Motion Planning Based on Genetic Algorithm for a Manipulator Provided in ROVs

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This paper describes a designing method used in motion planning for a manipulator incorporated into a remotely operated vehicle (ROV). This method consists of path planning for a manipulator tip and posture planning for the manipulator in a workspace divided into cubes. Each planning employs two types of genetic algorithms. One is used to generate suitable tip positions. The other is used to generate candidates for a secure manipulator’s posture that will be consistent with the tip position. The secure manipulator’s posture, which avoids obstacles, was chosen from generated candidates based on an evaluation that considers drag force. The manipulator’s motion was planned by repeatedly executing this process. In order to confirm the validity of this method, an experiment was performed using the manipulator with seven degrees of freedom in an environment with large obstacles.

1. Introduction

In a deep-sea investigation, a remotely operated vehicle (ROV), unmanned and hung down in the deep sea from a support mother ship by cables, plays an important role. The ROV is usually equipped with a manipulator; an operator on the support mother ship watches a monitor displaying the situation on the spot and operates the manipulator using a master-slave system. The ROV has been used in various missions including a previously scheduled mission to install sensors in certain locations and a mission to collect rocks and living organisms in response to the requests of scientists who were on the same ship1). In order to operate the manipulator to complete the target mission using a master module on the fluctuating ship, the operator must understand the surrounding environment and the situation of the manipulator using only limited visual information from the monitor, and operate properly. Therefore, the operator is required to have enough experience and skill to complete the target mission and to keep his mental and physical focus during the operation. The authors have been designing a system in which only the minimal command information required for the mission is inputted; subsequently, the manipulator autonomously performs motions. Here, the command information denotes a work position of the manipulator tip and environmental information. For example, the operator only directs the work and obstacle positions on the monitor, and the manipulator can autonomously perform the motions following the direction. Using this system, non-experts such as beginners and researchers can operate the manipulator freely according to their purposes, and the highly generalized system can be materialized, which does not depend on the experience or capabilities of the operators.

This paper describes the design method of the fundamental function of the abovementioned system used in autonomous motion planning for the manipulator to avoid obstacles. In the experiment, a manipulator with multi-joints simulated collecting a sample on the sea bottom in an environment with obstacles, and the validity of the proposed method was investigated.

2. Obstacle Avoidance

When the sea bottom is a workspace, obstacles that interfere with the mission of the ROV always exist. Therefore, motion planning of the manipulator, which is incorporated into the ROV, must avoid obstacles. It is more practical for the manipulator to have redundant joints to the work environment and the contents of the mission.
In the manipulator’s avoidance of obstacles, the method of using a configuration space (C space) has been adopted, in which an obstacle domain is described by a joint angle space. However, when the C space is used, the amount of description of the C space (total number of joints in the manipulator and increments of joint angles) strongly affects the efficiency of motion planning, and the amount of description will increase almost exponentially if the resolution of the C space is increased. Therefore, in order to construct the C space and perform posture search, an enormous storage area, computational complexity, and a special search algorithm are required. Although many methods for designing motion planning in the workspace have been proposed, in which interference between the manipulator and obstacles is dealt with using geometric conditions, an efficient method for the multi-joint manipulator with a spatially movable region and a redundant axis has not proposed. The authors have proposed a method consisting of tip path planning, in which a genetic algorithm (GA) was applied to the workspace, and posture planning, in which the redundant axis is efficiently used and redundancy of the manipulator is not damaged. Moreover, since this method constructs only a simple kinematic model as a mathematical model, this method can deal flexibly with alteration of the end effector during operation and with inverse kinematic problems of changing degrees of freedom. In future development of the ROV, mounting and removing the end effector according to the mission are important when considering the ROV’s workability.

### 3. Tip Path Planning by GA

In this method, the workspace of the manipulator is considered as a 3-dimensional discrete real-space divided into cubes, as shown in Fig. 1. All the target tip positions that are chosen by tip path planning can be expressed by cube positions in the workspace. Moreover, when an obstacle exists in the workspace, a group of cubes, forming a rectangular parallelepiped containing the obstacle in it, is defined as an obstacle domain, and is used for evaluating the positional relationship between the obstacle and the manipulator. This obstacle domain is actually bigger than the obstacle. In the workspace in which the obstacle domain is defined, in order to avoid the obstacle domain, cubes are chosen in serial order to make a cube sequence; this cube sequence is used as target tip positions of the manipulator.

