Modeling of the Manipulation Operation on Sunken Submarines for the Underwater Remotely Operated Vehicle

Burlutskiy Nikolay, Butakov Vadim, Touahmi Yaniss, and Beom Hee Lee

***Abstract*—The necessity and scale of underwater works using autonomous underwater vehicles (AUVs) and underwater remotely operated vehicles (ROVs) is growing rapidly recently. One of the tasks solved by those types of robots is the investigation of sunken ships and sunken submarines in particular. The importance of using unpiloted underwater vehicles instead of piloted ones is evident considering the fact that the underwater environment is extremely dangerous for the crew, because it involves many risk factors. In this paper we consider the simulation of underwater ROV manipulation operations on sunken submarines.**

***Index Terms*—Manipulation operation, motion control system, virtual world, ROV.**

I. Introduction

ROVs have been involved in the deep ocean exploration since the late 1970s and their usage is constantly growing. Underwater robots have been implemented in mapping the ocean floor, oil and gas industry, ocean ecosystem studying and geological investigations. Underwater ROVs are usually controlled by an operator aboard a surface ship. Most ROVs are equipped with one or more video cameras and lights and may also carry other equipment such as a manipulator or cutting arm, water samplers, and measuring instruments to expand the vehicle's capabilities.

In this paper, special interest is paid to ROV manipulation operations on sunken nuclear powered submarines. This interest is due to the fact that sunken submarines can cause an ecological catastrophe because of ocean pollution so usually there is a necessity in underwater operations. Up to now, eight nuclear powered submarines have been sunk and several underwater operations on pollution localization were conducted [1], [2]. But in general, piloted underwater vehicles were applied that caused high risk for the crew of manned submersibles [3]. In our work we suggested implementation of ROV for the manipulation operation on sunken submarines and possible operation scenarios. This required the creation of a 3-dimensional virtual environment, including 3-dimensional models of the ROV, an investigated object (in our case it is a sunken submarine), the relief of the sea bottom where the sunken submarine lies. Moreover, it required modeling the control system of the ROV with its manipulation system and the possibility of controlling the ROV by operator via joystick. There are several commercial projects that allow simulation of underwater operations using ROVs [4]. But usually these systems are expensive and it is better to conduct preliminary off-line simulation. We created the 3-dimentional simulator for ROV manipulation operation and demonstrated the possibility of simulation of the ROV manipulation operations on the sunken submarine. We used modern technical means of modeling and design such as Matlab, Simulink, SimMechanics, Robotic Toolbox for Matlab and computer-aided design (CAD) systems such as Autodesk Inventor and Autodesk 3d Studio Max [5]-[7].

Manuscript received July 12, 2012; revised August 15, 2012.

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II. Proposed Modeling

A. ROV and Manipulation System Modeling

The 3-dimensional model of the ROV and the manipulation system onboard was created using the CAD program Autodesk Inventor 10.

Although sunken ships and submarines are lying on the ocean floor at different depths, sufficient interest is in deep water operations because of its complexity. There are several commercial ROVs which can operate in deep water and in our research we chose the "Quark" ROV produced by Smd Hydrovision Company as a model for manipulation operation [8]. This ROV is a work-class underwater robot and is widely used for the oil and gas industry. In our survey, this underwater vehicle seems as an appropriative choice because of reasonable balance between functionality, price and flexibility. The main characteristics of the 'Quark' ROV, in accordance with a Hydrovision specification, are shown in Table 1.

The Manutec R15 robotic manipulator was chosen as a prototype for simulated manipulation system. Manutec R15, produced by Siemens Company, is an industrial manipulator but in accordance with M. Boeke and E. Aust [9] we can consider this manipulator as a proper choice for the underwater ROV manipulator system because Manutec R15 can be easily modernized for the underwater task. The ROV model created with the installed manipulation system onboard is shown in Fig.1.

