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An Approach to Modeling a Kinematically Redundant Dual Manipulator Closed Chain System Using Pseudovelocities*

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AN APPROACH TO MODELING A KINEMATICALLY REDUNDANT DUAL MANIPULATOR CLOSED CHAIN SYSTEM USING PSEUDOVELOCITIES†

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ABSTRACT

The paper discusses the problem of resolving the kinematic redundancy in the closed chain formed when two redundant manipulators mutually lift a rigid body object. The positional degrees of freedom (DOF) in the closed chain are parameterized by a set of independent variables termed pseudovelocities. Due to the redundancy there are more DOF and thus more pseudovelocities than are required to specify the motion of the held object. The additional "redundant" pseudovelocities are used to minimize the distance between the vector of unknown joint velocities and a vector of "corrective" joint velocities in a Euclidean norm sense. This leads to an optimal solution for the joint velocities as a linear function of the Cartesian object velocities and the corrective velocities. The problem of determining the corrective velocities to avoid collisions of the links with a wall located in the workspace and to avoid joint range limits is illustrated by an example of two redundant planar revolute joint manipulators mutually lifting a rigid object.

KEYWORDS: interacting redundant manipulators, redundant pseudovelocities, collision and joint limit avoidance, corrective action

INTRODUCTION

When two serial link manipulators possessing N_1 and N_2 joints, respectively, mutually lift a rigid body object the values of the joint velocities of the manipulators are restricted by M rigid body kinematic constraints‡ [1]. M configuration degrees of freedom (DOF) are lost and the closed chain system has $(N_{12} - M)$ DOF, where $N_{12} = N_1 + N_2$. In our previous work [1], the configuration DOF were parameterized by $(N_{12} - M)$ independent scalar variables termed pseudovelocities. The joint velocities were expressed as linear functions of the pseudovelocities. When each manipulator is kinematically redundant $(N_i > M)$, there are more DOF than are required to control the translational and rotational motion of the object at its center of mass. In [1], M of the pseudovelocities were viewed as nonredundant, and were selected to be the components of translational and angular velocity of the object at its center of mass. On the other hand, the remaining $(N_{12} - 2M)$ pseudovelocities were viewed as being redundant. A dynamical model comprised of $(N_{12} - M)$ second order differential equations governing the motion of the closed chain was derived, where each of the equations is a linear function of an $((N_{12} - M) \times 1)$ vector containing the time derivatives of the pseudovelocities. Based on the model, a control scheme was proposed where each of the pseudovelocities was explicitly controlled to track a

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‡ $M = 6$ and $M = 3$ for spatial and planar dual manipulator configurations, respectively.

reference trajectory. Please note that with this approach the M object DOF and the $(N_{12} - 2M)$ redundant DOF are treated in the same way. They are equally important. An open problem not addressed in [1] is how to select reference trajectories for the redundant pseudovelocities.

This paper takes a different approach where the $(N_i - M)$ redundant pseudovelocities associated with manipulator i are used to induce joint self motions (i.e., motions of the joints that do not contribute to the motion of the held object) to make the vector of joint velocities tend towards a known vector of "corrective" joint velocities in some optimal sense. We propose to calculate the redundant pseudovelocities to minimize the distance between these vectors in a Euclidean norm sense. This leads to an optimal solution for the joint velocities containing a component that contributes to the object's motion and a self motion component that is a function of the corrective velocities. Since the object's motion is constrained to follow a reference trajectory whereas inducing joint self motions is optional, the control of the Cartesian pseudovelocities takes precedence over calculating the redundant pseudovelocities to minimize the aforementioned distance.

In our earlier work [2], an algorithm for calculating the corrective joint velocities was proposed to establish a joint limit avoidance capability for an *un*constrained manipulator. Here it is investigated if the corrective velocities can be determined to give each manipulator in the closed chain an additional capability via joint self motions. This will be illustrated by an example where the algorithm in [2] is extended to give each of two redundant planar revolute joint manipulators mutually holding a rigid object the complimentary and simultaneous capabilities of avoiding joint limits and avoiding collisions of the links with a wall located in the workspace. The planar configuration is shown in Figure 1. There are other approaches to collision avoidance when dual manipulators share a common workspace such as applying reflexive action [3], but kinematically redundant manipulators were not considered in the analysis. Other approaches to utilizing kinematic redundancy in the closed chain are discussed in [4, 5].

