Adaptive Impedance-controlled Manipulator Based on Collision Detection

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Abstract

This article provides a flexible-joint-manipulator, which incorporates with three means to make its mechanical arm come into compliant contact with the objects with a force kept within an acceptable range. At first, the Cartesian impedance control law is introduced on the basis of virtual decomposition to realize the compliance control. Then, adaptive dynamic joint compensators on all joints are used to achieve more precise control. Finally, a Cartesian force-feedback path generation is developed for collision detection and force control. Experiments are performed on a 4-degree of freedom (DOF) satellite on-orbit self-servicing (SOOSS) manipulator. The results of the trajectory tracking and collision experiments demonstrate the effectiveness and feasibility of the proposed method.

Keywords: flexible manipulators; impedance control; collision avoidance; adaptive control systems; trajectories; safety systems

1. Introduction

The development of robotics has aroused people’s ever-growing interest in dexterous robots destined for uses in space, medical treatments, and hazardous environment. A key problem the robots are facing is their ability to prevent themselves from collision accidents when performing manipulation in an unstructured environment[1-3]. To ensure the robot to work safely, it should be capable of carrying out compliant interaction with objects, detecting the possibility of collision and controlling the contact forces[4].

Safety-oriented design of the manipulator can be classified into two categories. One is the mechanical design including the reduction of inertia and weight and the introduction of compliant components such as the visco-elastic material cover, flexible joint, compliant shoulders, mechanical impedance adjusters, and visco-elastic passive trunks[5]. The contact force might also sharply increase to the point that it becomes too large not to induce collision even when the flexible mechanism has been used. Furthermore, highly flexible hardware design out of safety concern might cause decrease in precision and fast response of the end-effectors. The other is to introduce sensitive torque sensors for real-time detection of the forces imposed on the robot and control the interaction between the end-effectors of the manipulator and the environment[6-7]. Y. Yamada, et al.[8] proposed collision detection schemes based on the comparison of the actual motor torques to the reference torques calculated from a dynamic model of the manipulator. However, the schemes fail to exhibit the compliant contact between the end-effectors of the manipulator and objects with ignorance of uncertainties of the dynamic parameters of the manipulator.

Cartesian impedance control is one of the most intuitive approaches of interaction control, which provides a unified framework for achieving compliant behavior when robot interacts with unknown environment. It was extensively theorized by N. Hogan[9] and put in experimental application by H. Kazerooni, et al.[10]. S. A. Schneider, et al.[11] developed an object impedance control for cooperative manipulation. J. J. Gonzalez, et al.[12] introduced a hybrid impedance control scheme that utilized a desired force as the commanded variable and demonstrated the improved performances of an explicit force control structure with a similar degree of robustness. S. Morinaga, et al.[13] proposed a nonlinear impedance control for the colli-
sion detection system and used adaptive law to estimate the dynamic parameters of the manipulator. Additionally, A. Albu-Schäffer, et al. \cite{14} investigated a Cartesian impedance control of the German Aerospace Center light-weight arms with completely static state feedbacks and used proportional derivative (PD) control with gravity compensation to compensate the dynamics uncertainties. The dynamic equations in most of above control methods were based on the Lagrangian models. It was well known that they were very difficult to implement. Mostly, results were obtained only through simulations, disregarding manipulator inertia matrix or experiment on robot of one or two joints.

The article is meant to devise a new collision detection system with joint torque sensors for flexible joint manipulators. The system has considerable merit in model-based adaptive compliant control and ability to restrict the Cartesian force to the specified value when collision occurs. The virtual decomposition control (VDC) is adopted in the Cartesian impedance control, which uses subsystem dynamics to conduct control while keeping the rigorous stability of the entire system. The adaptive dynamics control law is introduced to compensate each joint friction. Furthermore, Cartesian force-feedback path planner is proposed for collision detection. Taking full advantage of the above three methods, the collision detection system has a modular structure thereby greatly simplifying its application to serial open chain robot systems and reducing the required computational loads by replacing one high-dimensional problem with several low-dimensional ones.

