Construction and Research of an Underwater Autonomous Dual Manipulator Platform

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***Abstract*—Underwater hydraulic manipulator with the advantages of heavy load and mature technology, is widely used in ROV and HOV, however, the autonomous operating ability of ROV or HOV's manipulator is relatively weak. To solve this problem, in this paper, an underwater autonomous dual manipulator platform is developed which would be utilized in key technology research on underwater IMR (Inspection, Maintenance and Repair), ocean exploration and other marine applications to alleviate the operating burden and improve working efficiency. Using the same manipulator configuration as the 6000m Scientific ROV of SIA, the platform is comprised of two underwater hydraulic manipulators and has a three-axis motion base of the manipulators. Additionally, the control system is based on the ROS (Robot Operating System) and MoveIt!. This paper tends to illustrate some fundamental research of the platform, such as the system overview of the platform, modeling, motion planning in Matlab and ROS, and the computer-based control of single manipulator.**

***Keywords*—Underwater autonomous manipulation; Dual manipulator system; Deep-sea hydraulic manipulator; Visual servoing**

I. INTRODUCTION

The underwater hydraulic manipulator equipped in ROV has become an essential tool for performing underwater tasks such as drilling, sampling, coring, and connector-mating in the fields of scientific research and ocean engineering. Most manipulators for underwater application are remotely driven in a master-slave configuration. Highly trained operator is necessary for the control and monitoring of these vehicles, which is mostly done from special ships. Lower cost and time saving are expected if these operations can be performed more efficiently by introducing autonomy in ROV operations.

In the past decade, the autonomous manipulation has been an important research issue in the field of underwater applications. Spenneberg et al. [1] showed a project C-Manipulator aiming at the development of an autonomous, modular, dual manipulator system for underwater applications. Ridao et al. [2] proposed the Intervention Autonomous Underwater Vehicle (I-AUV) to carry out underwater free-floating manipulation, such as valve turning and connector plug/unplug. Schjolberg et al. [3] showed the project Next Generation Subsea Inspection, Maintenance and Repair (NextGenIMR) toward autonomy of ROV.

Fig. 1. The underwater autonomous dual manipulator platform

Computer-based control of the manipulator is the fundamental problems. Hildebrandt et al. [4] proposed a computer-based control system, which can achieve forward kinematics, inverse kinematics, basic trajectory planning and graphical user interface. Shim et al. [5] presented the development of the workspace-control system and a working strategy to alleviate operator's burden in underwater works. To improve the control precision, Hildebrandt et al. [6] proposed a multi-layered controller approach for high precision end-effector control of hydraulic underwater manipulator systems. The real-time motion compensation for manipulator caused by ROV was studied in [7]. Aggarwal et al. [8] studied the autonomous trajectory planning and following of the Schilling robotics Orion7P manipulator.

Due to the limit of the underwater sensor, visual servoing is an important way to achieve the underwater autonomous control. Marchand et al. [9] presented a vision-based method to control the displacement of robot arm mounted on an underwater ROV. Hildebrandt et al. [10] studied the robust vision-based semi-autonomous underwater manipulation.

However, the basic theory and application are not perfect, and there are lots of problems to solve. Based on the SIA's 6000m Scientific ROV, we specially develop a platform to do the research and development work of underwater autonomous manipulation. For now, we have completed the

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design, manufacture and assembly of the platform, as shown in Fig. 1. Some basic research and experiments have been carried out, such as the modeling, motion planning in the Matlab and ROS, and computer-based control of single manipulator. More high level research and experiments will be further studied including obstacle avoidance, visual servoing, dual manipulator cooperation and autonomous manipulation in the future.

The paper is organized as follows. Section II gives an overview of the platform including hardware setup, software setup and control architecture. The kinematics modeling of the platform is introduced in Section III. Some simulation and experiments are presented in Section IV. Finally, Section V concludes the paper and presents the future work.

II. Platform Overview

A. Hardware setup

The platform is mainly formed by the underwater part and the surface part, which is showed in Fig. 2. The surface part includes four 55-inch video walls, the operating master arm, and autonomous control system; the underwater part includes SIA 7-function hydraulic servo manipulator, Schilling TITAN 4 underwater hydraulic manipulator, four 1080p HD underwater video cameras, four LED lights, monocular and binocular cameras, manipulation panel, three-axis motion base and hydraulic system. The manipulators are the core of the underwater system, which have the same configuration with SIA' 6000m scientific ROV. The manipulators specific parameters are given in TABLE I. .

