TRACKING CONTROL OF A REDUNDANT MANIPULATOR WITH THE ASSISTANCE OF TACTILE SENSING

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ABSTRACT—This paper presents a method to control the end-effector of a redundant manipulator tracking the surface closely with the assistance of tactile sensing, which is based on the idea of hybrid impedance control method. Not only should the position and force control be implemented, but also the actual contacting between the end-effector and the object’s surface should be monitored and sensed. The feedback contains both the force-torque information and the tactile sensing such as contact state, contact area and so on. Then several strategies of tactile sensing feedback are proposed to combine into the control algorithm. A 5-DOF redundant manipulator equipped with force/torque and tactile sensors is applied, and simulations and two groups of real experiments for the planar tracking task are made respectively. The results confirmed the effectiveness of the proposed strategies at last.

Key Words: Tactile sensing, hybrid impedance control, redundant manipulator

1. INTRODUCTION

Impedance control is a prominent example of compliant motion control algorithms, which provides a very suitable framework for autonomous manipulation by manipulator contacting with the environment [1] [2] [3]. It is often used in the cases of safe, light and passive movements, contacting with hard physical surfaces, small devices, and so on [1].

The idea of generalized impedance control was proposed by Hogan [1], because the position and force tracking accuracy of manipulator’s end-effector can be balanced by properly adjusting impedance parameters (stiffness and damping matrices) as a result of unexpected interactions with the environment. Anderson and Spong [4] proposed the hybrid impedance control (HIC), which is a unified approach for motion and force control. Chan et al. [5] developed a variable structure control scheme for impedance control of manipulators in the presence of both parametric uncertainties and external disturbances. Liu and Goldenberg [6] proposed a robust HIC method. Shadpey et al. [7] proposed an augmented HIC scheme for kinematically redundant manipulators combining redundancy resolution to achieve the regulation of the end-effector interaction with the environment and satisfy additional user-defined constraints. Oh et al. [8] presented an extended HIC scheme to achieve an inertial decoupling of the motion and force controlled subspaces and internal motion control using a minimal parameterization of motion and force controlled subspaces and the null-motion component.
For some complicated robotic manipulations in uncertain and dynamic environments, open
loop control will not be sufficient, it is essential to know whether contact has occurred and to
measure the parameters of contact between the sensor and an object such as the spatial distribution
of forces. The feedback of tactile sensing can be used to control force and torque at a specific
contact location, which is necessary for manipulating objects and controlling slippage [10].

Based on the above ideas, this paper presents a method to control the end-effector of a
redundant manipulator tracking the surface closely with the feedback of both force-torque and
tactile sensing information. The tactile sensor [13] provides a possible solution to know more
details about the contact between the robot and environment in terms of contact states and contact
areas [9]-[16].

To assist the tracking, tactile sensing offers a possible solution to the problems that the end-
effector of the manipulator makes a contact with the unknown environmental geometry based on
approach to opening doors for a dexterous robot, by combining both force-torque and tactile
sensor information. Schmidt et al. [13] used tactile exploration of objects to create a shape
representation and find stable grips, which are applied autonomously on the basis of visual
recognition. Lo et al. [15] used an integrated tactile feedback system for a multi-fingered robot
hand to enable a human operator to feel contacts/interactions between the robot finger and the
environment remotely. Iwata and Sugano [16] proposed a method that allows a robot to quantify
tactile recognition of a human touched by other people. Kikuuwe and Yoshikawa [17] proposed a
novel identification technique of robot perception of impedance, by which the impedance
parameters are estimated on-line based on position and force sensing.

In this paper, besides the essential part of force-torque sensing, we mainly focus on the study
of the tactile sensing feedback to the hybrid impedance controller, since tactile sensor can detect
whether contact has occurred and determine the contact area and geometry from the sensed data.

The other parts of the paper are organized as follows: In Section 2, the preliminary knowledge
of impedance control is presented. In Section 3, the tracking control of the manipulator is
proposed, which is based on the idea of hybrid impedance control that follows both the position
and force trajectory simultaneously. In Section 4, several strategies of tactile sensing feedback are
proposed. Simulations and experiments are made and the corresponding results are demonstrated
in Section 5. Some discussions are added in Section 6. The conclusion remarks are obtained in the
last section.

2. PRELIMINARY KNOWLEDGE OF IMPEDANCE CONTROL

Impedance control [1] tries to assign a prescribed dynamic behavior for a robot manipulator
while its end-effector is interacting with the environment and its desired performance is specified
by a generalized dynamic impedance as shown in Figure 1.

