A Time Delay Estimation Based Adaptive Sliding Mode Strategy for Hybrid Impedance Control

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This work was supported in part by the National Robotics Programme under its Robotics Enabling Capabilities and Technologies under Grant 192 25 00051, in part by the National Robotics Programme under its Robot Domain Specific under Grant 192 22 00058, and in part by the Agency for Science, Technology and Research.

ABSTRACT This paper is inspired by the automation of cleaning tasks required inside the endogenous environment. This work intends to develop a robust adaptive strategy for force-position control, using robotic manipulators. With this objective, the operational/task space is decoupled into two sub-spaces, and the impedance model for the manipulator is designed using the standard second-order filters. The impedance filter generates the reference commands for the inner loop, which assures bounded position and force tracking. A delay estimation based adaptive sliding mode strategy is proposed for carrying out the tracking objective, and its convergence is proved using the Lyapunov-Razumikhin theorem. The controller uses past data to estimate the uncertainties in the error dynamics and exploits the sliding mode strategy to provide robustness in the closed-loop. This technique circumvents the under/overestimation issues, and linear/nonlinear parametrization requirements in conventional adaptive schemes. Multiple numerical simulations and experiments are performed, and the results point to the validity of the proposed control law in real-world settings.

INDEX TERMS Hybrid impedance control, automation of cleaning, time delay based adaptive control, robot manipulator.

I. INTRODUCTION

The indoor cleaning tasks for public places like community centers, hospitals, apartments have become increasingly critical in present-day scenarios. The recent pandemic also emphasizes the need for proper sanitation and maintenance of all indoor setups, which are frequently coming in contact with the people. The human operators generally carry these tasks, and there is a need to automate the cleaning tasks for better safety and frequency of operations.

Automating cleaning tasks has been the focus of the robotic researchers for a while now [1]. Air-duct cleaning by moving platforms has attracted much attention due to its complexities and challenges [2]. The authors of the paper [3] developed a new technique for aircraft-canopy polishing. The cleaning of household items is generally carried out using human service robots (HSR) [4]. The paper [5] presented a new strategy for automatating can front cleaning. Similarly, automatic wiping and polishing tasks have been discussed in [6].

The above tasks require not only following a desired motion in the task space but also need to exert a pre-defined force for wiping/polishing surfaces [7]. In other words, a robot that is designed to automate these tasks should be able to simultaneously control the position of the end-effector and the force applied on the cleaning surface. As these tasks require the end-effector to remain in contact with the concerned environment, the end-effector movement is constrained (can not move freely in all directions) [8]. Similarly, the applied force should be in specific desired directions, and should not deviate much from the desired range [8].

The constrained manipulation of the robotic arm is carried out by selecting the suitable transformation from joint space to task space and formulating the Jacobian matrix for forward/inverse kinematics. A number of literature [9], discuss the stable manipulation using the robust control [10]–[12], adaptive control [13], [14], and model predictive control [15] techniques. Similarly, many force control techniques [16]
requirements a proper choice of decoupling matrix and impedance parameters (stiffness, damping) for better performance. Once this issue is sorted, the joint torques can be derived by using the large pool of robust and adaptive control techniques available in the literature [18], [24]–[27].

This work intends to focus on automating the indoor cleaning tasks, comprising of planar surfaces. The cleaning area may be a flat surface, an inclined plane [3], [5], or a dynamic moving plane like an escalator. The dynamic environment not only makes the friction force to vary but also make the force measurement inaccurate. Therefore, a conventional HIC may not assure satisfactory performance in such a setting. The adaptive strategies for HIC [25], [26] have issues with fast varying disturbances like contact forces. The sliding mode HIC [28] may have a chattering problem if proper care is not taken during implementation. Adaptive sliding mode technique may solve these issues but suffers from over/underestimation where the controller gains may shoot up or down near sliding surface [27]. This paper proposes a time delay estimation based adaptive sliding mode HIC scheme for this purpose. The proposed technique does not require the manipulator’s parameters to be known and robust to environmental uncertainties. Unlike the traditional adaptive HIC strategies [25], [26], the force measurements and impedance parameters are used for generating the feed-forward part of the control law. In contrast, the feedback part compensates for any uncertainties in the feed-forward part, and system dynamics.