2. Collision Detection of Manipulator

In order to realize safe and smooth robot-manipulation, as shown in Fig.1, a force-feedback path generation method together with adaptive impedance control is developed, which associates with three core technologies: ①path generation with Cartesian force feedbacks for collision detection; ②Cartesian impedance control to ensure compliant contacts between end-effectors of manipulator and objects; ③adaptive dynamics control to enhance the tracking accuracy of manipulator.

![Fig.1 Collision detection system.](image)

The above control functions are fulfilled by means of joint torque sensors installed on each joint. However and whenever the collision happens in the arm, the collision detection system will warrant the safety of the whole process of manipulation. In the following, these technologies will be described in detail.

3. Classical Cartesian Impedance Law

In the Cartesian impedance control, the target impedance behavior of a n-link manipulator is usually expressed by a second-order equation:

$$\mathbf{A}_d \ddot{x} + \mathbf{D}_d \dot{x} + \mathbf{K}_d x = \mathbf{F}_{\text{ext}}$$  \hspace{1cm} (1)

where $\dot{x} \in \mathbb{R}^n$ is defined as Cartesian position error, $\ddot{x} = x - x_d$, between real endpoint position $x$ and reference trajectory vector of the endpoint $x_d$. $\mathbf{A}_d$, $\mathbf{D}_d$, and $\mathbf{K}_d$ denote the symmetric and positive definite matrices of the desired inertia, damping, and stiffness, respectively, $\mathbf{F}_{\text{ext}}$ the external force vector. With the Jacobian $\mathbf{J}(q) = \partial \mathbf{f}(q)/\partial q$, Cartesian velocities $\dot{x}$ and accelerations $\ddot{x}$ can be deduced from the joint position $q$.

The relationship between the Cartesian coordinates $x$ and the joint torques can be written into

$$\mathbf{A}(x) \ddot{x} + \mathbf{\mu}(x, \dot{x}) \dot{x} + (\mathbf{J}(q)^{-1})^T \mathbf{g}(q) = (\mathbf{J}(q)^{-1})^T \tau + \mathbf{F}_{\text{ext}}$$  \hspace{1cm} (2)

where $q \in \mathbb{R}^n$ and $\tau \in \mathbb{R}^n$ are the joint angle’s vector and the joint torque’s vector, respectively, $\mathbf{g}(q)$ is the gravity term. The matrices $\mathbf{A}(x)$ and $\mathbf{\mu}(x, \dot{x})$ are given by

$$\mathbf{A}(x) = (\mathbf{J}(q)^{-1})^T \mathbf{M}(q) \mathbf{J}(q)^{-1}$$  \hspace{1cm} (3)

$$\mathbf{\mu}(x, \dot{x}) = (\mathbf{J}(q)^{-1})^T (\mathbf{C}(q, \dot{q}) - \mathbf{M}(q) \mathbf{J}(q)^{-1} \dot{\mathbf{J}}(q)) \mathbf{J}(q)^{-1}$$  \hspace{1cm} (4)

where $\mathbf{M}(q)$ represents the inertia matrix, $\mathbf{C}(q, \dot{q})$ the centrifugal/Coriolis term.

The classical impedance control law can be directly computed with Eq.(2). The control input $\tau = (\mathbf{J}(q)^{-1})^T \mathbf{r}$, which leads to the desired closed loop system Eq.(1), is given by

$$\mathbf{F}_r = \mathbf{A}(x) \ddot{x} + \mathbf{\mu}(x, \dot{x}) \dot{x} + (\mathbf{J}(q)^{-1})^T \mathbf{g}(q) - \mathbf{A}(x) \mathbf{A}^{-1} (\mathbf{D}_d \ddot{x} + \mathbf{K}_d \dot{x}) + (\mathbf{A}(x) \mathbf{A}^{-1} - \mathbf{I}) \mathbf{F}_{\text{ext}}$$  \hspace{1cm} (5)

