Abstract: This paper presents a robot control system using force control on a redundant industrial robot. The control system is based upon an active force feedback system using six axes force sensor attached to the robot’s end effector. The redundancy is used to explore a model for singularity avoidance based on different states of redundancy. The system is implemented and tested experimentally for one of the described states on a NACHI MR20 seven axes robot. The experimental results demonstrate the possibility to control a redundant industrial robot by force control.

Keywords: Redundant manipulator, Redundancy control, Force control, Singularity avoidance

1. INTRODUCTION

Industrial robots are used in a wide range of applications like spray painting, handling, welding, assembly, grinding etc. In some of these applications, the robot (thus, the tool attached to the robot’s end-effector) is in physical contact with the environment. In these applications, it’s required or desired to control the interaction forces on the interface between the robot and the environment. This can be either due to simplifying programming of the robot. The latter, applies especially to material removal processes like grinding and deburring.

Hirzinger (1983) and DeSchutter (1986) did the most comprehensive work on the development of force control. They were the first to use the active force control method using external force control, which is the most common way of implementing force feedback in a robot control system. DeSchutter (1986) also focused on the formulation of force controlled tasks in addition to implementation and experimental testing of them. He also performed a comparison of the External- and Hybrid force control scheme where he concluded that there will be a need for passive compliance in both of these, even though the Hybrid force control theoretically should run even on a stiff manipulator.

The gains of having more than six axes can mostly be attributed to more flexibility in the robot arm configuration. In terms of using a seven-axes robot with force control for process control tasks as e.g. assembly, grinding and drilling of holes, it can increase the space of which the robot is able to work, i.e. easily grind under a table or picking and placing in more complex environments. The redundancy can further be exploited to singularity avoidance.

Wampler (1986) introduced the damped least square method to overcome singularities. But the damped least square method has its disadvantages in loss of performance and increased tracking error (Chiaverini, 1997).

The choice of damping constant must be balanced with the required performance and allowed error. Nakamura (1987) introduced a variable damping factor and numerical filtering of the velocity component to overcome these drawbacks. Chiaverini (1997) proposed a modified inverse, using the damping factor only on the lowest singular values. Their results are shown to be more satisfying than those of the classical damped least square method, but there still is a problem of tuning the damping factor.

This paper presents a force control scheme with an approach for singularity avoidance by utilizing the redundancy. The LabVIEW Robotics Module 2011 was used for forward and inverse kinematics.

2. REDUNDANT KINEMATICS
This section will describe the appropriate redundant joints and discussing a few selection criterions that might be used. This includes rules based on joint angles to avoid singularities or based on other criterions. The angle of the redundant joint is called the arm-parameter. When the arm-parameter is changed, the kinematic model of the robotic arm must also be changed. This means that when changing the arm parameter, its corresponding value in the Denavit-Hartenberg (DH) matrix must be manipulated to match the new kinematics. And when selecting a redundant joint, the DH matrix itself must be selected to match the new kinematics. In many cases, the previous redundant joint will have a certain angle when selecting a new redundant joint. The value of the corresponding Twist or Rotation angle must be manipulated to match the current angle of the previous redundant joint. Conversely, the current angle of the joint now selected as redundant must be set as arm-parameter value.

When modeling for a given redundant joint, the joint is simply neglected, see figures 1, 2 and 4. If \( q_1 \) is selected as the redundant joint, it is important to also change the base transform. The base transform is the transformation from the origin of the base coordinate system to the first joint. Consequently, this changes if the first joint is neglected. The parameters defining the base are given in the DH matrix as "base".

The following experiments will use \( q_7 \) as the default redundant joint. It makes a decent choice for a default redundant joint as its rotational axis is close to the one of \( q_1 \). It will reduce the workspace if they approach parallelism because the difference in their contributions to the system becomes small. If \( q_1 \) is selected as the redundant joint, the robots reach will be reduced by the offset length between \( q_1 \) and \( q_2 \). It is therefore reasonable to use \( q_7 \) as the default redundant joint.

![Fig. 2. Wireframe of the NACHI MR20 with \( q_7 \) as the redundant joint.](image_1)

Given a situation where \( q_5 \) is approaching 0, the rotational axes of \( q_4 \) and \( q_6 \) is approaching a coaxial state. In such a case it can be desired to select \( q_4 \) as the redundant joint to avoid the singularity. If switching to \( q_4 \)-redundancy it is important to pay attention to the angle in \( q_2 \). The work space will be very limited if \( q_2 \) is low or close to zero because \( q_1 \) and \( q_4 \) will be parallel or close to so. It is therefore desired to manipulate the arm-parameter of the current redundant joint \( (q_1 \text{ or } q_7) \) to cause an angle in \( q_2 \). If \( q_5 \) is approaching zero. The arm parameter can thus be defined by a formula depending on \( Lq_2 \) and \( Lq_5 \) when \( q_{\text{red}} = q_4 \) as shown in Fig. 3.

