A Human-Safe Control for Collision Avoidance by a Redundant Robot Using Visual Information

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Abstract: With the rapid development of service robots, avoiding collisions with human beings is a most important requirement of robot control. In this paper, we propose a method in which a virtual potential field around a robot is established by stereovision to implement collision avoidance by using its redundant joints, while simultaneously completing a contact task with its hand.

Keywords: Safety Engineering, Human-Safe Robot, Collision Avoidance, Robotics, Redundant Robot,

1. Introduction

Since the 1970’s, industrial robots such as those used for sealing and welding have been extensively developed for large-scale production. Early on such properties as speed and high power were the primary considerations in robot design. In most factories, industrial robots were set up in an isolated workspace to protect human beings from mechanical injury as shown in Fig.1. At the same time, human operators and workers were strictly warned not to enter the workspace while robots were active. These safety strategies succeeded in reducing the danger of collisions between human beings and robots.

However, with the rapid development of service robots to support various tasks in our daily lives the situation has changed drastically. Unlike the conventional industrial robot, service robots must coexist and interact with human beings in a common space. As a result, the possibility of collisions between service robots and human beings has increased. Therefore, the primary requirements for service robots emphasize safety and ease of operation rather than power and speed.

Safety for human is now considered to be the primary guiding principle for engineers when producing a user-friendly robot design, and is considered in relation to both the robot’s appearance and control. In order to achieve these purposes, a visual sensor is used as the most convenient and effective device to monitor the environment around a robot. This makes it possible to detect a potential danger quickly so that the robot can respond in time to avoid injury to human beings.

In this paper, we propose a method of avoiding a robot-human collision using visual information. A stereovision setup is used to detect a person’s location. When someone is detected moving into a previously established virtual potential field around the robot, a virtual torque is generated to drive the robot’s redundant joints so as to avoid a possible collision. We present a criterion function to determine which redundant joints will be used. A control method is proposed for a redundant robot to simultaneously perform a contact task with its hand and collision avoidance with its redundant joints.

2. Collision Avoidance by Joint Virtual Impedance

The total number of joints of a robot is $n$, the number of degrees of freedom (expressed as DOF) required for a task with its hand is assumed to be $m$, and the robot control sampling period is $T(=5 \text{ ms})$. When $n$ is larger than $m$, the robot is called a redundant robot. The difference $n-m = r$, where $r$ is the redundant degrees of freedom. Generally, $m$ joints of the robot are used to perform the main task at hand, and $r$ joints are used for a secondary task. To facilitate the detection of a human’s location by image processing, a
mark is attached to the person’s body as a feature point.

2.1 Definition of a Virtual Potential Field

In order to detect a collision with a human in all possible directions, a virtual potential cylinder around a robot is defined in a computer as shown in Fig.2. The radius of the virtual potential cylinder is \( r_v \). At time \( t = kT \), a position vector \( e_v(k) \in \mathbb{R}^{3 \times 1} \) detected by stereovision quantitatively describes the feature point in the defined field. \( e_v(k) \) is

\[
e_v(k) = p_v(k) - p_v(k) \quad \text{... (1)}
\]

where \( p_v(k) \in \mathbb{R}^{3 \times 1} \) is the position of the feature point, and \( p_v(k) \in \mathbb{R}^{3 \times 1} \) is the position on the potential surface where the feature point impinges the surface and enters into the field.

2.2 Generation of a Virtual Torque

When a human being is detected inside the previously established potential field by stereovision, a virtual torque is generated to drive the redundant joints to move away from the human. In this paper, a virtual force \( f_v(k) \in \mathbb{R}^{3 \times 1} \) is generated by

\[
f_v(k) = D_v e_v(k) + K_v e_v(k) \quad \text{... (2)}
\]

where \( D_v \in \mathbb{R}^{3 \times 3} \) is the virtual damping matrix, and \( K_v \in \mathbb{R}^{3 \times 3} \) is the virtual stiffness matrix.

As shown in Fig.3, the generated virtual force \( f_v(k) \) can be converted to the joint virtual torque \( \tau_v(k) \in \mathbb{R}^{3 \times 1} \) by

\[
\tau_v(k) = \begin{bmatrix} J_x^T & J_y^T \end{bmatrix} f_v(k) \quad \text{... (3)}
\]

where \( J_x \) is the Jacobian of the links from the robot base to the link activated by the virtual force, and \( J_y \) is the Jacobian of the links from the robot hand to the link activated by the virtual force.