TABLE I. Manipulator Technical Parameters

Specifications	SIA7F	TITAN 4
Power Source	Hydraulic	Hydraulic
Control Source	Position	Position
Functions	7	7
Max. Reach	1900mm	1922mm
Lift at Full Reach	65kg	122kg
Depth Rating Standard	7000msw	4000msw
Weight in Air	85kg	100kg
Weight in Water	65kg	78kg

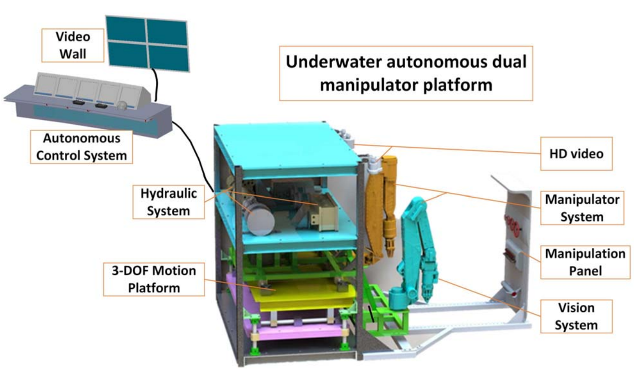

Fig. 2. The system overview of the platform

B. Software Setup

To reinforce software portability, reuse and sharing, Linux (Ubuntu 16.04) is used as the host operating system and all software modules are developed based on ROS middleware. MoveIt! [11, 12], a mobile manipulation software framework, is implemented to deal with motion planning. The two arms have similar control modes and software functions, as shown in Fig. 3. The software integrates three modules: joint servo control system, master arm system and autonomous control system. The slave computer receives control command from the host, sends feedback sensor data, and achieves joint servo control with PID algorithm. More details of master arm control system can be found in [13]. The autonomous control system is important for the platform, including forward kinematics, inverse kinematics [14], trajectory planning [15], visual servoing and cooperation. The kinematics and motion planning are developed using ROS and MoveIt!. The underwater image processing is the base to achieve target recognition and visual servoing. Another important function of this platform is to achieve dual manipulator cooperation, including full-constrained cooperative working, partly constrained cooperative working and non-constrained cooperative working. The cooperative motion planning is achieved in MoveIt! and the joint state synch in ROS.

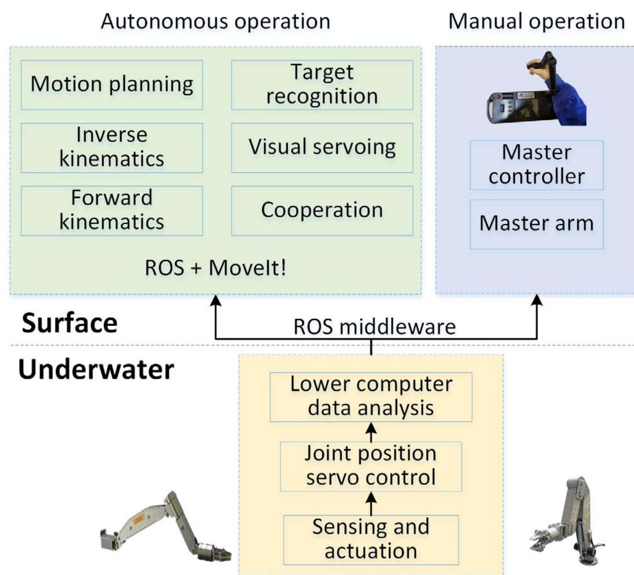

Fig. 3. Software system diagram of the platform

C. Control Architecture

Fig. 4 shows the control block diagram of each part of the system. The underwater live video, from four underwater HD PTZ cameras, is shown on the video walls and the videos can also be recorded by a DVR. The operators can monitor the operation process from multiple angles in real time by the videos. The monocular and binocular cameras equipped on the SIA7F and TITAN 4 manipulator wrist separately, can provide more detailed information for the manipulators to achieve the underwater visual servoing. The three-axis motion base can make the manipulators move along X, Y, Z axis by hydraulic cylinders with precise distance control or compensate the disturbance caused by the environment. The manipulators can be controlled by the autonomous motion controller or a master arm similar to the ROV.

