Proceedings of the 11th
KACC, October 1996

Local Path-Planning of A 8-*dof* Redundant Robot for the Nozzle Dam Installation/Detachment of the Nuclear Power Plants

°Ki C. Park† Pyung H. Chang† Seung H. Kim‡

†Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
373-1 Gusung-dong, Yusung-gu, Taejon, Korea
E-mail: kcpark@mecha.kaist.ac.kr

‡Advanced Robotics Development
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusung-gu, Taejon, Korea

Abstract: The nozzle dam task is essentially needed to maintain and repair nuclear power plants. For this task, an 8-*dof* redundant robot is studied with a local path-planning method[1] which is effective to find the optimal joint path in the constrained environment. In this paper, the method[1] is improved practically with the weight matrix and efficient algorithm to find working set. The effectiveness of the proposed method is demonstrated by simulation and animation.

Keywords: Redundant manipulator, Inverse kinematics, Local path planning, Kinematic control, Nuclear power plant, Nozzle dam task

1 Introduction

Installation of nozzle dam is needed to maintain and repair nuclear power plants. The location of nozzle dam is shown in Fig. 1. For reloading the nuclear fuel, it is needed to make reactor vessel filled with water. This, however, causes the water to penetrate into the steam generator, prohibiting from performing the related task of the electric-heat pipe system. To keep the steam generator from being submerged, it is required to install the nozzle dam before supplying reactor vessel with water.

At present, the installation task of nozzle dam is being performed entirely by human operators. To install the nozzle dam, an operator has to enter into the steam generator through man-way. Since the inside of the steam generator is full of high radiation, the operator suffers from a large amount of radiation. To remedy this problem and the related ones, usage of robot manipulators is being studied.

The robotic task in the steam generator, however, has such problems as (1) narrow inside of steam generator, (2) very narrow man-way, (2) relatively large nozzle dam, (3) possibility of collision with obstacles, (4) the joint limits and kinematic singularity of the manipulator. For this task, a seven-*dof* redundant manipulator on one-*dof* moving platform, named KAEROT, was constructed at KAERI(Korea Atomic Energy Research Institute). The platform mobility can be regarded as additional redundancy[1], so the manipulator to be considered becomes an 8-*dof* redundant manipulator.

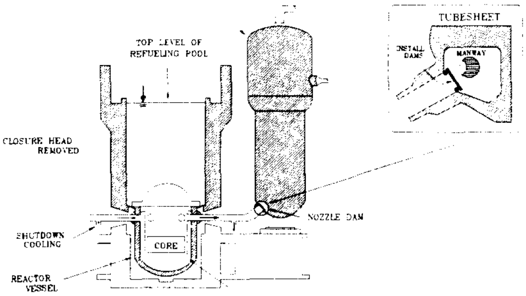

Figure 1: Location of nozzle dam in nuclear power plant

In order to resolve kinematic redundancy, several methods have been suggested using optimization of performance measures with adequate priority. For that purpose, however, it seems more natural and effective to use non-linear inequality constraints. Seraji and Colbaugh[2] used inequality constraints in the *configuration control* scheme in which inactive inequality constraints are ignored and only active ones are considered as if they were one of the main tasks. Sung et al.[3] pointed out, however, that this method, lacking a deactivation scheme, tends to limit the existence range of solutions, because the inequality constraints once activated stay active even after becoming useless,

Sung et al.[3] addressed the inverse kinematic problem of the redundant manipulators working in the circumstances above as a constrained optimization problem. As a solution, he proposed an inverse kinematic algorithm at velocity level using the Kuhn-Tucker condition[4]. It remedied the problem in the *configuration control* since inequality constraints can be discriminated by the Kuhn-Tucker condition whether active or not.

Sung et al.'s method[3], however, considering only one active inequality at a time, leaves its own limitations: When there exist, on one hand, more than one constraints (such as two obstacles at a time), it would have difficulty in handling these even with sufficient *dor*(degree of redundancy); on the other hand, when a manipulator has more than two *dor*, the method gives limitations to the existence range of solution. In addition, this method considers only a necessary condition of optimization resulting in algorithmic singularity, as well as a limitation to invertible workspace.

