PD with sliding mode control for trajectory tracking of robotic system

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Good tracking performance is very important for trajectory tracking control of robotic systems. In this paper, a new model-free control law, called PD with sliding mode control law or PD–SMC in short, is proposed for trajectory tracking control of multi-degree-of-freedom linear translational robotic systems. The new control law takes the advantages of the simplicity and easy design of PD control and the robustness of SMC to model uncertainty and parameter fluctuation, and avoid the requirements for known knowledge of the system dynamics associated with SMC. The proposed control has the features of linear control provided by PD control and nonlinear control contributed by SMC. In the proposed PD–SMC, PD control is used to stabilize the controlled system, while SMC is used to compensate the disturbance and uncertainty and reduce tracking errors dramatically. The stability analysis is conducted for the proposed PD–SMC law, and some guidelines for the selection of control parameters for PD–SMC are provided. Simulation results prove the effectiveness and robustness of the proposed PD–SMC. It is also shown that PD–SMC can achieve very good tracking performances compared to PD control under the uncertainties and varying load conditions.

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1. Introduction

Because of its simple form and popularity in engineers, PD/PID control has been widely used in many industrial applications such as robotic control, process control, and automatic control [1–12]. PD/PID control is a model-free linear control, and the control gains can be adjusted easily and separately. Indeed, a simple linear and decoupled PD/PID controller with appropriate control gains may lead to acceptable tracking performances for many applications.

It is well known that PD control with desired gravity compensation can guarantee global and asymptotic stability for a point-set tracking problem [1,4]. However, such a design relies on prior knowledge of the gravitational loading vector. The uncertainty of parameters for a controlled system will affect the final tracking performance of the controlled system. Researches on the global stability of trajectory tracking with robotic manipulators under PD control were given in [5–7]. Nunes and Hsu [7] proposed a causal PD controller with feedforward terms for the global tracking control of a robot manipulator where the derivative of tracking error was estimated through a lead filter. PID control is also applied for tracking control of robotic manipulators [8–11]. It was demonstrated [10,11] that a PID tracking control law with a feedforward term can guarantee the semiglobal stability of robotic systems.

To improve the trajectory tracking performance of robot manipulators, significant efforts have been made for seeking advanced control strategies. Achievements were obtained in developing adaptive control and robust control approaches that ensure globally asymptotical convergence of tracking errors [12–14]. Sliding mode control (SMC) [15–18] is one of the advanced controllers that have been developed considerably in robotic areas.

SMC or variable structure control evolved from the pioneering work in Russia in the early 1960s and has been studied extensively to control nonlinear dynamic systems with modeling uncertainties, time varying parameter fluctuation, and external disturbances [15,16]. SMC has been utilized in many different applications such as the design of robust regulators, model-reference systems, adaptive schemes, tracking systems, and state observers. SMC was successfully applied to problems such as automatic flight control, control of electric motors, chemical processes, space systems, and robotics. The developments and applications of SMC are detailed in some literature reviews [17,18].

SMC is characterized as high robustness. The sliding mode behavior is insensitive to model uncertainties and disturbances. Different types of SMC were proposed [19] to deal with tracking problems. One problem associated with SMC is the so-called chattering phenomenon that is high frequency oscillations of the controller output making the trajectories rapidly oscillating about the sliding manifold; another problem is the difficulty in the calculation of what is known as the equivalent control where certain knowledge of the system dynamics is required [15–20]. To avoid the calculation of equivalent control in standard SMC it is a motivation for the presented research.

A translational motion system, such as a CNC machine system, is a simple robotic system driven by multiple axes [21–24]. In such
A robotic system, each axis is driven and controlled separately and follows the command signal produced by the interpolator for the purpose of coordination of the axes. One of the main requirements for robotic systems is the good tracking performance of the system, and many control algorithms, such as PD control and SMC, are developed [21–24]. Another motivation of this research is to develop a simple and effective control method for translational motion systems.

A hybrid control scheme that switched between PD control and SMC was proposed in [20] for tracking control of robot manipulators, where PD control is used in the reaching phase and the semicontinuous sliding mode control is applied in the sliding mode phase. That study is a start point for our current research. A general goal of this current research is to find a simple and easy control law for trajectory tracking performance improvement of robotic systems. Considering the popularity and simplicity of PD control in industrial applications, we focus on the combination of PD control and SMC for the application of translational robotic systems, and propose a new control law to deal with trajectory tracking control problems.