TABLE I: Main Characteristics of ROV "Quark"

Characteristics	Value
Main Characteristics	
Depth rating	3000 meters max
Length*Width*Height	2000*1300*1400 mm
Weight	1500 kg
Payload through frame lift	1000 kg
Thrusters Characteristics	
Horizontal thrusters	4 thrusters HTE 300 BA
Vertical thrusters	2 thrusters THE 300 BA

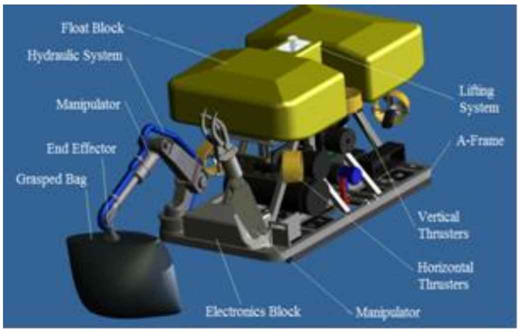

Fig. 1. ROV "Quark" with a manipulation system

B. Sunken Submarine Modeling

The 3-dimensional model of the sunken submarine with the sea bottom relief was created using Autodesk 3d Studio Max. As a prototype for modeling, the Soviet submarine K-278 was chosen. The submarine was modeled with a damaged hull, which is proposed as an area of manipulation operation. The modeled submarine lying at the sea bottom is shown in Fig. 2.

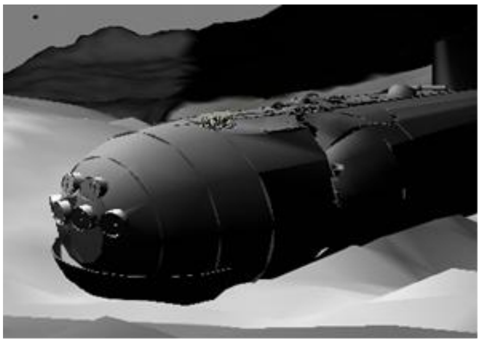

Fig. 2. 3D Model of the sunken submarine

C. Virtual Reality

After finishing models of the ROV with the manipulation system and sunken submarine, they were converted into the Virtual Reality Modeling Language (VRML) format and placed in a 3-dimensional virtual world. Due to the adaptation of that format, it is very easy to edit new worlds [10]. Also, it is possible to add visual effects, sources of light and adjust visibility properties of the environment. We used the VRBuilder application, which is integrated with the Matlab/Simulink environment. The Virtual Reality Tool helps to connect the virtual world with the Matlab environment. The VRBuilder interface is shown in Fig.3 and the modeled Virtual World is shown in Fig.4.

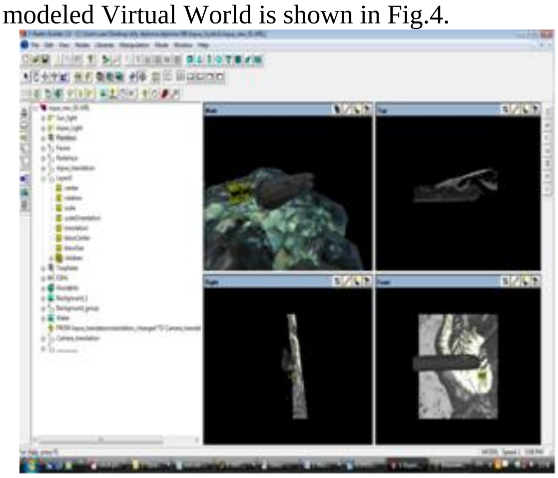

Fig. 3. Virtual reality builder interface.

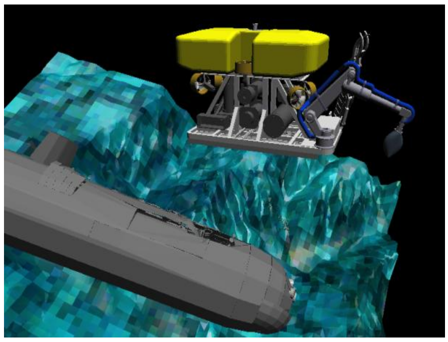

Fig. 4. Virtual world with the models

D. The ROV Motion Control System

1) Underwater vehicle kinematics

Six independent coordinates are required to completely describe the position and orientation of an underwater vehicle. For marine vehicles it is common to use the SNAME [11] notation summarized in Table II.

TABLE II: THE SNAME NOTATION FOR MARINE VEHICLES.

