OBSTACLE-AVOIDANCE ALGORITHM USING REFERENCE JOINT-VELOCITY FOR REDUNDANT ROBOT MANIPULATOR WITH FRUIT-HARVESTING APPLICATIONS

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ABSTRACT

Robot manipulators for harvesting fruits must be controlled to track the desired path of end-effector to avoid obstacles under the consideration of collision free area and safety path. This paper presents a robot path control algorithm to secure a collision free area with the recognition of work environments. The flexible space, which does not damage fruits or branches of tree due to their flexibility and physical properties, extends the workspace. Now the task is to control robot path in the extended workspace with the consideration of collision avoidance and velocity limitation at the time of collision concurrently. The feasibility and effectiveness of the new algorithm for redundant manipulators were tested through simulations of a redundant manipulator for different joint velocities.

Key Word : Redundancy, Velocity limitation, Path control algorithm

INTRODUCTION

Since redundant manipulators have more flexibility than general purpose ones used in industrial field, it has the advantages to perform the tasks such as singularity or obstacle avoidance maintaining high manipulability while tracking the desired end-effector trajectory.

In a point-of-view of mechanical design, only 6 degrees-of-freedom is required to perform tasks in a spatial workspace. In fruit harvesting, however, a manipulator elbow may collide with obstacles. The objects or obstacles (e.g., the branches of tree or immature fruits) may get damaged by the motion of manipulator. Thus, it is required to have an extra degree-of-freedom generating self-motion to perform complex tasks.

In fruit harvesting, obstacles to be avoided may be located on the task trajectory of end-effector so that a redundant manipulator which some joints can be configured free with a certain reference such as performance criteria. Much researches have been done in the area of redundant manipulators. Most methods to solve redundancy of manipulator include a cost function[1][5][6][7][10][11][12] such as performance criteria, which have a weighted value at a collision point to avoid obstacles and joint constraints[3] or cost functions that include the relations defined by relative distance between manipulator link and obstacles[4][5][6].

For a given end-effector position, using the gradient of the performance criteria projected onto its joint null-space to control the joint velocity makes the manipulator seek the optimal configuration[1][5][6][7][10][11][12]. Although many researchers have discussed how to specify such joint velocities (on the kinematic control), most of them have ignored the fact that manipulators are actually controlled by the specified joint torque [1][2] to provide a desired acceleration. This is the reason why the control by these schemes often leads to uncontrollable excessive joint torque and unstable conditions. In spite of this defect, it is suitable for real-time application since a kinematic control with local optimization has more computational simplicity.

In this paper, an effective algorithm, which drives the manipulator link along a specified trajectory of end-effector, was proposed. The algorithm uses the cost function which involve velocity vector to guarantee safe motion of the manipulator without collision considering the distance or density of recognized obstacles. For the sake of optimality, a differential relation between joint space and workspace velocities given by Jacobian was used for a kinematic control using a cost function. The algorithm proposed is capable of limiting impact of collision and workspace by choosing properly the magnitude of reference velocities corresponding to each link and the weight constant. The impact of collision also can be limited by physical properties of obstacles or manipulators.

OPTIMAL SOLUTION OF DIFFERENTIAL RELATIONS GIVEN BY JACOBIAN.

Basic concepts.

Redundant manipulators have an extra number of degrees-of-freedom (DOF). That is, the joint space coordinate set n is greater than the work-space coordinate set m. The effects of these extra DOF are easily seen from the differential relations given by the manipulator Jacobian. That is, the workspace velocities of end-effector is described as follows.

$$\dot{x} = J\dot{\theta} \qquad (1)$$

where J is the manipulator Jacobian J with a m x n matrix, $n > m$.

And the null space of Jacobian has at least n - m dimensions. From the above equation, it is seen that any change in velocity in the null-space has no effect on the workspace velocities, $\dot{x}$. Also, the manipulator is free to move in this configuration(depends on subspace). This type of motion is called self-motion since it is not observed at the end-effector. Generally, the inverse kinematic solution generates an infinite number of solutions θ for a given workspace position x. Thus, it is very difficult to choose a proper value of $\dot{\theta}$ for a given workspace trajectory $x_d(t)$, which satisfies additional requirements and constraints imposed on the manipulator (e.g., obstacles or singularity avoidance, stability, etc.). Therefore, a differential relation between joint-space and workspace velocities given by Jacobian was used to develop a kinematic control using a cost function. From the characteristics of redundant manipulator, it is possible to change a local joint position for a given workspace position x according to the direction given by the reference velocities. Since the obstacles in the environment for fruit harvesting is flexible, the probability of collision will be low if a joint solution for a safe direction can be obtained.