2.3 Joint Compliance Control

According to the joint virtual torque \( \tau_v(k) \) computed by Eq.(3), the virtual torque \( \tau_v(k) \in \mathbb{R}^{3 \times 1} \) acting on the redundant joints is

\[
\tau_v(k) = S_v \tau_v(k) \quad \text{... (4)}
\]

where \( S_v \in \mathbb{R}^{3 \times 3} \) is the given matrix. According to the compliance control algorithm, the desired joint velocity \( \dot{\theta}_v(k+1) \in \mathbb{R}^{3 \times 1} \) of the redundant joints is generated by using the computed virtual torque \( \tau_v(k) \) as

\[
\dot{\theta}_v(k+1) = (I - TM_v^{-1} D_v) \dot{\theta}_v(k) + TM_v^{-1} \tau_v(k) \quad \text{... (5)}
\]

where \( M_v \in \mathbb{R}^{3 \times 3} \) is the virtual mass matrix of the redundant joints, \( D_v \in \mathbb{R}^{3 \times 3} \) is the virtual damping matrix of the redundant joints, and \( I \) is the unity matrix.

3. Control of a Redundant Robot

3.1 Image processing and Interpolation

In order to detect an invasion into the given potential field of a human being, two CCD cameras (CV-M40, JAI Co.) were used. The cameras output images at a rate of 60 frames per second. An image processor board (GENESIS, Matrox Co.) was used for image input and processing. On this board there is an embedded digital signal processor C80 with which image input and image processing can be carried out simultaneously. Therefore, real-time image processing can be performed by the GENESIS board. The image processing sampling period is assumed to be \( T_c \) (1/60 s). As shown in Fig.4, the position \( p_v(i) \) of a feature point attached to a person’s body can be detected at every \( T_c \) by image processing.

Although image processing can be completed at the camera frame rate, the image processing sampling period \( T_c \)
is still longer than robot control sampling period \( T \). In order to apply the results of image processing to the robot control, it is necessary to interpolate so as to convert \( p_i(k) \) to \( p_j(k) \) by

\[
p_j(k) = \begin{cases} 
  p_i((i-1)+kT-(i-1)T_c) & \text{if } kT < (i+1)T_c, \\
  p_i[(i+1)+kT-(i+2)T_c) & \text{if } (i+1)T_c < kT < (i+2)T_c, \\
  p_i(i+1)+(kT-(i+1)T_c) & \text{if } (i+2)T_c < kT < (i+3)T_c, \\
\end{cases}
\]

\((k = 0, 1, 2, \ldots),\ (i = 0, 1, 2, \ldots) \) .......................... (6)

### 3.2 Desired Joint Velocity Generation of a Redundant Robot

Because a redundant robot has the flexibilities to adapt to various environments, it has been used in the studies of singularity avoidance\(^{6(7)}\) and obstacle avoidance\(^{8(13)}\). However, unlike earlier studies in which a known obstacle was assumed, the human’s location is unspecified in the present study. Therefore, a virtual potential field is defined by image processing so as to avoid a possible collision. During the action of collision avoidance, the robot is generally expected to carry out the main task with its hand and the main task should not be interrupted by the avoidance action. To achieve this goal, a control technique has been proposed in this paper by which a robot can carry out a compliance control with its hand and simultaneously avoid a possible collision by using its redundant joints.

At time \( t = kT \), the hand position of the robot is given as \( p_h(k) \in \mathbb{R}^{6\times1} \) from its kinematics, and its desired position is assumed to be \( p_h(d) \in \mathbb{R}^{6\times1} \). According to the compliance control law, the desired hand velocity \( p_h(k+1) \in \mathbb{R}^{6\times1} \) is generated by

\[
p_h(k+1) = (I - M_h(k)D_h(k))p_h(k) + TM_h(k)\left(f_h(k) - f_h(d)\right) + TM_h(k)K_h(p_h(d) - p_h(k)) \quad \text{......(7)}
\]

where

- \( M_h \in \mathbb{R}^{6\times6} \) : virtual mass matrix of the robot hand,
- \( D_h \in \mathbb{R}^{6\times6} \) : virtual damping matrix of the robot hand,
- \( K_h \in \mathbb{R}^{6\times6} \) : virtual stiffness matrix of the robot hand,
- \( f_h(k) \in \mathbb{R}^{6\times1} \) : desired force,
- \( f_h(d) \in \mathbb{R}^{6\times1} \) : force measured by a F/T sensor,
- \( p_h(k) \in \mathbb{R}^{6\times1} \) : hand velocity of the robot hand at \( t = kT \),
- \( p_h(d) \in \mathbb{R}^{6\times1} \) : desired hand position of the robot hand,
- \( \dot{p}_h(k) \in \mathbb{R}^{6\times1} \) : hand position of the robot hand.

