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Space Robot Path Planning for Collision Avoidance

Yuya Yanoshita and Shinichi Tsuda

Abstract—**This paper deals with a path planning of space robot which includes a collision avoidance algorithm. For the future space robot operation, autonomous and self-contained path planning is mandatory to capture a target without the aid of ground station. Especially the collision avoidance with target itself must be always considered. Once the location, shape and grasp point of the target are identified, those will be expressed in the configuration space. And in this paper a potential method, Laplace potential function, is applied to obtain the path in the configuration space in order to avoid so-called deadlock phenomenon. Some improvement on the generation of the path has been observed by applying path smoothing method, which utilizes the spline function interpolation. This reduces the computational load and generates the smooth path of the space robot. The validity of this approach is shown by a few numerical simulations.**

Key Words —**Space Robot, Path Planning, Collision Avoidance, Potential Function, Spline Interpolation,**

I. INTRODUCTION

In the future space development the space robot and its autonomy will be key features of the space technology. The space robot will play roles to construct space structures and perform inspections and maintenance of spacecrafts. These operations are expected to be performed in an autonomous manner in place of extravehicular activities by astronauts.

In the above space robot operations a basic and important task is to capture free flying targets on orbit by the robotic arm. For the safe capturing operation it will be required to move the arm from initial posture to final posture without collisions with the target.

The configuration space and artificial potential methods are often applied to the operation planning of the usual robot. This enables the robot arm to evade the obstacle and to move toward the target. Khatib[1] proposed a motion planning method, in which between each link of the robot and the obstacle the repulsive potential is defined and between the end-effecter of the robot and the goal the attractive potential is defined and by summing both of the potentials and using the gradient of this potential field the path is generated. This method is advantageous by its simplicity and applicability for real-time operation. However there might be points at which the repulsive force and the attractive force are equal and this will lead to the so-called deadlock.

In order to resolve the above issue, a few methods[2],[3] are proposed where the solution of Laplace equation is utilized. This method assures the potential fields without the local minimum, i.e., no deadlock. In this method by numerical computation Laplace equation will be solved and generates potential field. The potential field is divided into small cells and on each node the discrete value of the potential will be specified. Also in these methods there are some drawbacks, such as an increase of nodal points in order for the goal point to coincide with a nodal point and computational load by an expansion of the number of nodes. And further the derived solution, i.e., the path, is usually zigzag path which connects nodal points.

In this paper for the elimination of the above defects, spline interpolation technique is proposed. The nodal point which is given as a point of path will be defined to be a part of smoothed spline function. And numerical simulations are conducted for the path planning of the space robot to capture the target, in which the potential by solving the Laplace equation is applied and generates the smooth and continuous path by the spline interpolation from the initial to the final posture.

II. ROBOT MODEL

The model of space robot is illustrated in Fig.1.

The robot is mounted on a spacecraft and has two rotary joints which allow the in-plane motion of the end-effecter. In this case we have an additional freedom of the spacecraft attitude angle and this will be considered the additional rotary joint. This means that the space robot is three linked with 3 DOF (Degree Of Freedom).

The length of each link and the angle of each rotary joint are given by l_i and θ_i $(i = 1,2,3)$, respectively. In order to simplify the discussions a few assumptions are made in this paper:

-the motion of the space robot is in-plane, ,i.e., two dimensional one
-effect of robot arm motion to the spacecraft attitude is negligible
-robot motion is given by the relation of static geometry and not explicitly depending on time
-the target satellite is inertially stabilized.

In general in-plane motion and out-of-plane motion will be separately performed. So we are able to assume the above first one without loss of generality. The second assumption derives from the comparison of the ratio of mass between the robot arm and the spacecraft body. With respect to the third

Manuscript received December 1, 2008.
Y. Yanoshita is a post graduate student of the course of Aerospace , Graduate School of Engineering, Tokai University (email:.8amjm018@mail.tokai-u.jp)
S. Tsuda is with the department of Aeronautics and Astronautics, School of Engineering, Tokai University, Hiratsuka, Kanagawa Japan 259-1292 (email: stsuda@keyaki.cc.u-tokai.ac.jp)

assumption we focus on generating the path planning of the robot and this is basically given by the static nature of geometry relationship and is therefore not depending on the time explicitly. The last one means the satellite is cooperative.