Derivation of Obstacle Avoidance Algorithm.

As shown in Fig. 1, the workspaces recognized from sensor-based information are defined as collision-free area. The extended workspace is the area adjusted by considering the limits of reference velocity vector.

In this area, the manipulator moves safely by the limited motion due to the reference velocity of each link. This limited impact velocity prevents the links or objects from getting damaged by rigid obstacles.

If sensor-based information involving obstacles and work area is available for a collision free motion of each link, it is possible to know a safe direction which has no obstacle. In kinematic control, it is necessary to define a cost function restricted by the given reference velocities. The workspace velocities for an n-link redundant manipulator were considered as follows.

$$\begin{aligned} \dot{X}_1 &= J_1\dot{\theta} \\ \dot{X}_2 &= J_2\dot{\theta} \\ &\ \vdots \\ \dot{X}_n &= J_n\dot{\theta} \end{aligned} \tag{2}$$

Also, a quadratic cost function G was defined to get an optimal solution as follows.

$$G(\dot\theta) = k_1(\dot X_1 - J_1\dot\theta)^T(\dot X_1 - J_1\dot\theta) + k_2(\dot X_2 - J_2\dot\theta)^T(\dot X_2 - J_2\dot\theta) + \ldots\ldots + k_{n-1}(\dot X_{n-1} - J_{n-1}\dot\theta)^T(\dot X_{n-1} - J_{n-1}\dot\theta) \tag{3}$$

where $k_i(i=1,\ldots,n-1))$ is an arbitrary constant and $\dot X_i$ is the reference velocity involving safety direction and limited velocity of each link.
The resolved kinematic solution is to minimize the function G under the constraint of $\dot x_n = J_n\dot\theta$. If $\dot\theta$ is a regular part of the constraints, then there exist scalar λ_i's $(i=1,\ldots,m)$ that provide the stationary value for the following function at $\dot\theta_o$,

$$G(\dot\theta,\lambda) = k_1(\dot X_1 - J_1\dot\theta)^T(\dot X_1 - J_1\dot\theta) + k_2(\dot X_2 - J_2\dot\theta)^T(\dot X_2 - J_2\dot\theta) + \ldots\ldots + k_{n-1}(\dot X_{n-1} - J_{n-1}\dot\theta)^T(\dot X_{n-1} - J_{n-1}\dot\theta) + \lambda^T(J_n\dot\theta - \dot X_n) \tag{4}$$

The necessary conditions for an optimal solution, which satisfies the above cost function, are as follows.

$$\frac{\partial G}{\partial\dot\theta} = 0,\quad \frac{\partial G}{\partial\lambda} = 0 \tag{5}$$

From Eq. (4) and Eq. (5), the followings are obtained.

$$\frac{\partial G}{\partial\dot\theta} = -2k_1J_1^T\dot X_1 + 2k_1J_1^TJ_1^T\dot\theta - 2k_2J_2^T\dot X_2 + 2k_2J_2^TJ_2\dot\theta + \cdots - 2k_{n-1}J_{n-1}^T\dot X_{n-1} + 2k_{n-1}J_{n-1}^TJ_{n-1}\dot\theta - \lambda^TJ_n = 0 \tag{6}$$

$$\frac{\partial G}{\partial\lambda} = \dot X_n - J_n\dot\theta = 0$$

(7)

Rearranging Eq. (6) gives

$$(2k_1J_1^TJ_1 + 2k_2J_2^TJ_2 + \ldots + 2k_{n-1}J_{n-1}^TJ_{n-1})\dot\theta - (2k_1J_1^T\dot X_1 + 2k_2J_2^T\dot X_2 + \ldots + 2k_{n-1}J_{n-1}^T\dot X_{n-1}) - \lambda^TJ_n = 0 \tag{8}$$

To simplify Eq. (8), define the followings.

