Reference Adaptive Impedance Control: A New Paradigm for Event-Based Robotic and Telerobotic Control

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Abstract
A new paradigm of event-based robotic and telerobotic control, referred to here as the Reference Adaptive Impedance Control, is presented for partially constrained robotic and telerobotic tasks under uncertain or unknown environmental constraints. The reference adaptive impedance control determines the desired next state adaptively in such a way as to follow the optimal path from the current state, where the optimal path is generated with the environmental constraints updated through time. The embedded impedance control provides a mechanism for collecting more complete information on the environment. The reference adaptive impedance control also serves as a powerful tool for implementing shared control in teleoperation. A case study of robotic and telerobotic soil trenching is given with simulations.

1. Introduction
Most of conventional robot controllers have been designed to perform trajectory tracking, where the control signal is generated in such a way as to minimize the error from the reference defined by the planned trajectory. However, for many robotic tasks which require interactions with environments, to maintain the tracking error small may be difficult, if not impossible, due to the uncertainties and tolerances involved in the environments as well as robots. Applying the trajectory tracking control to partially constrained tasks, delays and tracking errors may cause a significant disruption of the planned path, as well as may lead to undesirable robot behaviors, e.g., large contact forces and jerky motions.

For robotic applications, it would be better to design a controller that determines the desired next state based on the current state, rather than based on tracking the preassigned reference trajectory. Such a controller should be better for handling errors, since the desired next state can be determined in such a way as to reach the goal state optimally from the current state based on the updated information on the environments and robots.

The reference adaptation described above differs fundamentally from the conventional impedance or compliance control [4]. Although the impedance or compliance control allows a robot to be deviated from the planned trajectory to cope with the uncertainties of environmental constraints, the allowed deviation is local to the preassigned reference. That is, its scope of compliance is rather limited.

The reference adaptation described above can be combined with impedance control. The impedance control can provide more complete information on the environmental constraints, which can be used for generating the optimal path from the current state. With the reference adaptive impedance control, the scope of compliance can be significantly extended.

In teleoperation, the master arm trajectory generated by the operator plays a role of the reference trajectory for the slave arm. Therefore, the concept of reference adaptation described above can be applied to teleoperation, leading to a new method of command interpretation and of implementing shared control.

2. Reference Adaptation
2.1 Trajectory vs. Path
A precise description of robotic tasks requires to define the trajectories of robot end-effectors or platforms in the position and/or force space. A trajectory, P(s(t)), is defined here as the time history of a trace of points or a continuous line connecting the initial and final points. P(s(t)) represents the coordinate, P, of a point, s, on the line at time t. A point on a line can be represented in terms of a generalized coordinate, s, 0 ≤ s ≤ l, where s represents the normalized length from the initial point, s=0, to the point of interest along the line. The normalization is done in such a way that s=1 at the final point. A path, P(s), is defined as a trace of points or a line, in the position and/or force space with no specification of time.

A trajectory, P(s(t)), carries not only the position and/or force but also the time rates such as the velocity and acceleration information along the line.

Note that the same end-effector path, P(s), can be formed by many different trajectory assignments, since it is possible to trace a line with a different speed.

2.2 Trajectory Tracking
To accomplish a given task, it is sufficient to accurately track the given reference trajectory, P(s(t)). Therefore, most of the conventional robot controllers are designed to perform trajectory tracking, where the control signal, u(t), is generated in such a way as to minimize the error between the actual and reference states at time t, as exemplified by the resolved motion and force control.

To maintain the tracking errors small, the trajectory tracking controller must have an accurate model of robots and environments. For many robotic tasks which require interactions with environments, it is difficult to obtain accurate models due to the uncertainties and tolerances inherent to the environments as well as robots. Such modeling errors cause tracking errors. For instance, while carrying out a debarring task, a robot may experience a delay or time slack due to unexpected irregularities on the surface. During a robotic peg-hole insertion task, a robot may experience a compliant motion or jamming that results in a path deviation or delay.

![Fig. 1: Discrepancies in the original and actual paths due to large delays or time slacks.](image)

In trajectory tracking, a large delay or time slack may cause a significant disruption of the original path. As shown in Fig. 1, assume that the robot end-effector is positioned at

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time \( k \) at \( P'(s(k-d)) \) due to the delay of \( d \): \( x(k) = P'(s(k-d)) \).

Since the trajectory tracking controller sets the next desired position, \( x^d(k+1) \), as \( P'(s(k+1)) \), regardless of \( x(k) \), the robot may take a new path from \( x(k) \) to \( P'(s(k+1)) \), resulting in a path very different from the original path.