KINEMATIC REDUNDANCY RESOLUTION

Let the $(M \times 1)$ vector v_o denote the the Cartesian velocity of the object at its center of mass with respect to a stationary world reference coordinate frame. In the closed chain, v_o can be expressed as a linear function of the joint velocities of either manipulator [1]:

$$v_o = A_i \, \dot{q}_i \tag{1}$$

where $\dot{q}_i$ denotes the $(N_i \times 1)$ vector of joint velocities of manipulator i and $A_i(q_i)$ is a $(M \times N_i)$ matrix. It is assumed that A_i has full rank $M \, (< N_i)$.

An underspecified solution to eq. (1) is given by:

$$\dot{q}_i = E_i \, v_o + F_i \, \nu_i \tag{2}$$

where E_i and F_i are $(N_i \times M)$ and $(N_i \times (N_i - M))$ full rank matrices, respectively, which satisfy the matrix identities $A_i \, E_i = I_M$ and $A_i \, F_i = 0_{M \times (N_i - M)}$. Here I_k signifies a $(k \times k)$ identity matrix and $0_{k \times l}$ a $(k \times l)$ matrix of zeros. The components of v_o constitute the Cartesian pseudovelocities in the closed chain. The components of the $((N_i - M) \times 1)$ vector ν_i are the redundant pseudovelocities associated with manipulator i. They parameterize the null space of A_i. Therefore $(F_i \, \nu_i)$ induces joint self motions which do not affect object motion. It is assumed that the quantities $\{E_i \, , \, F_i\}$ $(i$=1,2) are known (see [2] for methods to determine them) and that a reference trajectory for the center of mass of the held object has been specified. Thus v_o is known and the only unknown quantity in eq. (2) is ν_i.

