OBSTACLE-AVOIDANCE ALGORITHM WITH DYNAMIC STABILITY FOR REDUNDANT ROBOT MANIPULATOR WITH FRUIT-HARVESTING APPLICATIONS

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ABSTRACT

Fruit harvesting robots should have more diversity and flexibility in the working conditions and environments than industrial robots. This paper presents an efficient optimization algorithm for redundant manipulators to avoid obstacles using dynamic performance criteria, while the optimization schemes of the previous studies used the performance criteria using kinematic approach.

Feasibility and effectiveness of this algorithm were tested through simulations on a 3-degrees-of-freedom manipulator made for this study. Only the position of the end-effector was controlled, which requires only three degrees of freedom. Remaining joints, except for the wrist roll joint, which does not contribute to the end-effector linear velocity, provide two degrees of redundancy.

The algorithm was effective to avoid obstacles in the workspace even though the collision occurred in extended workspace, and it was found be to a useful design tool which gives more flexibility to design conditions and to find the mechanical constraints for fruit harvesting robots.

Key Word : Redundant manipulator, Dynamic stability, Performance criteria

INTRODUCTION

Generally, redundant manipulators give a flexibility to perform a complex task. Such a characteristics of redundancy can help manipulators avoid obstacles or singularity avoidance with high manipulability while tracking a specified end-effector trajectory. Consequently, redundant manipulators have more advantages and effectiveness for robots used in biological production such as fruit harvesting which has more complicated obstacles or environments than for industrial robots, which have well-known obstacles or environments.

Since a kinematically redundant manipulator has more degrees of freedom than the workspace coordinates required to track a desired trajectory, an infinite number of solutions for joint velocities $\dot{\theta}$ are obtained by inverse kinematics for the given workspace velocities $\dot{x}$. The robot manipulators not only requires a task tracking a given workspace trajectory but also requires many subtasks such as obstacles or singularities avoidance and maximizing manipulability. However, it is difficult to get inverse kinematic solutions satisfying such subtasks simultaneously. Many researchers have studied on this problem to guarantee an optimality of system[1]-[27]. For an example, a scheme projected onto the null space of Jacobian using the gradient vector of scalar function, which evaluates the performance of global system, was proposed by many researchers[1],[2],[3],[7][17][21]-[24],[27]. However, it does not guarantee global optimality for all components which affect the manipulator. In practice, however, it is required to have global optimality in order for the manipulator to perform a given task. An alternative scheme minimizing the integrated energy in the total system while performing tasks in order to guarantee global optimality was proposed[13]. Since a global optimization scheme has more computational complexity, it is not suitable for real-time computation.

Local optimization scheme that determines the joint velocities instantaneously using present redundancy and sensor-based information is suitable for real-time implementation[11]. Generally, local optimization scheme uses a cost function projected onto its null space of each joint on velocity level or considers the priority of task to find a optimal solution[8]-[10]. Yoshikawa et. al. suggested a performance index to avoid a singularity and to maintain the manipulability denoted by the Jacobian norm[2]. Maciejewski et. al. and Nakamura used the priority of task to get an optimal solution for the manipulators to perform combined multi-subtasks[4][7]. Since the path control using inverse kinematics based on the velocity level, which ignores its dynamics, may generate excessive joint torque, many researchers have studied on dynamic stability. Hsu, Hasuer and Sastry suggested a closed-loop control law that guarantees dynamic stability while tracking a given trajectory[25]. Chung et. al. proposed an algorithm for obstacle avoidance, which switches the acceleration projected onto the null space with kinematic performance criteria, using the Jacobian minor proposed by Chang[17][19].

However, these approaches have a limitation on solving an obstacle avoidance problem for fruit harvesting robots since the work environments are more complex. This paper presents an algorithm for redundant manipulators with dynamic stability which guarantees to avoid obstacles, using the kinematic definition [24][27], while tracking the desired end-effector trajectory with dynamic stability.