The feedback of external forces $\mathbf{F}_{\text{ext}}$ can be avoided when the desired inertia $\mathbf{A}_d$ is identical with the robot inertia $\mathbf{A}(x)$, so the classical Cartesian impedance control law becomes

$$\mathbf{F}_r = \mathbf{A}(x) \ddot{x} + \mathbf{\mu}(x, \dot{x}) \dot{x} + (\mathbf{J}(q)^{-1})^T \mathbf{g}(q) - \mathbf{D}_d \ddot{x} - \mathbf{K}_d \dot{x}$$  \hspace{1cm} (6)

4. Adaptive Cartesian Impedance Controls

4.1. VDC-based Cartesian impedance control

The above impedance control law depends on the
Lagrangian model, and the \( A(x) \) and \( \mu(x, \dot{x}) \) are difficult to obtain from Eq.(3) and Eq.(4), which might make the real time computation consume too much time. The difficulty would be overcome by introducing the VDC, which will be described below.

The manipulator is numbered sequentially from the base to the tip, in which the \( i \)th joint connect the \((i-1)\)th link with the \( i \)th link. Two coordinate frames \( A_i, B_i \) are located at the two end points of the \( i \)th link and are fixed to the \( i \)th joint and the end of the \((i+1)\)th link, with their \( z \)-axis in line with the \( i \)th joint axis and \((i+1)\)th joint axis, respectively.

First, given \( q_{i,d}, \dot{q}_{i,d}, \ddot{q}_{i,d} \), the required joint velocity and acceleration are expressed as

\[
\begin{align*}
\dot{q}_{i,e} &= \dot{q}_{i,d} + \dot{\lambda}_i(q_{i,d} - q_i) \\
\ddot{q}_{i,e} &= \ddot{q}_{i,d} + \ddot{\lambda}_i(q_{i,d} - q_i)
\end{align*}
\] (7)

where \( \lambda_i \) is a constant of the \( i \)th joint.

Denoted by \( \nu, \in \mathbb{R}^6 \), the vector of generalized linear/angular velocities expressed in frame * and the velocity propagation along the structure are:

\[
\begin{align*}
\nu_{d(i)} &= (U_{d(i)}^{(i-1)})^T \nu_{d(i-1)} + \dot{q}_i Z \\
\nu_{d(i),x} &= (U_{d(i)}^{(i-1)})^T \nu_{d(i-1),x} + \dot{q}_{i,x} Z \\
\nu_{B(i)} &= (U_{B(i)}^{(i)})^T \nu_{B(i-1)} \\
\nu_{B(i),x} &= (U_{B(i)}^{(i)})^T \nu_{B(i-1),x}
\end{align*}
\] (8)

where \( \nu_0 = 0 \), \( Z = [0 0 0 0 0 1]^T \), and \( U_{d(i)}^{(i-1)} \) is a force/moment transformation matrix that transfers a force/moment vector in frame \( A_i \) into the same force/moment in frame \( A_{i-1} \).

Considering the Cartesian impedance law Eq.(6), the total vectors of the required force \( F_{u,x} \) in all frames are given by

\[
\begin{align*}
F_{u, A(i)} &= f_{u,A(i)} + U_{d(i)}^{(i)} F_{u,B(i)} \\
F_{u,B(i)} &= U_{d(i)}^{(i+1)} F_{u,A(i+1)} \\
F_{u,B(x)} &= -U_0^{B(x)} [D_0(\dot{x} - \dot{x}_d) + K_d(x - x_d)]
\end{align*}
\] (9)

where \( f_{u,A(i)} \) the required force acting on the \( i \)th body, can be computed by

\[
\begin{align*}
f_{u,A(i)} &= M_i \ddot{q}_{i,x} + C_i \nu_{A(i),x} + g_i(q)
\end{align*}
\] (10)

where \( M_i, C_i \), and \( g_i(q) \) represent the constant inertia matrix, centrifugal/Coriolis term and the gravity term of the \( i \)th link, respectively.