II. MATHEMATICAL MODEL & CONTROL OBJECTIVE

The cleaning task is generally performed by the robotic manipulators, and the attached cleaning modules. The mathematical model for the robotic hand of any arbitrary DOF in the joint space, can be written in the form of an Euler-Lagrangian dynamics, i.e:

\[ M_j(q) \ddot{q} + C_j(q, \dot{q}) \dot{q} + F_j(q, \dot{q}) + G_j(q) + J(q)^T F_e = \tau_j \] (1)

where \( q \in \mathbb{R}^n \) is the joint state vector for the \( n \)-DOF manipulator. \( M_j(\cdot), C_j(\cdot), G_j(\cdot) \) and \( F_j(\cdot) \) represent inertia matrix, Coriolis matrix, Gravitational torque component, and friction component respectively. The matrix \( J(\cdot) \) is the manipulator Jacobian, \( \tau_j \) is torque input to the joints, and \( F_e \) is the forces arising due to contact with the external environment.

The manipulator Jacobian maps the end-effector’s position \( (x \in \mathbb{R}^m) \) in the task/operational space to the joint space \( q \in \mathbb{R}^n \). In general \( n \geq m \) for redundant manipulators, and \( m = n \) for non-redundant cases. Assuming the robot arm to be non-redundant, the dynamics of the end-effector in the task space can be expressed as:

\[ M_e(\xi) \ddot{\xi} + C_e(\xi, \dot{\xi}) \dot{\xi} + F_e(\xi, \dot{\xi}) + G_e(\xi) + F_e = \tau_e \] (2)

where \( M_e(\cdot) = J^{-T}(\cdot)M_j(\cdot)J^{-1}(\cdot), G_e(\cdot) = J^{-T}(\cdot)G_j(\cdot), F_e(\cdot) = J^{-T}(\cdot)F_j(\cdot), C_e(\cdot) = J^{-T}(\cdot)C_j(\cdot)J^{-1}(\cdot) - J^{-T}(\cdot)M_j(\cdot)J^{-1}(\cdot)J(\cdot)J^{-1}(\cdot), \) and \( \tau_e = J^{-T}(\cdot)\tau_j \).
A. IMPEDANCE CONTROL GOAL

The controller should be designed such that the joint torque \( \tau_e \) delivered assure simultaneous position and force tracking with desired dynamic effects. So, the control task space is categorized into two decoupled sub-spaces which would describe force control, and position control directions. Let’s define the two decoupled subspace as: \( x = [x_p, x_f] \), where \( x_p \) is the part of task space used for position control and \( x_f \) is the part used for force control. The desired dynamics to be imparted on these directions are defined by the following second order differential equation.

\[
M_d(\ddot{x} - \Sigma \dot{x}_d) + B_d(\dot{x}_p - \Sigma \dot{x}_d) + K_d \Sigma (x_p - x_d) - (I - \Sigma) F_d = -F_e \tag{3}
\]

where \( x_d \) is the desired trajectory along the position control, the matrices \( M_d, B_d, K_d \) denote desired inertia, damping and stiffness in the control directions, and \( F_d \) is the desired force need to be impacted. To decouple the force and position control directions, a diagonal matrix \( \Sigma \) is chosen, consisting of ones and zeros. The ones represent the required position control directions. The dynamics (3) represents the desired impedance of the manipulator in contact with the environment.

The impedance control scheme is originally designed such that the robot should follow the dynamics of a second-order spring mass damper system. So, (3) describes a 2nd order differential equation with the design parameters \( M_d, B_d, K_d, \Sigma \). As the cleaning surface is assumed flat, the parameter \( K_d \) is set to zero in force controlled direction, when in contact. This assures a proper steady-state force tracking. In other words, the desired impedance in force direction mimics a mass-dash pot system.

