An Adaptive Control Algorithm to Improve Singularity Avoidance in 7-DOF Redundant Manipulators

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ABSTRACT:
In this article, we consider the singularity avoidance of a redundant manipulator. It is shown that small perturbations caused by singularities can destabilize the whole system. Its realization would be rigorous physical damages to the robot. The remedy for such structural sensitivity to singularities consists in using an adaptive controller by which the control signal power is dominant over the unstable configurations. In this note, an adaptive algorithm to control redundant manipulators is proposed and its singularity avoidance performance as the secondary task is studied. An outer-inner loop controller called the augmented hybrid impedance control scheme is used. The inner loop consists of a Cartesian-level potential difference controller, a redundancy resolution scheme at the acceleration level, and a joint-space inverse dynamic controller. The proposed scheme works on the redundancy resolution block and is comprised of a multi-state function based on the Jacobean matrix of robot. We applied the proposed algorithm to a Mitsubishi PA10 7-DOF manipulator and simulation results proved the effectiveness of the algorithm.

KEYWORDS: Singularity Avoidance, Position and Force Control, Redundancy Resolution, Robotic Arm.

1. INTRODUCTION
There are several different strategies developed to control robots with extra DOF to do a specific job. These kinds of robots are called redundant and extra DOFs can be used for various tasks including singularity avoidance, obstacle avoidance, etc. In this paper, extra DOFs are used by modulating the control signal via a variable auxiliary signal originated from the control system and this process in which extra DOFs are being employed is called redundancy resolution.

In redundancy resolution the aforementioned auxiliary signal is built based on the position, velocity and acceleration parameters so as to be added to the main control signal and drift the robot out of the local traps. The proposed control structure is compared with the one used by Patel et al [1] and the properties are studied. Patel's work was concerned with robust position and contact force control for 7-DOF redundant robot arms. An outer–inner loop controller, called the augmented hybrid impedance control scheme was developed. A virtual 6-DOF force/torque sensor was taken into account to measure the interaction forces. These are fed back to the outer-loop controller that implements either a force or an impedance controller in each of the 6 DOFs of the tool frame. The inner loop consists of a Cartesian-level potential difference controller, a redundancy resolution scheme at the acceleration level and a joint-space inverse dynamic controller [1]. Position control strategies are in general inadequate for tasks involving interaction between manipulator and environment. Developing control schemes for tasks that need extensive contact with the environment (such as assembly, grinding, and surface cleaning) has been the subject of significant research in robotics.

Historically, force control approaches can be categorized into three classes, hybrid position/force control [2–4], impedance control [5], and hybrid impedance control (HIC) [6]-[7]. The main problem of hybrid position–force control is its failure to recognize the importance of the manipulator impedance [1]. Anderson and Spong [6] proposed an HIC scheme, and Liu and Goldenberg [7] introduced a robust HIC method. Introducing HIC was an attempt to combine impedance control and hybrid position/force control into a unified scheme. Hybrid control actually controls force and positions without any concern about the resulting impedance. HIC method controls force and position while carefully monitors the impedance [6]. The problem of force control for redundant manipulators has not become mature as much as its non-redundant counterpart. There has been some work addressing the
problem of force control in a redundancy resolution scheme. There are two major issues to be addressed in extending force control schemes for non-redundant manipulators to the case of redundant ones [1].

1) The nature of force control requires expressing the manipulators task in Cartesian space; therefore, such schemes are usually based on the Cartesian dynamic model of the manipulator. However, in the presence of redundancy, there is not a unique map from Cartesian space to joint space [1].

2) Most redundancy resolution techniques are at the velocity level, and simple extensions of these techniques to the acceleration level have resulted in the self-motion phenomenon [1].

Gertz et al. [8], Walker [9] and Lin et al. [10] have used a generalized inertia-weighted inverse of the Jacobian to resolve redundancy in order to reduce impact forces. A comparative study of redundancy resolution schemes at velocity, acceleration, and torque levels are presented in [11] in a common framework. Robust resolved acceleration-based controller that has a same architecture as the control scheme used in this paper gave the best result for tracking a trajectory in position subspace with an RMS error of 0.01 m.

A further modification on the redundancy resolution scheme based on a generalization of Gauss principle of least constraint has been presented in [12]. The results provided an RMS tracking error in position subspace of 0.0122 m [1].

