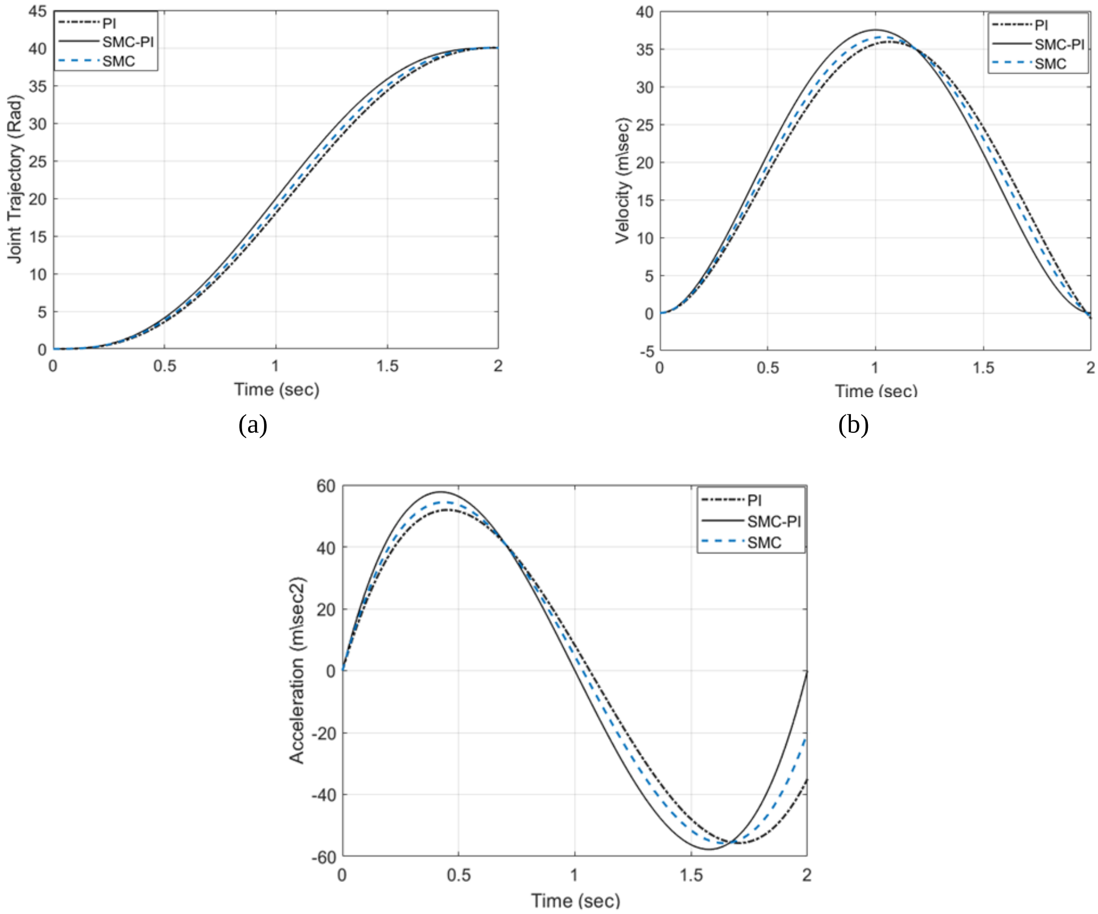


Figure 7. The comparison of tracking performance for hybrid PI-SMC with conventional (PI and sliding mode) controllers for (a) joint variables versus time, (b) joint velocity versus time, and (c) joint acceleration versus time for the second link

Table 2. The input parameters of link (2) for a trajectory of the manipulator robot

Variable	Trajectory input parameters	Value of parameters
L2	The link length no. 2	L2=0.85 m
M2	Mass of link no. 2	M2=1.75 kg
q	Joint vector	60° (radian)
$\dot{q}_o$	Initial angular velocity	0 (radian/sec)
$\ddot{q}_o$	Initial angular acceleration	0 (radian/sec^2)

Figure 8 clarifies the reference trajectory performance for the different results of the positions, angular velocity and angular acceleration. These derivatives of the joint had computed for the third link and joint. Where its parameters have been presented in Table 3 by using the PI hybrid slip mode controller to solve the differential equation of the system. In addition, compare these results with the traditional sliding technique and PI control outcomes in terms of 8(a) joint variables versus time, 8(b) joint velocity versus time, and 8(c) joint acceleration versus time.



(a) (b)

(c)

Figure 8. The comparison of tracking performance for hybrid PI-SMC with conventional (PI and sliding mode) controllers for (a) joint variables versus time, (b) joint velocity versus time, and (c) joint acceleration versus time for the third link

Table 3. The input parameters of link (3) for a trajectory of the manipulator robot

Variable	Trajectory input parameters	Value of parameters
L3	The link length no. 3	L3=0.8 m
M3	Mass of link no. 3	M3=1.70 kg
q	Joint vector	40° (radian)
$\dot{q}_o$	Initial angular velocity	0 (radian/sec)
$\ddot{q}_o$	Initial angular acceleration	0 (radian/sec^2)

4. CONCLUSION

In this paper, the trajectory of the arm robot with three links and joints with three degrees of freedom was studied and analyzed in detail to improve path planning. By achieving the planning process trajectory for the polynomial robot, the seventh-degree polynomial approach is employed to clarify the locomotion components connecting the first, middle, and last junctions at the joint space through defined path points with minimal travel time. The proposed hybrid PI-sliding mode unit controller is used to improve and adjust the path-planning trajectory of the robotic arm. This unit control generates correct paths. Which are required in a chain that passes through specific path points, and can meet the physical speed, mechanical speed as well as acceleration constraints of the manipulator. The results of the proposed method showed that it is an effective method when used in terms of response speed in reaching the desired location point without exceeding the maximum limits of torque, work requirements and control.

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