A moving surface can give rise to a varying external force, so the variable \( F_e \) is modeled as:

\[
F_e = K_e (x - x_e) + B_e (\dot{x})
\]

where \( x_e \) is the equilibrium position of the environment and \( K_e, B_e \) define stiffness, damping due to the environment, respectively. It should be noted that both \( K_e \) and \( B_e \) may vary due to the motion of the cleaning surface (in case of an escalator). So, an approximate value for them can be selected [23], [24], and the control law should be designed for compensating the inaccuracies.

One important aspect of impedance design is to ensure that the motion is controllable (not oscillating) while the manipulator loses contact. When the manipulator is free (\( F_e = 0 \)), and the desired force \( F_d \) is constant, the impedance dynamics \( (K_d = 0) \) becomes [24],

\[
M_d \ddot{x} + B_d \dot{x} = F_d.
\]

So the transient part of the velocity is decided by \( \frac{B_d}{M_d} \), whereas \( \frac{B_d}{M_d} \) can bound the maximum velocity. So, a suitable choice of \( M_d \) and \( B_d \) can ensure controllable velocity in the absence of contact, irrespective of reference position trajectory, and distance from the environment.

III. CONTROL LAW FORMULATION

Desired acceleration for the manipulator can be derived from (3) as:

\[
ad_d = M_d^{-1} [−B_d(\dot{x} - \Sigma \dot{x}_d)] - K_d \Sigma (x_p - x_d) + (I - \Sigma) F_d + F_e + \Sigma \ddot{x}_d. \tag{4}
\]

Similarly, the desired velocity and position from (4) can be expressed as:

\[
v_d = \int a_d dt, \quad p_{\text{d}} = \int v_d dt. \tag{5}
\]

By inverse dynamics cancellation approach, the force required by the manipulator to track the desired acceleration \( a_d \) is given by

\[
\tau_e = M_t(\cdot)a_d + C_t(\cdot) \int a_d dt + F_t(\cdot) + G_t(\cdot) + F_e. \tag{6}
\]

However, the system dynamics is generally unknown, and therefore one needs to take account of the uncertainties while developing a control law.

A. DELAY BASED ADAPTIVE ROBUST DESIGN

Due to possible variation in \( F_e \) (in case of dynamic), the desired acceleration and velocity are changed to

\[
ad = a_d + \delta a_d, v_d = v_d + \delta v_d
\]

Rewrite (2) as:

\[
M_t(q)\ddot{x} + S_n = \tau_e \tag{7}
\]

where the uncertain parts are combined into the term

\[
S_n = C_t(\cdot)\dot{x} + F_t(\cdot) + G_t(\cdot) - M_t(\cdot)\delta a_d - C_t\delta v_d
\]

As the system matrices in (7) are unknown, let’s choose a control law

\[
\tau_e = \hat{M} u_c + \hat{S}_n \tag{8}
\]

where \( \hat{S}_n \) is the estimate of \( S_n \), \( u_c \) is the combination of feedforward and robust component of the control law. The matrix \( \hat{M} \) is chosen as a constant diagonal matrix satisfying

\[
||M_t^{-1}(\cdot)\hat{M} - I|| < 1. \tag{9}
\]
The desired acceleration $a_d$ may contain some disturbances in force measurement $F_c$, so the term $u_c$ is selected as the combination of a feedforward component $u_f$ and robust component $u_r$ (to be decided later). The feedforward component is selected as

$$u_c = u_f + u_r,$$

where $k_d, k_p$ are two positive definite matrices. This paper differs from the conventional adaptive hybrid impedance literature in the sense that, the estimate $\hat{S}_n$ is derived using time delay estimation approach [29]. The estimate is derived as:

$$\hat{S}_n = \tau_e^l - \hat{M}a_d^l$$

(11)

where $\tau_e^l$ and $a_d^l$ denote the time delayed (by a small delay $l$) version of $\tau_e$, $a_d$. Using the delayed version of the estimate, the closed loop is converted into:

$$\hat{M}a_d + \hat{S}_n = \tau_e^l$$

(12)

where

$$\hat{S}_n = (M(\cdot) - \hat{M})a_v + \hat{M}a_d^l + S_n(\cdot) - \hat{M}u_c$$

Define an error vector $E = [e^T, \dot{e}^T]^T$, where $e = p_d - x$ and $\dot{e} = d_d - \dot{x}$. Expanding $\tau_e^l$, the closed loop dynamics (12) can be expressed as:

$$\dot{E} = A_1 E + A_2 E + B_0 S_c - B_0 u_r$$

(13)

where $u_r$ is a delayed version of $u_r$.

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0 & 0 \\ -k_d & -k_p \end{bmatrix}, \quad B_0 = \begin{bmatrix} 0 \\ I \end{bmatrix},$$

$$S_c = a_d^l - a_d^l + \hat{M}^{-1}(\hat{S}_n - \hat{S}_n)$$

The term $S_c$ is the error due to time delay estimation. As,

$$E_l = E - \int_{t}^{0} \dot{E}(t + r) dr$$

the equation (13) can be written as:

$$\dot{E} = A_o E + A_2 E + B_0 (S_c - u_r^l) - A_2 \int_{t}^{0} \dot{E}(t + r) dr$$

(14)

where $A_0 = A_1 + A_2$. It should be noted that the matrix $A_0$ can be made Hurwitz by proper selection of $k_d$ and $k_c$. Hence, there exist a set of positive definite symmetric matrices $P_o, Q_o$ such that

$$A_0^T P_o + P_o A_0 = -Q_0.$$

To select the robust component of the control law, which would negotiate the time delay error $S_c$. Define a sliding surface $\xi = B_o^T P_o E$, and select an adaptive switching law as:

$$u_r = k_r (\alpha_1 + \alpha_2 + \alpha_3) \tanh(\xi),$$

$$\dot{\alpha}_1 = \begin{cases} k_1 ||\xi|| \\ -k_2 ||\xi|| \end{cases}.$$

If

$$\begin{cases} \alpha_1 \leq \alpha_1^m \text{ or } (\xi > 0 \land \alpha_3 > \alpha_3^m \land \alpha_2 > \alpha_2^m) \\ \xi \dot{\alpha}_1 \leq 0 \land \alpha_3 \leq \alpha_3^m \land \alpha_2 \leq \alpha_2^m \end{cases} \quad \text{otherwise},$$

$$\dot{\alpha}_1 = \begin{cases} \frac{1}{\alpha_1} \frac{1}{\alpha_3} \frac{1}{\alpha_2} \frac{1}{\alpha_3} \frac{1}{\alpha_2} \\ 0 \end{cases} \quad \text{when } \begin{cases} \alpha_3 > \alpha_3^m \\ \alpha_3 \leq \alpha_3^m \end{cases} \quad \text{and } \begin{cases} \alpha_2 > \alpha_2^m \\ \alpha_2 \leq \alpha_2^m \end{cases} \quad \text{otherwise}.$$
for convergence analysis. For a Lyapunov function \( V(x(t)) \), the Razumikhin theorem points to the existence of a positive scalar \( v \) such that

\[
V(x(t_1)) < vV(x(t))
\]

for all \( t - 2l \leq t_1 \leq t \), where \( l \) is a finite delay time.

It should be noted that the closed loop dynamics can only be made stable by Razumikhin technique if the time delay error term \( S_c \) is bounded [27]. By ensuring the condition (9), the error \( S_c \) can be made upper bounded by a positive scalar [29], even though the constant is unknown, i.e.:

\[
||S_c|| \leq \tilde{a}_1
\]

where \( \tilde{a}_1 \in \mathbb{R}^+ \) and unknown.