The required torque \( \tau_{f,i} \) can be obtained by projecting \( F_{u,A(i)} \) on the corresponding joint axis via

\[
\tau_{f,i} = Z^i F_{u,A(i)}
\] (11)

It is clear that the VDC-based impedance controller greatly reduces the computational loads, although it has much more equations.

**Table 1** Computation loads of various controllers for n-link manipulator

<table>
<thead>
<tr>
<th>Methods</th>
<th>Additions</th>
<th>Multiples</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDC-based control</td>
<td>(98/3)(n^3 ) + ( (128/3)n^3 )</td>
<td>(637/3)(n^3 ) + ( (107/6)n )</td>
<td>2</td>
</tr>
<tr>
<td>Lagrangian based</td>
<td>(78/3)(n^3 ) + ( (512/3)n^3 )</td>
<td>(844/3)(n^3 ) + ( (76/6)n )</td>
<td>10n</td>
</tr>
</tbody>
</table>

**4.2. Flexible joint adaptive dynamics control**

The dynamics of the motor can be written into\[16\]

\[
B\ddot{\theta} + Z^T F_{u} + \tau_F = \tau_m
\] (12)

\[
Z^T F_{u} = K(\theta - q)
\] (13)

where \( \theta, q \) indicate the vector of the motor angle divided by the gear ratio and the joint angle, respectively, \( K \) and \( B \) the diagonal matrices which contain the joint stiffness and the motor inertias multiplied by the gear ratio squared, \( \tau_F \) is the friction, and \( \tau_m \) the generalized motor torque vector which is regarded as input variables.

In servo systems, steady-state errors and tracking errors are mainly caused by static friction, which depends on the velocity’s direction, payload and motor position as shown in Fig.2 and Fig.3. The friction model from the LuGre steady-state friction\[17\], payload-dependent friction\[15\] and motor-position-based friction, is expressed as

\[
\tau_F = g_2(\theta)\alpha_0 + \alpha_2 e^{-\theta/\alpha_1^2} \text{sgn}(\dot{\theta}) +
\]

\[
\alpha_0 \dot{H}(\theta) = Y(\theta, \dot{\theta}) K_F
\] (14)

\[
g_2(\theta) = (1 + \frac{\dot{\theta}}{|\dot{\theta}|} + g_2 \frac{|\dot{\theta}|^2}{2})
\] (15)

It covers Stribeck velocity \( v_s \), static friction at zero payload \( (\theta_0 + \alpha_1) \), viscous friction \( \alpha_2 \), and position-based friction \( H(\theta) \). Additionally, with \( g_1 > 0 \) and \( g_2 > 0 \), \( g_2(\theta) \) is used to emulate the load-dependent static friction effects. The complete friction model is

![Friction-velocity curve corresponding to joint 3 of satellite on-orbit self-servicing (SOOSS) robot.](image-url)
Fig. 3  Friction-motor angle curve at static velocity.

characterized by four uncertain parameter vectors:

\[ \mathbf{K}_f = \begin{bmatrix} a_0 & a_1 & a_2 & H(\theta) \end{bmatrix}^T \in \mathbb{R}^4 \]

and a corresponding regression matrix, \( \mathbf{Y}(\tau, \hat{\theta}) \in \mathbb{R}^4 \).

Taking into account the lower and upper bounds of the \( \mathbf{K}_f \) elements, by using the adaptive control law, Eq.(14) can be written into

\[ \hat{\mathbf{f}}_f = \mathbf{Y}(\tau, \hat{\theta}) \hat{\mathbf{K}}_f \]

Considering the joint flexibility, the joint position is updated by

\[ \hat{\mathbf{q}} = \theta - \frac{1}{K} \tau \]

Finally, incorporating the motor dynamics Eq.(12), the control torque at the \( i \)th motor to achieve the Cartesian impedance is computed by

\[ \tau_m = \mathbf{B}\hat{\theta}_i + \hat{\mathbf{f}}_f(\hat{\theta}, \tau) + \mathbf{r}_c(\tau_c - \tau) \]

where \( k_\tau \) is diagonal gain matrix, which is used as the state feedback to compensate the variation of centripetal and Coriolis terms as well as inertial couplings to implement variable joint stiffness and damping.