This paper presents a new controller called PD–SMC that combines PD control and SMC for trajectory tracking. In the proposed approach, a PD control law is designed to stabilize the nominal model and the SMC is used to provide the robustness and to compensate the uncertainty and disturbance of the controlled system. Model-free is a unique feature of the proposed PD–SMC that is distinct from a standard SMC. This paper is organized as follows. First, the dynamic model and the proposed PD control law, the following notations are introduced.

\[ E = X_d - X \]
\[ \dot{E} = X_d - \dot{X} \]
\[ \ddot{E} = \ddot{X}_d - \ddot{X} \]

where \( X_d, \dot{X}_d, \) and \( \ddot{X}_d \) are the desired position, velocity, and acceleration vectors, respectively. We assume all these vectors are bounded.

Substituting Eq. (2) into Eq. (1), the dynamic model can be rewritten in the form of tracking errors as

\[ M \ddot{E} + C \dot{E} + KE = P - F \]

where \( P = M \dddot{X}_d + C \ddot{X}_d + KX_d + D \) represents the desired control force vector.

For a translational robotic system, it is well known that the matrices \( C, K \) and \( M \) are constant [21–23]. Assume that the desired trajectories and the first and the second derivatives are bounded, for the desired control force \( P \), we have

\[ P \leq \| M \dddot{X}_d + C \ddot{X}_d + KX_d + D \| + \| P_b \| = P_b \]

where \( P_b \) is the boundary of the control force \( P \).

From Eq. (3), one can see that the system is stable and the tracking error will converge to zero if we have \( F = P \). That is the

![The desired ellipse](image1)

![The desired eight curve shape](image2)

Fig. 1. The desired trajectory shapes.
Fig. 2. Comparison of tracking performances with uncertainties. (a) Control results in the x-axis for both shapes, (b) control results in the y-axis for ellipse shape and (c) control results in the y-axis for eight curve shape.
idea of computing torque control [26]. To find the controlled input force $F$, the dynamic model should be known accurately, that is only possible theoretically but not practically.

To solve this problem, we propose the following robust PD–SMC law for trajectory tracking control of a translational robotic system.

$$F = K_P E + K_D \dot{E} + H \text{sign}(\dot{E} + \lambda E)$$

(5)

where $K_P$ and $K_D$ are the proportional and derivative control gains of PD control, $H$ is the SMC gain, $\lambda$ is the slide surface slope constant, and $\text{sign}()$ is the sign function.

**Remark 1.** From Eq. (5), one can see that the proposed PD–SMC control law is a combination of PD control and SMC. Therefore, it has the features of linear PD control and nonlinear SMC.

**Remark 2.** The proposed PD–SMC control law in Eq. (5) only involves the tracking errors and the derivative of the tracking errors and the dynamic model is not included in the control law. One feature of the proposed PD–SMC is that it is a model-free control law that is superior to a standard SMC where a normalized model is needed in order to calculate the equivalent control part of the standard SMC [16]. Therefore, it is easy to implement the PD–SMC control law for real applications.

Applying Eq. (5) to Eq. (3), the controlled system can be written as

$$\dot{E} + (K_P + K_D)E + (K+K_P)E = P - H \text{sign}(\dot{E} + \lambda E)$$

(6)

**Theorem.** Consider the translational robotic system (1) with the proposed PD–SMC control law (5), the controlled system will be globally stable and the final tracking error and its derivative are convergent to zeros, provided that the control gains and parameters are chosen as follows:

$$\lambda > 0$$

$$H \geq P_b > 0$$

$$\lambda_m(C + K_D) > \lambda \cdot \lambda_m(M)$$

$$\lambda_m(K + K_P) > \lambda^2 \cdot \lambda_m(M)$$

(7)

**Remark 3.** The conditions for choosing control parameters in Eq. (7) are conservative. Such a conclusion will be demonstrated through the following example verifications, see Section 4.4.

