AN INTUITIVE INTERFACE FOR NULLSPACE TEACHING OF REDUNDANT ROBOTS

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Abstract. In the growing field of service robotics, redundant manipulator arms provide enormous advantages compared to their non–redundant counterparts. But the fact that no intuitive approaches exist for handling highly redundant robots hinders the breakthrough of such superior mechanisms. In this paper a general algorithm is proposed which allows the intuitive configuration manipulation of a redundant robot during a teach phase. The proposed algorithm enables a teacher to handle highly redundant manipulators ($DoF \gg 6$) in a natural way using the same teach-device as used in TCP teaching.

1. Introduction

Recently the interest in service robotics application has rapidly grown. Various authors demonstrated the superior performances of redundant mechanisms as "all-purpose" manipulators, for an overview see Siciliano(1990). The redundancy of such manipulator enhances their flexibility in adapting to new environments, which is essential for service robotics. But there is still a gap between current research in redundant robotics and a user friendly intuitive redundant robot controller, allowing a non-expert user to teach and handle the redundant degrees of freedom (DoF).

Non-redundant manipulators can be taught by guiding their tool center point (TCP) with a 6 DoF teach-device. But as the number of redundant joints rises, the configuration of the manipulator is not explicitly controllable with the TCP teach-device. Especially teaching higher redundant arms[1] is an open research subject.

In this paper a general approach is introduced for intuitive configuration management during the teach phase. Common 6 DoF teach-devices,

[1]Robot arms with more than one redundant DoF

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like the DLR SpaceMouse on a standard industry robot panel (see figure 1), can be utilized, so no further hardware will be required.

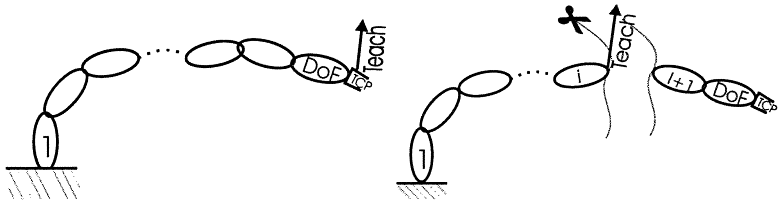
Figure 1. Standard industry robot user interface with buttons and the DLR SpaceMouse

Section 2 develops the intuitive configuration management approach. In section 3 results are presented.

2. Intuitive configuration management approach

Recent teaching algorithms enable the teacher to point out different Cartesian positions, constituting a Cartesian trajectory. This procedure is sufficient for non-redundant robots, because of their distinct relationship between joint space and Cartesian space. Redundant mechanisms provide additional DoFs, which are — untill now — not explicitly considered during the Cartesian teach phase. Therefore, the manipulator configuration cannot be specified during teach phase, which may lead to an undesired behavior of the redundant robot.

Current-day teaching is mainly performed via some 6 DoF teach-device, attached to the tool center point (TCP) of the manipulator. Extending this approach, we will consider attaching the teach-device to an arbitrary joint i. Cutting the kinematic chain of the robot at the joint i while fixing the TCP, we obtain two kinematic subchains (see figure 2). The Cartesian position of one kinematic subchain is modified by the commands of the teach-device. As a result, the user is able to introduce a desired nullspace motion.



(a) Robot represented as a kinematic chain, the teach device is attached to the TCP

(b) Kinematic chain of the robot is divided at joint i into two subchains, the teach device is attached to joint i while the TCP remains fixed

Figure 2. Robot represented as a kinematic chain

The maximum DoF $m^\star$ for this kind of motion is of course dependent of the minimum DoF of the two subchains divided by joint i and the degree of redundancy $r = DoF - 6$.

$$m^\star(i) \leq \min(r, i, DoF - i) \tag{1}$$

Equation (1) shows the maximum possible DoF $m^\star(i)$ as function of the attached joint i, which of course is dependent on the smallest DoF of both sub-chains. As this equation implies, even though the redundant inverse kinematics problem is an underdetermined problem, this kind of motion is overdetermined, since it is specified by a 6 DoF teach-device.

Several algorithms are known in literature to solve the redundancy problem, e.g. the Moore–Penrose pseudo inverse Whitney(1969) or constraint optimization algorithms based on quadratic programming Cheng, Chen and Sun(1992) Park, Chung and Youm(1996). For algorithms of this kind a subtask has to be defined which serves as nullspace criterion. In the following, three different formulations for the nullspace criteria are developed.

As first formulation, we will interpret the commands of the teach-device as desired Cartesian speed $\dot{\boldsymbol{x}}_i$ of joint i. So the differential relationship for the first subchain will be:

$$\dot{\boldsymbol{x}}_i = \boldsymbol{J}_i \dot{\boldsymbol{q}}_i^\star \tag{2}$$

where $\boldsymbol{J}_i$ is the $(6 \times i)$ Jacobian matrix, considering the joints 1 to i only, and $\dot{\boldsymbol{q}}_i^\star$ is the $(i \times 1)$ joint speed vector of the joints 1 to i. The inversion of (2) leads to a vector of desired joint speed:

$$\dot{\boldsymbol{q}}_i^\star = \boldsymbol{J}_i^\dagger \dot{\boldsymbol{x}}_i \tag{3}$$

where $\boldsymbol{J}_i^\dagger$ is the pseudo inverse of $\boldsymbol{J}_i$, since $\boldsymbol{J}_i$ typically is a non-square matrix.