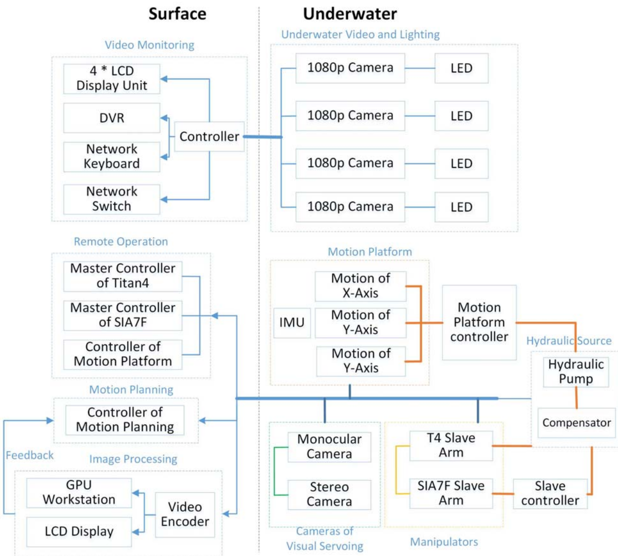

Fig. 4. Control system diagram of the platform

III. MODELING

The SIA7F manipulator is a 7-function deep sea hydraulic manipulator developed by Shenyang Institute of Automation and can be controlled by a master arm [13]. The kinematics model and D-H parameters can be found in [16].

The TITAN 4 manipulator, developed by Schilling Robotics [17], has the dexterity and accuracy necessary to perform the fine movements needed for complex tasks. The coordinate systems is shown in Fig. 5 and the D-H parameters is shown in TABLE II. .

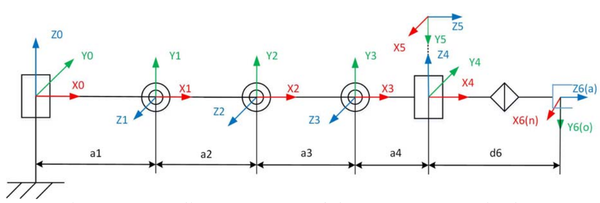

Fig. 5. Coordinate systems of the TITAN 4 manipulator

TABLE II. D-H PARAMETERS OF TITAN 4 MANIPULATOR

i	$\theta(^\circ)$	d(mm)	a(mm)	$\alpha(^\circ)$
1	-120～120	0	121	90
2	-32.5～87.5	0	851	0
3	-172～98	0	483	0
4	-90～90	0	133	-90°
5	-90～90	0	0	-90°
6	360	336	0	0

As shown in Fig. 6, the system is composed by 2 manipulators and each equipped with N_i joints (i=1,2,…,6). There are many useful coordinates in the system: the world coordinate $\{W\}$, the base coordinates $\{B_1\}$ $\{B_2\}$, the end-effector coordinates $\{T_1\}$ $\{T_1\}$ and the object coordinate $\{C\}$.

The transformation matrixs of each end-effector with respect to base frames of each arm are fomula (1),

$$\mathbf{T}_k = \begin{bmatrix} \mathbf{R}_k & \boldsymbol{t}_k \\ 0 & 1 \end{bmatrix} \quad (k=1,2) \tag{1}$$

where $\mathbf{R}_k$ is a 3×3 orientation matrix and $\boldsymbol{t}_k$ is a 3×1 position vector. The differential kinematics is expressed as the formula (2),

$$\dot{\boldsymbol{x}}_k = \frac{\partial \boldsymbol{f}_k(\boldsymbol{q}_k)}{\partial \boldsymbol{q}_k}\dot{\boldsymbol{q}}_k = \mathbf{J}_{Ak}(\boldsymbol{q}_k)\dot{\boldsymbol{q}}_k \quad (k=1,2) \tag{2}$$

where the $6\times N_k$ matrix $\mathbf{J}_{Ai}$ is the analytical Jacobian of the k-th manipulator, the $\boldsymbol{q}_i$ is a 6×1 vector composed of the joint positions.