### 2.3 Reference Adaptation

With the conventional trajectory tracking controller, the tracking errors may not only cause a significant disruption of the original path, but also may lead to undesirable robot behaviors. For instance, assume that a robot is under jamming during a peg-hole insertion operation. A continuous increase in the position error may lead to an excessively large contact force, such that a sudden release from the jamming may cause the end-effector to jerk and jump.

For robotic applications, it should be better to design a controller that determines the desired next state, \( x^d(k+1) \), based on the current state, \( x(k) \), rather than based on tracking the reference trajectory with \( P'(s(k+1)) \). By allowing the desired next state to be determined based on how to reach the goal state from the current state in compliance with the current environmental constraints updated through time, the errors and abnormalities in control can be better dealt with.

The control strategy in which the desired next state is determined based on the current state is referred to here collectively as the Reference Adaptive Control.

There are two approaches for implementing the reference adaptive control. The first approach, referred to here as the Fixed Path Approach, puts an emphasis on following the original reference path exactly while allowing tolerance in velocity tracking. This approach, often termed as the Event-Based Control [1,2], first identifies the point on the original path, \( P'(s(k-d)) \), which is the closest from the current point \( x(k) \). Then, the desired next point, \( x^d(k+1) \), is determined as

\[
\begin{align*}
\mathbf{F} &\mathbf{P}'(s(k-d)) = \min \{ \| x(k) - \mathbf{F}'(s(k-t)) \| \} \forall \mathbf{F}'
\end{align*}
\]

The fixed path approach to the reference adaptive control works best for the cases where the environmental uncertainties cause unpredictable delays and time slacks in tracking the original trajectory.

The second approach, referred to here as the Optimal Path Approach, puts emphasis on following the optimal path from the current state to the goal state. In this approach, the desired next state, \( x^d(k+1) \), is determined at each \( k \) in such a way as to follow the optimal path from \( x(k) \) to the goal state, as shown in Fig. 2. The optimal path from \( x(k) \) to the goal state can be generated by applying the optimality criteria such as minimum time and energy to the system model updated through time. The optimal path approach can be more general and powerful than the fixed path approach, and can avoid the local minima problem such as limit cycles that may be encountered by the fixed path approach [1]. However, the algorithm for generating the optimal path is problem dependent and may need to depend on heuristics.

### 2.4 Reference Adaptive Impedance Control

The reference adaptive control described above differs fundamentally from the impedance or compliance control [4]. In the impedance or compliance control, the allowed deviation at \( k \) is referenced to \( P'(s(k)) \) for all \( k \), limiting the scope of compliance to be local around \( P'(s(k)) \). In the reference adaptive control, the scope of compliance is theoretically unbounded since the reference is constantly shifted to the current state. However, the impedance control, combined with reference adaptive control, helps obtain more complete information on the environmental constraints, and, thus helps update the system model more effectively. By analyzing how the actual trajectory is deviated from the reference trajectory in compliance with the environmental constraints, the information on environmental constraints can be collected.

The combination of the reference adaptive control with the impedance control can be done simply by letting the desired states of the impedance control law be determined adaptively. To be more specific, let us first define the desired impedance in the Cartesian space as follows:

\[
\begin{align*}
\mathbf{f}(k) - \mathbf{f}'(k) &= \mathbf{k}_a(x(k) - x^d(k))) + \\
\mathbf{k}_e(x(k) - x^e(k)) + \mathbf{k}_p(x(k) - x^p(k))
\end{align*}
\]

where \( f \) and \( x \) represent respectively the force and position vectors. The impedance control law can be obtained from (1) by solving for \( x(k) \):

\[
\begin{align*}
\dot{x}(k) &= \mathbf{f}'(k) + \mathbf{k}^{-1}_a (f(k) - \mathbf{f}'(k)) \text{ and } \\
\dot{x}(k) &= \mathbf{k}_e (x(k) - x^e(k)) - \mathbf{k}^{-1}_e \mathbf{k}_p (x(k) - x^p(k))
\end{align*}
\]

The reference adaptive impedance control law is of the same form as that of impedance control law, (2), except that the desired states, \( x^d(k) \), \( x^e(k) \) and \( x^p(k) \) are determined based on either the fixed path or the optimal path approach to reference adaptation, as described in Sec. 2.3. Note that we may set the sampling interval of reference adaptation longer than that of the impedance control.