DYNAMIC CONTROL LAW WITH OBSTACLE AVOIDANCE

Differential kinematics of robot manipulator can be expressed as follows, using the manipulator Jacobian which can be denoted by J.

$$\dot{x} = J\dot{\theta} \tag{1}$$

And the general form of manipulator dynamics is represented by

$$M(\theta)\ddot{\theta} + N(\theta, \dot{\theta}) = \tau \tag{2}$$

The joint torque $\tau \in R^{n \times m}$ necessary to realize the desired acceleration $\ddot{\theta}$ is calculated by using the dynamic model described by Eq. (2). Differentiating Eq. (1) with respect to time t, the following differential relation for accelerations is obtained.

$$\ddot{x} = \dot{J}\dot{\theta} + J\ddot{\theta} \tag{3}$$

In the resolved acceleration control [Takase 1976; Luh,Walker, and Paul 1981], the joint velocities $\ddot{\theta}$ are determined for the specified end-effector accelerations in the cartesian coordinate, $\ddot{x}_a$. Since the Jacobian J is not square (m > n), the Pseudo-inverse J^+, as shown below, must be used to obtain the inverse relation[Hsu,Hauser and Sastry 1988].

$$\ddot{\theta} = J^+(\ddot{x} - \dot{J}\dot{\theta}) + \ddot{\theta}_N \tag{4}$$

where $\ddot{\theta}_N$ is a vector field projected onto the null space of J. A new Pseudo-inverse J^+ using the reference velocity of the i^{th} link, which guarantees to avoid obstacles and extends the workspace, is defined as a unique matrix which satisfies the following conditions like the Moore-Penrose generalized inverse of Jacobian.

$$\begin{aligned} &JJ^+J = J, &\quad &J^+JJ^+ = J^+. \\ &(J^+J)^T = J^+J, &\quad &(JJ^+)^T = JJ^+. \end{aligned} \tag{5}$$

If $J \in R^{(n \times m)} (m > n)$ is of full rank (the manipulator must not be in a singular configuration), the following relation is obtained.

$$J^+ = W^{-1}J^T(JW^{-1}J^T)^{-1} \tag{6}$$

where J^+ satisfies $JJ^+ = I$ (I is the identity matrix) as well as Eq. (5). As shown In Eq. (6), J^+ is a weighted Pseudo-inverse. If it has the relation $W = M^TM$ as proposed by Kazerounian and Nedungadi[26], the weighted Pseudo-inverse is weighted by squared inertia matrix to avoid instability

situation.
From Eq. (2) and (4), a control law to track a given workspace trajectory can be specified as follows. Let the control τ be given by

$$\tau = M\{J^{+}(\ddot{x}_d + K_v\dot{e} + K_p e - \dot{J}\dot{\theta}) + \phi_N\} + N \tag{7}$$

where $e \triangleq x_d - x$ is the tracking error, K_v and K_p are matrices with constant feedback gains, and ϕ_N is a vector in the null space of J. If the manipulator does not pass through a singularity, then the control law by specified by Eq. (7) guarantees that the tracking error converges to zero[25]. The closed loop system is given by

$$M\ddot{\theta} + N = M\{J^{+}(\ddot{x}_d + k_v\dot{e} + k_p e - \dot{J}\dot{\theta}) + \phi_N\} + N \tag{8}$$

Eq. (8) is simplified as follows.

$$\begin{aligned}\ddot{\theta} &= J^{+}(\ddot{x} - \dot{J}\dot{\theta}) + \ddot{\theta}_N \\ \ddot{\theta} &= J^{+}(\ddot{x} + K_v\dot{e} + K_p e - \dot{J}\dot{\theta}) + \phi_N\end{aligned} \tag{9}$$

Since M is uniformly positive definite, combining Eq. (4) and Eq. (9) yields.

$$J^{+}(\ddot{e} + K_v\dot{e} + K_p e) = \ddot{\theta}_N - \phi_N \tag{10}$$

Premultiply Eq. (10) by J, then the following relation is obtained since $JJ^{+} = I$ when J is of full rank and $\ddot{\theta}_N - \phi_N$ belongs to the null space of J.

$$\ddot{e} + K_v\dot{e} + K_p e = 0 \tag{11}$$

Eq. (11) implies that e goes to zero exponentially by a proper choice of K_v and K_p (e.g., $K_v = k_v I$ and $K_p = k_p I$ with $s^2 + k_v s + k_p$; a Hurwitz polynomial).