Motion Components	Forces and moments	Linear and angular velocities	Position and Euler angles
Surge (x direction)	X	u	x
Sway (y direction)	Y	v	y
Heave (z direction)	Z	w	z
Roll (rotation over x axis)	K	p	ϕ
Pitch (rotation over y axis)	M	q	Θ
Yaw (rotation over z axis)	N	r	ψ

The coordinates are grouped into two vectors, where

$$\eta = [x\ y\ z\ \varphi\ \theta\ \psi]^{T} \quad (1)$$

denotes the position and orientation, and

$$\nu = [u\ v\ w\ p\ q\ r]^{T} \quad (2)$$

denotes linear and angular velocities. The position coordinates

$$p^{e} = [x\ y\ z]^{T} \quad (3)$$

are decomposed in an Earth-centered and Earth-fixed frame (ECEF). However, for local navigation it is convenient to use a local North East Down (NED) coordinate frame instead. Linear and angular velocities are decomposed in the body fixed frame. The 6DOF kinematic equations are written as

$$\dot{\eta} = J(\eta)\nu \quad (4)$$

where $J(\eta)$ is a nonlinear transformation matrix.

2) Underwater vehicle dynamics

The nonlinear dynamic equations of motion can be expressed in a compact form as [12]:

$$\begin{aligned} &\dot{\eta} = J(\eta)\nu \\ &M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau + w \end{aligned} \quad (5)$$

where M is the inertia matrix of the vehicle including added mass, $C(\nu) = C_{RB}(\nu) + C_A(\nu)$ is the centrifugal and Coriolis matrix, is the hydrodynamic damping matrix, D(v) is the vector of gravity and buoyant forces, τ is the control input vector of forces and moments, and w is a vector of environmental disturbances.

Equations (5) are not practical for controller design. For slender and symmetric vehicles it is possible to separate the system into three non-interacting (or lightly interacting) systems. The three subsystems and their state variables are:

- *Speed u(t)*
- *Steering: v(t), r(t), y(t)*
- *Diving: w(t), q(t), Θ(t), z(t)*

In this work, simplified models of the speed, steering and diving subsystems were obtained but due to the paper length limitation their derivation is omitted [13], [14].

TABLE III: MAIN PARAMETERS OF THE ROV MOTION CONTROL

ROV center	Parameter description	Dimension
φ, θ, ψ	Yaw, pitch, roll	*rad*
X,Y,Z	Surge, heave, sway	*m*
J	Moment of inertia	$N \times m \times s^2$
m_Σ	ROV mass + joined mass	*kg*
λ_i	Joined mass coefficient	$N \times m$
C_i	Hydrodynamic coefficients	$N \times m / rad$
U_x, U_y, U_z	Surge, heave, sway loop voltages	*Volt*
$U_\varphi, U_\theta, U_\psi$	Yaw, pitch, roll loop voltages	*Volt*
F_x, F_y, F_z	Surge, heave, sway forces	*N*
$M_\varphi, M_\theta, M_\psi$	Yaw, pitch, roll moments	$N \times m$
$P_1 \ldots P_6$	Thrusters forces 1…6	*N*

3) ROV motion control scheme description

The ROV motion control system was made in Matlab/Simulink and uses a joystick as an input signal device [15]. By using the joystick it is possible to manipulate the ROV in the generated 3-dimensional virtual environment. The main blocks of the ROV motion control system are as follows:

a) *Input control signal block (ICSB);*
b) *ROV center of mass control system (CMCS) block;*
c) *ROV orientation control system (OCS) block;*
d) *Input signal for propulsion and steering system (ISPSS) block;*
e) *Propulsion and steering system (PSS) block;*
f) *ROV dynamics block;*
g) *Visualization block;*

A scheme of the described control system, modeled in Matlab/Simulink, is shown in Fig. 5.

Main parameters of the ROV motion control system in Fig.5 are described in Table III below.