$$\Sigma_1 = 2k_1J_1^TJ_1 + 2k_2J_2^TJ_2 + \ldots + 2k_{n-1}J_{n-1}^TJ_{n-1} \Rightarrow \sum_{i=1}^{n-1}2k_iJ_i^TJ_i$$

$$\Sigma_2 = 2k_1J_1^T\dot X_1 + 2k_2J_2^T\dot X_2 + \ldots + 2k_{n-1}J_{n-1}^T\dot X_{n-1} \Rightarrow \sum_{i=1}^{n-1}2k_iJ_i^T\dot X_i \tag{9}$$

Substituting Eq. (9) into Eq. (8) yields

$$\Sigma_1 \dot{\theta} - \Sigma_2 - \lambda^T J_n = 0 \tag{10}$$

Rewriting Eq. (7) gives

$$\therefore\ J_n \dot{\theta} = \dot{X}_n \tag{11}$$

Now, it is necessary to have the matrix inverse Σ_1^{-1} to get the joint velocity $\dot{\theta}$ for a given desired workspace velocity $\dot{x}$. Since $\Sigma_1 = \begin{bmatrix} \Sigma_1^{m\times m} & 0 \\ 0 & 0 \end{bmatrix}$ is square and of full rank or singular, however, the inverse matrix doesn't exist. Thus, it is necessary to modify the matrix Σ_1 without loss of its physical properties.

Premultiplying $2k_n J_n^T$ to the both sides of Eq. (7) gives

$$2k_n J_n^T J_n \dot{\theta} = 2k_n J_n^T \dot{X}_3 \tag{12}$$

Rewriting Eq. (12) yields

$$2k_n J_n^T J_n \dot{\theta} - 2k_n J_n^T \dot{X}_3 = 0 \tag{13}$$

Adding Eq. (13) and Eq. (8) gives

$$\begin{aligned}&(2k_1 J_1^T J_1 + 2k_2 J_2^T J_2 + \dots + 2k_{n-1} J_{n-1}^T J_{n-1} + 2k_n J_n^T J_n)\dot{\theta} \\ &-(2k_1 J_1^T \dot{X}_1 + 2k_2 J_2^T \dot{X}_2 + \dots + 2k_{n-1} J_{n-1}^T \dot{X}_{n-1} + 2k_n J_n^T \dot{X}_n) - \lambda^T J_3 = 0\end{aligned} \tag{14}$$

Similar to the approach used for Eq. (10), Eq. (14) can be simplified as follows :

$$\hat{\Sigma}_1 \dot{\theta} - \hat{\Sigma}_2 - \lambda^T J_n = 0 \tag{15}$$

where $\hat{\Sigma}_1 = 2k_1 J_1^T J_1 + 2k_2 J_2^T J_2 + \dots + 2k_n J_n^T J_n = \sum_{i=1}^{n} 2k_i J_i^T J_i$

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$\hat{\Sigma}_2 = 2k_1 J_1^T \dot{X}_1 + 2k_2 J_2^T \dot{X}_2 + \dots + 2k_n J_n^T \dot{X}_n = \sum_{i=1}^{n} 2k_i J_i^T \dot{X}_i$

Since the matrix $\hat{\Sigma}_1$ is square($n\times n$) and of full rank, the following relation is obtained by the use of the matrix inverse $\hat{\Sigma}_1^{-1}$:

$$\dot{\theta} = \hat{\Sigma}_1^{-1}(\hat{\Sigma}_2 + \lambda^T J_n) \tag{16}$$

Substituting Eq. (16) into Eq. (15) yields

$$J_n(\hat{\Sigma}_1^{-1}\Sigma_2 + \hat{\Sigma}_1^{-1}\lambda^T J_n) = \dot{X}_n \tag{17}$$

Rewriting Eq. (17) with respect to λ gives

$$\lambda=(J_n\ \hat{\Sigma}_1^{-1}J_n)^{-1}(\dot{X}_n-J_n\ \Sigma_1^{-1}\Sigma_2) \tag{18}$$