Recently, Park and Chang[1] have remedied the aformentioned problems through the formulation which takes full advantage of Lagrange multiplier method, Kuhn-Tucker condition, and active/working set method. This method can deal with as many active constraints as the number of *dor* at a time, and thus can extend to a manipulator with more than one *dor*. The sufficient conditions as well as necessary ones also were derived to get rid of any limitations to the invertible workspace. The effectiveness of the algorithm was verified with the two simulation examples: a 4-*dof* planar redundant manipulator and a 7-*dof* spatial redundant manipulator.

The goal of this paper is to practically improve the method proposed by [1] through some modifications and to apply to a newly developed 8-*dof* redundant manipulator.

2 Kinematic Properties of KAEROT

The D-H(Denavit-Hatenberg) coordinate and notation of KAEROT are shown in Fig. 2 and Table 1, respectively. Table 2 shows the joint limits of 8-*dof* KAEROT.

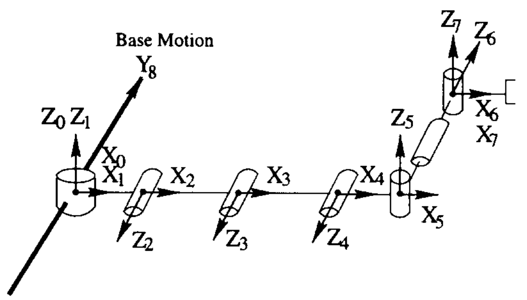

Figure 2: D-H coordinate of 8-*dof* KAEROT

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0^o	0.0 mm	0.0 mm	θ_1
2	90^o	279.5 mm	0.0 mm	θ_2
3	0^o	689.3 mm	0.0 mm	θ_3
4	0^o	482.6 mm	0.0 mm	θ_4
5	-90^o	133.6 mm	0.0 mm	θ_5
6	-90^o	0.0 mm	375.0 mm	θ_6
7	90^o	0.0 mm	0.0 mm	θ_7

Table 1: D-H notation of 7-*dof* arm

axis	KAEROT Notation		DH Notation	
	min.	max.	min.	max.
1	-135.00 °	135.00 °	-135.00 °	135.00 °
2	-147.18 °	122.82 °	-156.68 °	113.32 °
3	-167.82 °	102.18 °	-158.32 °	111.68 °
4	-90.00 °	90.00 °	-90.00 °	90.00 °
5	-90.00 °	90.00 °	-180.00 °	0.00 °
6	-90.00 °	90.00 °	-180.00 °	0.00 °
7	-90.00 °	90.00 °	0.00 °	180.00 °
8	0 mm	500 mm	0 mm	500 mm

Table 2: Joint limits of 8-*dof* KAEROT

3 Path-Planning Method

3.1 Review of [1]

The kinematic equation of redundant manipulators is given in general as follows:

$$\boldsymbol{f}(\boldsymbol{\theta}) = \boldsymbol{x} \tag{1}$$

where $\boldsymbol{x}$ denotes an m-dimensional vector representing the location of end effector w.r.t. the base coordinate system in the workspace, $\boldsymbol{\theta}$ an n-dimensional vector representing joint variables, and $\mathbf{f}$ a vector consisting of m scalar functions, with $m < n$. Both the joint-limits and obstacles to be avoided may be represented by p inequality constraints such as

$$\boldsymbol{r}(\boldsymbol{\theta}) \leq \mathbf{0}(\in \Re^p) \quad or \quad R_i(\boldsymbol{\theta}) \leq 0 \ (i = 1, \cdots, p) \tag{2}$$

where $\boldsymbol{r} = \mathbf{0}$ corresponds to the boundary of the obstacle, and $\boldsymbol{r} < \mathbf{0}$ the permissible region outside of that boundary. Furthermore, when an additional performance is desired, one can achieve it by maximizing a performance measure such as the manipulability measure under the constraints (1) and (2).