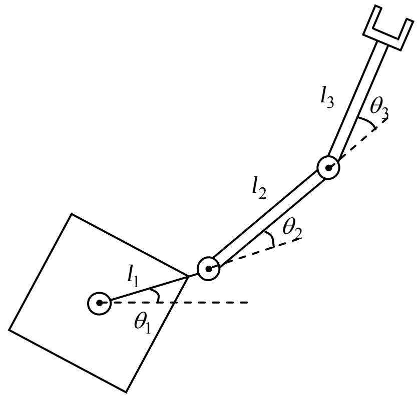

Fig.1 Model of Two-link Space Robot

III. PATH PLANNING ALGORITHM

A. Laplace Potential Guidance

The solution ϕ of the Laplace equation (1) is called a Harmonic potential function

$$\nabla^2\phi = \sum_{i=1}^{n} \frac{\partial^2\phi}{\partial x_i^2} = 0 \qquad (1)$$

and its maximum and minimum values take place only on the boundary. In the robot path generation the boundary means obstacle and goal. Therefore inside the region where the potential is defined, no local minimum takes place except the goal. This eliminates the deadlock phenomenon for path generation[3].

The Laplace equation can be solved numerically. We define two dimensional Laplace equation as below:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0 \qquad (2).$$

And this will be converted into the difference equation and, then solved by Gauss-Seidel method. In equation (2) if we take the central difference formula for second derivatives, the following equation will be obtained:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0$$
$$\Rightarrow \frac{\phi(x+\Delta x, y) - 2\phi(x,y) + \phi(x-\Delta x, y)}{\Delta x^2} + \frac{\phi(x, y+\Delta y) - 2\phi(x,y) + \phi(x, y-\Delta y)}{\Delta y^2} = 0 \qquad (3)$$

where $\Delta x, \Delta y$ are the step (cell) sizes between adjacent nodes for each x, y direction. If the step size is assumed equal and the following notation is used:

$$\phi(x+\Delta x, y) = \phi_{i+1,j}$$

then, equation (3) is expressed in the following manner:

$$\phi_{i+1,j} + \phi_{i-1,j} + \phi_{i,j+1} + \phi_{i,j-1} - 4\phi_{i,j} = 0 \qquad (4).$$

And as a result, two dimensional Laplace equation will be converted into the equation (5) as below:

$$\phi_{i,j} = \frac{1}{4}(\phi_{i+1,j} + \phi_{i-1,j} + \phi_{i,j+1} + \phi_{i,j-1}) \qquad (5).$$

In the same manner as in the three dimensional case, the difference equation for the three dimensional Laplace equation will be easily obtained by the following:

$$\phi_{i,j,k} = \frac{1}{6}(\phi_{i+1,j,k} + \phi_{i-1,j,k} + \phi_{i,j+1,k} + \phi_{i,j-1,k} + \phi_{i,j,k+1} + \phi_{i,j,k-1}) \qquad (6).$$

In order to solve the above equations we apply Gauss-Seidel method and have equations as follows:

$$\phi_{i,j}^{n+1} = \frac{1}{4}(\phi_{i+1,j}^{n} + \phi_{i-1,j}^{n+1} + \phi_{i,j+1}^{n} + \phi_{i,j-1}^{n+1}) \qquad (7)$$

where $\phi_{i,j}^{n+1}$ is the computational result from the ($n+1$)-th iterative calculations of the potential.

In the above computations, as the boundary conditions, a certain positive number Φ_0 is defined for the obstacle and 0 for the goal. And as the initial conditions the same number Φ_0 is also given for all of the free nodes. By this approach during iterative computations the value of the boundary nodes will not change and the values only for free nodes will be varying. Applying the same potential values as the obstacle and in accordance with the iterative computational process, the small potential around the goal will be gradually propagating like surrounding the obstacle. The potential field will be built based on the above procedure.

Using the above potential field from 4 nodal points adjacent to the node on which the space robot exists, the smallest node is selected for the point to move to. This procedure finally leads the space robot to the goal without collision.