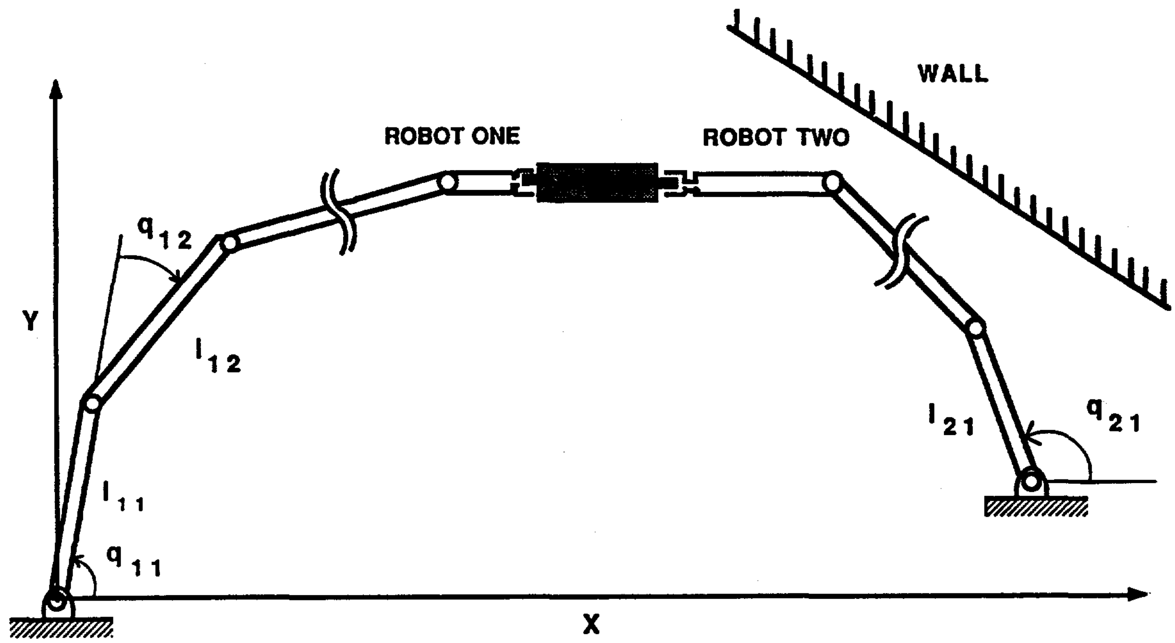

Figure 1. Closed Chain With Two Planar Manipulators

Let $\dot{q}_i^c$ denote an $(N_i \times 1)$ vector of "corrective" joint velocities which represents a desired target or goal that the joint velocities of manipulator i should tend to in some optimal manner. It must be emphasized that $\dot{q}_i^c$ is a *not* a "reference" trajectory to be explicitly tracked by $\dot{q}_i$ using servo control techniques. Besides, the N_i components of $\dot{q}_i$ cannot be independently controlled to track reference trajectories because their values must satisfy M rigid body kinematic constraints $A_1\,\dot{q}_1 - A_2\,\dot{q}_2 = 0_{M\times 1}$ arising from eq. (1) . It is assumed that $\dot{q}_i^c$ has a component lying in the null space of A_i but it may also have a component which is orthogonal to every vector in the null space in the general case. $\dot{q}_i^c$ is a known function of the measured or sensed variables associated with manipulator i and is calculated by an algorithm furnished by the designer. An example of such an algorithm to give two interacting planar manipulators the capabilities of avoiding collisions with a wall located in the workspace and avoiding joint limits is presented in the next section.

In this paper we propose to determine ν_i to minimize the distance between $\dot{q}_i$ and $\dot{q}_i^c$ in a Euclidean norm sense. To accomplish this objective, a performance index is introduced:

$$P_i = (\dot{q}_i - \dot{q}_i^c)^T\,(\dot{q}_i - \dot{q}_i^c) = (E_i\,v_o + F_i\,\nu_i - \dot{q}_i^c)^T\,(E_i\,v_o + F_i\,\nu_i - \dot{q}_i^c) \quad (3)$$

where superscript T denotes a transpose and where eq. (2) has been applied. The necessary optimality condition is obtained from $d\,P_i/d\,\nu_i = 0_{(N_i-M)\times 1}$. Solving this equation for ν_i and substituting the result into eq. (2) yields the symbolic solution for the joint velocities of manipulator i:

$$\dot{q}_i = E_i\,v_o + F_i\left(F_i^T\,F_i\right)^{-1}F_i^T\,(\dot{q}_i^c - E_i\,v_o) = A_i^T\,(A_i\,A_i^T)^{-1}v_o + F_i\left(F_i^T\,F_i\right)^{-1}F_i^T\,\dot{q}_i^c \quad (4)$$

Eq. (4) was obtained by choosing E_i to be:

$$E_i = A_i^T\,\beta + F_i\,\gamma \quad (5)$$

where β and γ are $(M \times M)$ and $((N_i - M) \times M)$ parameter matrices, respectively. Using this definition, $(E_i\,v_o)$ always contains a component $(A_i^T\,\beta\,v_o)$ which contributes to the held object's motion, but it may also contain a component $(F_i \gamma v_o)$ which induces joint self motions in the general case. Interestingly, the self motion component of $(E_i v_o)$ vanishes from the final solution for $\dot{q}_i$ in eq. (4) . It is easy to verify that $\beta = (A_i A_i^T)^{-1}$ by premultiplying eq. (5) by A_i.

Although the vector of corrective velocities does not lie entirely in the null space of A_i, eq. (4) reveals that $\dot{q}_i^c$ has been projected into the null space (of A_i) by its coefficient matrix. Therefore any "corrective action" applied to the system using $\dot{q}_i^c$ does not affect the motion of the held object.

CALCULATION OF CORRECTIVE ACTION

Let $\dot{q}_{i,j}^c$ denote the corrective velocity corresponding to the jth joint of manipulator i. In this section an algorithm is presented for calculating $\dot{q}_{i,j}^c$ for each and every joint that, when used in conjunction with eq. (4) , induces self motions of the joints of each manipulator to avoid collisions of the links with a wall located in the workspace and to avoid joint limits. It is assumed that the dual-manipulator closed chain is a planar system, and that all manipulator joints are of the revolute type.

Wall Collision Avoidance Strategy

Suppose there is a wall that is perpendicular to the the plane of motion located in the workspace of the closed chain system (see Figure 1). This wall is modeled by a straight line:

$$y = a\,x + b \tag{6}$$

Further, let the position of the outer end of the jth link of manipulator i be signified by the coordinates $(x_{i,j},\, y_{i,j})$ with respect to a stationary world reference frame. The Cartesian coordinates are related to the joint coordinates by:

$$(x_{i,j}\,,\, y_{i,j}) = \left\{ x_{i,j-1} + l_{i,j}\,\cos\left(\sum_{p=1}^{j} q_{i,p}\right)\,;\, y_{i,j-1} + l_{i,j}\,\sin\left(\sum_{p=1}^{j} q_{i,p}\right)\right\} \tag{7}$$

where $(1 \le j \le N_i)$ and $(x_{i,0},\, y_{i,0})$ is the position of the base of manipulator i. $q_{i,j}$ and $l_{i,j}$ signify the jth joint angle and jth link of manipulator i, respectively.