![Fig. 3. Tracking errors for the eight curve shape under different initial errors. (a) Negative initial error and (b) Positive initial error.](image-url)
Fig. 4. Comparison of tracking performances with varying friction and loading. (a) Control results in the x-axis for both shapes, (b) Control results in the y-axis for ellipse shape and (c) Control results in the y-axis for eight curve shape.
3. Stability analysis

Preposition. Let matrix $Q$ be a symmetric matrix expressed as

$$Q = \begin{bmatrix} A & B \\ B^T & C \end{bmatrix}$$  \hspace{1cm} (8)

Let $S$ be the Schur complement \cite{25} of matrix $A$ in $Q$, that is

$$S = C - B^T A^{-1} B$$  \hspace{1cm} (9)

Then the matrix $Q$ is positive definite if and only if $A$ and $S$ are both positive definite \cite{25}. It means if $A > 0$ and $S > 0$, then $Q > 0$.

To prove the stability of the proposed PD–SMC control law, first, we prove that the following matrix $Q$ is positive definite:

$$L = \begin{bmatrix} K + K_P & \lambda M \\ \lambda M & M \end{bmatrix}$$  \hspace{1cm} (10)

Proof. Choosing PD control gains to make sure that the matrix $K + K_P > 0$; we know that matrix $M$ is symmetric positive definite, i.e., $M = M^T$, $M > 0$. From conditions (7), we have

$$\lambda_M(K + K_P) > \lambda^2 \Lambda_M(M)$$  \hspace{1cm} (11)

From (11) we conclude

$$K + K_P - \lambda^2 M > 0$$  \hspace{1cm} (12)

As $K + K_P > 0$ and $M > 0$, according to the property of positive definite matrix, we have

$$M^{-1} - \lambda^2 (K + K_P)^{-1} > 0$$  \hspace{1cm} (13)

Furthermore, based on (13) and $M > 0$, from the property $\text{MNN} > 0$, we have

$$M - \lambda^2 M(K + K_P)^{-1} M > 0$$  \hspace{1cm} (14)

Considering $M = M^T$, we have

$$S = M - \lambda^2 (K + K_P)^{-1} (\lambda M) > 0$$  \hspace{1cm} (15)

According to the Preposition and Eq. (9), we prove that the matrix $L$ in Eq. (10) is positive definite.

Define the following Lyapunov function:

$$V(\dot{E}(t), \dot{E}(t)) = \frac{1}{2} (\dot{E}^T \dot{E}) + \frac{1}{2} \dot{E}^T(C + K) \dot{E}$$  \hspace{1cm} (16)

As the matrix $L$ is positive definite and $C + K_P$ is also positive definite from Eq. (7), therefore we conclude that $V$ is a positive definite function. Applying Eq. (10) into Eq. (16) and differentiating $V$ with respect to time, we obtain

$$\dot{V} = (\dot{E}^T \dot{E}) \left[ \begin{array}{cc} K + K_P & \lambda M \\ \lambda M & M \end{array} \right] \left( \begin{array}{c} \dot{E} \\ \dot{E} \end{array} \right) + \dot{E}^T(C + K) \dot{E}$$  \hspace{1cm} (17)

Substituting Eq. (6) into (17), we have

$$\dot{V} = \dot{E}^T(K + K_P) \dot{E} + \lambda \dot{E} \dot{E}^T M \dot{E} + \lambda \dot{E}^T M \dot{E} + \lambda \dot{E} \dot{E}^T(C + K) \dot{E}$$  \hspace{1cm} (18)

If we choose the control gains according to (7), we can make sure that

$$\begin{cases} (C + K) - \lambda M > 0 \\ K + K_P > 0 \end{cases} \hspace{1cm} (19)$$

It means that the first two items in Eq. (18) are negative definite.

Based on condition (7), we have

$$(\dot{E}^T + \lambda \dot{E}^T) H \text{sign}(\dot{E} + \lambda \dot{E}) = |\dot{E}^T + \lambda \dot{E}^T| \dot{H} > |\dot{E}^T + \lambda \dot{E}^T| |P_b| > (\dot{E}^T + \lambda \dot{E}^T)^T P$$  \hspace{1cm} (20)

From Eq. (20), we have

$$(\dot{E}^T + \lambda \dot{E}^T)(P - H \text{sign}(\dot{E} + \lambda \dot{E})) < 0$$  \hspace{1cm} (21)

According to Eqs. (19) and (21), we can demonstrate

$$\dot{V} \leq 0$$  \hspace{1cm} (22)

Since function $V$ is a positive definite function and $\dot{V}$ is a negative definite function, the robotic system in Eq. (1) controlled by the proposed PD–SMC in Eq. (5) is globally asymptotically stable based on the Lyapunov method, and the tracking error and derivative are zeros.