It is known that the relation between the hand velocity \( \dot{p}_h(k) \) and the joint velocity \( \dot{\theta}_h(k) \in \mathbb{R}^{n\times1} \) at \( t = kT \) can be expressed as

\[
\dot{p}_h(k) = J_h \dot{\theta}_h(k), \quad \text{..........................(8)}
\]

where \( J_h \in \mathbb{R}^{6\times6} \) is the Jacobian and \( n = m + r \). If the Jacobian \( J_h \) is separated into two parts, Eq.(8) can be rewritten as

\[
\dot{p}_h(k) = J_h \dot{\theta}_h(k) + J_r \dot{\theta}_r(k), \quad \text{..........................(9)}
\]

where

- \( J_h \in \mathbb{R}^{6\times6} \) : Jacobian of non-redundant joints,
- \( \dot{\theta}_h(k) \in \mathbb{R}^{n\times1} \) : non-redundant joint velocity,
- \( J_r \in \mathbb{R}^{6\times6} \) : Jacobian of redundant joints,
- \( \dot{\theta}_r(k) \in \mathbb{R}^{m\times1} \) : redundant joint velocity.

In order to avoid a possible collision using the redundant joints of the robot, the desired joint velocity \( \dot{\theta}_r(k+1) \) of its redundant joints can be obtained by Eq.(5). Therefore, the desired joint velocity \( \dot{\theta}_h(k+1) \) of the non-redundant joints in Eq.(9) can be calculated by

\[
\dot{\theta}_h(k+1) = J_h \dot{\theta}_h(k+1) - J_r \dot{\theta}_r(k+1), \quad \text{..........................(10)}
\]

Using \( \dot{\theta}_h(k+1) \) and \( \dot{\theta}_h(k+1) \) generated by Eq.(5) and Eq.(10) respectively, the desired joint velocity \( \dot{\theta}_h(k+1) \) can be written as

\[
\dot{\theta}_h(k+1) = I_m \dot{\theta}_m(k+1) + I_r \dot{\theta}_r(k+1), \quad \text{..........................(11)}
\]

where

\[
I_m = \begin{bmatrix} m \\ \vdots \\ \vdots \\ 0 \end{bmatrix}, \quad I_r = \begin{bmatrix} m \\ \vdots \\ \vdots \\ 0 \end{bmatrix}
\]

Compared with the method using the pseudoinverse of Jacobian, the proposed method shown in Eq.(11) has a merit of less computation so as to increase the processing speed\(^{11}\).

### 3.3 A Criterion Function to Determine the Redundant Joints

The desired joint velocity \( \dot{\theta}_h(k+1) \) of the redundant robot is generated by Eq.(11) in terms of the computed joint velocities \( \dot{\theta}_h(k+1) \) and \( \dot{\theta}_h(k+1) \). However, the specific joints that are redundant have still not been selected. As stated above, because in the present study it is unspecified just where and when a human being may enter the defined potential field, the person’s location is an important factor to be considered when determining which joints should be the redundant joints.

In this study, a criterion function is proposed to determine the redundant joints. The criterion function \( P(k) \) at time \( t = kT \)
is defined by
\[ P(k) = w_1 c_1(\theta(k)) + w_2 c_2(k), \] .......................... (12)
where \( w_1 \) and \( w_2 \) are the given weighting coefficients. 
\( c_1(\theta(k)) \) is defined as the manipulability\(^{(14,15)} \) of the robot at 
time \( t=kT \) and is computed by
\[ c_1(\theta(k)) = \sqrt{\text{det}(J'_r(\theta(k)) \cdot J'_r(\theta(k)))}, \] .......................... (13)
where \( J'_r(\theta(k)) \) is the Jacobian matrix of the robot at 
time \( t=kT \).
\( c_2(k) \) is defined as the distance between the detected feature 
point and the nearest link of the robot at time \( t=kT \) as 
indicated in Fig.2. The distance \( c_2(k) \) can be calculated by
\[ c_2(k) = r_e - |e_r(k)|, \] .......................... (14)
When the feature point is outside of the defined potential 
field, the distance \( c_2(k) \) is set equal to 0.