B. Spline Interpolation

The path given by the above approach does not assure the smoothly connected one. And if the goal is not given on the nodal point, we have to partition the cells into much more smaller cells. This will increase the computational load and time.

In order to eliminate the above drawbacks we propose the utilization of spline interpolation technique. By assigning the nodal points given by the solution to via points on the path, we try to obtain the smoothly connected path with accurate initial and final points.

In this paper the cubic spline was applied by using MATLAB command.

C. Configuration Space

When we apply the Laplace potential, the path search is assured only in the case where the robot is expressed to be a point in the searching space[3]. The configuration space(C-Space), where the robot is expressed as a point, is used for the path search. To convert the real space into the C-Space the calculation to judge the condition of collision is performed and if the collision exists, the corresponding point in the C-space is regarded as the obstacle. In this paper when the potential field was generated, the conditions of all the points in the real space, corresponding to all the nodes, were calculated. The judgment of intersection between a segment constituting the robot arm and a segment constituting the obstacle at each node was made and if the intersection takes place, this node is treated as the obstacle in the C-Space.

IV. Numerical Simulations

Based on the above approach the path planning for capturing a target satellite was examined using a space robot model. In this paper we assume the space robot with two dimensional and 2 DOF robotic arm as shown in Fig.1.

The length of each link is given as follows:

$$l_1 = 1.4[m],\ \ l_2 = 2.0[m],\ \ l_3 = 2.0[m],$$

and the target satellite was assumed 1 m square. The grasp handle, 0.1 m square, was located at a center of one side of the target. So this handle is a goal of the path.

Let us explain the geometrical relation between the space robot and the target satellite. When we consider the operation after capturing the target, it is desirable for the space robot to have the large manipulability. Therefore in this paper the end-effecter will reach the target when the manipulability is maximized. In the 3DOF case, not depending on the spacecraft body attitude, the manipulability is measured by $\theta_2,\ \theta_3$. And if we assume the end-effector of the space robot should be vertical to the target, then all of the joints angles are predetermined as follows:

$$\theta_1 = 160.7°,\ \ \theta_2 = 32.8°,\ \ \theta_3 = 76.5°,$$

and these are goal of the path. As all the joints angles are determined, the relative position between the spacecraft and the target is also decided uniquely. If the spacecraft is assumed to locate at the origin of the inertial frame $(0,\ \ 0)$, the goal is given by $(-3.27,\ \ -2.00)$ in the above case. Based on these preparations, we can search the path to the goal by moving the arm in the configuration space.

Two simulations for path planning were carried out and the results are shown below.

A. 2 DOF Robot

In order to simplify the situation, the attitude angle(Link 1 joint angle) is assumed to coincide with the desirable angle from the beginning. We treat to look for the path from the beginning to the goal state for the remainders. The coordinate system was assumed as shown in Fig.2. θ_1 was taken into consideration for the calculation of the initial condition of the Link 2 and its goal angles:

Initial condition: $\theta_2 = -64.3°, \theta_3 = 90°$

Goal condition : $\theta_2 = -166.5°, \theta_3 = 76.5°$.

In this case the potential field was computed for the C-Space with 180 segments. Fig.3 shows the C-Space and the hatched large portion in the center is given by the obstacle mapped by the spacecraft body. The left side portion is a mapping of the target satellite. Fig.4 shows a generated path and this was spline-interpolated curve by using alternate points of discrete data for smoothing.

The conversion of the generated path into the real space is given by Fig.5. The path has no collision with target satellite and is expressed as smoothed curve.