The cube to be the target tip position is searched in serial order by applying GA in each plane from the tip position of the initial posture of the manipulator to the work position. In the workspace coordinate system shown in Fig. 2, GA is executed in each XY plane on the Y axis from a START point toward a GOAL point, and each cube to be the target tip position is chosen.
Hereafter in this paper, GA in tip path planning is denoted as GAtp. The genotype\(^9\) of an individual in GAtp indicates the position of the cube in the XZ plane, as shown in Fig. 3, and is represented by binary numbers. In GAtp, gene manipulation is applied to reproduction, crossover, and mutation. And fitness\(^9\) \(F_{tp}\) is obtained from equation (1) in which each term is made to be dimensionless.

\[
F_{tp} = \alpha_1 f_{tp_1}/\sum_{i=1}^{j} f_{tp_{1i}} + \alpha_2 f_{tp_{2i}}/\sum_{i=1}^{j} f_{tp_{2i}} + \alpha_3 f_{tp_{3i}}/\sum_{i=1}^{j} f_{tp_{3i}} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)
\]

\(i\) : Individual number. ( \(i = 1, \ldots, j\) )

\(j\) : Number of individuals

\(f_{tp_1}\) : Distance from a cube position indicated by an individual number \(i\) to a work position (GOAL).

\(f_{tp_2}\) : Average collision danger values according to a distance from a cube position indicated by an individual number \(i\) to an outside cube of an obstacle domain.

\(f_{tp_3}\) : Distance from a present manipulator tip position to a cube position indicated by an individual number \(i\).

\(\alpha_{1,2,3}\) : Weighting coefficient.

As shown in Fig. 4, the collision danger value is chosen according to the distance \(C_{dist}\) from a cube position indicated by an individual (individual cube position) chosen by GAtp to an outside cube of an obstacle domain, which is located on the straight line between the center of the obstacle domain and the individual cube position, and is established as shown in Table 1.

Since the obstacle domain is larger than the actual obstacle, as mentioned before, the cube located on the outside of the obstacle domain remains a certain distance from the obstacle. In GAtp, a cube that exists in a distance of [i] from the cube located on the outside of the obstacle domain is excluded from the search objects since this cube becomes the cube that forms the obstacle domain. The position of the cube chosen by GAtp is secured to have no contact with the obstacle. In GAtp, an

<table>
<thead>
<tr>
<th>(C_{dist}) [mm]</th>
<th>Danger Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ~ (CS)</td>
<td>0</td>
</tr>
<tr>
<td>(CS) ~ (CS+130)</td>
<td>200</td>
</tr>
<tr>
<td>(CS+130) ~ (CS+210)</td>
<td>150</td>
</tr>
<tr>
<td>(CS+210) ~ (CS+230)</td>
<td>75</td>
</tr>
<tr>
<td>(CS+230) ~ (CS+260)</td>
<td>25</td>
</tr>
<tr>
<td>(CS+260) ~ (CS+280)</td>
<td>5</td>
</tr>
<tr>
<td>(CS+280) ~</td>
<td>0</td>
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</tbody>
</table>

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individual with smaller fitness has a higher possibility of existing as an individual of the next generation, and the individual cube position becomes a more suitable position as a target tip position of the manipulator. Therefore, an individual cube position with minimal fitness among all the generations obtained by GAtp, which is executed on a XZ plane, is chosen as the target tip position.

4. Posture Planning by GA

Posture planning of the manipulator is performed whenever one target tip position is chosen on each XZ plane in tip path planning. The posture of the whole manipulator to avoid an obstacle is decided with materializing the target tip position. Therefore, candidates for the manipulator’s posture are generated to materialize the target tip position, followed by the evaluation of the generated posture candidates; consequently, a candidate with the highest evaluation value is chosen as the manipulator’s posture at the target tip position.

4.1 Generation of Posture Candidates

The posture candidates of the manipulator, which materialize the previously planned target tip position, are generated by GA. Hereafter in this paper, GA in posture planning is denoted as GAmP. In this method, the genotype of the individual in GAmP is expressed by the change value of the angle of each joint of the manipulator, and the phenotype is expressed by the tip position and the tip posture in which the present posture of the manipulator is considered with the change value of angle shown by the genotype, as shown in Fig. 5. Since the genotype is expressed by the change value of angle of each joint instead of the angle of each joint, the posture candidate to materialize the target tip position can be searched by considering the present posture. In GAmP, similar to GAtp, gene manipulation is performed by using individual fitness \(J^g\), which is obtained from equation (2); the probability of existing as an individual of the next generation becomes higher as its fitness is smaller.

\[
F_{p_g} = eTPosition_g / \sum_{k=1}^{6} eTPosition_k + 1 / (1 + e^{-\lambda(1-r)^{eTPosture_g}}} / \sum_{k=1}^{6} eTPosture_k \]

\[
eTPosition_g = \sqrt{(x_e - X_e)^2 + (y_e - Y_e)^2 + (z_e - Z_e)^2} \]

\[
eTPosture_g = \sqrt{(ya_e - Ya_e)^2 + (pi_e - Pi_e)^2 + (ro_e - Ro_e)^2} \]

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Individual number. \( g = 1, \ldots, h \) 

Number of individuals. 