The next steps for deciding the redundant joints are as 
follows:
(1) The calculation of \( P(k) \) given by Eq.(12) must be 
performed for all possible ways of selecting the redundant 
joints.
(2) Select the redundant joints so as to obtain the maximum 
\( P(k) \).
(3) Repeat step (1) and step (2) at every robot control 
sampling instant to decide which are the redundant joints.

Using the proposed method explained in sections 3.2 and 
3.3, the main task performed by the robot hand and the 
secondary task of avoiding a collision with a human being
by using the redundant joints can be carried out 
simultaneously.

### 3.4 Applying the Control Algorithm to a 
Redundant Robot

In this paper, a 7-DOF robot (PA-10, Mitsubishi Heavy 
Industry Co.) was used in the experiments. A force/torque 
sensor (F/T 10/100, BL AUTOTEC Ltd.) was set up at its 
end-effector. The robot hand was required to perform a 
contact task with 6-DOF control, and the single remaining 
joint was used as a redundant joint to avoid a collision. 
Therefore, we have \( n=7, m=6, \) and \( r=1 \). According to Eq.(4), 
the virtual torque \( \tau_r(k) \) is expressed as
\[ \tau_r(k) = s^T r \tau_v(k), \] .......................... (15)
where vector \( s^T \) is given by
\[ s^T = \begin{bmatrix} 0 & \cdots & 1 & \cdots & 0 \end{bmatrix}^T \]
redundant joint

The joint compliance control generated by Eq.(5) is 
rewritten as
\[ \dot{\theta}_r(k+1) = (1 - T^{-1}D) \dot{\theta}_r(k) + T^{-1} \tau_r(k), \] .......................... (16)
A block diagram for controlling the 7-DOF robot is 
proposed as shown in Fig.5, where \( A \) is robot kinematics, 
and \( R \) is the coordinate transformation matrix.

![Fig. 5 Block diagram of the proposed control algorithm for a 7-DOF robot PA-10 (n=7, m=6, r=1)](image-url)
In Fig.5, after position \( p_d(i) \) of the feature point attached to a human subject’s body is detected by feature processing, an interpolation is performed by Eq.(6) to convert \( p_d(i) \) to \( \tilde{p}_d(k) \). A virtual torque, \( \tau_v(k) \), is computed with Eqs.(3) and (15), and then the joint compliance control is generated by Eq.(16). At the same time, the desired hand velocity, \( \dot{\theta}_c(k+1) \), is computed by Eq.(11) based on the compliance control law. The desired joint velocity, \( \dot{\theta}_c(k+1) \), is generated by calculating \( \dot{\theta}_c(k+1) \) and \( \dot{\theta}_c(k+1) \) by Eq.(11). Finally, the computed joint velocity, \( \dot{\theta}_c(k+1) \), is sent to the servo drivers to control the robot.

### 4. Experiments

#### 4.1 Task descriptions

Experiments were carried out to confirm the effectiveness of the proposed control method. A lighting ball was made by a plastic ball in which a light bulb was inserted. It was used as the feature point attached to the human subject’s body. The diameter of the ball was 0.05m. Parameters of the control and the hand compliance control used in the experiments are shown in Table 1. Parameters used in the potential field, the virtual torque, the joint compliance effect, and the proposed compliance control were experimentally determined by trial and error.

As depicted in Fig.6, seven joints of the robot are named as S1, S2, S3, E1, E2, W1 and W2 while joint S3 is the redundant joint. While the robot hand was required to perform the task of tracing a given 2D half-circle in \( x-y \) plane with a specified force in the \( z \) axis based on the compliance control law given by Eq.(7), the lighting ball moved slowly into the potential field and came close to the link between joint S3 and joint E1. Collision with the lighting ball was avoided by use of the redundant joint S3.

#### 4.2 Experiment results

Two experiments were carried out. In the first experiment, the lighting ball did not enter the defined potential field when the robot carried out the given task with its hand. Position and force results obtained in the first experiment are shown in Fig.7. Force \( f_z \) shown in Fig.7 was almost exactly controlled at the desired force \( f_{zd} \), which suggests that the desired compliance control was achieved.

In the second experiment, the lighting ball entered the potential field several times while the robot carried out the given task with its hand. In this experiment, only contact force was controlled in \( z \) direction so that \( f_z \) was exactly kept at \( f_{zd} \), as shown in Fig.8(a). The values of \( c_1 \) and \( c_2 \) are shown in Fig.8(b), and joint angles are shown in Fig.8(c).