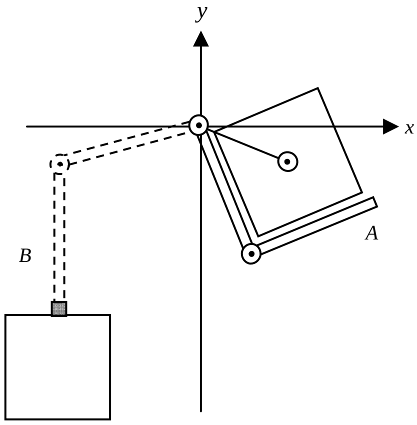

Fig.2 2 DOF Path Planning Problem

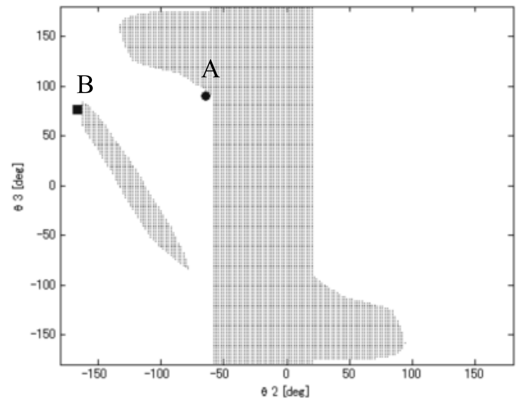

Fig.3 2 DOF C-Space

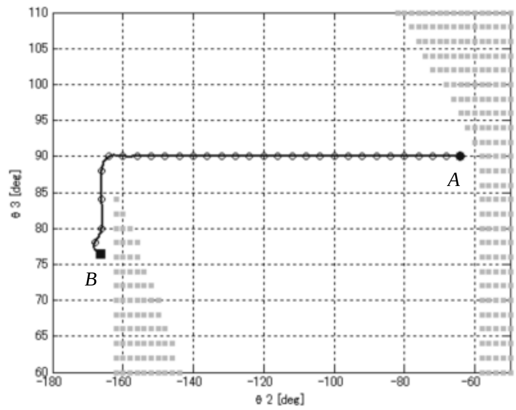

Fig.4 Path in C-Space(2 DOF)

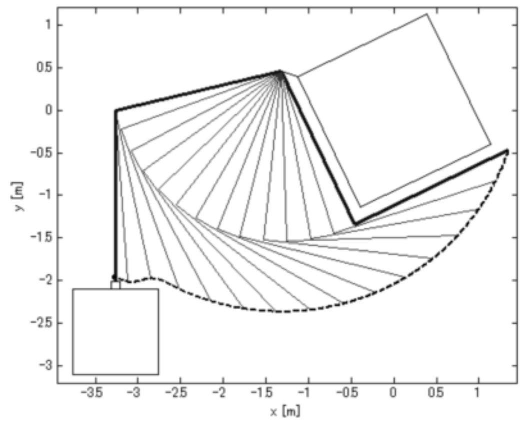

Fig.5 Path of Robotic Arm in Real Space(2 DOF)

B. 3 DOF Robot

Fig.6 shows a path planning case in which the spacecraft attitude motion is incorporated:

Initial Conditions: $\theta_1 = -90°$, $\theta_2 = 135°$, $\theta_3 = 90°$

Goal Conditions : $\theta_1 = 160.7°$, $\theta_2 = 32.8°$, $\theta_3 = 76.5°$.

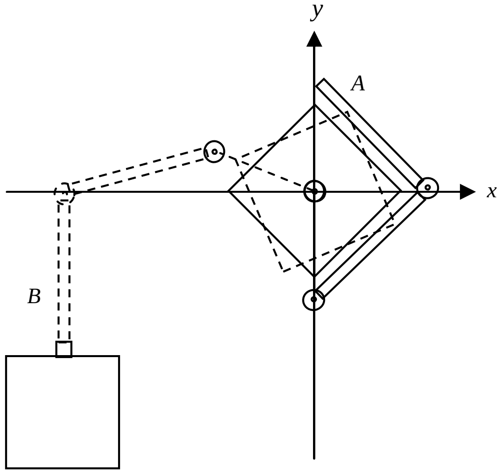

Fig.6 Path Planning Problem (3 DOF)

In this example the potential field was computed by generating the C-Space with 36 segments of joint angles. Fig.7 illustrates the C-Space and the surrounding of this space derives from the mapping of the spacecraft body. The central portion is given by the mapping of the target satellite. The white colored volume is free space for joint travel.