Therefore, the inverse kinematic problem of a redundant manipulator under kinematic constraints such as joint-limits and obstacles becomes a constrained optimization problem of the following form:

- maximize $H(\boldsymbol{\theta})$
- subject to $\boldsymbol{f}(\boldsymbol{\theta}) = \boldsymbol{x}, \quad \boldsymbol{r}(\boldsymbol{\theta}) \leq \mathbf{0}$ (3)

where $\boldsymbol{\theta} \in \Re^n$, $H \in \Re^1$, $\boldsymbol{f} \in \Re^m$, $\boldsymbol{r} \in \Re^p$, and $H, \boldsymbol{f}, \boldsymbol{r} \in C^2$.

An index set of active inequality constraints is so-called an active set and is defined as

$$A = \{i : R_i(\boldsymbol{\theta}) = 0\}. \tag{4}$$

The index set of this active inequality constraints, which is used for the algortihm, is defined as

$$W = \{i : R_i(\boldsymbol{\theta}) = 0, \mu_i \leq 0\} \tag{5}$$

and is denoted a working set.

where R_i is an i^{th} element of $\boldsymbol{r}$. To solve this problem, a Lagrange function L is defined as follows:

$$L(\boldsymbol{\theta}, \boldsymbol{\lambda}, \boldsymbol{\mu}) = H(\boldsymbol{\theta}) + \boldsymbol{\lambda}^T(\boldsymbol{f}(\boldsymbol{\theta}) - \boldsymbol{x}) + \boldsymbol{\mu}^T \boldsymbol{r}(\boldsymbol{\theta}) \tag{6}$$

where $\boldsymbol{\lambda} \in \Re^m$, $\boldsymbol{\mu} \in \Re^p$.

By using the Lagrange multiplier method, Kuhn-Tucker condition, and working set method, the following necessary conditions are derived:

$$\begin{aligned} \boldsymbol{f}(\boldsymbol{\theta}) &= \boldsymbol{x} \quad (\in \Re^m) \\ \boldsymbol{r}_w(\boldsymbol{\theta}) &= \mathbf{0} \quad (\in \Re^w) \\ Z_w \nabla H &= \mathbf{0} \quad (\in \Re^{(n-m-w)}) \end{aligned} \tag{7}$$

where $\boldsymbol{r}_w$ is a w-dimensional vector consisting of inequality constraints in the working set, and $\boldsymbol{Z}_w \in \Re^{(n-m-w)\times n}$ is a null space matrix of the extended task space spanned by $\boldsymbol{f}$ and $\boldsymbol{r}_w$. As the parameters for judging whether the corresponding inequality constraints are included in the working set or not, the Lagrange multiplier for minimization is defined as:

$$\boldsymbol{\mu}_w = -\boldsymbol{S}(\boldsymbol{J}_{ew}\boldsymbol{J}_{ew}^T)^{-1}\boldsymbol{J}_{ew}\nabla H \geq \mathbf{0} \text{ for } i \in W \tag{8}$$

$$\mu_i = 0 \text{ for } i \notin W \tag{9}$$

where $\boldsymbol{S} = [\mathbf{0}_{w\times m} \vdots \boldsymbol{I}_{w\times w}] \in \Re^{w\times(m+w)}$. The sufficient condition for minimization is that

$$Z_w(\nabla^2 L)Z_w^T \tag{10}$$

is positive definite.

Through these formulations, an inverse kinematic algorithm using gradient projection is derived as follows:

$$\dot{\boldsymbol{\theta}} = \boldsymbol{J}_{ew}^+ \begin{pmatrix} \dot{\boldsymbol{x}} \\ \mathbf{0} \end{pmatrix} + k_h(\boldsymbol{I} - \boldsymbol{J}_{ew}^+\boldsymbol{J}_{ew})\nabla H \tag{11}$$

where $\boldsymbol{J}_{ew}^+ = \boldsymbol{J}_{ew}^T(\boldsymbol{J}_{ew}\boldsymbol{J}_{ew}^T)^{-1}$.