The force result shown in Fig.8(a) shows that the desired compliance effect was also achieved in the second experiment even if the lighting ball entered the potential field several times while the hand performed the tracing task. In Fig.8(b), the \( c_2 \) curve falls below the boundary of the

<table>
<thead>
<tr>
<th>Table 1  Parameters used in the experiments</th>
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<tbody>
<tr>
<td>Potential field and virtual impedance parameters:</td>
</tr>
<tr>
<td>( r_v = 0.3 ) m</td>
</tr>
<tr>
<td>( K_v = \text{diag}[2 \ 2 \ 2] \ N/m )</td>
</tr>
<tr>
<td>( D_v = \text{diag}[1 \ 1 \ 1] \ N \cdot s/m )</td>
</tr>
<tr>
<td>Weight coefficients defined in Eq. (12):</td>
</tr>
<tr>
<td>( w_1 = 1.0, \ w_2 = 0.0 ) for no obstacle</td>
</tr>
<tr>
<td>( w_1 = 0.2, \ w_2 = 0.8 ) for obstacle detected</td>
</tr>
<tr>
<td>Joint compliance control parameters in Eq.(16):</td>
</tr>
<tr>
<td>( M_1 = \text{diag}[m_{j1} \ m_{j1} \ m_{j1} \ m_{j2} \ m_{j2} \ m_{j2}], )</td>
</tr>
<tr>
<td>( m_{j1} = 0.3 ) kg, ( m_{j2} = 0.3 ) kg ( \cdot ) m (^2)</td>
</tr>
<tr>
<td>( D_1 = \text{diag}[d_{j1} \ d_{j1} \ d_{j1} \ d_{j2} \ d_{j2} \ d_{j2}], )</td>
</tr>
<tr>
<td>( d_{j1} = 8 ) N ( \cdot ) s/m, ( d_{j2} = 8 ) N ( \cdot ) m ( \cdot ) s/rad,</td>
</tr>
<tr>
<td>( K_v = \text{diag}[0 \ 0 \ 0 \ 0 \ 0 \ 0] ),</td>
</tr>
<tr>
<td>Hand compliance control parameters in Eq.(7):</td>
</tr>
<tr>
<td>( M_h = \text{diag}[m_{h1} \ m_{h1} \ m_{h1} \ m_{h2} \ m_{h2} \ m_{h2}], )</td>
</tr>
<tr>
<td>( m_{h1} = 1.2 ) kg, ( m_{h2} = 0.7 ) kg ( \cdot ) m (^2)</td>
</tr>
<tr>
<td>( D_h = \text{diag}[d_{h1} \ d_{h1} \ d_{h1} \ d_{h2} \ d_{h2} \ d_{h2}], )</td>
</tr>
<tr>
<td>( d_{h1} = 310 ) N ( \cdot ) s/m, ( d_{h2} = 110 ) N ( \cdot ) m ( \cdot ) s/rad</td>
</tr>
<tr>
<td>( K_v = \text{diag}[K_{h1} \ K_{h1} \ 0 \ K_{h2} \ K_{h2} \ K_{h2}], )</td>
</tr>
<tr>
<td>( K_{h1} = 670 ) N/m, ( K_{h2} = 400 ) N ( \cdot ) m/rad</td>
</tr>
<tr>
<td>( f_d = [0 \ 0 \ f_{zd} \ 0 \ 0 \ 0]^T, \ f_{zd} = -4 ) N</td>
</tr>
<tr>
<td>Description of the desired trajectory:</td>
</tr>
<tr>
<td>Center of the circle: ( [0.7 \ m \ 0 \ 0.435 \ m]^T )</td>
</tr>
<tr>
<td>Radius of the circle: ( 0.15 ) m</td>
</tr>
</tbody>
</table>
(1) This paper proposes a control method to avoid collisions between a human being and a robot by the redundant joints of the robot. In order to detect human’s unspecified location, a potential field is established to generate a virtual torque. The greatest advantage of the proposed method is that a possible collision can be avoided automatically, without requiring any action by nearby human beings.

(2) A criterion function is presented to determine the redundant joints. A control method is also proposed for a redundant robot to simultaneously carry out a contact task with its hand and perform collision avoidance with its redundant joints. The effectiveness of the proposed method has been demonstrated by experiment.

6. References