In general, it is not guaranteed that the manipulator avoids singularities while tracking a given end-effector trajectory. Therefore, it is very important to choose a value of ϕ_N. Sometimes the situation in which the manipulator configuration is in a singularity position must be considered. In this study, the new Pseudo-inverse of J can be found using the singular value decomposition. Since $JJ^{+} \neq I$ at a singularity, Eq. (11) will be true only if $\ddot{e} + K_v\dot{e} + K_p e$ is in the range of J. Fortunately, a proper choice of ϕ_N (in the null space of J) can help the manipulator avoid singularities.

Also it is required to satisfy the following conditions in order to choose ϕ_N carefully. When $(x, \dot{x})$ are considered as the outputs of the system, the components of joint velocities in the null space of J are unoverservable.

Unless we use ϕ_N to control the components of joint velocities, the manipulator may have undesirable configurations or even become unstable.

The objective is to control the joint velocities in the null space of J in order to have a good system behavior (e.g., stability) and to accomplish a given subtask such as the avoidance of obstacles or singularities.

First, the situation to make the null space joint velocity track a given null-space velocity is considered as follows. Let a vector function $g(\cdot)=\Sigma_1{}^1\Sigma_2 \in R^m$ be given, and the null space joint velocity track the projection of g onto the null space of J. Since $(I-J^+J)$ are the vectors projected onto the null space of J, this is the same as

$$e_N \triangleq (I-J^+J)(g-\dot{\theta}) \tag{12}$$

The inverse kinematic solutions for Eq. (1) are infinite since the joint coordinates have more than the workspace coordinates. Therefore, in a sense of least square norm consideration, the solution can be obtained as follows, and it converges to zero.

$$\dot{\theta}=J^+\dot{x}+(I-J^+J)g \tag{13}$$

where $\dot{x}$ means the desired trajectory of end-effector velocity and g is the cost function that provide to perform a subtask(e.g., singularity or obstacle avoidance).

The following describes how to derive ϕ_N to get the desired result. Substituting Eq. (1) into Eq. (13) gives

$$\dot{\theta}=J^+J\dot{\theta}+(I-J^+J)g \tag{14}$$

From Eq. (14), the null space error can be derived, by subtracting $\dot{\theta}$ from both sides, as follow.

$$e_N=-(I-J^+J)\dot{\theta}+(I-J^+J)g=(I-J^+J)(g-\dot{\theta}) \tag{15}$$

Also, ϕ_N can be easily defined as follows. Similarily to Eq. (9) belonging to the null space of J(when J is of full rank), the relation is given by

$$\ddot{\theta}=J^+(\ddot{x}-\dot{J}\dot{\theta})+\phi_N \tag{16}$$

Rewriting Eq. (16) and solving for ϕ_N leads to

$$\phi_N=\ddot{\theta}-J^+\ddot{x}+J^+\dot{J}J^+\dot{x}+J^+\dot{J}(I-J^+J)g$$

$$= \ddot{\theta} - J^{+}\ddot{x} + J^{+}\dot{J}g - J^{+}\dot{J}(g - \dot{\theta}) + J^{+}\dot{J}(I - J^{+}J)(g - \dot{\theta})$$
$$= \ddot{\theta} - J^{+}\ddot{x} + J^{+}\dot{J}\dot{\theta} + J^{+}\dot{J}e_N$$
$$= \ddot{\theta} - J^{+}(\ddot{x} - \dot{J}\dot{\theta}) + J^{+}\dot{J}e_N$$
$$= (I - J^{+}J)\ddot{\theta} + J^{+}\dot{J}e_N \tag{17}$$

If the manipulator does not pass through a singularity, the control can be expressed by the following relation, which has the same form as the one given by Eq. (7).

$$\phi_N = \ddot{\theta}_{null} + J^{+}\dot{J}e_N \tag{18}$$

where $\ddot{\theta}_{null}$ is null-space acceleration. Then, the tracking error e converges to zero and the joint velocity converges to the null space of J, i.e., $e_N \rightarrow 0$.

As shown in Eq. (18), ϕ_N may have two kinds of variables for task manipulation. For example, one is to optimize joint torque and the other is to avoid obstacles.