As already suggested, the constant \( \tilde{a}_1 \) is unknown, and the robust part of the control law \( u_r \) tries to nullify its effect. In this direction, define a composite Lyapunov function

\[
V = V_1 + \frac{1}{2}((a_1) - \tilde{a}_1)^2 + \frac{1}{2}Y_1\tilde{a}_1^2 + \frac{1}{2}Y_2\tilde{a}_1^2
\]

where

\[
V_1 = \frac{1}{2}E^TP_oE,
\]

\( Y_1, \ Y_2 \) are two positive constants defined later. The Razumikhin’s theorem for \( V \), can be expressed as:

\[
V(E(t_1), \alpha_1(t_1), \alpha_2(t_1), \alpha_3(t_1)) < vV(E(t), \alpha_1(t), \alpha_2(t), \alpha_3(t))
\]

\[
\Rightarrow E^T(t_1)P_oE(t_1) < vE^T(t)P_oE(t) + \theta(t_1)
\]

where

\[
\theta(t_1) = v\frac{l}{k}((a_1(t) - \tilde{a}_1)^2 - (a_1(t) - \tilde{a}_1)^2) + Y_1(\tilde{a}_1^2(t_1) - \alpha_1^2(t)) + Y_2(\tilde{a}_1^2(t_1) - \alpha_1^2(t)).
\]

The time derivative of \( V \) along (14) can be expressed as:

\[
\dot{V} = -\frac{1}{2}E^TQ_oE + \xi^T H(t) - \int_{-l}^{0} E^TP_oA_2[A_1E(t + r) + A_2E(t + r - l) + B_oH(t + r)] dr
\]

where \( H(t) = S_c - u_r \). The last term inside the integral can be simplified as:

\[
\int_{-l}^{0} [E^TP_oA_2A_1E(t + r) + E^TP_oA_2E(t + r - l) + \xi E^TP_oA_2B_oH(t + r)] dr.
\]

Using Razumikhin’s theorem and few simple matrix manipulation:

\[
-\int_{-l}^{0} E^TP_oA_2A_1E(t + r)] dr \leq \frac{1}{2} \frac{l}{k} E^TP_oE
\]

\[
+ \xi E^TP_oA_2A_1P_2^{-1}A_1^T \xi^T P_oE + \frac{1}{k} \int_{-l}^{0} \theta(t + r) dr
\]

\[
-\int_{-l}^{0} E^TP_oA_2E(t + r - l)] dr \leq \frac{1}{2} \frac{l}{k} E^TP_oE
\]

\[
+ \xi E^TP_oA_2P_2^{-1}A_2^T P_oE + \frac{1}{k} \int_{-l}^{0} \theta(t + r - l) dr
\]

\[
-\int_{-l}^{0} \{E^TP_oA_2P_2^{-1}A_1^T P_oE + \frac{1}{k} \int_{-l}^{0} \theta(t + r) dr\}
\]

Using these simplifications, the time derivative of \( V \), can be expressed as:

\[
\dot{V} \leq -\frac{1}{2}E^T(Q_o - l\Gamma)E + \xi^T(S_c - u_r) + \gamma_1 + \gamma_2||\xi||
\]

(20)

where

\[
\gamma_1 = \frac{2v}{k}P_o + \nu P_oA_2P_2^{-1}A_1^T + A_2^T P_o \Gamma A_2
\]

(21)

The constant \( \gamma_1, \ \gamma_2 \) are derived using Lipschitz properties, i.e:

\[
||u_r - u_r'|| \leq \gamma_2
\]

(22)

\[
\frac{1}{2k} \left| \int_{-l}^{0} \left((H(t + r)B_oP_oB_oH(t + r)) + \theta(t + r) + \theta(t + r - l) dr \right) \right| \leq \gamma_1
\]

(23)

Proposition 1: The closed loop system (14) is stable, only if the time-delay \( l \) satisfies:

\[
l \leq \frac{\lambda_{\min}(Q_o)}{||\Gamma||}
\]

(24)