A redundancy resolution method was proposed in [12] which approached the problem through optimization. There was also a process of task-priority formulations for kinematic control which was implemented.

2. PROPOSED THEORY

2.1. Redundancy Resolution

Patel et al. [1] mapped the CRA trajectory into joint space in the redundancy resolution part of AHIC to calculate the JTA trajectory. The task prioritized and singularity robust formulation of redundancy resolution permits the use of extra DOF for fulfilling user defined additional task(s), e.g. See [13–15]. The target acceleration for each additional task \( \ddot{Z}_i \) is calculated as Equation (1).

\[
\ddot{Z}(t) = (M^{-1}) \dddot{q} + (-F^e + (I - S_\omega)F^d) \\
- B^{-1}_\omega (\dddot{Z} - S_\omega \dddot{q}) - K_\omega \dot{S}_\omega (Z - \dddot{q}) + S_\omega \dddot{q} 
\]

Shadpey [16] described the formulation of different additional tasks such as JLA, moving object avoidance, multiple points force control, and posture optimization. In this paper, the JLA task has been implemented (see [16] for a detail description). In the AHIC scheme, redundancy resolution is implemented at the acceleration level. The damped least-squares solution is given by Equation (2).

\[
\ddot{q}^* = A^+ b 
\]

Where

\[
A = J^Tp_\omega Jp_\omega + J^T\omega Wo + J^T\omega Wo, \\
b = J^T\omega (\dddot{P}_\omega - \dddot{J}_\omega \dot{q}) + J^T\omega (\dddot{Q}_\omega - \dddot{J}_\omega \dddot{q}) + J^T\omega \dddot{Z}_i 
\]

Where \( Jp (3 \times 7) \) and \( Jo (3 \times 7) \) are the Jacobian matrices projecting the joint rates to linear and angular velocities of the frame \( (T), \dddot{P}_\omega \), and \( \omega \), respectively. The matrices \( Wp (3 \times 3) \), \( Wo (3 \times 3) \), and \( Wv (3 \times 3) \) are diagonal weighting matrices to assign priority to position/force tracking, orientation/torque tracking, and the singularity avoidance tasks.

The subscript \( c \) refers to additional task. However, the redundancy resolution scheme employed in this paper, is based on task augmentation and therefore if the number of specified secondary tasks corresponds to a non-singular square augmented Jacobian, the damped least-squares has a unique solution.

Moreover, since singularity avoidance was considered as an additional task, the square Jacobian never reached a singular configuration. Hence, the notion of dynamic inconsistency does not arise here, since the null space of the Jacobian is in fact empty. Moreover, a velocity feedback term \( \dot{\lambda} \) is introduced in redundancy resolution _Equation (1)_ to prevent instability. A proper value of \( \dot{\lambda} \) can ensure the stability of the solution [17]. This is also suggested by Luca et al. [18].

To verify the performance of the modified redundancy resolution scheme presented by Patel et al. [1], a simulation was performed. Considering the worst-case performance, the final position/orientation was selected such that makes the robots posture approach a singular configuration. This induces a high null-space component on the joint velocities. In this paper this part of the problem is being solved by having robot away from singular configurations by updating control signal. Simulations showed that by the use of proposed adaptive algorithm, the position/force control algorithm by Patel et al [1] invigorates and makes its singularity avoidance better. In this part, the control signal maps from Cartesian space to joint space and a signal can be added to the control signal to modify shortages or increase the robot capability to do special tasks. For example, the control signal may be charged in this part so that takes the robot away from singular configurations. Actually the robot becomes close to the singular points but control signal is so designed that takes the robot away. A signal named ALPHAZ is defined as noted in Appendix a. ALPHAZ is added to the control signal which is obtained in redundancy resolution.
2.2. Experimental Results and Analysis

There is a parameter in Appendix (a) named LAND which determines how the signal ALPHAZ affects the control signal. By increasing LAND, working time and singularity avoidance increases continuously but the upper limit is almost 150 seconds which is three times greater than that of Patel’s work [1]. Two procedures are proposed to improve the singularity avoidance. First procedure is to define LAND as a multi-state function dependent to the inverse determinant of matrix J*J’. First procedure is implemented by defining a function as expressed in Appendix b. Second procedure is to change vector b.

The variation of robot runtime is presented in TABLE 1, while parameters are being changed compared with those of Patel’s work. The variation profile of robots runtime is presented in TABLE 2, while parameters are being changed in a three-state function. In this paper, reference signals were assumed to be sinusoidal and corresponding results are shown in TABLE 3 in comparison with those of Patel’s work.