It should be mentioned that the standard SMC law will cause the controlled system chattering due to the switching action of the control law of the sign function, and the same chattering problem exists in the PD–SMC in Eq. (5). To avoid the chattering problem, a saturation function can be chosen and the proposed control law in Eq. (5) can be modified as follows:

$$F = K_P \dot{E} + K_P \dot{E} + H \text{sat}(\dot{E} + \lambda \dot{E}), \Phi$$  \hspace{1cm} (23)

where $\Phi$ is a constant diagonal matrix that determine the boundary layer of the sliding surface.

$$\text{sat}(\dot{E} + \lambda \dot{E}), \Phi$$  \hspace{1cm} (24)

When the control law in Eq. (23) is used, the final tracking error $\dot{E}$ is maintained within a guaranteed precision $\varepsilon$ that is called the boundary layer width \cite{16}, which can be obtained as follows:

$$\varepsilon = \frac{\Phi}{\lambda}$$  \hspace{1cm} (25)

From Eq. (25), one can see that the maximum final tracking error can be controlled by properly choosing the boundary layer $\Phi$ and the slope constant $\lambda$.

4. Simulation verifications

In this section, a 2 DOF translational robotic system is used as an example to demonstrate the effectiveness and robustness of the proposed PD–SMC. The parameters of the motion system are assumed as follows:

$$M = \begin{bmatrix} 10 & 0 \\ 0 & 5 \end{bmatrix} \hspace{1cm} C = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix} \hspace{1cm} K = \begin{bmatrix} 20 & 0 \\ 0 & 20 \end{bmatrix}$$

An ellipse shape and an eight curve shape in $XY$ plane are tracked using different control methods. The desired trajectories are defined as follows:

An ellipse shape: \hspace{1cm} $x_d = 0.3(1 - \cos(\omega t))$

$y_d = 0.15 \sin(\omega t)$
An eight curve shape:
\[
\begin{align*}
  x_d &= 0.3(1 - \cos(\pi t)) \\
  y_d &= 0.15 \sin(2\pi t)
\end{align*}
\]

where \( \omega = \pi \) and \( t \in [0, 2] \) s. The desired trajectories are shown in Fig. 1.

In all the simulations, a normal uncertainty and a nonlinear friction are assumed as
\[
D = \begin{bmatrix}
  3x + 0.2\text{sgn}(x) + d_1 \\
  2y + 0.2\text{sgn}(y) + d_2
\end{bmatrix}
\]

where \( d_1 \) and \( d_2 \) are random noise signals to simulate the uncertainty and disturbance.

In the simulations, the control gains are selected according to (7) and shown as follows:

**PD control**

\[
K_p = \begin{bmatrix}
  3000 & 0 \\
  0 & 1000
\end{bmatrix}, \quad K_d = \begin{bmatrix}
  0 & 600 \\
  0 & 600
\end{bmatrix}
\]

for ellipse shape tracking

\[
K_p = \begin{bmatrix}
  3000 & 0 \\
  0 & 3000
\end{bmatrix}, \quad K_d = \begin{bmatrix}
  0 & 1800 \\
  0 & 1800
\end{bmatrix}
\]

for eight curve shape tracking

**SMC control**

\[\lambda = 100\]

Fig. 5. Tracking performance under different PD gain factors, (a) Tracking performance in the x-axis, (b) Tracking performance in the y-axis for the ellipse shape and (c) Tracking performance in the y-axis for the eight curve shape.
\[
H = \begin{bmatrix}
100 & 0 \\
0 & 50
\end{bmatrix} \quad \Phi = \begin{bmatrix}
0.08 & 0 \\
0 & 0.06
\end{bmatrix}
\]
for ellipse shape tracking

\[
H = \begin{bmatrix}
100 & 0 \\
0 & 100
\end{bmatrix} \quad \Phi = \begin{bmatrix}
0.08 & 0 \\
0 & 0.08
\end{bmatrix}
\]
for eight curve shape tracking

It should be mentioned that the condition in Eq. (7) is conservative, which lets to more flexible selections of control gains in the PD–SMC control law. In the following parts, different cases are examined to deal with different situations. All the parameters and control gains listed above are used in PD control, SMC, and PD–SMC.