![Figure 1. Modeling of the impedance control](image-url)
The desired impedance has the following form:

\[ M_d (\ddot{x} - \ddot{x}_d) + B_d (\dot{x} - \dot{x}_d) + K_d (x - x_d) = -F_e \]  

(1)

where \( x, \dot{x}, \) and \( \ddot{x} \) are the position, velocity and acceleration of the end-effector of the manipulator. \( x_d, \dot{x}_d, \) and \( \ddot{x}_d \) are the reference position, velocity and acceleration. \( M_d, B_d \) and \( K_d \) are positive-definite matrices representing inertia, damping and stiffness respectively, which are usually chosen to be diagonal, rendering the system decoupled, and \( F_e \) is the environmental reaction forces.

However, the impedance control is only a position control scheme, it has not any attempt to follow a command force trajectory. Then the hybrid impedance control is presented in the next section, which is a combination of two fundamental control strategies, the position-based and force-based impedance control.

3. TRACKING CONTROL OF THE MANIPULATOR

The whole system in this paper can be regarded as a rigid manipulator in contact with a compliant environment and the desired impedance is assumed to be a mass-spring-damper system, which is usually modelled as a linear spring in parallel with a dashpot as shown in Figure 1. The end-effector of the manipulator is equipped with the tactile sensor, which will provide much contacting information to the proposed control algorithm.

3.1 Hybrid Impedance Control of the Manipulator

3.1.1 Position-Based Impedance Control

Since the impedance control is in essence a position control scheme, let \( e_p \) be the position tracking error, \( e_p = x - x_d \), then the desired equation (1) of the position-based impedance control has the following form:

\[ M_d \ddot{e}_p + B_d \dot{e}_p + K_d e_p = -F_e \]  

(2)

where \( M_d, B_d \) and \( K_d \) have the same definitions as before and \( F_e \) is the contact force exerted by the end-effector on environment.

3.1.2 Force-Based Impedance Control

To follow the reference force, the desired impedance of force control is defined by:

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

(3)

where \( x, \dot{x}, \) and \( \ddot{x} \) are the position, velocity and acceleration of the end-effector of the manipulator and \( F_d \) is the desired force.

3.1.3 Hybrid Impedance Control

Tracking a desired path with the target force, either position-based impedance control or force control is not enough for the task, then the hybrid impedance control finds a way to the solution,
which is a combination of two fundamental control strategies, both the desired positions are commanded and a force trajectory is followed [4].

Therefore, by combining (2) and (3), the proposed hybrid impedance can be defined as follows:

$$M_d(\ddot{x} - S\ddot{x}_d) + B_d(\dot{x} - S\dot{x}_d) + K_d S(x - x_d) - (I - S) F_d = -F_e$$  \hspace{1cm} (4)$$

where $S$ is a diagonal matrix with ones and zeros on the diagonal line while ones relate to position-controlled subspaces and zeros relate to the force-controlled subspaces. Here the task space is divided into orthogonal position and force controlled subspaces using the selection matrix $S$. $F_d$ is the desired force.

From (4) it is not difficult to find that the hybrid impedance control is switched by the selection matrix $S$. When $S = 0$, the desired equation of motion is identical to the equation of position-based impedance control (2) and when $S = 1$, the desired impedance will have the equation of the force-based impedance control (3).

As shown in Figure 2, the inner and outer loop control strategy can be combined to achieve the closed-loop dynamics. A compliant impedance behavior is designed in an outer loop based on the desired impedance in the position-controlled subspaces and the desired force in the force-controlled subspaces. The main responsibility of the inner loop is to select the input torque for the arm forward dynamics.

3.2 Outer Loop Design of the Proposed Control

The spaces are split into the main task $X$ and additional task $N$ corresponding to position-controlled and force-controlled subspaces respectively and their trajectories of accelerations ($\ddot{x}$ of main tasks and $\ddot{x}_N$ of additional tasks) have the following forms:

$$\ddot{x} = S_x \ddot{x}_d - M_d^{-1} [B_d (\dot{x} - S\dot{x}_d) + K_d S_x (x - x_d) - (I - S_x) F_d + F_e]$$ \hspace{1cm} (5)$$

$$\ddot{x}_N = S_N \ddot{x}_N - M_d^{-1} [B_d (\dot{x}_N - S_N \ddot{x}_d) + K_d S_N (x_N - x_N) - (I - S_N) F_N + F_e] \hspace{1cm} (6)$$

where $S_x$ and $S_N$ are diagonal elements of the selection matrix $S$, $S = \text{diag}(S_x, S_N)$ and similarly, $M_d = \text{diag}(M_{Xd}, M_{Nd})$, $K_d = \text{diag}(K_{Xd}, K_{Nd})$, $B_d = \text{diag}(B_{Xd}, B_{Nd})$, $F_d = \text{diag}(F_{Xd}, F_{Nd})$ and $F_e = \text{diag}(F_{Xe}, F_{Ne})$.