The line passing through the point $(x_{i,j},\, y_{i,j})$ that is perpendicular to the wall is:

$$y = -\frac{1}{a}\,(x - x_{i,j}) + y_{i,j} \tag{8}$$

and the distance from $(x_{i,j},\, y_{i,j})$ to the wall is:

$$d_{i,j} = (a\,x_{i,j} - y_{i,j} + b)\,/\,\left(\pm\sqrt{a^2+1}\right) \tag{9}$$

where the sign in the denominator is chosen such that $d_{i,j}$ is nonnegative.

Let $\alpha_{i,j}$ signify the angle between the "perpendicular line" defined by eq. (8) and link $l_{i,j}$, which is measured positive in the counterclockwise sense with respect to the perpendicular line (see Figure 2). $\alpha_{i,j}$ can be expressed as a function of the slopes of $l_{i,j}$ and the perpendicular line:

$$\tan(\alpha_{i,j}) = \{a\,(y_i - y_{i-1}) + (x_i - x_{i-1})\}\,/\,\{a\,(x_i - x_{i-1}) - (y_i - y_{i-1})\} \tag{10}$$

Let the positive quantity tol^d denote a constant threshold distance from the wall. If the distances from the tips of one or more of the lower $(N_i - 2)$ links of manipulator i to the wall are less than tol^d, it is regarded that a shutdown or damage to the manipulator are imminent due to those links colliding with the wall. Accordingly, it is desired to compute corrective velocities for the joints corresponding to these links that, when