4.3. Stability proof

A nonnegative accompanying function for the manipulator is chosen to be:

\[ V_{A(i)} = \frac{1}{2} \sum_{i=1}^{4} \left( (\mathbf{v}_{A(i),i} - \mathbf{v}_{A(i)})^T \mathbf{M}_i (\mathbf{v}_{A(i),i} - \mathbf{v}_{A(i)} + (\mathbf{\theta}_d - \hat{\mathbf{A}}(\hat{\mathbf{x}})) \mathbf{k}_\mathbf{f} (\mathbf{\theta}_d - \hat{\mathbf{\theta}}) + \frac{1}{2} (\hat{\mathbf{x}})^T \mathbf{A}(\hat{\mathbf{x}}) \right) \]

This function contains the kinetic energy of the link and the motor, the potential energy of the link elasticity, and the energy corresponding to the controller. Note that \( \mathbf{M}_i \) and \( \mathbf{B} \) are constant matrices, \( \mathbf{A} \) is the symmetric and positive definite matrices of the manipulator inertia. Differentiating Eq.(20) and applying Eqs.(9), (10), (12), and (19) yield

\[ V_{A(i)} \leq \frac{1}{2} \sum_{i=1}^{4} \left( (\mathbf{v}_{A(i),i} - \mathbf{v}_{A(i)})^T (\mathbf{F}_{A(i),i} - \mathbf{F}_{A(i)}) + (\mathbf{v}_{A(i),i} - \mathbf{v}_{A(i)})^T \mathbf{U}_{B(i)} (\mathbf{F}_{B(i)} - \mathbf{F}_{B(i)}) \right) + \hat{\mathbf{x}}^T \mathbf{A}(\hat{\mathbf{x}}) \leq \sum_{i=1}^{4} (\mathbf{W}_{A(i)} - \mathbf{W}_{B(i)}) + (\hat{\mathbf{x}})^T \hat{\mathbf{A}}(\hat{\mathbf{x}}) \]

where \( \mathbf{W}_{A(i)} \) and \( \mathbf{W}_{B(i)} \) represent the virtual power flows at two interfaces of the \( i \)th link. Because Links of the robot are connected, then

\[ \mathbf{W}_{A(i)} = \mathbf{W}_{B(i-1)} \]

Given \( \mathbf{W}_{A(1)} = 0 \) and applying Eq.(1), it follows that

\[ \sum_{i=1}^{4} (\mathbf{W}_{A(i)} - \mathbf{W}_{B(i)}) = \mathbf{W}_{A(1)} - \mathbf{W}_{B(4)} = - (\hat{x} - \hat{x}_d)^T \mathbf{A}_d (\hat{x} - \hat{x}_d) \]

where \( \hat{x} \) is the estimated external force, \( \hat{x}_d \) is the desired external force, \( \hat{x}_d \) is the desired external force, \( \hat{x}_d \) is the desired external force, \( \hat{x}_d \) is the desired external force.

Therefore, the point \( x = x_d \) is globally asymptotically stable.