The outer loop outputs the acceleration trajectories reflecting the desired impedance in the position-controlled subspaces as pointed in (2), and the desired force in the force-controlled subspaces as pointed in (3).

3.3 Inner Loop Design of The Proposed Control

3.3.1 Redundancy Resolution

In view of the dynamic control of the manipulators in task space concerned, the computation of joint acceleration is quite needed, which is the output of the redundancy resolution as shown in Figure 2. For the redundant manipulator, the differential kinematics equations have the following forms:

$$\dot{x} = J_e(q)\dot{q}$$ \hspace{1cm} (7)$$
\[ \ddot{x} = \dot{J}_e(q)\dot{q} + J_e(q)\ddot{q} \quad (8) \]

where \( J_e(q) \) is the Jacobian matrix of the end-effector.

Since the null space exists for the redundant manipulator [15], the Jacobian matrix is not square, then the joint acceleration can be solved by the pseudo inverse of the Jacobian matrix \( J_e^+ \):

\[ \ddot{q} = J_e^+(\ddot{x} - \dot{J}_e\dot{q}) \quad (9) \]

In this paper, by following the weighted damped least-squares solution [7], the joint accelerations transformed from the Cartesian accelerations can be obtained as

\[ \ddot{q} = \left[ J_e^T W_e J_e + J_N^T W_n J_N + W_v \right]^{-1} [ J_e^T W_e (\ddot{x} - \dot{J}_e\dot{q}) + J_N^T W_n (\dddot{x}_N - \dot{J}_N\dot{q}) ] \quad (10) \]

where \( W_e, W_n \) and \( W_v \) are diagonal positive-definite weighting matrices that assign priority between the main, additional and singularity robustness tasks.

### 3.3.2 Computed Torque Controller

The inner-loop control is to select an input to the actuators which makes the end-effector tracking the desired trajectories generated by the outer loop. The computed torque controller produces the joint torque as the input of the manipulator-dynamics as shown in Figure 2.

**Figure 2. Block diagram of hybrid impedance control**

With the joint accelerations generated by the redundancy resolution (10), the inverse dynamics equation of the manipulator in the joint space can be written as

\[ \tau_u = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) - J_e^T F_e \quad (11) \]
where $\tau_u$ is the output joint torque output by inner loop, $q$ is the joint variable, $M(q) \in \mathbb{R}^{n \times n}$ is a symmetric and positive definite joint inertia matrix, $C(q, \dot{q}) \dot{q} \in \mathbb{R}^n$ is the Centripetal and Coriolis force, $G(q) \in \mathbb{R}^n$ is the gravity force, $J_e$ is the Jacobian matrix and $F_e \in \mathbb{R}^n$ is the contact force on the tip from the environment.

Combining the dynamics equation (2) with equation (11), the input torque of the position-based impedance control has the following form:

$$
\tau_u = M(q)J_e^T(q)(M_d^{-1}(-F_e - B_d \dot{e}_p - K_d e_p) - \dot{J}_e \dot{q}) + C(q, \dot{q})\dot{q} + G(q) - J_e^T F_e \quad (12)
$$

Similarly, for the force-based impedance control, the input torque can be obtained as:

$$
\tau_u = M(q)J_e^T(q)(M_d^{-1}(F_d - F_e - B_d \dot{x}) - \dot{J}_e \dot{q}) + C(q, \dot{q})\dot{q} + G(q) - J_e^T F_e \quad (13)
$$

### 3.4 Arm Dynamics

The input $\tau_u$ from the inner loop to the arm dynamics is to make the end-effector of the manipulator track a desired trajectory generated by the outer loop.