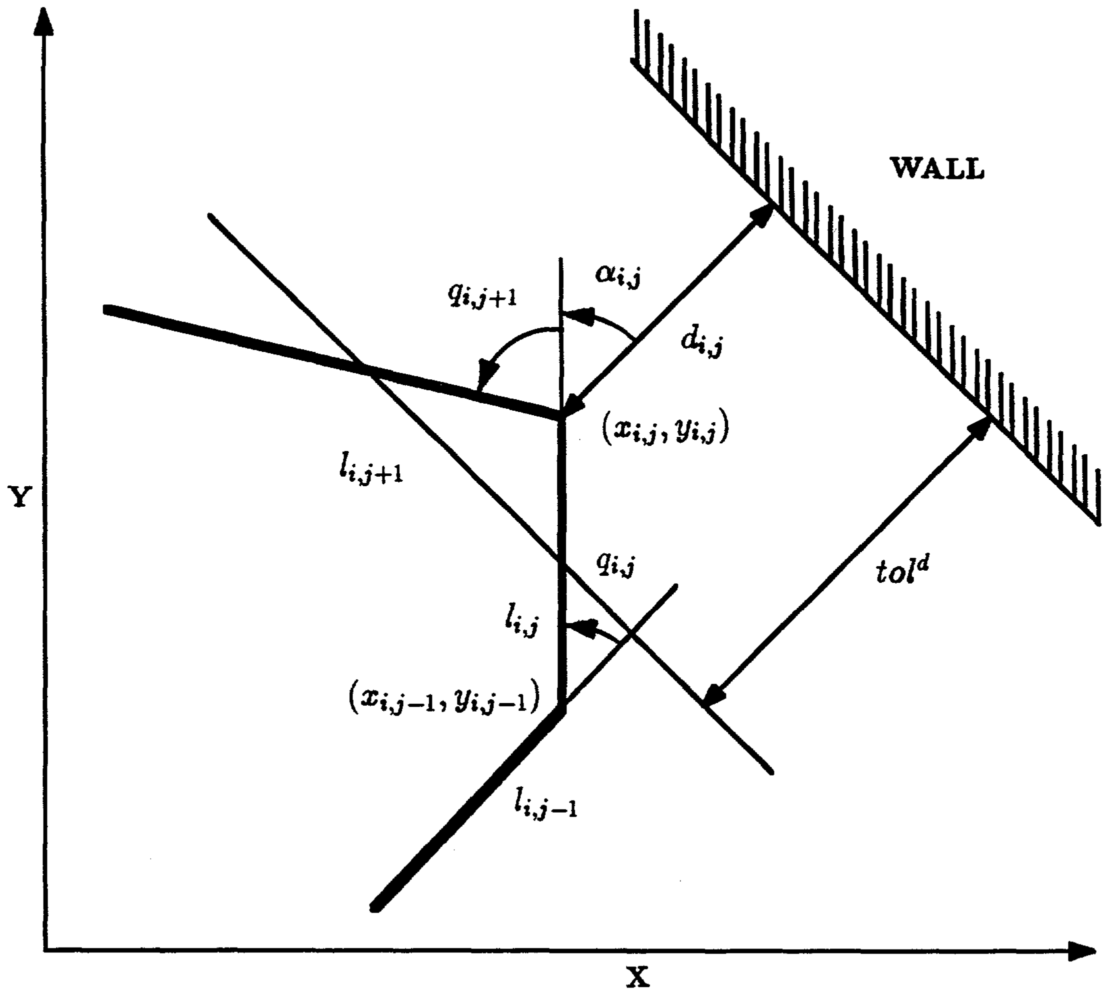

Figure 2. Parameters for Wall Collision Avoidance

used in conjunction with the optimal solution for the joint velocities given by eq. (4) , tends to move them away from the wall using self motion of the joints.[§]

Joint Limit Avoidance Strategy

The corrective velocities for the two outermost joints of manipulator i and for those joints (among its lower $(N_i - 2)$ joints) whose corresponding link tips are located at a distance greater than tol^d from the wall can be calculated to provide a joint limit avoidance (JLA) capability via joint self motions when used in conjunction with eq. (4) .

Let $q_{i,j}^{max}$ and $q_{i,j}^{min}$ signify the absolute hardware limits in the range of joint j of manipulator i. In our strategy, the positive, constant angles tol_i^{hi} and tol_i^{lo} are

[§] It is important to note that the trajectory of the outermost N_ith link of each manipulator is determined because the trajectory of the held rigid object is specified and each manipulator securely holds the object. Therefore, self motions of the joints do not affect the trajectory of the N_ith link, and the corrective velocities for the outermost two joints of each manipulator are not computed in the wall collision avoidance strategy.

introduced to define the ranges $\left(q_{i,j}^{max} - tol_i^{hi}\right) < q_{i,j} < q_{i,j}^{max}$ and $q_{i,j}^{min} < q_{i,j} < \left(q_{i,j}^{min} + tol_i^{lo}\right)$. When $q_{i,j}$ lies within either of these ranges, it is regarded that a shutdown and damage to the manipulator are imminent due to the joint reaching a limit. Accordingly, a corrective velocity $\dot{q}_{i,j}^c$ is desired to drive joint j back into the range $\left(q_{i,j}^{min} + tol_i^{lo}\right) \leq q_{i,j} \leq \left(q_{i,j}^{max} - tol_i^{hi}\right)$.

Based on the aforementioned strategies, the algorithm for wall collision avoidance (WCA) and JLA is presented next.

The Proposed Algorithm

$\dot{q}_{i,j}^c$ is calculated for each and every joint ($i = 1,\ 2\,;\ j = 1,\ 2,\ \ldots\ N_i$) by the following conditional algorithm, where distance $d_{i,j}$ is computed as a function of the measured joint angles $\{q_{i,1},\ q_{i,2},\ \ldots,\ q_{i,j}\}$ using eqs. (7) and (9) whenever ($j \leq N_i - 2$):

$0 < d_{i,j} < tol^d$ **and** $j \leq N_i - 2$: Calculate $\alpha_{i,j}$ by eq. (10) and $\dot{q}_{i,j}^c$ for WCA using:

$$0 \leq \alpha_{i,j} \leq 90^o \textbf{ and } q_{i,j} \leq \left(q_{i,j}^{max} - tol_i^{hi}\right) : \dot{q}_{i,j}^c = \frac{z_i^d\, \dot{q}_{i,j}^{max}}{tol^d}\left(tol^d - d_{i,j}\right) \quad (11)$$

$$0 \leq \alpha_{i,j} \leq 90^o \textbf{ and } q_{i,j} > \left(q_{i,j}^{max} - tol_i^{hi}\right) : \dot{q}_{i,j}^c = 0$$

$$-90^o \leq \alpha_{i,j} < 0 \textbf{ and } q_{i,j} \geq \left(q_{i,j}^{min} + tol_i^{lo}\right) : \dot{q}_{i,j}^c = -\frac{z_i^d\, \dot{q}_{i,j}^{max}}{tol^d}\left(tol^d - d_{i,j}\right) \quad (12)$$

$$-90^o \leq \alpha_{i,j} < 0 \textbf{ and } q_{i,j} < \left(q_{i,j}^{min} + tol_i^{lo}\right) : \dot{q}_{i,j}^c = 0$$