3.2 Modified Algorithm with Weight Matrix

In this section, the aforementioned algorithm is modified with weight matrix. As is well known, there are two basic reasons for using the weight matrix. Firstly, the inverse kinematic algorithm (11) has a kind of disagreement with a view point of the metric unit. For example, the pseudo-inverse methods resulted from the minimization of joint velocity norm $\dot{\theta}^T\dot{\theta}$. But, this norm has a dimension of $[rad^2/s^2 + mm^2/s^2]$ in this case, since one of the joints is prismatic.

Secondly, each joint may need different weighting for the movement. Thus, the weighted norm $\dot{\theta}^T M\dot{\theta}$ can be dimensionless and can give some desirable weighting to the joints by introducing the weight matrix M.

Then, the modified method is as follows:

$$\dot{\theta} = J^+_{ewM}\begin{pmatrix}\dot{x}\\ 0\end{pmatrix} + k_h(I - J^+_{ewM}J_{ewM})\nabla H \quad (12)$$

where

$$J^+_{ewM} = M^{-1}J^T_{ew}(J_{ew}M^{-1}J^T_{ew})^{-1}. \quad (13)$$

Similarly, the Lagrange multipliers are obtained as:

$$\mu_w = -S(J_{ew}M^{-1}J^T_{ew})^{-1}J_{ew}M^{-1}\nabla H \geq 0 \quad (14)$$

3.3 Effective Algorithm to Find Working Set

There may be two approaches to use the active set in a practical sense. The one is to consider that the inequality constraints have a kind of safety factor for obstacles. This can be done by using the larger boundary for the obstacles than real one as follows:

- real boundary of obstacle : $R_1^* \leq 100$
- boundary with safety factor : $R_1 \leq 98$

With the predefined active set (4) as a detection measure of collision, slight penetration into the boundary cannot be avoided. But, if the boundary has sufficient safety factors, no collision can occur in reality. This needs careful selection of the safety factor depending upon obstacles, task speed, and sampling rate, etc.

The other method is not to use the safety factors. This needs to inspect whether the robot meets any limits or not before the robot proceeds. This paper selects this second method. For this end, active set should be redefined in a practical sense as follows:

$$A = \{i|R_i \geq 0\} \quad (15)$$

Hence the goal of avoiding obstacles including joint limits becomes to make $A = \{\}$ for all t in this paper.

The procedures to find working set is as follows:

START :

1. Find the optimal initial joint pose $\theta(0)$ and initial Working Set $W(0)$.
2. Let $W = W(0)$ and $k = 0$.

BASIC :

1. Find next joint pose θ from $\dot{x}(k)$, $\theta(k)$, W.
2. Obtain μ and A from θ and W.
   - If $W = \{\}$, then
     (a) If $A = \{\}$, then
       - $\theta(k+1) = \theta$, $W(k) = W$, $\mu(k+1) = \mu$.
       - $k = k+1$ and go to BASIC.
     (b) If $A \neq \{\}$, then
       - $W = A$ and goto BASIC .
   - $W \neq \{\}$, then
     (a) $A = \{\}$, then
       i. If $\mu_j < 0$ for all $j \in W$, then
         - $\theta(k+1) = \theta$, $W(k) = W$, $\mu(k+1) = \mu$.
         - $k = k+1$ and go to BASIC .
       ii. If $\mu_j = 0$ for $j \in W$, then
         A. If $j \notin W(k-1)$, then
           - $\theta(k+1) = \theta$, $W(k) = W$, $\mu(k+1) = \mu$.
           - $k = k+1$ and goto BASIC
         B. If $j \in W(k-1)$, then
           - $\theta(k+1) = \theta$, $W(k) = W$, $\mu(k+1) = \mu$.
           - $E = \{j|\mu_j = 0\}$, $W = W(k-1) - E$
           - $k = k+1$ and go to BASIC.
         C. If $\mu_j > 0 (j \in W(k))$, then
           - $E = \{j|\mu_j > 0\}$, $W = W(k-1) - E$
           - go to BASIC
     (b) If $A \neq \{\}$, then
       i. If $w_k < n-m$, then
         - $W = W(k-1) + A$
         - goto BASIC
       ii. If $w_k = n-m$, then
         - $E = \{j|R_j \subset R_i,\ j \in W(k),\ i \in A\}$
         - $W = W(k-1) - E + A$
         - go to BASIC

