Method of Supervisory Control of Manipulator Mounted on Underwater Vehicle

A Yu Konoplin¹,², A P Yurmanov¹,²

¹Institute of Marine Technology Problems FEB RAS, 5a Suhanova str., Vladivostok, 690091, Russian Federation
²Far Eastern Federal University, 8 Suhanova str., Vladivostok, 690950, Russian Federation

E-mail: konoplin@marine.febras.ru

Abstract. The report describes the new supervisory control method for a multi-link manipulator mounted on an underwater vehicle, providing visual control of manipulation operations. The proposed method allows to build complex spatial movement trajectories of a multi-link manipulator working tool along a work object surface, using data obtained from onboard multibeam sonars or technical vision systems. Target designations of the operator determine the trajectory type, its position and orientation in a work area. To form target designations and visual observation of manipulator working tool movements along a given trajectory, a TV camera is used that changes its optical axis spatial orientation. The developed method is implemented in the C++ programming language, as well as numerical simulation of a multi-link underwater manipulator supervisory control in the virtual V-REP environment. To visualize the method, the graphical shell is written using "OpenGL Core".

1. Introduction
Currently, underwater vehicles (UV) equipped with multi-link underwater manipulators (UM) are actively used for research and development of the World Ocean [1-3]. The most of manipulation operations are performed under the control of these UV operators in manual or supervisory modes [4]. At the same time, operators are guided only by video images, without direct contact with the object of manipulation. This often leads to rapid fatigue, unavoidable errors, and decrease in the quality of technological and research works. To improve the efficiency of manipulation operations performing with work objects surfaces (taking the surface layer of soil by a ground-collecting box, non-contact cleaning of extended structures from silting and fouling with the help of a hydraulic monitor), the paper is aimed to create the method for supervisory implementation of manipulation operations by the UM installed on the UV. This method should be able to project any complex spatial trajectories of the UM working tools (WT) on the work objects surfaces, using data obtained from onboard multibeam sonars or technical vision systems. Target designations set by the operator define the trajectory type, its position and orientation in the work area. In this case, the specified trajectories can be defined as analytical equations, sets of points, or in other ways that determine the desired sequence of points by which the UM WT should move along. If the object of work has a known shape, the trajectory of movement on its surface can be formed in advance [5] and projected on the real underwater object surface using the proposed method.
In addition, during manipulation operations in the supervisory control mode, the operator should have visual control of the operation, i.e. the optical axis of the TV camera fixed on the rotating platform of the UV should always be directed towards the UM WT.

2. Formation of UM trajectories in the supervisory control mode

In the process of manipulative operations, the UV is fixed in the hang mode [6-8] over the object of work, which is located in the scanning zone of onboard sonars. First, using the known methods [9, 10] and technical vision systems, the triangulation surface of a bottom or an underwater object is constructed. Then the operator points the optical axis of the camera at the work object and sets the start and break points that belong to this object and determine the beginning and end of the WT movement along the trajectory. Projecting of the WT desired trajectory on the work object section, enclosed between points \( A_1 \) and \( A_2 \), begins with computing of these target points coordinates.

If the camera is directed at the point \( A_i \), where \( i=1,2 \), the system of coordinates (SC) \( xy\bar{z} \), where \( x \), \( y \) and \( z \) are axes of the SC rigidly connected to the UV body. The origin of this SC is located in the UV center of buoyancy \( O \), \( x \) axis coincides with the horizontal-longitudinal axis of the UV, \( z \) axis coincides with the vertical axis of the UV, \( y \) axis is right-handed. The position of this camera is determined by the predefined point \( P_i = [p_{ix}, p_{iy}, p_{iz}] \), located on the optical axis, and its orientation is determined by the unit vector \( \vec{d}_i = [d_{ix}, d_{iy}, d_{iz}] \). In this case, the optical axis of the camera coinciding with the vector \( \vec{d}_i \), which leaves the point \( P_i \) in the direction of the work object surface, is described by the equation [1]:

\[
A_i = P_i + t_i \vec{d}_i
\]

where \( t_i \) is a parameter that varies within \([0, \infty)\).

The object model constructed using the Delaunay triangulation algorithm is a set of triangular plates stitched together. Each \( k \)-th triangle in this triangulation is defined in the SC \( xyz \) by the coordinates of three vertices \( V_{k0}, V_{k1}, V_{k2} \in R^3 \), where \( k = 1, g \), \( g \) is the number of triangles.