$\left(d_{i,j} \geq tol^d\right.$ **and** $j \leq N_i - 2)$ **or** $j > N_i - 2$: Calculate $\dot{q}_{i,j}^c$ for JLA based on the measured value of $q_{i,j}$ using:

$$q_{i,j}^{min} < q_{i,j} < \left(q_{i,j}^{min} + tol_i^{lo}\right) \ :\ \dot{q}_{i,j}^c = \frac{z_i\, \dot{q}_{i,j}^{max}}{tol_i^{lo}}\left(q_{i,j}^{min} + tol_i^{lo} - q_{i,j}\right) \quad (13)$$

$$\left(q_{i,j}^{max} - tol_i^{hi}\right) < q_{i,j} < q_{i,j}^{max} \ :\ \dot{q}_{i,j}^c = \frac{z_i\, \dot{q}_{i,j}^{max}}{tol_i^{hi}}\left(q_{i,j}^{max} - tol_i^{hi} - q_{i,j}\right) \quad (14)$$

$$\left(q_{i,j}^{min} + tol_i^{lo}\right) \leq q_{i,j} \leq \left(q_{i,j}^{max} - tol_i^{hi}\right) \ :\ \dot{q}_{i,j}^c = 0$$

where $\dot{q}_{i,j}^{max} (> 0)$ denotes the maximum or peak time rate of change of joint $q_{i,j}$. In eqs. (11) and (12), z_i^d is a constant scaling factor whose value is restricted to the range:

$$0 < z_i^d \leq 1 \quad (15)$$

z_i^d is introduced to enable to designer to specify a scaled peak velocity ($z_i^d\, \dot{q}_{i,j}^{max}$) in the WCA scheme. Scalar z_i in eqs. (13) and (14) is defined in a similar manner for the JLA scheme.

The WCA portion of the algorithm is conditioned on the value of $\alpha_{i,j}$ *and* the sub-range that the measured value of $q_{i,j}$ lies in. Consider eq. (11), which is the equation of a line segment connecting (but not including) the points $\left(d_{i,j} = 0,\ \dot{q}_{i,j}^c = z_i^d\, \dot{q}_{i,j}^{max}\right)$ and $(tol^d\,,\ 0)$. It is easy to see that $\dot{q}_{i,j}^c$ is positive and that its magnitude is based on the distance from the tip of link $l_{i,j}$ to the wall when calculated by eq. (11). Observing Figure 2, the basic idea here is to apply a corrective action to induce $q_{i,j}$ to rotate counterclockwise which moves the outer tip of link $l_{i,j}$ away from the wall. However, it is logical that eq. (11) be applied only when $q_{i,j}$ does not lie in its upper prohibitive subrange. Indeed, to calculate $\dot{q}^c_{i,j}$ using eq. (11) when $q_{i,j} > q^{max}_{i,j} - tol^{hi}_i$ may reduce the possibility of $l_{i,j}$ colliding with the wall at the expense of increasing the already high possibility of $q_{i,j}$ reaching its upper range limit. No corrective action can be applied to joint $q_{i,j}$ to alleviate this situation, and we set $\dot{q}^c_{i,j}$ to zero.

By observing Figure 2 and applying the same reasoning, $\dot{q}^c_{i,j}$ is calculated as a negative quantity using eq. (12) when $(-90^o \leq \alpha_{i,j} < 0)$, provided that $q_{i,j}$ does not lie in its lower prohibitive subrange. But if $q_{i,j} < q^{min}_{i,j} + tol^{lo}_i$, $\dot{q}^c_{i,j}$ is set to zero.