Proof: The dynamics (14) can be stable, if the first term in R.H.S of equation (20) is negative definite. For that to happen,

\[
(Q_o - l\Gamma) > 0 \Rightarrow l \leq \frac{\lambda_{\min}(Q_o)}{||\Gamma||}
\]

Exploiting (15), (11), and (8) on (20), the Lyapunov stability analysis can be carried out further. Let’s consider the scenario when

\[
a_1 \leq a_1^m \text{ or } (\xi \xi > 0 > a_2 > a_2^m)
\]

Exploiting (15) for this scenario, (20) can be rewritten as:

\[
\dot{V} \leq -\frac{E^T(Q_o - l\Gamma)E}{2} + \gamma_1 + \gamma_2||\xi|| + \gamma_1(\alpha_1 + \alpha_2 + \alpha_3)(tan(\xi)) + (\alpha_1 - \tilde{a}_1)||\xi||
\]

(25)

From (15),

\[
\dot{V} \leq -\frac{E^T(Q_o - l\Gamma)E}{2} + ||\xi||\left(\tilde{a}_1\xi + \gamma_1(\alpha_1 + \alpha_2 + \alpha_3)(tan(\xi)) + (\alpha_1 - \tilde{a}_1)||\xi||
\]

As \( k \) \( > 1 \),

\[
\dot{V} \leq -\frac{E^T(Q_o - l\Gamma)E}{2} \leq -\frac{\lambda_{\min}(Q_o - l\Gamma)}{2}||E||^2
\]

Hence, by exploiting Barbalat’s lemma [29], we get

\[
\lim_{t \to \infty} \dot{V} = 0 \Rightarrow \lim_{t \to \infty} E = 0
\]
Now consider the opposite scenario, for which the term $\dot{V}$ can be written as:

$$
\dot{V} \leq -\frac{E^T(Q_o - I\Gamma)E}{2} + \gamma_1 + \gamma_2||\xi|| + \gamma_1 \alpha_2 \dot{\alpha}_2 + \gamma_2 \alpha_3 \dot{\alpha}_3 + \xi^T(S_c - k_c (\alpha_1 + \alpha_2 + \alpha_3) \tanh(\xi)) - \frac{k_2}{k_1}(\alpha_1 - \tilde{\alpha}_1)||\xi||
$$

Exploiting (15), and the fact that $||\xi|| \leq ||B_o^T P_o|| ||E||$, one can derive

$$
\dot{V} \leq \frac{-\gamma_{\min}(Q_o - I\Gamma)}{2} ||E||^2 + \gamma_1 + \gamma_2 ||B_o^T P_o|| ||E|| + \frac{2k_2}{k_1} ||E|| + \frac{2\gamma}{\lambda_{\min}(Q_o - I\Gamma)} ||B_o^T P_o||
$$

Hence, the closed loop system is assured to be uniformly ultimately bounded (UUB), with a bound

$$
B_n = b_n + \sqrt{\frac{2\gamma}{\lambda_{\min}(Q_o - I\Gamma)}} \sqrt{\frac{b_n^2 + 2\gamma}{\lambda_{\min}(Q_o - I\Gamma)}}
$$

The closed loop steady state error $B_n$ can be made arbitrary small by selecting a small delay and a larger $Q_o$. Generally, the delay can be chosen as small as the sampling time for better accuracy. The above analysis can be summarized as the following theorem.

**Theorem 1:** Let proposition 1 holds true. If a control law is chosen as given in (8), (11) and (15) in the task space, then the unknown manipulator dynamics asymptotically converge to the described impedance dynamics (2). ⊙

**NOTE:** The theorem assures bounded tracking, provided the delay is bounded by the condition (24). However, the amount of delay directly affects the steady-state error ($B_n, b_n$ in UUB condition), and the sampling interval restricts the minimum delay. As the sampling has to be faster to get a smaller steady-state error, there exists a trade-off between condition (24) and small, steady-state error.