To find the target point \( A_i \) coordinates at the intersection of the optical axis of the camera and the resulting triangulation surface, first you need to determine which of all \( g \) triangles is currently intersected by the axis (1). To do this, use the Moller – Trumbor algorithm [11] which based on information about the point \( P_i \) coordinates, the vector \( \vec{d}_i \), elements, and the coordinates of the vertices \( V_{k0}, V_{k1}, V_{k2} \) of all \( g \) triangles, allows to determine the \( k \)-th triangle through which the axis (1) passes.

The triangle \( k \) with vertices \( V_{k0}, V_{k1}, V_{k2} \) that intersects the axis (1) is found from the conditions [11]:

\[
0 \leq u_{ik} \leq 1, \quad 0 \leq v_{ik} \leq 1, \quad u_{ik} + v_{ik} \leq 1, \quad \text{where} \quad u_{ik}, v_{ik} \quad \text{are the point} \quad A_i \text{ barycentric coordinates relative to the vertices of the} \quad k \text{-th triangle.}
\]

In this case, the coordinates of the point \( A_i \) of the intersection of the optical axis of the camera with the triangle \( k \) are determined by the equation [4, 5]:

\[
A_i = P_i + \frac{(P_i - V_{k0}) \times (V_{k1} - V_{k0}) \cdot (V_{k2} - V_{k0}) \cdot \vec{d}_i}{(\vec{d}_i \times (V_{k2} - V_{k0})) \cdot (V_{k1} - V_{k0})}
\]

To apply the desired trajectory of the UM WT to the work object surface, it is necessary to build the projecting rays which comes out of the points \( b'_j \) belonging to the trajectory, where \( j = 1, c \), \( c \) is the number of projecting rays. These rays should be directed to the object surface. If the desired trajectory can be given in analytical form \( y = f(x) \) in the plane \( Oxy \) of the SC \( xyz \), the specified direction of the rays is determined by the unit vector \( \vec{a} \in R^3 \), which is directed opposite to the \( z \)-axis
direction. The intersections of the projecting rays with the surface triangulation model form a sequence of points $B_j$, which will form the trajectory of the UM WT along the surface of the object.

To find the points $b'_j$, it is necessary to define the coordinates of the auxiliary points $b_j$ (see Fig. 1), built on the basis of a given trajectory (not shifted to point $A_1$), as follows:

$$
\begin{align*}
    b_{x\mu} &= b_{x(j-1)s} + g \\
    b_{y\mu} &= f(b_{x\mu}) \\
    b_{z\mu} &= 0
\end{align*}
$$

where $f(b_{x\mu})$ is the dependence of $y$ on $x$ according to the given analytical equation $y = f(x)$, $b_{xs} = 0$; $g$ is the step along the $x$ axis that determines the number of auxiliary points $b_j$. This step is set depending on the trajectory parameters, as well as on the level of detail of the underwater object scan. Increasing the number of $b_j$ points increases the accuracy of the generated trajectory but increases the number of further calculations.

**Figure 1.** The building of auxiliary points $b_j$.

The desired WT trajectory is initially set in the SC $xyz$ and begins to be plotted from the beginning of this SC ($b_{xs} = 0$) along the $x$ axis. Therefore, this trajectory has to be transformed so that it is located between the points $A_1, A_2$. To do this, it is necessary to rotate all the vectors connecting the beginning $O$ of the SC $xyz$ with the points $b_j$ by the angle $\angle(x; A_j A_i) = \varphi$ using the rotation matrix around the $z$ axis [12]. Thereafter, the resulting vectors should be shifted along the $x$ and $y$ axes by the values $A_{x}$ and $A_{y}$, respectively. As a result, the coordinates of the desired points $b'_j$ will be determined using the equation:

$$
\begin{bmatrix}
\cos \varphi & -\sin \varphi & 0 \\
\sin \varphi & \cos \varphi & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    b_{x\mu} \\
    b_{y\mu} \\
    b_{z\mu}
\end{bmatrix}
+ 
\begin{bmatrix}
    A_{x} \\
    A_{y} \\
    0
\end{bmatrix}
=
\begin{bmatrix}
    b'_{x\mu} \\
    b'_{y\mu} \\
    b'_{z\mu}
\end{bmatrix}
$$

Coordinates of points $B_j$, the sequence of which describes the applied desired UM WT trajectory located between the points $A_1, A_2$ specified by the operator, are determined using the Moller-Trumbor algorithm in the form:
\[ B_j = b'_j + \frac{((b'_j - V_{k_0}) \times (V_{k_1} - V_{k_0})) \cdot (V_{k_2} - V_{k_0})}{(\vec{\sigma} \times (V_{k_2} - V_{k_0})) \cdot (V_{k_1} - V_{k_0})} \vec{\sigma} \]

As a result, the resulting sequence of points \( B_j \) forms a trajectory.