4 Simulation

The goal of the simulation example is to move and to place a nozzle dam from the narrow manway to the nozzle ring dexterously without colliding with obstacles and joint limits. For this purpose, the inequality constraints for the joint limits of KAEROT are described as:

$$\begin{aligned} R_{2i-1} &= \theta_{i,min} - \theta_i \leq 0\ (i = 1, 2, \cdots, 8) \\ R_{2i} &= \theta_i - \theta_{i,max} \leq 0\ (i = 1, 2, \cdots, 8) \end{aligned} \quad (16)$$

As a performance measure to be minimized, the sum of an inverse of manipulability measure and a potential function is selected for avoiding singularities and obstacles, which is expressed as:

$$H = \frac{1.0}{\sqrt{\det(JJ^T)}} + \sum_{j=0}^{N}\frac{1.0e^{-6}}{(P_i - P_{nozzle\ dam})^2} \quad (17)$$

where P_i is a point on the manipulator, which tends to collide with obstacles.

Fig. 3 shows the optimal joint motion of KAEROT when using the proposed method. Through the animation performed, it was observed that no collision with obstacles and joint limits occurred. The corresponding optimal joint trajectory is shown in Fig. 4. Fig. 5 shows working set and positive Lagrange multipliers.

According to the transition of the working set $(0,0) \Rightarrow (8,0) \Rightarrow (8,16) \Rightarrow (8,0)$ with the joint path, it is shown that two *dor* are effectively used to satisfy the 8-th and the 16-th inequality constraints. But the platform motion appears to be negligible compared with the result of [1] which showed excellent platform mobility. This may come from the performance of 7-*dof* redundant arm, i.e 7-*dof* redundant arm even without the platform redundancy is sufficient to perform the given task.

5 Conclusion

This paper considers the improvement of a local path-planning method[1] with inequality constraints and its application to a newly developed 8-*dof* redundant manipulator for the nozzle dam task of nuclear power plants. The improvement has been done with the weight matrix and an effective algorithm to find working set. The effectiveness of the proposed method has been verified through the successful results of application by using simulation and animation.

REFERENCES

[1] K.C. Park and P.H. Chang, "Kinematic Control of Redundant Manipulators in a Constrained Environment and its Application to a Nozzle Dam Task for a Nuclear Power Plant," *Proc. KACC*, pp.1162-1165, 1995.

[2] H. Seraji and R. Colbaugh, "Improved Configuration Control for Redundant Robots," J. Robotic Systems, Vol.7, No.6, pp.897-928, 1990.

[3] Y.W. Sung, D.K. Cho, M.J. Chung and K. Koh, "A Constraints-based Method of the Inverse Kinematics for Redundant Manipulators," *IROS*, pp.531-538, 1994.

[4] D.G. Luenberger, *Linear and Nonlinear Programming*, 2nd ed. Addison-Wesley Publishing Company, 1984.