The well known pseudo inverse solution with nullspace projection Nakamura, Hanafusa and Yoshikawa(1987) can be utilized as a solution to the redundant inverse kinematics problem. As redundant subtask, equation (3) is applied, leading to:

$$\begin{aligned} \dot{\boldsymbol{q}} &= \boldsymbol{J}^\dagger \dot{\boldsymbol{x}} + \dot{\boldsymbol{q}}_0 & (4)\\ \dot{\boldsymbol{q}}_0 &= \left(\boldsymbol{I} - \boldsymbol{J}^\dagger \boldsymbol{J}\right) \begin{pmatrix} \dot{\boldsymbol{q}}_i^\star \\ \boldsymbol{0} \end{pmatrix} & (5) \end{aligned}$$

A second possibility, which will reduce the computational load, is to utilize the Jacobian transposed matrix $\boldsymbol{J}_i^T$ Sciavicco and Siciliano(1996) instead of the pseudo inverse. The data of the teach-device can be defined to be forces $\boldsymbol{F}_i$ pulling at joint i, such that

$$\boldsymbol{\tau}_i^\star = \boldsymbol{J}_i^T \boldsymbol{F}_i \tag{6}$$

whereas $\boldsymbol{\tau}_i^\star$ represents the vector of joint moments, which can be mapped to a motion with a constant factor α:

$$\dot{\boldsymbol{q}}_i^\star = \alpha \boldsymbol{\tau}_i^\star \tag{7}$$

Similar to the first possibility, the resulting vector $\dot{\boldsymbol{q}}_i$ can be used as subtask (4). This possibility is of course computationally much more efficient, since no additional inversion is necessary.

As a third possibility we will formulate the problem for constraint optimization algorithms Cheng, Chen and Sun(1992) Park, Chung and Youm(1996) Schreiber, Otter and Hirzinger(1999). The teach-device is defined as a Cartesian command which modifies the desired position $\boldsymbol{x}_{i,d}$ of joint i. Thus we are able to define an approximation error $\boldsymbol{e}_i$, which will be minimized by a constraint optimization algorithm:

$$\boldsymbol{e}_i = (\boldsymbol{x}_i - \boldsymbol{x}_{i,d}) \tag{8}$$

As we consider an iterative approach, we will use the index j for the jth iteration step. We derive that

$$\begin{aligned} \boldsymbol{x}_{i,j+1} &= \boldsymbol{x}_{i,j} + \boldsymbol{J}_i \Delta \boldsymbol{q}_{i,j} & (9) \\ \boldsymbol{e}_{i,j+1} &= \boldsymbol{J}_i \Delta \boldsymbol{q}_{i,j} + \boldsymbol{x}_{i,j} - \boldsymbol{x}_{i,d} & (10) \\ &= \boldsymbol{J}_i \Delta \boldsymbol{q}_{i,j} + \Delta \boldsymbol{x}_{i,j} & (11) \end{aligned}$$

Since the manipulator's Jacobian $\boldsymbol{J}$ is known, $\boldsymbol{J}$ could be used instead of $\boldsymbol{J}_i$. In this case a velocity transform of $\dot{\boldsymbol{x}}_i$ has to be performed Craig(1989, p. 180). Since we are only considering a kinematic subchain, the additional columns of $\boldsymbol{J}$ have to be cancelled out:

$$^{TCP}\dot{\boldsymbol{x}}_i = \begin{bmatrix} {}_i^{TCP}\boldsymbol{R} & -{}_i^{TCP}\boldsymbol{R}\,{}^i\boldsymbol{P}_{iTCP\times} \\ \boldsymbol{0} & {}_i^{TCP}\boldsymbol{R} \end{bmatrix} {}^i\dot{\boldsymbol{x}}_i \qquad (12)$$

${}_i^{TCP}\boldsymbol{R}$ is the orientation transform between the frame of joint i and that of the TCP, also ${}^i\boldsymbol{P}_{iTCP\times}$ is the cross product operator of the translation vector $\boldsymbol{P}_{i,TCP}$ between joint i the TCP:

$$\boldsymbol{P}_\times = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix} \qquad (13)$$

Equation (1) shows, that the rank of the problem depends on the smaller rank of both sub-chains. Therfore the required Jacobian $\boldsymbol{J}_i$ may be formulated as well for the upper-reversed sub-chain DoF to i for $i > \frac{DoF}{2}$. So the resulting reversed Jacobian $\boldsymbol{J}_i^R$ has fewer rows, which reduces the computational load.