In this case of task manipulation, its closed loop equation can be represented as follows.

$$M\ddot{\theta} + N = M\{J^{+}(\ddot{x}_d + k_v\dot{e} + k_p e - \dot{J}\dot{\theta}) + (I - J^{+}J)M^{-1}N + J^{+}\dot{J}e_N\} + N$$
$$e_N \triangleq (I - J_b^{+}J)(g - \dot{\theta}) \tag{19}$$

where J_b^{+} is the weighted Pseudo-inverse using $W(\Sigma = [\sum_{i=1}^{n} J_i^T J_i])$, which is used for obstacle avoidance and generation of flexible joint space, proposed by Ryuh[27], and J^{+} is the inertia weighted Pseudo-inverse[26].

SIMULATION

Simulation by numerical analysis was carried out to evaluate how effectively the proposed algorithm reduces torque required for the kinematic task such as obstacle avoidance. The simulation was applied to a planar three-link manipulator, which has links of a unit length with the mass of 10 kg so that they are modeled as uniform thin rods. A Kinematic task was specified as a path of the end-effector in the Cartesian coordinates, with zero initial and final velocities. Joints are assumed to start at rest from a given initial arm configuration $[\theta_0 = (\pi, \frac{\pi}{2}, 0)]$. The 4^{th}-order Runge-Kutta integration algorithm was applied to obtain joint positions and velocities from the NODE of forward dynamics.

Variation in torque for the joints are shown in Fig. 1 and Fig. 2 for the proposed algorithm and the conventional unweighted algorithm, respectively. It is noticed that torque variation for the unweighted algorithm is excessive at the start while that for the proposed algorithm is rather smooth.

Fig. 3 shows the simulation results for obstacle avoidance obtained from the proposed and the unweighted algorithms, respectively. It is noticed that the link configuration with the proposed algorithm had no collision with obstacles while that with the unweighted algorithm proposed by Hsu, Hauser and Sastry had collision with an obstacle.

Fig. 4 shows the link configurations for 4 different reference velocities with the proposed algorithm. It is noticed that excessively large values of reference velocity (such as (c) and (d) in Fig. 4) might cause collision with obstacles.

From the simulation results, the following conclusions were drawn.

(1) The proposed algorithm can generate more stable command torque for a multiple task than the conventional algorithm.

(2) A kinematic performance criteria can contribute to increasing the dynamic stability while performing a kinematic task such as obstacles or singularity avoidance as shown in Fig. 4.

(3) The kinetic and kinematic performance criteria in the proposed algorithm can significantly reduce excessive command torque at different levels of reference velocity.

CONCLUSION

The concept of dynamic stability with kinematic performance criteria was introduced into the inverse kinematic problem of redundant manipulators, and an inverse kinematic solution was derived taking into account the reference velocity to avoid obstacles. Numerical simulation was performed to verify the effectiveness and performance of the proposed algorithm. It was confirmed that a kinematic task can be achieved with dynamic stability by the mutual aids between dynamic optimality and kinematic performance criteria.

The obstacle avoidance problem could be solved by the reference velocity given by sensor-based information used to determine the manipulation variable. It is concluded that the proposed algorithm was suitable for avoiding obstacles with dynamic stability by the reference velocity given from sensor-based information.

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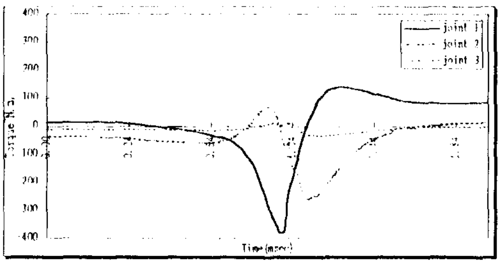

Fig. 1 Variation in control torque with the new algorithm developed.