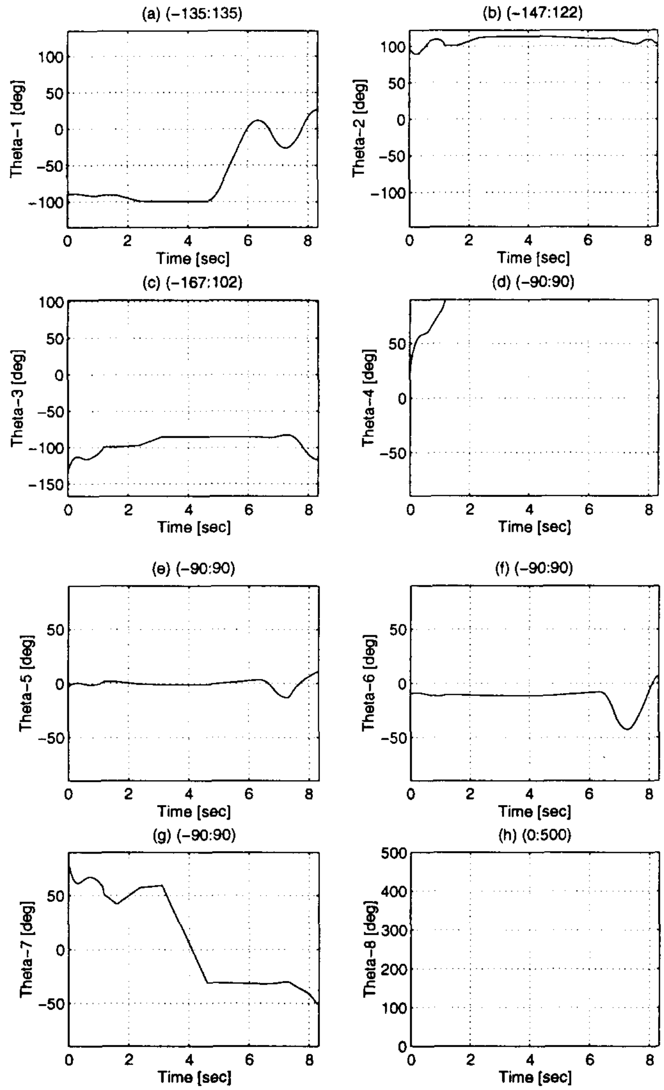

Figure 4: Optimal Joint Trajectory

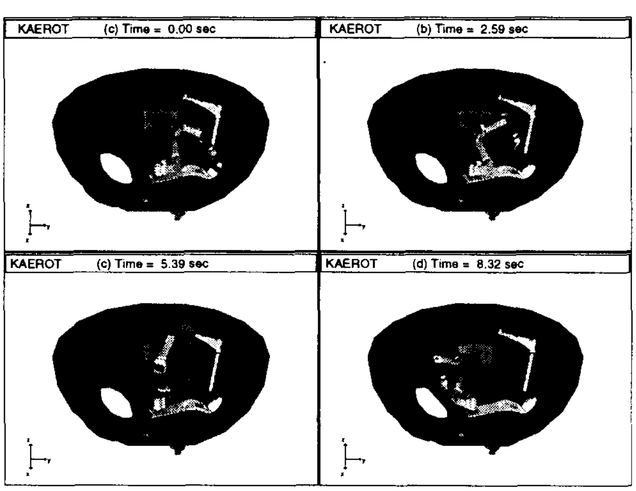

Figure 3: Optimal Joint Motion of KAEROT

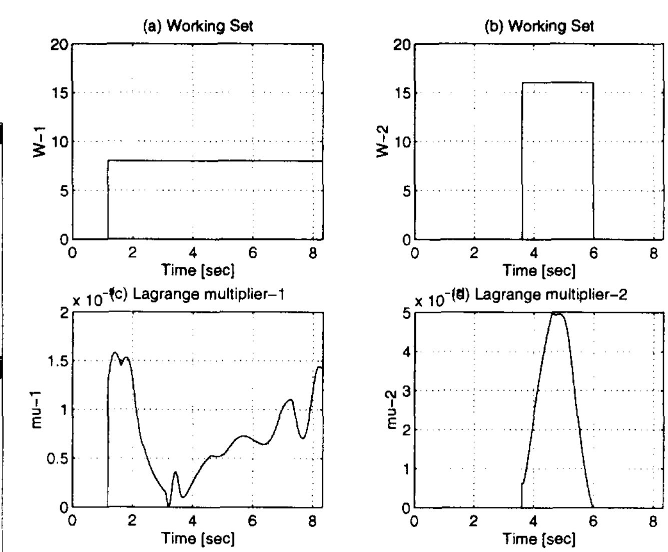

Figure 5: Working set, Lagrange multipliers