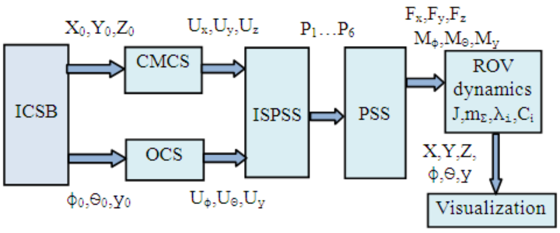

Fig. 5. ROV motion control system

Input control signal block (ICBS) allows controlling 6DOFs of ROV via joystick and a manipulation system is controlled by a data-driven control which is described in section *D*.

the following demands: the overshoot is less than 7%; the velocity transient time is less than 2.5 sec and the position transient time is less than 4 sec; there is no static error if the input disturbance is constant.

Input signal for propulsion and steering system (ISPSS) block transforms voltage signals of ROV thrusters Ui into ROV thruster forces Pi.

Propulsion and steering system (PSS) block transforms ROV thrusters forces Pi to forces Fi and moments Mi applied to the ROV gravity center. Frankly speaking, this block is relevant only for the ROV "Quark" and is not universal for other ROVs because of the difference in the propulsion systems. In equation (6) there are the forces and moments. The scheme of the ROV for the forces and moments calculation is shown in Fig.6.

$$
\begin{aligned}
F_x &= (P_1 + P_2)\cos\alpha + (P_3 + P_4)\cos\beta \\
F_y &= (P_2 - P_1)\sin\alpha + (P_4 - P_3)\sin\beta + (P_6 - P_5)\sin\gamma \\
F_z &= (P_5 + P_6)\cos\gamma \\
M_\varphi &= (P_5 - P_6)(b\sin\gamma + l_3\cos\gamma) \\
M_\theta &= -(P_5 + P_6)c\cos\gamma \\
M_\psi &= (P_2 - P_1)(l_1\cos\alpha + a_1\sin\alpha) + (P_4 - P_3)(l_2\cos\beta + a_2\sin\beta) + (P_6 - P_5)c\sin\gamma
\end{aligned}
\quad (6)
$$

where α, β, γ, l_1, l_2, l_3, a_1, a_2, b, c are ROV geometric parameters shown in Fig. 6.

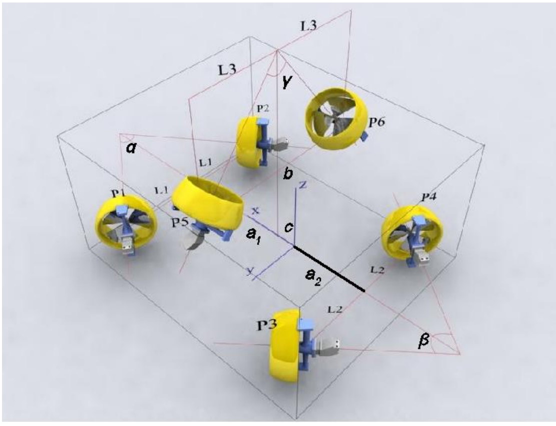

Fig. 6. ROV Thrusters position scheme

The ROV dynamics block realizes underwater vehicle dynamics as described above in section *D2*. In this block, differentiation equation of motion is solved and ROV position and orientation vector with angular and linear velocities are calculated.

Visualization block connects the control systems of ROV and the manipulation system with a virtual world which user can see in the window. This block, as was explained in subsection *C*, is generated on the basis of the Virtual Reality Toolbox [16].

E. The ROV Manipulation System Motion Control

The motion control system of the ROV manipulation system was made using the Robotics Toolbox for Matlab [17]. In this paper the inverse kinematics for the 6-axes manipulator Manutec R15 was solved and the grip of it moves by preprogrammed trajectory. Preprogrammed trajectory of the end-effector assumes that we implemented data-driven control for the manipulator. Data-driven control is ideal for tasks that feature repetitive maneuvers, such as a subsea mission on a sunken submarine. In contrast to direct teleoperation, where the operator directly controls the telemanipulator and uses only video displays for feedback, the computer offers a means of automatically generating joint commands and uncoupling undesired motions of the ROV [18].

F. Manipulation Motion Influence on the ROV Positioning Stability

During the manipulation operations the movement of the manipulator influences on the positioning of the ROV. In this paper, two calculations for positioning stability tests were completed. First, we estimated the influence of the forces at the point of the manipulator mounted on the forefront of the ROV [19]. These manipulator reaction forces cause the ROV to move and they must be compensated by thrusters. Second, we estimated how the center of gravity and center of the volume change their position when the manipulator moves.