### 3. Reference Adaptation in Teleoperation

In teleoperation, the master arm trajectory generated by the operator is interpreted as the reference trajectory the slave arm to follow. Therefore, the same principle that led to the reference adaptive impedance control can be applied to teleoperation. For instance, a time slack or delay due to environmental constraints may cause the slave arm path deviated from the commanded path if the command interpretation is based on \( x^d(k+1) \) = \( P'(s(k+1)) \), where \( P'(s(k+1)) \) represents the slave arm position corresponding to the current master arm position. This problem may be handled by the force feedback: feeling the force proportional to the error between the commanded and actual positions, the operator may slow down or stop the master arm to wait for the slave arm to catch up. To do so allows the tracking error of the slave arm to be maintained within a certain bound.
Following the optimal path approach to reference adaptation, a new form of command interpretation can be formulated for teleoperation: the desired next state, $x^{d}(k+1)$, of the slave arm is determined in such a way that the kinematic relationship between $x_{m}(k)$ and $x_{m}(k+1)$ of the master arm be the same as that of $x_{s}(k)$ and $x_{s}(k+1)$ of the slave arm, as illustrated in Fig. 3. More precisely,

$$x^{d}(k+1)=x_{s}(k)+T_{m}^{-1}[x_{m}(k+1)-x_{m}(k)]$$

(3)

where $T_{m}$ represents the homogeneous transformation defining the kinematic correspondence between the master and slave arms. Note that the communication delay between the master and slave arms is not taken into consideration.

The approach for interpreting the operator's command in teleoperation based on (3) is referred to here as the Reference Adaptive Command Interpretation.

With the reference adaptive impedance control implemented in the slave arm, a teleoperator system can be operated by shared control by allowing the operator to determine the desired next state of the slave arm based on the reference adaptive command interpretation, while the required compliance is automatically taken care of by the embedded impedance control.

4. Examples

To help understand the reference adaptation presented above, we introduced the following two simple examples: 1) a robotic peg-hole insertion task and 2) a teleoperation in a cluttered environment.

4.1 Peg-Hole insertion

A robot is assigned a task to insert a peg into a hole along the fixed path, a vertical straight-line, as shown in Fig. 4. Assume that there exists a slight horizontal misalignment between the peg and hole due to uncertainties and tolerances associated with part dimensions as well as robot control. In the case where the robot is assumed to be rigid or non-compliant and is subject to the trajectory tracking control, the peg will stop following the generated trajectory at the contact point on the chamber. However, the contact force will keep increasing while the desired next peg position, $x^{d}(k+1)$, is further away from the contact point (Fig. 4(a)). With the reference adaptive control based on the fixed path approach, the contact force can be maintained small since the desired next state, $x^{d}(k+1)$, is defined as the next point along the path from $x(k)$ for each $k$, although the peg may still be stuck at the contact point (Fig. 4(b)). With the reference adaptive control based on the optimal path approach, the robot can alter the given path at the contact point toward the goal by identifying a misalignment from the measured contact force (Fig. 4(c)).

A similar control pattern is expected with the impedance control. However, the impedance control may allow the task to be successful through local compliance, if the misalignment is small, as shown by the dotted pegs in Fig. 4(d) and (e). The reference adaptive impedance control based on the optimal path approach can handle the case of large misalignment through the modification of the reference path beyond the local compliance (Fig. 4(f) and (g)).

4.2 Teleoperation in a cluttered environment

Assume that a slave arm is operated in an environment with a thin wall at $y=6$ and an ellipsoidal object at $x=y=2.2$, as shown in Fig. 5. Without realizing a collision of the slave arm with the object in time, the operator may advance the master arm well beyond the contact point, $C_{1}$, as shown in Fig. 5(a). The slave arm may experience a large contact force at the contact point as the master arm advances further. With the reference adaptation based on the fixed path approach, the contact force can be kept small, although it requires the master arm trajectory between the index operations (where the kinematic
5. Case Study: Robotic and Telerobotic Soil Trenching

Assume that a robot with a scoop at the end-effector is engaged in a soil trenching task, as shown in Fig. 6. The dynamics of soil trenching is very complicated with the soil property either unknown or varying unpredictably. Therefore, the robot controller should be able to modify a preplanned trenching trajectory adaptive to the varying soil properties. The proposed reference adaptive impedance control is expected to provide such capabilities.

5.1 Kinematic Modeling

We assume that the trenching trajectory lies on the 2D plane, the trenching plane. In Fig. 6, PUMA 560 is configured in such a way that the trenching trajectory lies on the plane.

First, we approximate the geometry of the scoop, S, at the end-effector as an arc of a circle of radius R with an arc angle of θ, S = arcr(R, θ), as shown in Fig. 7. The position and orientation of the scoop is represented by the position (x, y, z) and orientation (roll, pitch, yaw), respectively, by the location of the center of circle, P, and of the tip of the scoop, S₂, with reference to the 2D trenching plane frame.

We consider that the robotic soil trenching consists of three distinct stages of operation: the penetration, the sweeping, and the piling, as shown in Fig. 8.