Since the reaction force between the end-effector and the environment can also be acquired, the generated actuators’ accelerations can be obtained by

$$
\ddot{q} = M(q)^{-1} (\tau_u - J_e^T F_e - C(q, \dot{q})\dot{q} - G(q)) \quad (14)
$$

### 4. TACTILE SENSING STRATEGIES IN THE CONTROL ALGORITHM

It is well known that tactile sensors determine various aspects of the environment through direct contact with objects within that environment [10], these sensors can be used to ascertain the distribution of forces over an area, and can also be used to sense shape parameters, location, and orientation of objects touching with the sensor.

In this paper, tactile sensors are used to produce the texel-voltages of all the sensor cells that always can be converted to the pressure based on the transducer characteristics, which can be used to get the pressing forces of all resistive sensor cells. The contact data (texel-voltage) of tactile sensor will be directly transferred into the control algorithm.

Therefore, besides from the force-sensing feedback, tactile sensing can provide some useful and crucial information to the problems when the end-effector of the manipulator will make a contact with the unknown environmental geometry. Some of the tactile sensing strategies are proposed as follows.

- **To detect whether the contact has occurred.** Safety is always the first to be considered to avoid making large physical failures and damaging to the environment and the manipulator system. The first strategy will ensure the safety based on working state of sensor cells.
- **To judge the general contact information by the distribution of contact points.** From this second strategy, the contact type will be acquired from the pressure-value (or texel-voltage) distribution of sensor cells and contacted points can be known easily.
- **To know the contact area from the number of tactile sensing cells.** In third strategy, the size of contact area can be calculated directly by summing up the number of contacted sensor cells, but note that the error will be determined by the resolution of tactile sensor cell.
To avoid large pressures of some critical points. Since the texel-voltage values of sensor cells can be obtained easily, some corresponding strategies should be made to avoid large pressures on some points and the quick response should be made when they occur.

Summarized from the above tactile sensing strategies, we can say that the tactile sensing feedback plays an important role in the contacting control of the manipulator.

5. SIMULATIONS AND EXPERIMENTS

Tracking successfully on the surface of an object will be determined not only by the surface shape but also by the material of the object. In this paper, only planar surfaces are considered, and two kinds of contacted boards are used to show different physical characteristics in different environments.

In order to show and verify the importance of the tactile sensing feedback in the contact, two cases are illustrated in the experiments, and the end-effector will contact with foam plate and hard board respectively, which aims to test the tracking control abilities of the redundant manipulator in two different environments.

5.1 Experimental Setup

A five-DOF redundant manipulator is applied in this experiment. The link-lengths of the manipulator are $a_1 = 0.375m$, $a_2 = 0.337m$, $a_3 = 0.308m$ and $a_4 = 0.2851m$, the masses are $m_1 = 3.8kg$, $m_2 = 6.6kg$, $m_3 = 2.7kg$, $m_4 = 1.8kg$ and $m_5 = 1.05kg$ and the initial velocities will be set zero. The motor modules are communicated and controlled through CAN bus, while force and tactile sensing data will be transmitted through RS-232 cables and then will be sent back to PC for controlling strategies.

The weighting diagonal elements in the weighting matrices of the redundancy resolution have the values of $W_e = 10; W_n = 100; W_r = 20$. The impedance parameters in two directions have the diagonal values of $M_d = 5; B_d = 200; K_d = 3000$. The stiffness of virtual constraint environment has the diagonal value of $K_e = 10000N/m$. The environment can often be simulated as an elastically compliant system with stiffness $K_e$ along the Cartesian axis of interest. Therefore, interaction force between the robot and the constraint is given by Hooke’s law as

$$F_e = K_e(x - x_e),$$

where $x_e$ is the nominal position of the environment.

The 5-DOF manipulator applied in the paper is composed of two kinds of PowerCube modules as shown in Figure 3, in which each module is controlled by servo motor and communicated via a CAN-bus with the controlling PC. Two kinds of sensors are equipped on the manipulator: one is the six-axis force/torque sensor which is mounted between the end-effector and the last joint, the other is the tactile sensor having arc-like touching surface which is installed at the tip of end-effector, providing a spatial resolution of 3.4mm with 70 sensor cells. The output voltage of a resistive sensor cell in the electrical circuit can be detected on real-time, and the pressure or force on it will be obtained from the transducer characteristics. The measured data of force-torque and tactile sensor are sent back as the feedback to controller by serial communication.