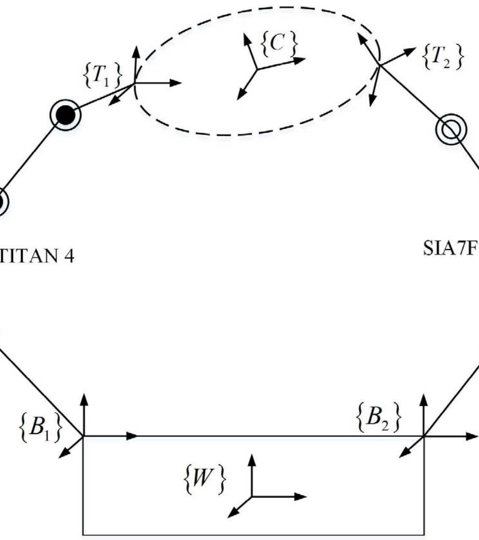

Fig. 6. Coordinate systems of dual manipulator system

IV. EXPERIMENT

A. Dual manipulator simulation in Matlab

Dual manipulator cooperative operation is a common application scenario of ROV. Two underwater manipulators carry out the similar trajectory to grasp or transport the same object. The experiment was simulated in Matlab and the simulation time is 50s. The manipulators have similar start position and end position and the trajectory is a circular arc. Fig. 7 shows the following trajectory of the two manipulators in the Matlab. Fig. 8 and Fig. 9 show the changes of the joint angles when carrying out the similar trajectory simultaneously. It is showed from the results that the basic cooperative tasks can be achieved.

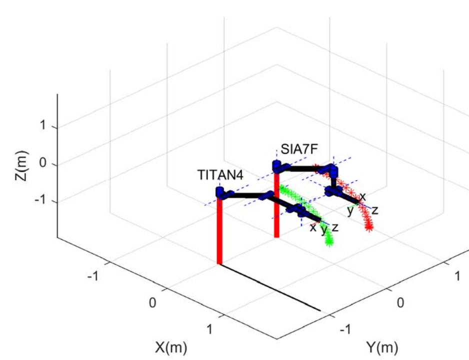

Fig. 7. The dual manipulator following trajectory simulation

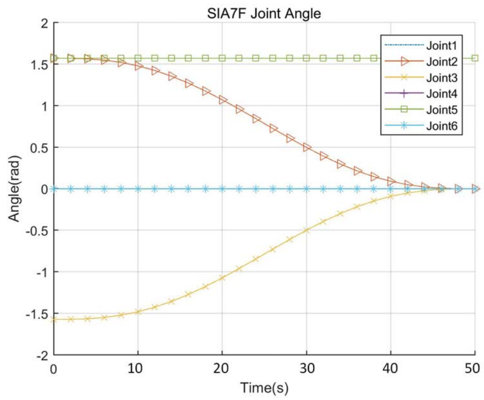

Fig. 8. The joint angle of SIA7F manipulator

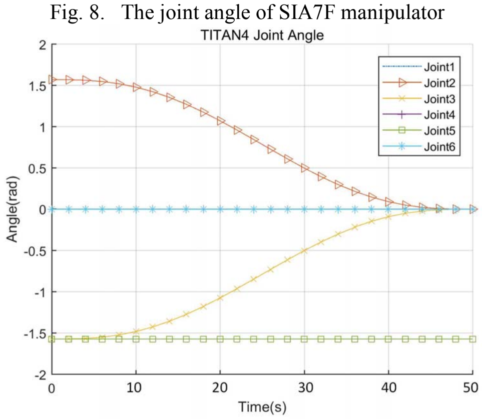

Fig. 9. The joint angle of TITAN 4 manipulator

B. *Dual manipulator simulation in MoveIt!*

A ROS-based architecture are used to integrate all of the components of software, so a suitable model in ROS is needed. Since the mechanical structure is complex, we firstly simplify the model of platform in SolidWorks software and then import it into the MoveIt! with URDF format. The motion planning and dual manipulator collaborative tasks can be simulated conveniently. Some basic motion planning tasks are studied as shown in Fig. 10. .

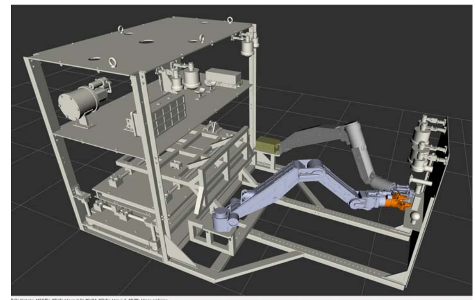

Fig. 10. The dual manipulator platform simulation in MoveIt!