Substituting Eq. (18) into Eq. (11), and rewriting it with respect to $\dot{\theta}$ gives

$$\begin{aligned}\dot{\theta} &= \hat{\Sigma}_1^{-1}\Sigma_2+\ \hat{\Sigma}_1^{-1}J_n^T(J_n\ \hat{\Sigma}_1^{-1}J_n^T)^{-1}\dot{X}_n \\ &-\ \hat{\Sigma}_1^{-1}J_n^T(J_n\ \hat{\Sigma}_1^{-1}J_n^T)^{-1}J_n\ \hat{\Sigma}_1^{-1}\Sigma_2\end{aligned} \tag{19}$$

Rearranging Eq. (19) yields

$$\begin{aligned}\dot{\theta} &= \hat{\Sigma}_1^{-1}J_n^T(J_n\ \hat{\Sigma}_1^{-1}J_n^T)^{-1}\dot{X}_n \\ &+\ \hat{\Sigma}_1^{-1}\Sigma_2-\ \hat{\Sigma}_1^{-1}J_n^T(J_n\ \hat{\Sigma}_1^{-1}J_n^T)^{-1}J_n\ \hat{\Sigma}_1^{-1}\Sigma_2\end{aligned} \tag{20}$$

Defining a new inverse of Jacobian $J^+=\hat{\Sigma}_1^{-1}J_n^T(J_n\ \hat{\Sigma}_1^{-1}J_n^T)^{-1}$, Eq. (20) can be simplified as follows.

$$\dot{\theta}=J^+\dot{X}+(I-J^+J)\ \hat{\Sigma}_1^{-1}\Sigma_2 \tag{21}$$

As shown in Eq. (21), a new Pseudo-inverse was derived as a weighted form of the modified quadratic form of accumulated Jacobian of each link, and the reference velocity does not affect the homogeneous solution. Consequently, the reference velocity has no effect on end-effector velocity so that the redundancy can be used to avoid obstacles.

This provides a simple method of formulation which involves the process of optimality.

SIMULATION

For numerical simplicity of simulation, a planar three-link manipulator was adopted. Links of unit length were modeled as a uniform thin rod without mass. The tasks of the manipulator are to track a given end-effector trajectory without collision with obstacles, and to pass through the obstacle area according to the direction vector with zero initial and final velocities, and at the same time to move each link along its joint trajectory into the safety area, for a given reference velocity, using the redundancy. The arm starts from $\theta_0=(\pi,-\frac{\pi}{2},0)$.

Fig. 2 is a simulation result, which is drawn from a complete solution of Eq. (21) for the trajectory for the redundant manipulator. In this figure, it is observed that the gradient of performance criterion($g(=\nabla H)=\Sigma_1^{-1}\Sigma_2$) make the redundant manipulator move each link without collision with obstacles. That is, the reference velocity helps the manipulator move the null space joint into the safety area.

Fig. 3 is a simulation result, which is drawn from a homogeneous solution of Eq. (21) for the trajectory of the redundant manipulator. Since the end-effector moves along its desired trajectory as shown in Fig. 3, it is proved that the weighted pseudo matrix inverse yields the homogeneous solution of Eq. (21), that is, $\dot{\theta}=J^{+}\dot{x}$ for a given trajectory of the end-effector.

Fig. 4 and Fig. 5 shows the simulation results obtained using the Moore-Penrose generalized inverse of Jacobian and the above null-space projection velocity. As shown in these figures, the manipulator collides with the obstacles.

Fig. 6 shows a variation in joint angles for the 4 different levels of reference velocities. It is noticed that the variation in joint angles increases drastically for a reference velocity beyond a certain level.

Fig. 7 shows the trajectories of the manipulator for the 4 different reference velocities. It is noticed that the manipulator may collide with an obstacle like Fig. 7(d) if the reference velocity is not properly chosen.

CONCLUSION

In this paper, a new control algorithm for redundant robot manipulators to avoid obstacles with a weighted pseudo inverse was proposed. Using the sensor-based information and the reference joint velocities, the manipulator can be moved to the safety space without a collision of manipulator links and obstacles. The feasibility and effectiveness of the algorithm proposed was tested by simulation. It turned out the weighted pseudo inverse and null-space term used in the algorithm proposed were useful tools to solve the joint solution problem for a redundant manipulator. A further study on an optimal control of redundant manipulator with dynamic stability is needed.