In the first case, interaction forces caused by manipulator motion were calculated in accordance with D'Alembert's principle in equation (7). Figure 7 shows interaction forces F_x, and F_y between the ROV and the manipulator, where the manipulator is mounted on the forefront of the ROV.

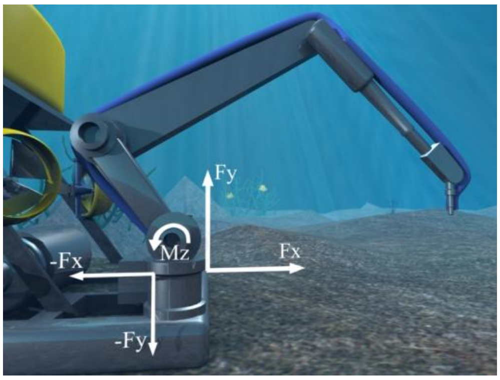

Fig. 7. Interaction forces between the ROV and the manipulator.

$$\sum_{i=1}^{n}(F_i - m_i a_i)\delta r_i = 0 \qquad (7)$$

where

F_i – applied forces,

m_i – are the masses of the particles in the system,

a_i – are the accelerations of the particles of the system,

δ_{ri} – is the virtual displacement of the system.

It other words, for the hover of the ROV during manipulation operation, maximum forces $F_{thruster}$ of ROV thrusters must be more than a total reaction force caused by manipulator motion. In our estimation, we obtained that the total force $F_{reaction}$ is equal to 1.7 *kN* and is much smaller than the ROV force of 12 *kN* which can be achieved by thrusters. Thus, the ROV can hover during performing a manipulation task.

Second case is caused due to the motion of the gravity center and the center of volume when the manipulator propagates. As a result of the manipulator workspace analysis, it was concluded that the center of gravity displacement in the worst case is less than 1.6% and the center of volume displacement is less than 2%. This means that even in the worst case thrusters of the ROV will be able to compensate the influence of the manipulator movement.

G. Simulation of the ROV Manipulation Operations

After modeling, we integrated the ROV control system, the ROV manipulation system, its 3-dimensional models and virtual world with the sunken submarine lying at the sea bottom. As a result, the simulation of ROV manipulation operations on the sunken submarine can be conducted. The manipulation operation considered in this paper is as follows [20]. The ROV moves to the sunken submarine hull surface and stops. This step can be performed by the operator via joystick. After the full stop in a working area which is defined near the distortion in the submarine hull, the ROV begins performing the manipulation task (only manipulator is working and data-driven control is implemented). After finishing the manipulation operation, the ROV moves from the working space and also is controlled by user via joystick. So, control systems of the ROV and the manipulator are working in sequence. This scenario was taken as a possible manipulation operation on the sunken submarine [20]. Results of that simulation are shown in Fig.8.

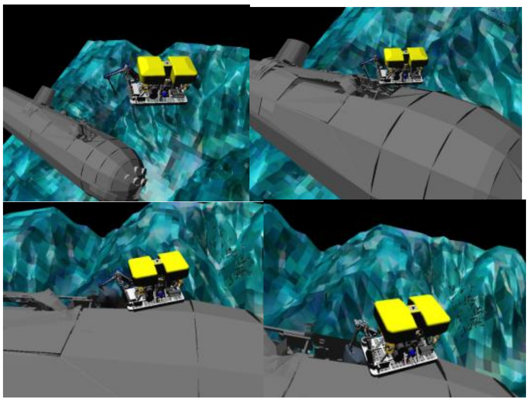

Fig. 8. Simulation of the ROV manipulation operation

III. Conclusions

Described simulator for the manipulation operations of the ROV on the sunken submarine can be a useful tool for preliminary simulation and allows performing dynamic animation in real time. The simulation is animated demonstratively due to the use of a three dimensional environment with animated models and visual effects (lights, fog, plankton etc.). One disadvantage of the paper is that an object interaction is not taken into consideration, particularly the ROV and the sunken submarine. Also, time-varying ocean currents should be modeled since they are of great influence on ROV movement [21]. This simulator can be a base for further AUV and ROV studying and especially we have interest in cooperative ROV and AUV modeling [22].

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