Target tip position chosen in tip path planning. 

Tip position at the manipulator’s posture shown by individual \( g \). 

Work tip posture. 

Tip posture at the manipulator’s posture shown by individual \( g \). 

Number of XZ planes from a START point to a GOAL point. 

Gain. 

Threshold value. 

\( X_g, Y_g, Z_g \) and \( Y_{a_g}, P_{i_g}, R_{o_g} \) are phenotypes of the individual in GAmp and obtained from a kinematic model that can be established from a simultaneous transformation matrix between a standard coordinate system, which is installed in the base of the manipulator, and a tip coordinate system, which is installed in the tip of the manipulator. The first term on the right side of equation (2) is essential to search an individual that indicates a tip position close to the target tip position, and the second term on the right side of that is essential to an individual that indicates the tip posture close to the work tip posture. The work tip posture is suitable for performing the target mission at the work position (a GOAL point in Fig. 2), and is a known parameter in this method. This work tip posture is preferably considered near the work position, and should not be overestimated at the initiation of the motion or during the motion process. As the second term on the right side of the equation, the work tip posture is evaluated by giving a weighting coefficient using the Sigmoid function. In this method, since tip path planning and posture planning are performed separately on each XY plane toward the work position, the value of the weighting coefficient must be diverged when the posture candidate is searched at the target tip position, chosen on an arbitrary XZ plane near the work position. 

In this method, as a result of performing GAmp, all the individuals with fitness below a certain value in each generation can be considered as posture candidates to materialize the target tip position. Unless more posture candidates than the previously set number are generated at one target tip position, a new initial group must be formed, and GAmp must be executed repeatedly until the number of the posture candidates reaches the number of the upper limit in a generation or reaches the number of the lower limit in the final generation. 

### 4.2 Evaluation of Posture Candidate 

The optimum posture can be chosen by evaluating all the posture candidates generated by GAmp. The evaluation is performed using the evaluation value \( E_m \) that is obtained from the equation (5), and the manipulator’s posture is more suitable at the target tip position as this value is smaller. 

\[
E_m = \beta_1 e_{i_m} / \sum_{i=1}^{m} e_{i_k} + \beta_2 e_{2_m} / \sum_{i=1}^{m} e_{2_k} + \beta_3 e_{3_m} / \sum_{i=1}^{m} e_{3_k} + \delta e_{4_m} / \sum_{i=1}^{m} e_{4_k} 
\]  

\( m \) : Posture candidate number. \( m = 1, \ldots, n \) 

\( n \) : Number of posture candidates. 

\( e_{i_m} \) : Posture change value from present posture to posture candidate \( m \). 

\( e_{2_m} \) : Collision danger value with obstacle from present posture to posture candidate \( m \). 

\( e_{3_m} \) : Total projected area from present posture to posture candidate \( m \). 

\( e_{4_m} \) : Error between the tip posture indicated by posture candidate \( m \) and the work tip posture. 

\( \beta_{1,2,3} \) : Weighting coefficient. 

\( e_{i_m} \) can be obtained from equation (6) and evaluates a candidate with smaller posture change by considering the change value.
of joint angle from the present posture to the posture candidate \( m \).

\[ e_{1m} = \sqrt{\sum_{q=1}^{\text{NumJo}} \left( \sum_{a=1}^{\text{NumL}} \frac{l_a}{L} \Delta \theta_q \right)^2} \]  

(6)

\( q \) : Joint number. \((q = 1, \ldots, \text{NumJo})\)

\( \text{NumJo} \) : Number of joints.

\( a \) : Link number moved by joint \( q \).

\( \text{NumL} \) : Number of links moved by joint \( q \).

\( l_a \) : Effective length of link \( a \) moved by joint \( q \).

\( L \) : Effective length of the whole manipulator.

\( \Delta \theta_q \) : Angle change value of joint \( q \) (genotype of the posture candidate).