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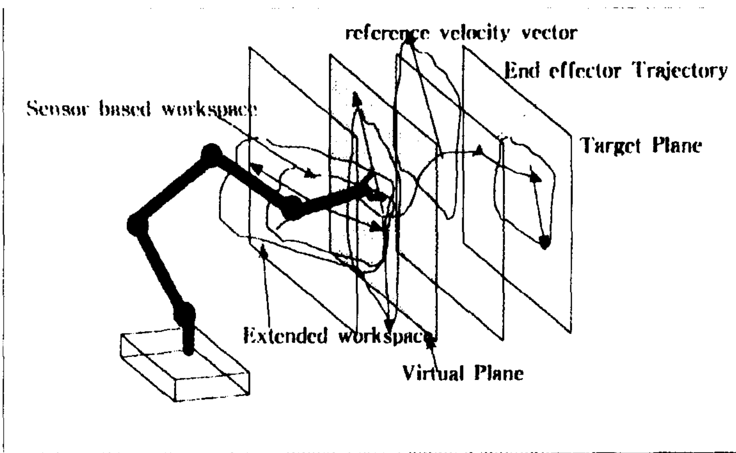


Fig.1 Modeled workspace

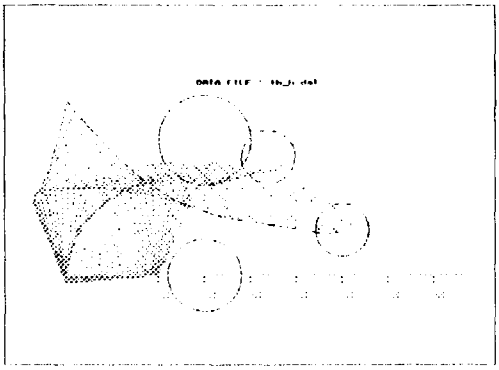


Fig. 2 A simulation result with

$\dot{\theta} = J^{+}\dot{X} + (I - J^{+}J)\,\hat{\Sigma}_1^{-1}\Sigma_2$

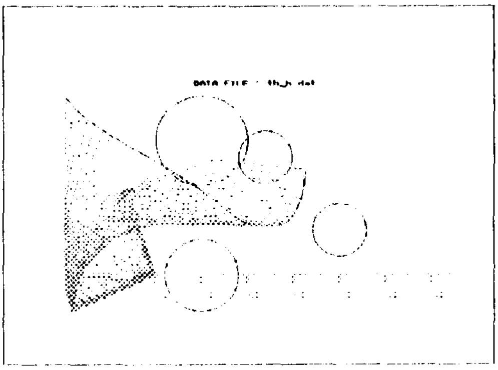


Fig. 3 A simulation result with

$\dot{\theta} = J^{+}\dot{X}$

($J^{+} = W^{-1}J^{T}(JW^{-1}J^{T})^{-1}$ is the weighted pseudo inverse using reference velocity)