![Graph showing signal X versus its reference signal for LANDA1=1 and LANDA2=0.2](image)

Equation (5) shows the formula which is used in the redundancy resolution.

\[
A_i = ((\text{transpose}(J_i) * W_p * J_i + W_v)^{-1})^* (\text{transpose}(J_i) * W_v * (\vec{F} - \vec{J}_i * q))
\]

In Equation (5) matrices W_p and W_v are as indicated in Equation (6) and Equation (7).

\[
W_p = \text{Landa1} * \text{eye(3)}
\]

\[
W_v = \text{Landa2} * \text{eye(7)}
\]

Table 1: Variation of robot runtime with 2-state function for Landa compared with Patel’s work

<table>
<thead>
<tr>
<th>Sense</th>
<th>High_det</th>
<th>Robots runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proposed Method</td>
<td>Patel’s Method</td>
</tr>
<tr>
<td>0.01</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>0.001</td>
<td>50</td>
<td>31</td>
</tr>
<tr>
<td>0.0001</td>
<td>50</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>0.001</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>0.0001</td>
<td>40</td>
<td>&lt; 2</td>
</tr>
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</table>

Table 2: Variation of Robot Runtime with 3-state function for Landa

<table>
<thead>
<tr>
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<th>Sense</th>
<th>Most_det</th>
<th>Robots runtime</th>
</tr>
</thead>
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<tr>
<td>50</td>
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<td>100</td>
<td>32</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>0.00001</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3: Variation of Robot Runtime with parameter LAND compared with Patel’s work

<table>
<thead>
<tr>
<th>LAND</th>
<th>Robots runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proposed Method</td>
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<td>30</td>
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<td>150</td>
<td>58</td>
</tr>
</tbody>
</table>

3. DISCUSSION

Singularity avoidance is one of the important issues in the robotic communities. In this paper, we introduced an adaptive algorithm based on Augmented Hybrid Impedance Control scheme to improve the singularity avoidance performance and studied different structures on a seven degree of freedom manipulator. We showed that the proposed algorithm increases the robots capability to bypass the singular configurations. A comparison was performed between this algorithm and the original work. Simulation results showed that getting feedback from velocity and implementing an adaptive controller tended to a more smooth motion with respect to the original work. They also proved that robot behaves more flexible when it is near singularities, in comparison to that of original work in which a constant singularity avoidance strategy was used. We fed back the Jacobean-norm of the robot to the redundancy resolution and established a decision making tool based on the current Jacobean state of the robot. It was proved that it made the proposed adaptive algorithm effective. One may apply the same algorithm to obstacle avoidance additional tasks. They should
investigate the algorithm and change its weighting matrices and mathematics and especially its adaptive strategy, in order to use the algorithm.

4. CONCLUSION
In this note, we have established the fact that an adaptive control algorithm tends to a better singularity avoidance performance in redundant manipulators. We have also shown that redundancy resolution at the acceleration level with a velocity feedback, would dynamically ignore the singular configurations of the robot. Although these facts follow from adaptive system notions, we have not seen this aspect of adaptive control theory discussed in the control literature which mainly emphasizes adaptive controller realizations.

In [1] a constant singularity avoidance strategy was used but it was proved in this article that an adaptive singularity avoidance algorithm in the redundancy resolution of the redundant manipulators, lead to a smoother motion of the robot and enriches its singularity avoidance capability. In [2], [3], [5] and [6], Hybrid Impedance Position/Force Control was addressed but their focus was on the control algorithm itself. The results of our note draw attention to the fundamental differences between constant and adaptive control strategies in Augmented Hybrid Impedance Control when even small perturbations are present due to singularity, and shows that unless due attention is paid to the adaptive class, the existing theory can in fact produce control system designs which are not stable enough against singularities.

5. APPENDIX
a) Code 1

```matlab
land=150;
b=[1;1;1;1;1;1;1];
Iden=eye(7);
JP=J’/(J*J’);
alphaz = (Iden-JP*J)*b;
alphaz=alphaz*land;
```

b) Code 2

```matlab
Sense = 0.01;
high_det=50;
if det>high_det
    land = sense;
else
    land = 150;
end
```

6. ACKNOWLEDGMENT
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REFERENCES