The design parameter $\alpha_1$ in (15) can be used to modify the robustness against the estimation error due to time delay. Similarly, the parameters $\alpha_2$ and $\alpha_3$ can be used to alter the closed-loop performance/stability. Other design scalars like $k_r, \alpha_1^n, \alpha_2^n, \alpha_3^n$ may be tuned by trial and error.

**V. SIMULATION**

A two-link manipulator is used for simulation, whose parameters are $m_1 = 10$ kg, $m_2 = 5$ kg, $l_1 = 0.2$ m, $l_2 = 0.1$ m, $g = 9.81$ m/s². The system matrices are given by:

$$
M_j = \begin{bmatrix}
M_1 & M_2 \\
M_2 & M_3
\end{bmatrix},
F_j = \begin{bmatrix}
0.5 \text{sgn}(\dot{q}_1) \\
0.5 \text{sgn}(\dot{q}_2)
\end{bmatrix}
$$

$$
M_1 = (m_1 + m_2)l_1^2 + m_2 l_2(l_2 + 2l_1 \cos(q_2))
M_2 = m_2 l_2(l_2 + l_1 \cos(q_2)), M_3 = m_2 l_2^2
$$

$$
M_j = \begin{bmatrix}
C_1 & C_2 \\
0 & C_3
\end{bmatrix},
G_j = \begin{bmatrix}
G_1 \\
G_2
\end{bmatrix}
$$

$$
C_1 = -m_2 l_1 l_2 \sin(q_2) \dot{q}_2, C_2 = C_1 - m_2 l_1 l_2 \sin(q_2) \dot{q}_1,
C_3 = -C_1, G_2 = m_2 g l_2 \cos(q_1 + q_2)
$$

$$
G_1 = G_1 + m_1 g l_1 \cos(q_1) + m_2 g l_1 \cos(q_1).
$$

The Jacobian matrix is given by:

$$
J = \begin{bmatrix}
\sin(q_1) + \sin(q_1 + q_2) & \sin(q_1 + q_2) \\
\cos(q_1 + q_2) & \cos(q_1 + q_2) + \cos(q_1)
\end{bmatrix}
$$

The impedance parameters are selected as:

$$
M_d = \text{diag}(13, 6), B_d = \text{diag}(30, 60), K_d = \text{diag}(250, 0).
$$

The external force is modeled using:

$$
K_e = \text{diag}(0, 180N/m), B_e = \text{diag}(0, 80 N \cdot \text{sec/m}).
$$

To model the variation in the external force due to movement of handrail a disturbance signal $0.2 \sin(0.5t)N$ is added to $f_e$. The desired force to be exerted is taken as $F_d = 3.5 N$, where as the desired trajectory in position controlled direction is taken as $\dot{x}_d = 0.3 \sin(t)m$.

For realizing the controller the following parameters are chosen:

$$
\dot{M}_f = 0.05I, \quad k_d = -30, \quad k_p = -150.
$$

For this choice of $\dot{M}_f$, the condition for bounded time delay estimation error can be satisfied, and the control gains $k_p, k_d$, with the matrix $Q_o = I$, gives rise to

$$
P_o = \begin{bmatrix}
0.1168 & -0.5000 \\
-0.5000 & 2.5167
\end{bmatrix}
$$

Choosing the sampling time equal to the delay $l = 0.001$ sec, the constants $v = 1.006, \kappa = 0.08$ satisfy the delay time requirement in proposition 1. The gain parameters of $u_r$ are chosen as $\alpha_1 = 0.005, \alpha_2^n = \alpha_3^n = 0.5$, where as other parameters are chosen by trial and error.

The closed loop simulations are carried out without any external disturbances are presented in figure 4-8. Figure 4 shows the position tracking along x-direction, whereas figure 5 shows force tracking. The steady state error for the force tracking is very small, which can be further reduced by a smaller sampling time.

The evolution of the sliding surface shown in figure 6 points to some initial transient, which may arise due to large error at initial conditions. The adaptive gains shown in figure 7, 8 and 9 remain bounded for all time, which confirms our convergence analysis.