Figure 2 shows an example of a formed sinusoidal trajectory that is laid along the surface of the pipeline for its cleaning. The trajectory consists of a set of points \( B_j \). It should be noted that in order to ensure the UM WT high-precision passage along the formed complex trajectories, methods of automatic correction of the trajectories [13] and speed [14] of this WT should be used.

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3. Software implementation and modelling of the supervisory control method

The developed method is implemented in the C++ programming language. Simulation was performed in the V-Rep virtual environment, where various objects were formed to perform manipulative operations with their surfaces. The PUMA-type kinematic scheme of the UM with three degrees of mobility was chosen (see Fig. 3). The UV body was simulated with the rotating camera platform attached to it. The operation of a multi-beam sonar with a resolution of 32*32 points was also simulated (see Fig. 3). The input data for the created program is a set of points belonging to the bottom surface, obtained using a sonar.
The developed program builds the bottom surface triangulation model (see Fig. 4A) using the algorithm [9]. Next, the program calculates the coordinates of the target points $A_i$ (see Fig. 4B). Thereafter, an array of initial points $b'_j$ of projecting rays is formed, and the points of intersection of these rays with the surface are found (see Fig. 4C).

![images](image1.png)

**Figure 4.** a) – triangulation model of the bottom surface, b) – triangulation model of the bottom and target points of the trajectory, c) – points of the UM trajectory.

To find the intersection point of the projecting ray with the object triangulation surface using the Moller-Trumbor algorithm, it is necessary to check the presence of intersection points for each ray with all the triangles forming the surface. When the search for the intersecting triangle begins from the first one for each ray, it may take a long time to find all the intersecting points due to limited computing resources, especially when there are a large number of projecting rays and/or triangles. To solve this problem, it is necessary to reduce the number of false operations, that is, operations in which the selected triangle will not have intersection points with the ray. The algorithm was implemented that allows to significantly reduce the computational complexity. The essence of the algorithm is that the program memory stores the coordinates of the vertices of the triangle where the last intersection was found (point $B_j$). When searching for the point $B_{j+1}$, the intersection is checked first for the triangle, where $B_j$ was found. If the intersection was not found, the search for the desired triangle begins in normal mode, starting from the first one.

For the visual representation of constructed triangulation surfaces, as well as further control over the trajectory formation, the graphical shell was created using the "OpenGL Core" libraries. The graphical interface displays the surface of the work object and the resulting trajectory in real time. For clarity, target points are also displayed on this surface.

**4. Visual control of manipulative operations**

In the supervisory control mode, an operator must have visual control of the manipulation operation. That is, when a UM moves along a formed trajectory, its WT should always be in the centre of the video frame. In [15], the method is described that provides automatic guidance of the optical axis of the camera to the midpoint of the UM WT during its operation. The method was implemented as a system that calculates and sets such rotation angles of the camera platform axes at which the camera optical axis intersects the WT midpoint. Calculations are performed based on information about the current WT location coordinates.

The software implementation of the system was performed in the V-Rep environment, and the hardware implementation was performed on the created laboratory complex. This complex includes the TV camera mounted on the two-stage rotary platform (see Fig. 5), the PUMA-type manipulator...
with three degrees of mobility which is controlled by a master replicator. The Arduino Mega 2560 controller was used as a computing device, and the video image obtained from the TV camera was displayed in real time on the computer monitor.

When using this system, an operator does not have to additionally control the rotary platform of the camera. Proposed system makes it easier to perform manipulative operations in manual mode, as well as provides constant visual monitoring and video recording of the UM WT movements in supervisory or automatic modes.

![Laboratory complex.](image)

5. Conclusion
The presented method for the supervisory control of the UM mounted on the UV allows to perform soil sampling and cleaning of underwater structures using a hydromonitor in the supervisory mode, as well as other works where it is necessary to move the UM WT along the surfaces of underwater objects. This method was implemented as a software to build the triangulated surface models of objects and to project onto them desired spatial WT trajectories based on the parameters defined by the operator. In addition, the system was implemented that provides visual control and video recording of manipulative operations by automatically pointing the optical axis of the TV camera to the WT. The simulation results confirmed the efficiency of the proposed method and the possibility of using in real time scale.

6. References
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