5. Cartesian Force-feedback Path Generation

Torque sensors are fixed on each joint for Cartesian impedance control. Thus, the manipulator can feel the external force from any joint and present smooth contact by way of the above impedance controller. However, the force will increase when collision happens only by using the impedance control approach. Thus a collision detection device should be arranged not only to detect the possible collision at the ends of robot but also to control the contact force. Taking advantage of Cartesian impedance control, the estimated external force \( \hat{\mathbf{f}} \) can be calculated from Eq.(6):

\[ \hat{\mathbf{f}} = \mathbf{D}_d \hat{\mathbf{x}} + \mathbf{K}_d \hat{\mathbf{x}} \]

A threshold of the contact force \( \mathbf{F}_{cd} \) is used to check if collision occurs. In a certain detection period \( \Delta t \), collision occurs when

\[ \int_0^{\Delta t} |\hat{\mathbf{f}}| dt \geq \int_0^{\Delta t} |\mathbf{F}_{cd}| dt \]

and the real external force equals \( \mathbf{F}_{cd} \) at the same time

\[ \mathbf{F}_{cd} = \mathbf{D}_d (\hat{x} - \hat{x}_{pg}) |_{\Delta t} + \mathbf{K}_d (x - x_{pg}) |_{\Delta t} \]

Let \( C_1(\hat{\mathbf{f}}) \) and \( C_2(\hat{\mathbf{f}}) \) be the coefficients of \( x_d \) and the force feedback path planner, then the Cartesian force-feedback path generation has the form of

\[ x_{pg} = C_1(\hat{\mathbf{f}}) x_d + C_2(\hat{\mathbf{f}})(\hat{\mathbf{f}} - \mathbf{F}_{cd}) \]

Also, the path generation should meet the following requirements:

(1) When the collision does not happen, then \( x_{pg} = x_d \), so \( C_1(\hat{\mathbf{f}}) = \text{diag}(1,1,1,1,1) \) and \( C_2(\hat{\mathbf{f}}) = \text{diag}(0,0,0,0,0) \);
$C_2(\dot{f})$ as a function of estimated external force increases while the $\dot{f}$ rises; 

$C_1(\dot{f}) \in (0, 1]$, $C_2(\dot{f}) \in [1, 0]$, and $x_{pg}, \dot{x}_{pg}, \ddot{x}_{pg}$ are all continuous and bounded; 

$C_1(\dot{f}) + C_2(\dot{f}) = \text{diag}(1,1,1,1,1,1)$.

Then inserting Eq.(27) into Eq.(26), the coefficient of force-feedback path planner $C_2(\dot{f})$ takes the form:

$$C_2(\dot{f}) = \begin{cases} 
\frac{F_{cd} - \dot{f}}{K_d(x_d - \dot{f} + F_{cd}) + D_d(\dot{x}_d - x_d)} & \text{Collision} \\
0 & \text{Others}
\end{cases}$$

Replacing all the $q_{cd}, \theta_{cd}, x_{cd}$ in the adaptive Cartesian impedance control by the $q_{pg}, \theta_{pg}, x_{pg}$ of the force-feedback path generation, the collision detection system is developed and the contact force in Eq.(9) can be acquired:

$$F_{n, \theta(i), n}(\dot{x}_d) = \begin{cases} 
-\frac{U_0^{\theta(i)}}{U_0^{\theta(i)}} F_{cd} & \text{Collision} \\
-\frac{U_0^{\theta(i)}}{D_d(\dot{x}_d - x_d) + K_d(\ddot{x}_d - x_d)} & \text{Others}
\end{cases}$$

When the collision happens, the contact force can be easily kept within the bounds of expected force $F_{cd}$.

6. Experiments

6.1. Experimental manipulator

Experiments are performed on a 4-degree of freedom (DOF) SOOSS manipulator\[18-19\]. All four joints are the same in the macro structure driven by a brushless DC motor through a harmonic driving gear of ratio 1:160. A potentiometer and a magnetic encoder are equipped to measure the absolute angular position of the joint and the motor respectively. The motor phase current $i_b$ and $i_b$ are measured by two linear Hall sensors for joint torque control. The joint torque sensor is designed based on shear strain theory. Eight strain gauges are fixed in a crossed manner on the output shaft of the harmonic driving gear to construct two full-bridges for measuring joint torques. Additionally, a JR3 torque sensor is arranged at the end of the manipulator just to measure the force from the end-effectors.