To show the impedance tracking abilities of the proposed controller, define the auxiliary error vector as

$$
eaux = M_d(\ddot{x} - \Sigma \dot{x}_d) + B_d(\dot{x}_p - \Sigma \dot{x}_d) + K_d(\Sigma_x - x_d) - (I - \Sigma)F_d + F_e
$$

The figure 10 shows that $eaux \rightarrow 0$ in position controlled direction and tends to a very small steady state value in force controlled direction. It confirms asymptotic impedance tracking ability of the proposed controller.

To validate the effectiveness of the proposed control law, the simulation is repeated with the added uncertainties in the
The effect of the disturbance can be observed from the initial transient errors in position tracking (figure 11), and small oscillations in force tracking (figure 12), even though the error is small. By reducing the sampling interval, these errors can be further reduced.

VI. EXPERIMENTAL RESULTS
For implementation of the proposed controller, a Toyota HSR platform is chosen as the test-bed. The HSR is a position...
controlled robot, and therefore the torque command has to be transformed before implementation. We have used a simple torque-position transformation [30], which is given by

\[
q_{\text{ref}}(k) = k_{\text{ref}}^{-1} \tau_c(k - 1) + q(k - 1)
\]  

(26)

where \(q_{\text{ref}}(k)\) represents commanded position, \(k_{\text{ref}}\) is a positive constant, \(\tau_c(k - 1)\) is the torque sample from previous instant. Even though it is not an exact approach, it has been shown to work satisfactorily in the literature [30], [31]. The constant parameter \(k_{\text{ref}}\) is tuned by trial and error for a few known desired trajectory, before fixing it to \(k_{\text{ref}} = 15\). The controller is implemented using python-ROS interface, and the sensor measurements are collected using ROS package. For all experiments, the sampling interval is chosen as 1 ms.

The HSR is manually moved near the handrail, and only two joints (arm flex and wrist flex) are activated for the experiment. Initially, the desired position is set as \(0.3 \sin(t) m\) for 20 secs, and changed to a constant value \(0.25 m\) after that. The response of the gripper position is plotted in figure 13.

The small steady state error can be explained by the inaccuracies in the torque-position transformation.

The proposed controller is compared with a proportional derivative (PD) controller, conventional adaptive controller [25], [26] and a sliding mode controller [28]. The desired trajectory is set as \(0.3 \sin(t) m\) for 20 secs, after which it is changed to \(0.2 \sin(t) m\). The comparison results are presented in the following figures.

As the PD controller acts without any model knowledge, a comparatively inferior, trajectory and force tracking can be observed from the figure. It is observed that the steady-state trajectory tracking for the conventional adaptive and sliding mode impedance controller is similar to the proposed controller. However, both methods give rise to comparatively larger transient errors, both in trajectory and force tracking. The transient errors in the conventional adaptive controller are due to the comparatively slower adaptation to the desired trajectory changes and the sudden change in the impedance during initial contact. The sliding mode controller does not
suffer from slowness, but it suffers from discontinuity of the control law, whose effects can be observed as perturbations in the force tracking error. The proposed controller is not slow to adapt, does not suffer from chattering, and does not have over/underestimation issues. Hence, it has comparatively better performance in both the trajectory as well as force tracking. The initial transient errors for the proposed controller can be explained by the time delay based estimation technique, which comes to effect after a small initial time period. The effect can be suppressed by saturating the control law beyond the region of interest.

VII. CONCLUSION

A new strategy is proposed for hybrid impedance controller design using time delay estimation technique. The standard second order impedance filter is used to generate the reference trajectories for the inner loop. The control law comprises of a feed-forward segment and an adaptive sliding mode segment. The adaptation technique does not suffer from over/underestimation problems and does not need regressor matrix computation. The controller is suitable for cleaning handrails, escalators, and other plane surfaces, which is verified through numerical simulations and experiments.

ACKNOWLEDGEMENT

The authors would like to thank, the National Robotics Programme, the Agency for Science, Technology and Research, and SUTD for their support.

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