The optimal penetration motion of the scoop during the penetration stage is a circular motion rotated about the scoop center, P (Fig. 8(a)). The circular motion will minimize the amount of soil that should be displaced by the scoop during penetration. This implies that the optimal path of the scoop during penetration is determined by the location of P. By representing the current scoop position and orientation, S₁(k), in terms of P(k) and S₂(k) during the penetration, the desired next scoop position and orientation, S₁(k+1), can be obtained by rotating the scoop around P(k) and computing S₁(k+1) from P(k) and S₂(k+1).

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We assign the property index of 1 to the soil of nominal hardness, and assign the property index of larger or less than 1 depending on whether the soil is harder or softer than the nominal. The reaction force and torque are assumed proportional to the value of property index.

5.3 Adaptive Reference Impedance Control

The adaptive reference impedance controller designed for the robotic trenching task consists of three layers of control: Reference Adaptive Control, Impedance Control, and PID control, as shown in Fig. 10. The desired tip velocity obtained by the impedance controller is transformed into the desired velocities of individual joints that are fed into corresponding joint PID controllers. The reference adaptive controller sets the desired next state of the impedance controller based on the optimal path obtained at each sampling time. The sampling intervals, T₁, T₂, and T₃, of the reference adaptive controller, the impedance controller, and the PID controller, respectively, may not be the same but T₁≤T₂≤T₃.

The desired impedance at Sₖ is defined as

\[ f_{\text{des}}(\dot{q}(k)) = \sum_{i=1}^{n} K_i \left( \dot{q}_i(\dot{q}(k)) - \dot{q}_i^*(\dot{q}(k)) \right) \]

where \( K_i = [k_{i1}, k_{i2}, k_{i3}] \), \( k_{i1} = \|s_{i1}\|, k_{i2} = \|s_{i2}\|, k_{i3} = \|s_{i3}\| \), and \( K_0 \) and \( K_3 \) are preassigned 3x3 diagonal matrices. Then, the impedance control law can be obtained from Eq. (4) by

\[ \dot{q}_i^*(\dot{q}(k)) = \dot{q}_i^*(\dot{q}(k)) - \sum_{i=1}^{n} \frac{1}{k_i} \left( f_{\text{des}}(\dot{q}(k)) - f_{\text{act}}(\dot{q}(k)) \right) \]

At each sampling time, k, of the reference adaptive controller, the desired next position and velocity of \( s_{i1} \) and \( s_{i2} \) (k+1) are determined by identifying the location of the scoop center, P(k), and generating the optimal path by rotating the scoop about P(k).

In teleoperation with shared control, the reference adaptive controller can be replaced by the operator, where the operator determines the desired next position and velocity of \( s_{i1} \) based on the visual and force feedbacks.

5.4 Simulation

We simulate the reference adaptive impedance control applied to the robotic and telerobotic trenching task described above. In the simulation, the performance of reference adaptive impedance controller is compared with that of other controllers: impedance controller and PID controller.

The simulation is performed with various soil properties: nominal, harder than nominal, and softer than nominal properties of soils. The nominal property is assigned arbitrarily to the soil of unknown property for the generation of initial trenching trajectory.

Robotic Trenching

The reference adaptive impedance control is implemented in the Cartesian space, such that the resolved motion, the Cartesian velocity of the tip, is transformed to joint motions by

(a) Trenching paths generated for softer soil

(b) Trenching paths generated for harder soil.
results are similar to the robotic trenching with the reference adaptive impedance control. It is shown that the operator with a higher force sensitivity performs better than that of lower force sensitivity, as seen from the dash-dotted and solid lines in Fig. 14(a) and (b). This explains why a skilled operator can do a better job than a novice.

6. Conclusions
It has shown that the proposed reference adaptive impedance control provides a robot with the capability of flexibly interacting with uncertain or unknown environment beyond the local compliance provided by conventional compliance control. This is the result of the reference adaptation at the current state, or of generating the optimal path from the current state, with the information on the environment gathered through time based on the impedance control. It has also shown that the proposed control paradigm provides a powerful means of implementing the shared control in teleoperation with a new and more flexible command interpretation method, referred to here as the reference adaptive command interpretation.

Due to the simplicity in its control structure, the proposed reference adaptive impedance control is easy to implement, as shown in the case study. However, the algorithm for obtaining the optimal path from the current state is dependent upon the problem itself, and may not be easily formulated in some cases. An algorithm based on heuristic rules may be used instead, as will be more clarified in the future research. We plan to further investigate the proposed reference adaptive impedance control with other robotic and telerobotic applications as well as with experimentations.

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