The logic of the JLA portion of the algorithm is now explained. Eq. (13) is the equation of a line segment connecting (but not including) the points $\left(q_{i,j} = q^{min}_{i,j} + tol^{lo}_i,\ \dot{q}^c_{i,j} = 0\right)$ and $\left(q^{min}_{i,j},\ z_i\,\dot{q}^{max}_{i,j}\right)$. Likewise, eq. (14) is the equation of line segment between the points $\left(q^{max}_{i,j} - tol^{hi}_i,\ 0\right)$ and $\left(q^{max}_{i,j},\ -z_i\,\dot{q}^{max}_i\right)$. It is easy to see that $\dot{q}^c_{i,j}$ is positive when calculated by eq. (13). This is logical since it is desired to rotate joint $q_{i,j}$ counterclockwise away from the lower hardware limit. By the same reasoning $\dot{q}^c_{i,j}$ is negative when evaluated using eq. (14). It should be mentioned that the JLA algorithm given here, unlike the WCA algorithm, is directly applicable to the spatial case.

When $d_{i,j} > tol^d$ (if applicable, i.e., if $j \leq N_i - 2$) and $\left(q^{min}_{i,j} + tol^{lo}_i\right) \leq q_{i,j} \leq \left(q^{max}_{i,j} - tol^{hi}_i\right)$, no correction action is needed for joint $q_{i,j}$ and $\dot{q}^c_{i,j}$ is set to zero. It follows that if all of the lower $(N_i - 2)$ links of manipulator i are sufficiently away from the wall and all N_i of its joints lie in their respective center subranges, then $\dot{q}^c_i = 0_{N_i \times 1}$ and there is no corrective action applied to manipulator i. This supports our contention that the corrective action component in the joint velocity solution is nonzero only when it is detected, by sensing, that it is required. This reduces the computational burden and yields a minimum Euclidean norm solution for $\dot{q}_i$.

The approach given here contrasts sharply from the result obtained using gradient projection [6, 7, 8], where the solution for $\dot{q}_i$ would contain one or multiple terms that project the gradients of scalar functions into the null space of A_i. In some approaches, each term represents a distinct secondary criteria, e.g., joint limit- and wall collision-avoidance. The problem is that each gradient projecting term is always computed, regardless of whether or not any links are close to the wall or any joints are close to their hardware range limits. In the author's opinion this computation is wasteful when feedback sensing indicates that manipulator i is in a configuration where JLA and WCA are not needed.

The aforementioned gradient projection technique would assign a scalar weighting factor to each gradient projecting term to establish a priority of importance among the multiple secondary criteria. On the other hand, the algorithm presented here for calculating $\dot{q}^c_{i,j}$ is done on a joint by joint basis depending on sensed conditions.

CONCLUSION

The paper proposed an alternative approach to applying the "redundant" pseudovelocities to the modeling of the closed chain motion of two serial link, kinematically redundant manipulators mutually lifting a rigid body object. In our previous work the redundant pseudovelocities were treated in the same way as the "nonredundant" pseudovelocities (i.e., those assigned to be the Cartesian velocities of the held object) and were explicitly controlled to track reference trajectories. Here the redundant pseudovelocities were applied to resolve the kinematic redundancies of the manipulators, where it was assumed that their joint self motions do not affect the motion of the held object. An optimal solution for the joint velocities was determined by applying the redundant pseudovelocities to minimize the distance between the vector of joint velocities and a vector of "corrective" velocities $\dot{q}_i^c$ in a minimum Euclidean norm sense. Based on an example of a planar dual-manipulator closed chain, a novel algorithm for calculating the components of $\dot{q}_i^c$ was proposed where $\dot{q}_{i,j}^c$ is computed to (i) induce joint $q_{i,j}$ to rotate in a direction that moves the tip of link $l_{i,j}$ away from a wall located in the workspace if it is within a critical distance to the wall (however, if $q_{i,j}$ is to be rotated counterclockwise (clockwise) but the joint lies in close proximity to its upper (lower) range limit, $\dot{q}_{i,j}^c$ is set to zero), or if condition (i) tests false or if $q_{i,j}$ is one of the two outermost joints of manipulator i , to (ii) induce joint $q_{i,j}$ to move away from an upper or lower hardware range limit if it is in close proximity to either limit, or if condition (ii) tests false, to (iii) set $\dot{q}_{i,j}^c$ equal to zero. Thus each corrective velocity is computed only when it is needed. An interesting aspect of our approach is that when none of the joints are in close proximity of their range limits and none of the links are in close proximity to the wall, the corrective velocities are set to zero and there is no corrective action (self motion) component in the joint velocity solution.

The future work involves simulating the proposed redundancy resolution method to test its effectiveness and determining how to calculate the corrective velocities to avoid collisions with an object of complex shape that cannot not be described by an analytic expression.

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