4.1. Tracking control with uncertainty and noise

First of all, the proposed PD–SMC is applied for the tracking control of an ellipse shape and an eight curve shape, and the comparisons with PD control and SMC are presented in Fig. 2. Fig. 2(a) shows the tracking errors and the required control forces in the x-axis for both shapes, and Fig. 2(b) and (c) shows the tracking errors and the required control forces in the y-axis for the ellipse shape and the eight curve shape, respectively. From this figure, we can see that the proposed PD–SMC obtained much better tracking performance than PD control, and a slight better performance than SMC. It should be noticed that the SMC control method needs prior knowledge of the dynamic model of the controlled system, but PD–SMC is a model-free control method. On the other hand, the required control forces for

![Fig. 6. Tracking performance under different SMC gain factors. (a) Tracking performance in the x-axis, (b) Tracking performance in the y-axis for the ellipse shape and (c) Tracking performance in the y-axis for the eight curve shape.](image-url)
both SMC and PD–SMC are larger than those controlled by PD control. Such a result is anticipated, as much control effort should be paid in order to achieve more accurate tracking performance.

4.2. Tracking control with initial errors and disturbances

To check the response speed of the proposed PD–SMC with respect to initial errors, simulations are conducted and Fig. 3 shows two different initial errors conditions for the eight curve shape tracking where Fig. 3(a) is a case of negative initial errors of 0.01 m for both axes while Fig. 3(b) is the case of positive initial errors of 0.1 m for both axes. From this figure, one can see that both SMC and PD–SMC have very fast responses to overcome the initial errors, while PD control is much slower to correct the initial errors. Comparing Fig. 3 with the corresponded tracking errors in Fig. 2, one can see that, after passing a very short period of time (around 0.2 s), the tracking performances are almost the same for PD–SMC and SMC methods. It demonstrated the fast response speed of the PD–SMC with initial error conditions. It should be mentioned that a similar conclusion is obtained for the tracking control of an ellipse shape under initial error conditions. For this scenario, the standard SMC is better than the PD–SMC in terms of the response speed for correcting the initial errors.

4.3. Tracking control with varying conditions

To verify the robustness and effectiveness of the proposed PD–SMC, a case with varying friction and mass (loading) at different time is simulated and compared with other control laws. It is assumed

![Controlled force for different boundary layer](image)

![Error for different boundary layer](image)

![Factor of boundary layer](image)

Fig. 7. Tracking performance under different boundary layers, (a) Tracking performance in the x-axis, (b) Tracking performance in the y-axis for the ellipse shape and (c) Tracking performance in the y-axis for the eight curve shape.
that an additional friction of $50|v|$ (where $v$ is the velocity of the axis) is added at $t=\frac{2}{3}$ s, and an additional loading of 10 kg is added at $t=\frac{4}{3}$ s, respectively. Fig. 4 shows the tracking errors and the required control forces for the ellipse shape and the eight curve shape under three different control methods. From this figure, one can observe that there are no significant changes at the changing points for both SMC and PD–SMC when the varied conditions are added. For the varying conditions, it is clearly shown that the PD–SMC can obtain very good tracking performances, while PD control had much degraded tracking performance. This simulation demonstrated the robustness and effectiveness of the proposed PD–SMC to compensate the varying friction and the loadings.

4.4. Control parameters effect on tracking performance

In previous subsections, comparisons of tracking performances are conducted under different conditions based on the same control parameters for all three control methods, and it is demonstrated that the PD–SMC can ensure very small tracking errors in all the situations compared with PD control. In this subsection, the effect of control parameters on tracking performances between PD–SMC and standard SMC are examined. In the simulations, five different factors to the normal control parameters, which are set as 0.2, 0.5, 1, 2, and 5, are considered in the tests to explore the effects of control parameters on the tracking errors and control forces.