C. *The circle trajectory of SIA7F manipulator*

In order to test the performance of trajectory following, a circle trajectory is carried out on the SIA7F manipulator. First, we generate the circle trajectory in Matlab, as shown in Fig. 12.. Then, we send the trajectory to the controller of SIA7F manipulator to following. Fig. 11 shows the set value

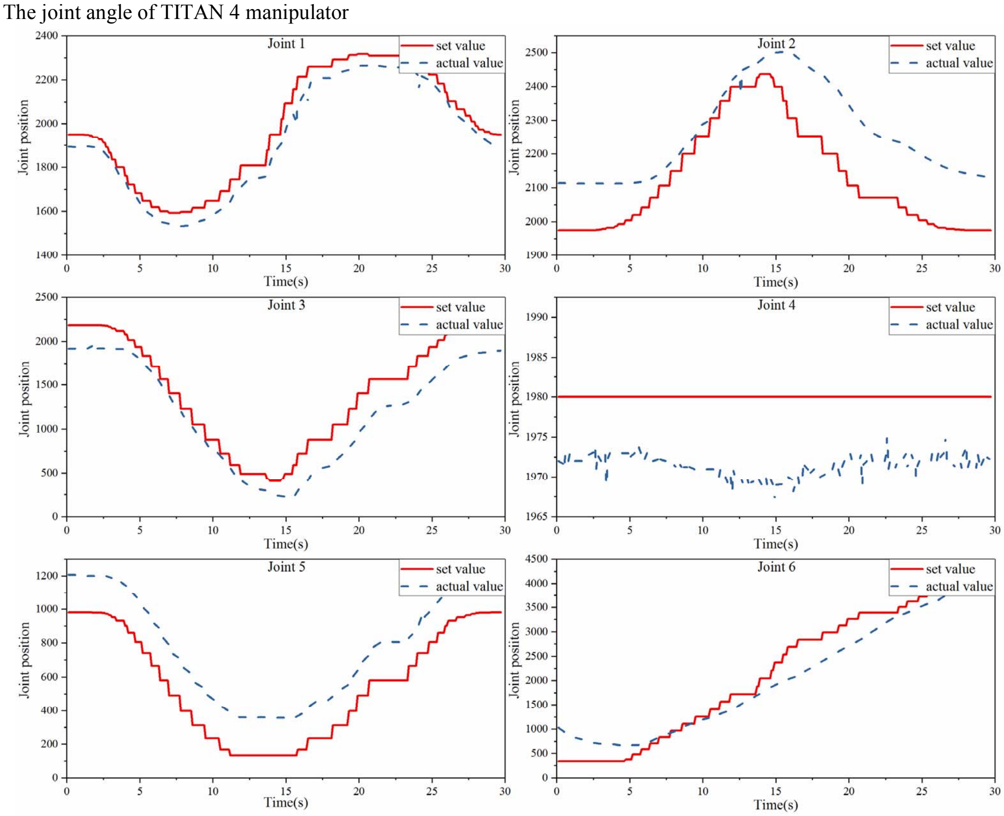

Fig. 11. Result of SIA7F manipulator executing circle trajectory

and actual value of six joints. We can see from the result that the manipulator can follow the trajectory as a whole but not accurate enough. Therefore, the controller should be optimized to improve the motion control accuracy.

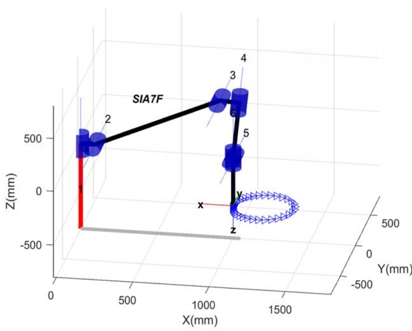

Fig. 12. The circle trajectory simulation of SIA7F manipulator

V. Conclusion And Future Works

In this paper, an underwater autonomous dual manipulator platform has been presented to illustrate the key research of underwater autonomous manipulation and cooperation. We have accomplished the design and construction of the platform. The physical structure, hardware, software, functions architecture and modeling of the platform are introduced. Then the basic simulation and experimental results were carried out to demonstrate the potential of the system in the aspect of autonomous manipulation.

Based on the fundamental research above, the high level applications and more underwater experiments will be further studied in the future. First of all, we will test the whole system in the water poor. Then the applications of visual servoing such as grasping an object autonomously will be carried out. In addition, the dual manipulator cooperation will be researched. Finally, the method will be tested in the SIA's 6000m ROV.

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