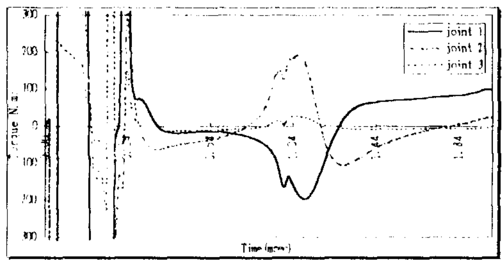

Fig. 2 Variation in control torque with the Hsu algorithm

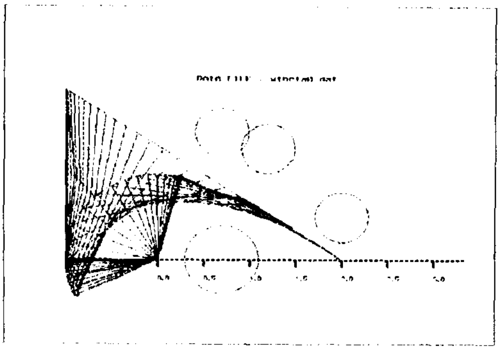

Fig. 3 Joint configuration with the new algorithm developed.

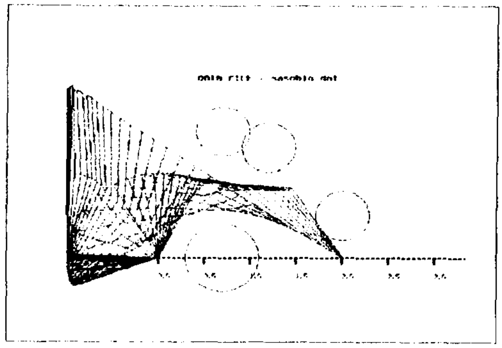

Fig. 4 Joint configuration with the Hsu algorithm

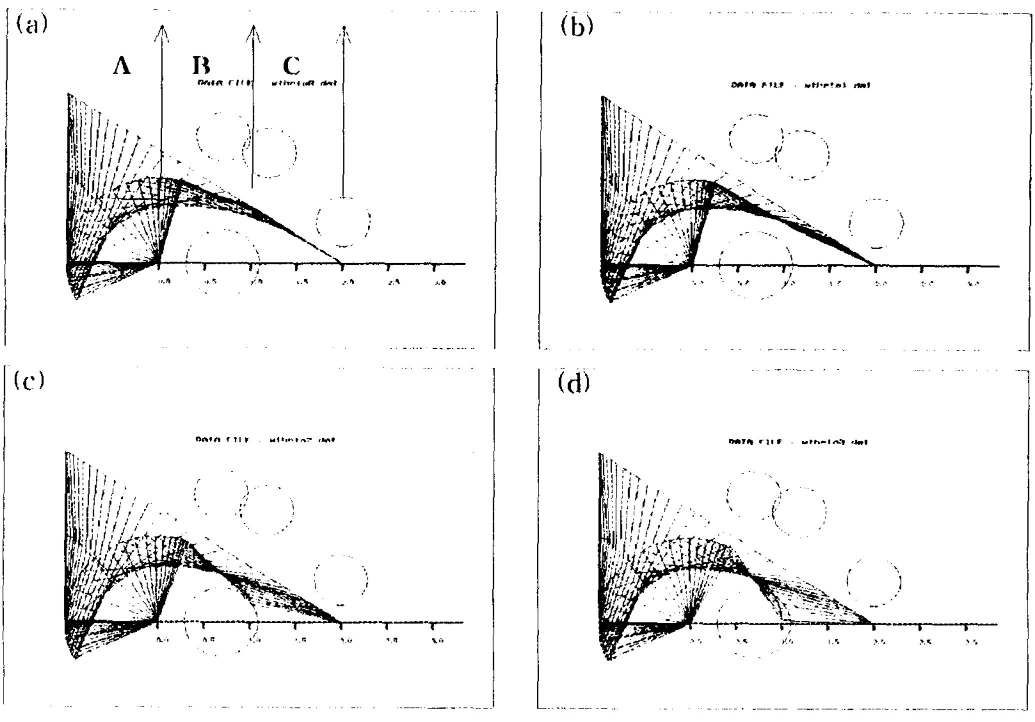

Fig. 4 Joint configurations for 4 different levels of reference velocities with the order of magnitude in a<b<c<d in Obstacle Area B (In Obstacle Area A, all have the same magnitude and direction of reference velocities).