Fig. 8. Tracking performance under different slope of slide surfaces. (a) Tracking performance in the x-axis, (b) Tracking performance in the y-axis for the ellipse shape, and (c) Tracking performance in the y-axis for the eight curve shape.
4.4.1. The effect of PD gains

First, we examine the effect of PD control gains on tracking performance for trajectory tracking control of the two considered shapes. Different factors of PD control gains, from 0.2 to 5 times of the normal values, are used to control the trajectories. Fig. 5 shows the comparison results for tracking errors and control forces between PD–SMC and standard SMC. From Fig. 5, one can see that PD–SMC is slightly superior to the standard SMC for all the selected PD control gains in terms of reducing tracking errors. But there is no significant difference for the tracking errors and the control forces under different PD control gain situations. It also demonstrates that the conservative condition of Eq. (7) for the choice of the PD control gains. Even for small control gains where Eq. (7) is invalid, the tracking errors are still in a small range. Such a result can be explained as follows: the PD control part of the proposed PD–SMC mainly contributed to the normal stabilization of the controlled system, forcing the tracking errors in the boundary layer of the slide surface. After entering the boundary layer, the tracking performance is dominantly controlled by the SMC control part.

4.4.2. The effect of SMC gain

In this simulation, different factors for the SMC gain $H$ are used to check the effects on tracking performances. Fig. 6 shows the results under five different factor levels. From this figure, one can see that the tracking performances did not improve by increasing the SMC gain, rather the required control forces increase dramatically. Therefore, a reasonable SMC gain is good for the reduction of the required control forces, and a very high SMC gain is not necessary in terms of the small trajectory tracking errors and limited control forces. It also shows that for relatively large SMC gain, the proposed PD–SMC is better than the standard SMC in terms of reducing tracking errors.

4.4.3. The effect of boundary layer

Boundary layer has some effects on the required control forces. Fig. 7 shows the tracking performances for different boundary layer situations. Generally speaking, the larger the boundary layer, the larger the tracking errors for the PD–SMC, and the smaller the control force for PD–SMC and standard SMC. If a large boundary layer is selected, a relatively large tracking error is allowed in the control process, and a smaller and smoother control force is required. To balance the tracking error and the control force, a proper choice for the boundary layer is helpful for good tracking performance.

4.4.4. The effect of the slope of slide surface

In a large range of the slope constant $\lambda$ of the slide surface, the tracking performances controlled by the PD–SMC is better than the standard SMC, see Fig. 8. It is observed that larger control forces are required if a big value of the slope $\lambda$ is chosen. Under the same boundary layer condition, a large value of $\lambda$ implies that a small value of the velocity error is required; therefore, a large control force is required to push the tracking errors approach to the slide surface.

5. Conclusions

In this paper, we studied the trajectory tracking control problem of robotic systems and proposed a new PD–SMC control method. PD–SMC is a combination of PD control and SMC, having the advantages of linear control and nonlinear control in the sense of simplification and robustness of the control law. The proposed PD–SMC control law is a feedback control law that only involves the tracking errors and the derivative of the tracking errors. One advantage of the proposed PD–SMC is that it is a model-free control law that is distinct from a standard SMC. The simplicity and easy design of the PD–SMC is another advantage compared with a standard SMC. Simulation results demonstrated that PD–SMC is superior to PD and as good as a standard SMC in terms of good tracking performance under the uncertainties, disturbances, and varying load conditions.

Different levels of the control parameters are used to examine the effects on tracking performances. From the simulation results, it demonstrated that the proposed PD–SMC is slightly better than a standard SMC in terms of reducing tracking errors in most levels of the factors. It also showed that the variations of the PD control gains do not have significant effect on the tracking errors and the control forces. Such a conclusion came from the nature of the PD control in the proposed PD–SMC, which is used to bring the tracking errors to the boundary layer of the slide surface. On the other hand, the SMC parameters have large effects on the tracking errors and especially the required control forces. It concluded that a relatively low SMC gain, a smaller slope of the slide surface, and large boundary layer can make the required control forces in small ranges for the proposed PD–SMC.

From the simulation results, one can see that the control parameters of the PD–SMC have significant and complicated effects on tracking performance and the required control forces. Therefore, it is a challenge for the proper selection of control gains when applying the proposed PD–SMC. In future work, we will conduct the optimization of control parameters based on the genetic algorithm or particle swarm optimization.

References