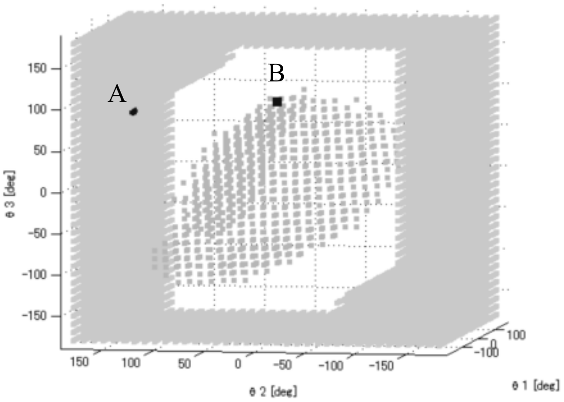

Fig.7 C-Space for 3 DOF Case

When we consider the rotation of spacecraft body, -180 degrees are equal to +180 degrees and, then, the state over -180 degrees will be started from +180 degrees and again back to the C-Space. For this reason the periodic boundary condition was applied in order to assure the continuity of the rotation. Fig.8 shows the result of the path generation. For the simplicity to look at the path, the mapped volume by the spacecraft body was omitted. Also for the simplicity of the path expression the chart which has the connection of -180 degrees in the θ_1 direction was illustrated. From this figure it is easily seen that over -180 degrees the path is going toward the goal C. B and C are the same goal point.

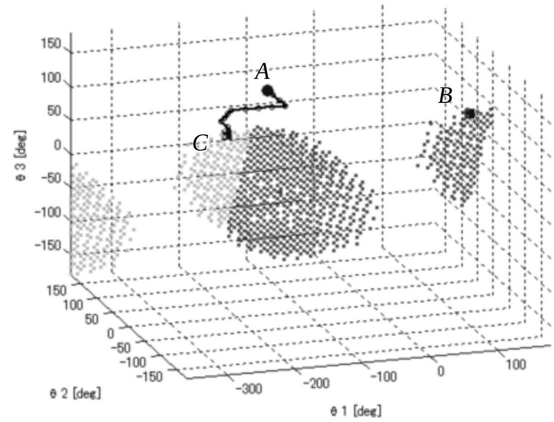

Fig.8 Path in C-Space (3 DOF)

The same spline interpolation was carried out as in 2 DOF case for the generation of the smooth path.

Fig. 9 shows the enlarged path from another view angle.

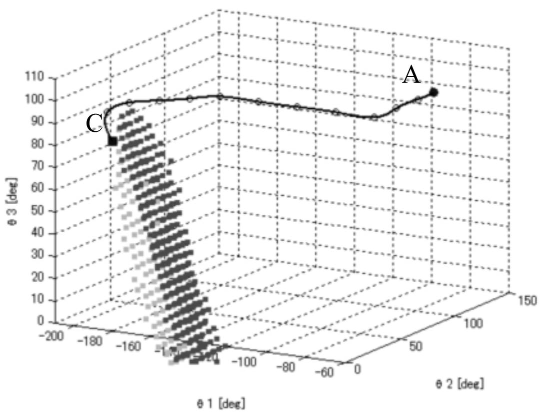

Fig.9 Path (Enlarged) in C-Space (3 DOF)

The chart shows no collision with the obstacle and the path reached the goal. And when we convert the path into the real space, smooth path is given by Fig. 10 without collision.

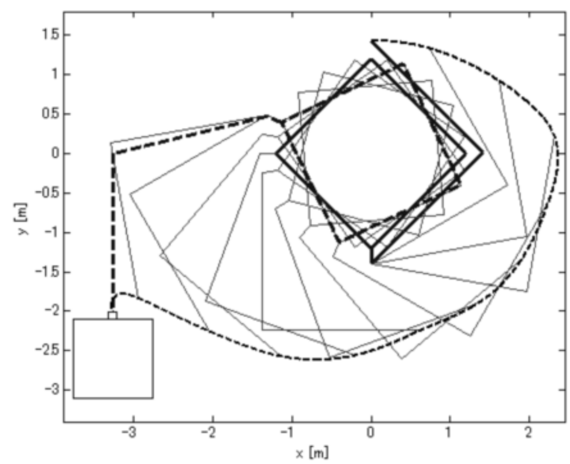

Fig.10 Robotic Arm Path in Real Space

V. CONCLUSION

In this paper a path generation method for capturing a target satellite was proposed. And its applicability was demonstrated by numerical simulations. By using interpolation technique the computational load will be decreased and smoothed path will be available. Further research will be recommended to incorporate the attitude motion of the spacecraft body affected by arm motion.

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