\( e_{2m} \) can be obtained from equation (7), and is an element for evaluating the collision danger value of the whole manipulator with an obstacle considering the motion time when the manipulator changes from the present posture to posture candidate \( m \). As shown in Fig. 6, the collision danger value with an obstacle is chosen according to the distance \( \text{Ldist} \) between each unit point, which is defined on each series link of the manipulator and the cube, which is located on the outside of the obstacle domain on the straight line between each unit point and the center of the obstacle domain, and established as shown in Table 2.

\[ e_{2m} = \int \left\{ \sum_{r=1}^{\text{numSL}} \left( \sum_{u=1}^{\text{numOBS}} \text{DVsl}_{r,u}(t) \right) / \text{numOBS} \right\} / \text{numSL} \ dt \]  

(7)

\( r \) : Series link number.

\( \text{NumSL} \) : Number of series links.

\( u \) : Obstacle (domain) number.

\( \text{NumOBS} \) : Number of obstacles (domains).

\( \text{DVsl}_{r,u} \) : Collision danger of series link \( r \) with obstacle domain \( u \).

\( \text{average of danger values according to } \text{Ldist} \text{ at each unit point on } r \)

Here, a posture candidate with a series link to the state of [I] is removed from the objects for evaluation because of the high danger of interfering with an obstacle. As shown in Fig. 6, such interference is chosen by the radius \( R\text{sph} \) of the sphere \( \text{SHP} \), in which each unit point \( \text{sIP} \) on the series link is defined as its center, and is checked at all the unit points.

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points. Using a detailed setting of $R_{sph}$ at each unit point, the interference can be checked by considering the accurate shape and size of the arm of the manipulator that becomes an object. This interference check is also performed virtually in the process from the present posture to the posture candidate for the evaluation. In this case, a posture candidate with a series link to the state of [I] is also removed from the objects for evaluation.

$e_{w_m}$ can be obtained from equation (8), and shows the projected area of the manipulator against the fluid when it changes from the present posture to the candidate posture $m$. Moreover, $e_{w_m}$ can evaluate the influence of the fluid drag force accompanied by the posture change and its motion time. The fluid drag coefficient is a function of the Reynolds number and should be a fixed value near 1.2 ($10^3<Re<5\times10^5$)\(^{(12)}\), since each series link is assumed to be a shape of column in this method.

\[
e_{w_m} = \sum_{r=1}^{numSL} (2R_{sl}, H_{sl}, \sin \phi_r(t) + R_{sl}, \cos \phi_r(t)) \, dt \tag{8}
\]

$R_{sl}$: Radius of column approximating series link $r$.

$H_{sl}$: Link length of series link $r$.

$\phi_r$: Posture of series link $r$ to fluid.

$e_{w_m}$ can be obtained from equation (9), and is an element for evaluating the posture candidate $m$ close to the work tip posture. Since this matter is dealt with in equation (2), the candidate postures generated near the work position materialize the work tip posture to some degree.

\[
e_{w_m} = \sqrt{(Y_{a_m} - Y_{a_n})^2 + (P_{i_m} - P_{i_n})^2} \tag{9}
\]

$Y_{a_n}, P_{i_n}, R_{o_n}$: Tip posture at the manipulator’s posture shown by the posture candidate $m$.

In $e_{w_m}$, in order to improve the evaluation rate near the work position using the weighting coefficient, which uses the Sigmoid function, $\delta$ is defined as in equation (10).

\[
\delta = \text{sigmoid}(Y) = (\beta_1 + \beta_2 + \beta_3)/(3 \times (1 + e^{-\mu(Y-\zeta)})) \tag{10}
\]

$\mu$: Gain ($\mu < \lambda$)

$\zeta$: Threshold value. (number of XZ planes where $\delta$ diverges: $\delta < \sigma$)

### 4.3 Decision of Postures

The evaluation values of the posture candidates that are not removed from the evaluation objects by the interference check with the obstacle domain are obtained by equation (5), and the posture candidate with the minimum evaluation value is chosen as the manipulator’s posture at the target tip position. When all the posture candidates are removed from the evaluation objects by the interference check, a new initial group is formed and GAmp is executed, then the regenerated posture candidates are evaluated. When all the regenerated posture candidates are removed from the evaluation objects, the cube position, shown by an individual with the next smallest fitness in GAtp, which has chosen the target tip position, is to be a new target tip position, and posture planning is performed again. This procedure will be repeatedly carried out until the number of the posture candidates for the evaluation objects reaches the previously established number (see Fig. 7).