The adaptive Cartesian impedance controller incorporated with VDC is experimentally achieved in the SOOSS DSP/FPGA hardware architecture which is especially designed for the manipulator (see Fig.4, where $\theta_{d(i)}$ is the motor angle of the $i$th link). The Cartesian impedance controller of Eqs.(7)-(11) and the trajectory generation are implemented at the floating point DSP, and the adaptive dynamics joint controller Eq.(19) together with the motor field-oriented-control are performed on each joint’s field programmable gate array (FPGA). Two controllers are connected to 25 Mbps MLVDS serial data bus with the cycle time less than 200 $\mu$s. Furthermore, the control frequency of the Cartesian and joint controllers are up to 5 kHz and 20 kHz, respectively\[18-19\].

A major practical step for the implementation of the proposed controller structure is the parameter identification. The robot kinematic and dynamic parameters have been calculated with high accuracy through 3-D mechanical CAD programs. Through field-oriented control and off-line experimental estimation, the bounds of the friction parameters can be obtained with Eq.(16). Finally, $K$ can be calculated with Eq.(13) in the experiment of the joint impedance control, in which the joint contacts are supposed rigid for measuring the joint torque and the bias of motor position.

![Fig.4 Internal architecture of robot controller.](image-url)
Table 2 lists the manipulator parameters, where \( a_i \) is the length of the \( i \)th link, \( \{L_i\} \) represents the coordinates of the \( i \)th link.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( L_1 )</th>
<th>( L_2 )</th>
<th>( L_3 )</th>
<th>( L_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_i/\text{mm} )</td>
<td>0</td>
<td>530</td>
<td>390</td>
<td>225</td>
</tr>
<tr>
<td>( D_i/(\text{°}) )</td>
<td>–90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( d_i/\text{mm} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \theta_i/(\text{°}) )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Mass/( \text{kg} )</td>
<td>4.229</td>
<td>7.730</td>
<td>6.640</td>
<td>4.020</td>
</tr>
<tr>
<td>( B_i/(\text{kg} \cdot \text{m}^2) )</td>
<td>1.857</td>
<td>1.857</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>( v_i/(\text{rad} \cdot \text{s}) )</td>
<td>0.006 5</td>
<td>0.006 5</td>
<td>0.005 4</td>
<td>0.005 4</td>
</tr>
<tr>
<td>( K_i/(\text{N} \cdot \text{m} \cdot \text{rad}^{-1}) )</td>
<td>72.154</td>
<td>72.154</td>
<td>58.128</td>
<td>58.128</td>
</tr>
</tbody>
</table>

To illustrate the validity of the proposed methods, three experiments are performed. First, the results between the adaptive dynamic controller and the fixed-parameters controller are compared. Then, a Cartesian impedance experiment is carried out to compare the VDC-based and the curtailed classical impedance controller. Finally, the collision detection experiment is conducted using the proposed method.

6.2. Adaptive dynamic experiment

Dynamic compensation experiments are run on a single joint. As shown in Fig. 5, the joint tracks the variable frequency sine curve in free space by adaptive impedance controller, fixed-parameter impedance controller, and no-friction impedance controller. Their tracking errors are 0.03, 0.05, and 0.20 rad, respectively. Furthermore, adaptive impedance controller shows none of stick-slip behavior, which demonstrates the feasibility of the adaptive joint dynamics compensation.

6.3. Cartesian impedance experiment

The Cartesian impedance experiment is aimed at testing the performances of the VDC-based Cartesian impedance controller when the end-effector works in a constrained space. The desired position of the end-effector is set to produce a sine motion with vertical displacements of 70 mm along the \( z \)-axis of the base frame. A baffle is placed at –357 mm on \( z \)-axis to keep the end-effector moving within 52 mm bounds.