Conclusion Deciding which of the above mentioned configuration management schemes is optimal depends on the requirements of the redundancy resolution system. The introduced scheme can be augmented by dexterity optimization or collision avoidance according to the features of the redundancy resolution system. The proposed method is of great use for service robotics, since a model of the environment for proper collision avoidance date may be unknown. In the next section, some results of the application of the proposed nullspace manipulation method will be discussed.

3. Application and Results

The previously discussed method has been applied to our system, which is used for service robotics. The new 7 DoF DLR light weight robot (see figure 3) is mounted on a mobile platform. The whole mechanism totals up to 10 DoF.

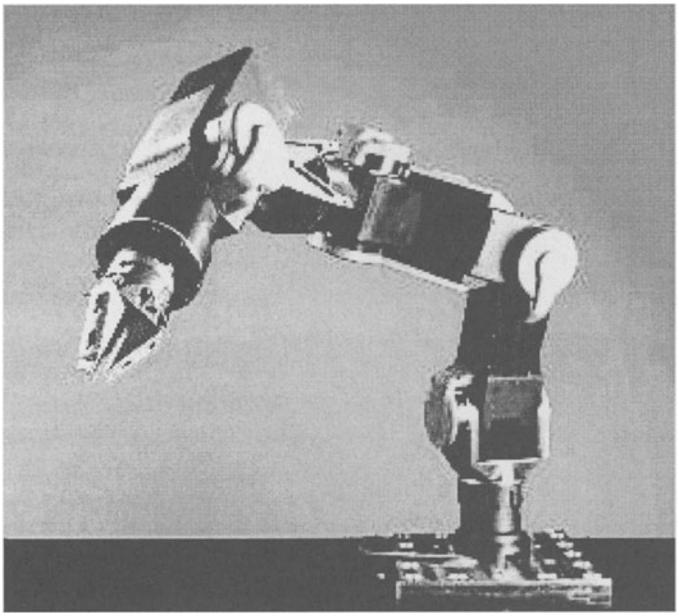


Figure 3. 7 DoF DLR lightweight robot

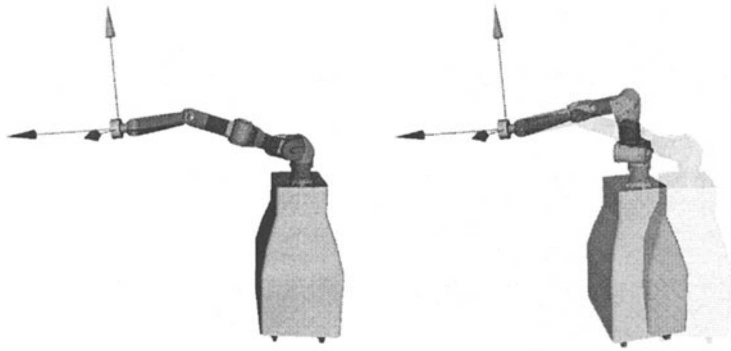
The previously described methods of the intuitive nullspace management algorithm have been implemented and tested. The user could attach the teach-device to a joint or to the TCP of the highly redundant robot. As the user modifies the configuration $\boldsymbol{q_m}$ of a teach point, the system stored the configuration $\boldsymbol{q_m}$. On replay of the learned trajectory, the configuration $\boldsymbol{q_m}$ is applied as subtask.

A first observation was that the user preferred attaching the teach-device to "exposed" joints, such as the elbow joint or the base joint of the DLR lightweight robot, since the nullspace movement of those joints could be imagined easily. A simple motion example is shown in figure 4, where a successive intuitive nullspace motion has been commanded from an arbitrary start configuration. As can be easily seen, the robot follows the introduced commands, which have been given via the teach-device.

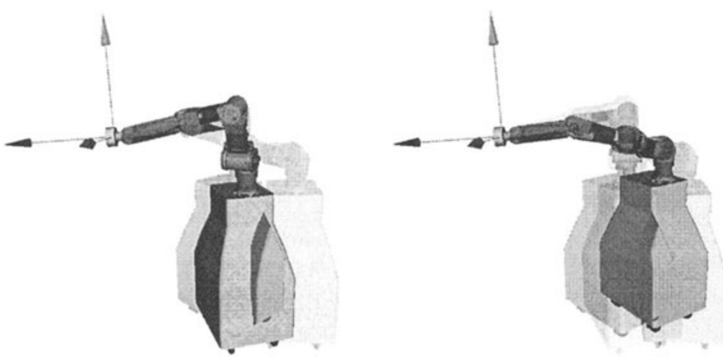
4. Conclusion

We introduced the intuitive nullspace manipulation approach. This approach is a necessary step on the way to intuitive usage of redundant robots. The approach extends classical teaching, such that commonly used 6 DoF teach-devices can still be applied.

As the intuitive management of additional DoF grows, the main prej-



(a) Start configuration (b) Motion along -X direction



(c) Motion along Y direction (d) Motion along X direction

Figure 4. Example of an intuitive successive null motion on the DLR lightweight robot mounted on a mobile platform totalling 10 DoF. The teach-device has been attached to the first joint of the lightweight robot.

udices against redundant robots will vanish. These robots have superior abilities, which are of essential importance in the field of service robotics.

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