In order to keep the end-effector of the manipulator in a horizontal posture vertical to the contacted surface, the whole configuration of the manipulator should be adjusted with the geometrical constraints of all joint angles. Therefore not only should the position be tracked, but also the orientation will be controlled during the motion. The Jacobian matrices mapping from
Figure 3. Configuration of the whole manipulator system

Joint space to task space will be extended into two parts as \[ \begin{bmatrix} \dot{x}_p \\ \dot{x}_o \end{bmatrix} = \begin{bmatrix} J_p \\ J_o \end{bmatrix} \dot{q} \], where \( x_p \) and \( x_o \) are the position and orientation of the end-effector while \( J_p \) and \( J_o \) are the Jacobian matrices of position subspace and orientation subspace respectively.

5.2 Simulations and Results

Here the parameters used in the simulation have the same values as our real manipulator. The desired trajectory is defined as moving from one point to another point and then back to the origin point. In another orthogonal direction, the force control will be implemented with the desired force \( F_d = -13 \) N. At the same time, the orientation control of the manipulator's end-effector is kept vertical to the contacted surface. The simulation time is set to 4 seconds. In the simulation, the desired trajectory is followed well and the desired force is tracked well by the reaction force measured, as shown in Figure 4, which validates the idea of hybrid impedance control algorithm.

Figure 4. The reaction force measured in the simulation
5.3 Experiments and Results

Two experiments are made to follow the same path trajectory and the same desired force as in the simulation. However two different real environments are applied: the first experiment is designed to show the case of contacting with soft environment and the second one is to contact with hard environment. The experimental time is set to 8 seconds.

5.3.1 Contacting with a Soft Object

In this case, the reaction force tracks the desired force in the later part, but at the beginning, a big impact exists as shown in Figure 5. The force error between the measured force and desired force becomes smaller and smaller. Since the tactile sensor cells respond immediately to the pressure, the texel-voltages of all the sensor cells are measured and recorded as shown in Figure 6.

Figure 5. Reaction force measured in the experiment of contacting with foam plate

![Figure 5](image)

Figure 6. Texel-voltage of tactile sensor cells in the experiment of contacting with foam plate

![Figure 6](image)

The contacted area can be calculated through small cells, so the number of contacted sensor cells is also recorded as shown in Figure 7. Because of the characteristics of the soft object, there are more contacted sensor cells in average than the hard object (it can be verified later), which shows the big contacting surface. Here the texel-voltage is not linear to the contacted area because one cell will have a max-voltage when it enters its saturation state.
5.3.2 Contacting with a Hard Object

Similar as the above case, the measured reaction force, the texel-voltages of all the sensor cells and the number of contacted sensor cells are shown in Figure 8, 9 and 10, respectively. Comparing between two groups of experimental results, it is not difficult to find that the number of contacted sensor cells in the second case (Figure 10) is smaller than the first case (Figure 7) since the hard object has less deformation than the soft one. Therefore it has smaller contact area. The material of the contacted environment plays a very important part. From Figure 8 and Figure 5, it can be found that the second case has bigger force error and the performance is not as good as the first case. It can also be validated by the big range in two figures (Figure 9, 10) of the second case.

6. DISCUSSIONS

The following points are discussed from our research:

- Many techniques of redundancy resolution are used to search the null space, therefore the search direction and the solutions are determined by evaluation of chosen performance criteria. In this paper, we applied the most popular method, the Gradient Projection Method (GPM)[15] to utilize the redundancy to avoid mechanical joint limits.
In most cases, the contact type is modelled as point contact, however, in this work, the contact is surface contact, which is defined to be equivalent to the sum of a group of point contacts. The contact area can be calculated by the number of contacted cells.

The tactile sensor of arc-like shape is used in the experiment, which has such advantages in contacting work as the contacted area will become larger if the force is exerted bigger.

The contacted sensor cells are easy to reach saturation state under high pressure, therefore tactile sensing feedback gives helpful information if the external force locates in a reasonable range as demonstrated by the experiments.

In the experiment, tactile sensing is mainly used to detect whether the contact exists and to calculate the contacted area.

7. CONCLUSIONS

The paper presents a way to control a redundant manipulator contacting with various environments with the aid of tactile sensing feedback. The environment is modeled as a mass-spring-damper system and hybrid impedance control is applied to manage both the motion and force of the end-effector of the manipulator. Due to the important feedback information about contacting from tactile sensors, several strategies of tactile sensing feedback are proposed and then
are used in the tracking control algorithm. In order to evaluate the proposed strategies, two groups of real experiments are made on soft and hard objects respectively and the results demonstrate that tactile sensing feedback is very helpful in performing robot tracking control tasks.

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