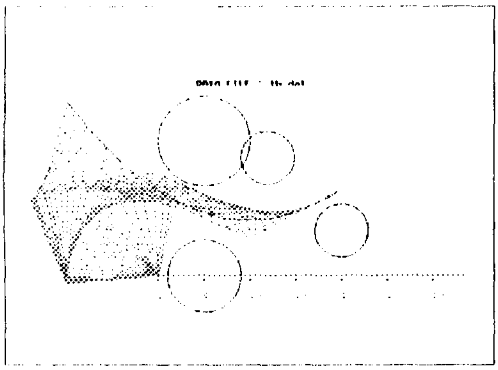


Fig. 4 A simulation results with

$\dot{\theta} = J^{\#}\dot{X} + (I - J^{\#}J)\,\hat{\Sigma}_1^{-1}\Sigma_2$

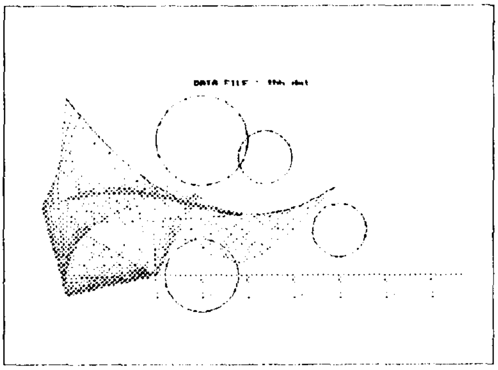
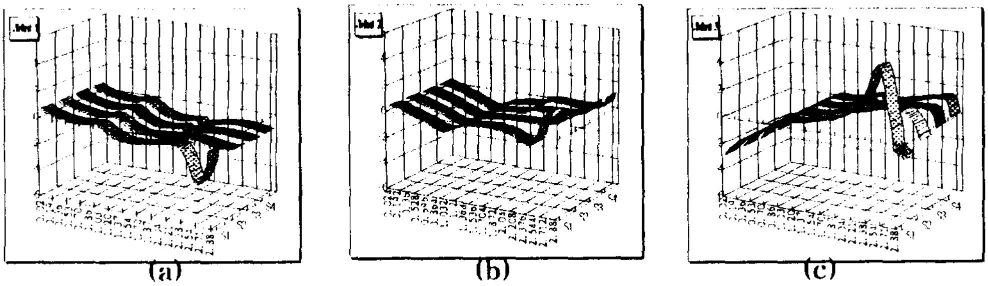


Fig. 5 A simulation result with

$\dot{\theta} = J^{\#}\dot{X}$

($J^{\#}$ is the Moore-Penrose Generalize inverse, $J^{\#} = J^{T}(JJ^{T})^{-1}$)



(a) (b) (c)

Fig. 6 Variation in joint velocities for the different levels of reference velocity.

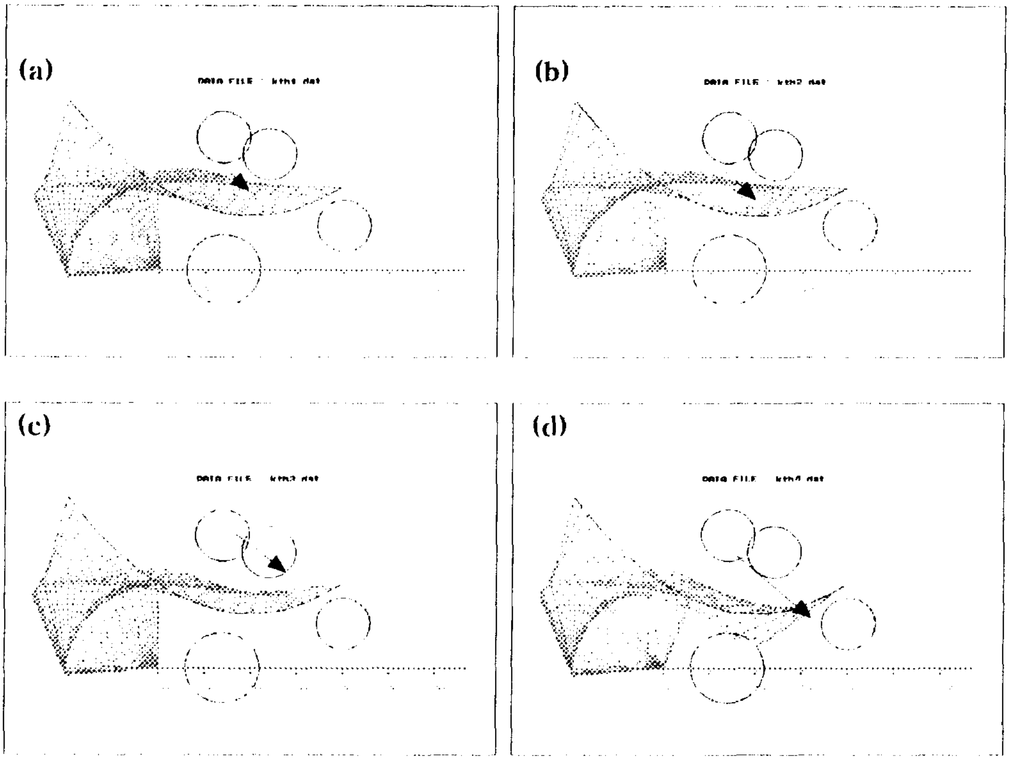


Fig. 7 Simulation results of joint configuration for the different magnitudes of reference velocity with the same direction(the order of magnitude : $a<b<c<d$)