The stiffness and damping parameters of the SOOSS manipulator are listed in Table 3. In order to carry out a comparison, the classical Cartesian impedance control Eq.(6), which ignores the inertia and centrifugal/Coriolis terms has also been tested. The results in Fig. 6 show evident differences that are present in the performances of the two schemes. In the classical impedance, large bias occurs when the end-effector departs from the constrained plane, and dithering appears when the end-effector is working with high acceleration, since the inertia and centrifugal/Coriolis terms are not implemented in advance. These phenomena do not take place in the VDC-based impedance controller since Eq.(10) has embraced the inertia and centrifugal/Coriolis terms in it. It can be concluded that the VDC-based impedance controller not only reduces the computation loads but also has good performances.

6.4. Collision detection

In order to show the effectiveness of the proposed collision detection control system, a collision detection experiment has been conducted. The experiment is carried out in the following way (see Fig. 7): ①The desired trajectory of the end-effector is along a vertical line to approach the object, and then along a horizontal line to push it. ②The actual motion of the object is in an incline plane with an unknown angle. This motion will cause the end-effector to collide with the plane easily. ③An instant external force is exerted on the end-effector to cause another instant collision. The Cartesian force-feedback path generation and adaptive Cartesian impedance control are used in the experi-

![Fig.5](image-url) Position tracking ability of adaptive, fixed-parameter, and no-friction impedance controllers.

![Fig.6](image-url) Sine tracking along \( z \)-axis in a constrained space by VDC-based and classical impedance controllers.
ment. The desired stiffness and damping matrices, and the detected collision forces are listed in Table 3, and the detection time $\Delta t$ in Eq.(25) is chosen as 10 $\mu$s.

Figs.8(a)-8(d) show the results of Cartesian trajectory tracing of the manipulator. Figs.8(e)-8(h) illustrate the related measured Cartesian forces. When the end-effector contacts with the object, the position error of the end-effector between the real and the desired trajectories along the $z$-axis and $R_y$-axis is significantly deviated from zero. This is expected and is called an elastic contact. Small errors can also be observed in the components along the $x$-axis and $y$-axis due to existence of contact friction. As the contact force equals to the desired collision force, the feedback force generation comes into play. The required trajectory continuously departs from the desired trajectory with the force kept to the desired value and without real trajectory dithering and large force oscillation. As Fig.7 shows, an instant external force of $z$-axis is operated on the end-effector at 31 s. The manipulator follows through the instant external force and keeps the external force close to the desired collision force (see Fig.8). Once the instant external force disappears, the manipulator will elastically follow the inclined plane because of the impedance controller.

Table 4 shows the time domain analysis of the whole system. The whole system control cycle can be cut down to 200 $\mu$s owing to using the VDC-based Cartesian impedance controller. Influenced by the flexibility of the joints, the force beyond the specified value is much higher than the position beyond the specified value, and the system response time is up to
200 ms. It can be asserted that the compliant behavior and collision detection are successfully achieved.

Table 4 Time domain analysis of the collision detection system

<table>
<thead>
<tr>
<th>Joint control cycle</th>
<th>Cartesian control cycle</th>
<th>Steady state error (force, moment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 µs</td>
<td>200 µs</td>
<td>2 mm (1N, 0.5N/m)</td>
</tr>
</tbody>
</table>

Response time

| 200 ms | 0.5% | 20% |

Table 4 Time domain analysis of the collision detection system

7. Conclusions

In this article, a collision detection system by means of joint torque sensors is developed. The interaction between the end-effector of manipulator and environment is of a compliant nature by using Cartesian impedance controller based on VDC. Precise trajectory tracing is fulfilled through an adaptive dynamic joint controller. A continuous path planner with Cartesian force-feedbacks is proposed to detect the collision and keep the force within the desired value thus protecting the manipulator. The effectiveness of the method was validated by a trajectory tracing experiment and a collision experiment on a 4-DOF flexible robot. With the proposed adaptive Cartesian impedance control and path planner, the robot will be manipulated smoothly in an unknown environment.

References


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