3. When \( q_{\text{red}} \) is set to \( q_4 \), the following must be set: \[ \angle q_{\text{red}} = \angle q_4 \text{ and } \angle q_1 \cup \angle q_7 = \angle q_{\text{red}}. \]

![Fig. 3. Selection rules for selecting \( q_4 \) as the redundant joint.](image_2)

It is not desired to use \( q_1 \) as the redundant joint unnecessarily, since this will reduce the reach of the robot. The movement of \( q_1 \) is on the other hand often used in between tasks. The robot may perform a task in one area, and then use \( q_1 \) to move to a new area to perform new task. By using \( q_1 \) as the redundant joint when the robot is in place for a new task will allow six-DOF within the area. This enables a great flexibility in obstacle avoidance. The robot may in this case be regarded as a six-axes robot mounted concentric on a turntable.

![Fig. 4. Wireframe of the NACHI MR20 with \( q_4 \) as the redundant joint.](image_3)

![Fig. 5. Wireframe of the NACHI MR20 with \( q_1 \) as the redundant joint.](image_4)

3. THE CONTROL SYSTEM

The implemented control system is an active force control system, where the force control is added as an external control loop around the original positional loop. Extended Task Space Formulation is utilized in order to handle the NACHI MR20s seven joints.

![Fig. 6. Wireframe of the NACHI MR20 with \( q_1 \) as the redundant joint.](image_5)
The ETSF is implemented in the inverse kinematics in the force loop allowing the controllability of the redundant joint. The position vector contains position and orientation in addition to the angle of the redundant joint, thus \( \Delta p = [x \ y \ z \ A \ B \ C \ q_{\text{red}}] \). The angle of the redundant joint, \( q_{\text{red}} \), is then removed from the vector and entered into the DH-matrix of the robot definition. The inverse kinematics is then calculated based on \( \Delta \theta = [x \ y \ z \ A \ B \ C] \). The angle \( q_{\text{red}} \) is then added to \( \Delta \theta \) resulting in \( \Delta \theta \).

Fig. 6. Block diagram of the extended task space formulation.

The ETSF was, as previously mentioned, implemented in an external force control loop, as shown in Fig. 7. The difference between the reference force \( F_{\text{ref}} \) and the measured contact force \( \mathbf{F} \) is input to the force controller. From the control deviation, the force controller, which usually is an I- or PI-controller (De Schutter, 1986), calculates a correction \( \Delta \mathbf{p} \) to the robot’s nominal position \( \mathbf{p}_{\text{nom}} \). It is important to notice that the tool stiffness \( k \), is included in the force feedback loop and behaves as a part of the total feedback gain.

Fig. 7. Block diagram of the control system with active force control in an external loop using ETSF.

4. EXPERIMENTAL RESULTS

The control system was implemented on a NACHI MR20 robot, Fig. 1. The control system was running on a PC in LabVIEW. The step response for the force feedback loop is shown in Fig. 8. The bandwidth was approximately 1.5Hz.

Fig. 8. Step response of the force feedback system.

Experiments were conducted with different selection matrices (S) with the reference force vector \( R = [0 \ 0 \ 0 \ 0 \ 0 \ 0] \). The redundant joint was set to \( q_r \) during the experiments. To test the positioning abilities were the S set to \( S1 = [1 \ 1 \ 1 \ 0 \ 0 \ 0] \). The result is illustrated in Fig. 9 and 10. The tools orientation is kept stationary whilst the position is manipulated by applying force.

Fig. 9. Forces applied to tool with \( S=S1=[1 \ 1 \ 1 \ 0 \ 0 \ 0] \).

Fig. 10. Delta position/orientation and Force/Torque for operation with \( S=S1=[1 \ 1 \ 1 \ 0 \ 0 \ 0] \).

The selection matrix were then set to \( S=S2=[0 \ 0 \ 0 \ 1 \ 1 \ 1] \). This was done to test the ability to change the orientation using force control. The expected result was a stationary TCP while the tool rotates about it as shown in Fig. 11 and 12.
The control were then tested with $S=S_3=[1 1 1 1 1 1]$. Both tool position and orientation were now controllable by applying force to the tool. The results are shown in Fig. 13 and 14.

The redundant kinematics were tested by holding the tool position and orientation stationary while jogging the redundant joint, $q_2$. ($S=S_3=[1 1 1 1 1 1]$). The results are shown in Fig. 15 and 16. Notice that the tool position and orientation is kept relatively stationary while the internal configuration of the robot arm changes.
implementation of ETSF was tested through experiments with $q_7$ as the redundant joint. The results show that the robot is able to reconfigure whilst forces were applied on the tool.

REFERENCES


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6. CONCLUSION

A force control system with an approach for singularity avoidance for a redundant industrial robot has been presented.

It has been shown that the proposed system structure give good results for force control of a redundant robot. The