### 5. Manipulator’s Motion

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In this method, as shown in Fig. 2, tip path planning is performed on each XZ plane on the Y axis from the work start position (a START point) toward the work position (a GOAL position), and each target tip position is chosen on each XZ plane. Whenever a target tip position is chosen on the XZ plane, posture planning is performed, and consequently, the manipulator’s posture is chosen, followed by the change of the manipulator into that posture. By repeating this procedure, the manipulator can avoid obstacles and move to the work position with the posture suitable for the surrounding environment. Fig. 7 shows the flow chart of this method. The time required for one posture change of the manipulator is a parameter that is established when motion planning is initiated; the angular velocity $V_q(t)$ of each joint that can be obtained from equation (11) is a control command to the manipulator.

$$V_q = \Delta \theta_q / n \Delta s$$

Assuming a case in which the manipulator moves at the angular velocity that is obtained from equation (11), the abovementioned virtual interference check with obstacles during the posture change process is performed $n$ times at the manipulator’s posture of every step time $\Delta s$.

6. Experiment

6.1 Outline

Using this method, the experiment simulated sample collecting on the sea bottom. As shown in Fig. 8, there are 2 large obstacles occupying the manipulator’s workspace between the work start position (a START point) and the work position (a GOAL point). The manipulator must move in this closed workspace without colliding with the obstacles, and its tip must collect a sample on the sea bottom. In the experiment, a fluid is assumed to evenly flow parallel to the Z axis of the workspace.
coordinate system (Fig. 8). Moreover, the position of a sample on the sea bottom (work position) and the position and shape of obstacles (environmental information) must be known before motion planning is initiated. This is the command information that will be given from an operator on board during the actual mission of the ROV. Each parameter used in this experiment is shown in Table 3.

6.2 Results
By using this method, the tip of the manipulator could reach the work position, avoid the obstacles, and collect a sample on the sea bottom. Fig. 9 shows each target tip position chosen by tip path planning and the manipulator’s posture at the position. Fig. 10 shows the manipulator’s posture at each step time $\Delta t$ as the trajectory of the manipulator’s motion in this experiment.

Based on these results, the path of the target tip position was proven to go in-between two obstacles. This means that GAmp chose a cube position indicated by an individual that showed lower collision danger value with each obstacle and chose the shortest path toward the work position. In this case, all the manipulator’s postures that were chosen during posture planning could ingeniously avoid obstacles, and posture candidates with smaller posture changes have been chosen in serial order during the posture change process, securing the distance from the obstacle domains by an interference check with it. In this experimental environment, in order to collect a sample on the sea bottom, the manipulator needed to go in-between two obstacles. Therefore, the manipulator could not complete the mission when larger posture changes were repeated. Each manipulator’s posture chosen during posture planning had an effective redundancy, and GAmp could efficiently find the suitable posture candidate from a vast posture search space.

Fig. 11 shows the trajectory of the manipulator’s motion using the same work environment and command information in a case in which $e_{sm}$ was not considered as an element for evaluating posture candidate. Since the fluid was assumed to evenly flow parallel to the Z axis of the workspace coordinate system, the area surrounded by the outline of the manipulator’s motion in this figure represents the projected area of the manipulator throughout all its motions. Thus, $e_{sm}$ was proven to function effectively to inhibit the projected area of the manipulator throughout all its motions as compared with the case in which $e_{sm}$ was not considered during the evaluation.

7. Conclusion
This paper described the method used in the autonomous motion planning of the manipulator for the ROV, in which the work position and environmental information were provided. In this method, GA was applied to the inverse kinematic problem of the redundant manipulator. Then, by evaluating the generated posture candidates, highly generalized posture planning with effective redundancy was designed. With regard to the interference check to avoid obstacles, the shape of the manipulator and size of its arms were established in detail, and the distance to the obstacles was correctly evaluated. In the experiment using this method, it was confirmed that the manipulator could follow the planned motions and reach the target work position, avoiding obstacles in a severe environment in a closed workspace. Moreover, it was proved that the fluid drag force exerted on the manipulator could be reduced by a decrease in the product of the projected area and the motion time of the manipulator’s
motion.
In a future study, the system applying this method will be incorporated into a remote terminal of the ROV and its practicability will be verified in the actual sea area. Moreover, an effective presentation method of the work position and work environment will be considered, the effect of the manipulator’s motion on posture maintenance of the ROV body will be analyzed, and comprehensive motion planning for a manipulator linking to the body’s motion will be designed.

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