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Research paper

Optimal configuration and parametric design of an underwater vehicle manipulator system for a valve task

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ABSTRACT

An underwater vehicle manipulator system (UVMS) has several applications including mining, exploring, and building underwater structures. The current study presents a method to design and optimize an UVMS configuration by measuring the performance of various design alternatives. The concept of a dual-arm manipulator was proposed, and a design alternative was developed for the dual-arm manipulator. Additionally, modified dynamic manipulability that considers hydrodynamic effects was selected to measure the performance of design alternatives. Each alternative was optimized by using a genetic algorithm to maximize dynamic manipulability through a desired task. Optimized alternatives were compared, and the optimal design of a dual-arm manipulator was selected from the alternatives. The proposed method considered hydrodynamic effects on an UVMS to design and optimize a dual-arm UVMS.

1. Introduction

Underwater operations are important in oceanic industries. An underwater vehicle manipulator system (UVMS) is necessary for safety and efficiency in an underwater environment because of the prevalence of harsh conditions. Therefore, previous studies designed and developed various types of UVMS. McLain et al. developed an UVMS by attaching a single arm manipulator on an OTTER vehicle and controlled the system by using enhanced hydrodynamics force calculations [1]. Kim et al. attached a 3-degree-of-freedom (DOF) manipulator on an ODIN to design an UVMS and performed dynamic analysis with respect to the system [2]. Cieslak et al. created an UVMS by using a GIRONA500 autonomous underwater vehicle (AUV) and ECA/CSIP micro 4-DOF arm [3]. Carrera et al. make robotic arm to learn valve turning task with learning algorithm for underwater operation [4]. Simetti et al. proposed the control framework and verified the framework by experiment for Trident project [5]. Conti et al. developed manipulation strategy for free floating UVMS [6]. Recently, Stuart et al. developed an UVMS termed as Ocean One to perform underwater operations by using an underactuated end-effector [7].

A previous study proposed a tilt thrusting underwater robot (TTURT) with four tilting thrusters. The robot was termed as TTURT, and it was controlled by a selective switching controller and achieved 6-DOF motion with a reduced number of actuators [8,9]. The platform-module concept was applied on the TTURT in which it was possible to attach various modules on the TTURT. An extant study also presented a dual-arm manipulator concept and verified its advantages in compensating

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disturbances [10]. Therefore, the present study involves designing and attaching a dual-arm manipulator module on a TTURT to develop UVMS.

A position of end-effector and various subtasks can be achieved simultaneously by using a redundant manipulator in task-based control. With task priority, subtasks such as obstacle avoidance, joint torque optimization, and disturbance compensation can be accomplished without interfering main task, following desired trajectory. The null space projection method is common way to solve redundancy and set priority between tasks. Khatib presented the operational space formulation and expand the formulation to redundant manipulator [11]. Hollerbach optimized joint torque of the redundant manipulator by using null space projection method [12]. The redundant manipulator also used in UVMS. We previously compensated disturbance on the vehicle with joint torque of a dual-arm manipulator with null space projection method [10]. Han minimized restoring moment of the UVMS with redundancy resolution method [13].

Various methods have been presented for designing and optimizing manipulators. Wenger et al. proposed three cost functions to determine the performance of manipulators that are based on kinematics of manipulators [14]. Yang et al. presented an optimization method to minimize the DOF of a manipulator with respect to a specific task [15]. Ceccarelli et al. proposed an optimization algorithm that optimized workspace characteristics and length of links with respect to specified workspace constraints [16]. Lee et al. designed a prismatic-revolute-revolute manipulator to achieve specific predefined points [17]. Previous studies explored various cost functions. However, there is a paucity of studies that consider the dynamic properties of a manipulator while optimizing the manipulator.

Manipulability can correspond to a reasonable cost function to optimize manipulators. Yoshikawa proposed not only the concept of manipulability but also kinematic manipulability which indicates the performance of manipulator numerically. Moreover, some properties of kinematic manipulability are presented in the paper [18]. Previous studies explored various types of modified manipulability to expand the concept of manipulability. Yoshikawa described a few variations of manipulability; first, discussed dynamic properties for kinematic manipulability including inertia, Coriolis, and gravity, and secondly proposed the concept of dynamic manipulability [19]. Not only that but Yoshikawa also considered rotational motion of an end-effector and presented the concept of rotational manipulability [20]. Shen et al. described a manipulability measurement method in multi-wire driven mechanisms with both geometrical and force constraints [21]. Singh et al. modified manipulability to determine velocity characteristics of a manipulator and performed the optimization of a manipulator [22]. Lee et al. designed a dual-arm manipulator and verified its performance with respect to modified manipulability [23]. It is necessary to modify manipulability to consider an underwater environment including hydrodynamic damping and additional inertia to use manipulability as a performance indicator of UVMS.

The present study proposes a design method based on modified dynamic manipulability to determine UVMS configuration in which underwater properties are considered. A rotating handle valve operation was selected as an objective task because it corresponds to a fundamental task in the industry. The concept of a dual-arm manipulator was followed to create four design alternatives by dividing DOFs with respect to each arm of the manipulator. The design alternatives of the dual-arm manipulator were designed to have redundancy to perform subtasks simultaneously with main task. The kinematics and dynamics of design alternatives were solved. Additionally, dynamic manipulability proposed by Yoshikawa [19] was modified to contain the drag effect and additional inertia that correspond to hydrodynamic effects. Each design alternative was optimized to maximize the total modified dynamic manipulability through a desired trajectory. The desired trajectory was generated by using a gradient projection method to maximize the total modified dynamic manipulability. The design alternative corresponding to the highest total modified dynamic manipulability after optimization was selected as the optimal configuration of a dual-arm manipulator. This was followed by discussing the optimization results and properties of the cost function.

The rest of the paper is organized into four parts. Section 2 describes the creation of dual-arm manipulator design alternatives. Furthermore, this section includes determining the solution for the kinematics and dynamics of each alternative. The optimization problem is presented in Section 3. The selection of an optimal configuration of the dual-arm manipulator is discussed in Section 4. Finally, Section 5 discusses the study conclusions.

2. System analysis

2.1. Concept of UVMS

The UVMS presented in the study was designed by attaching a dual-arm manipulator module on an existing underwater platform TTURT. Fig. 1 describes the concept of an UVMS, namely TTURT, which was developed in a previous study in which 6-DOF motion is achieved with four tilting thrusters [8,9]. TTURT can perform 6-DOF hovering task with reduced number of actuators. The platform-module concept was applied to the design of a TTURT, and thus various modules such as manipulators can be attached to TTURT. It is possible to easily create the UVMS by attaching a dual-arm manipulator module on the TTURT. The TTURT involves two attaching points on the top and bottom. Therefore, a manipulator is attached on the top, and the other manipulator is attached on the bottom.

The dual-arm manipulator consists of two parts. The first part of the manipulator corresponds to a clamping manipulator. The clamping manipulator is used to anchor the entire system on a point. In a manner similar to that of a human diver, the UVMS achieves a desired task with respect to strong disturbances by holding a point. The second part of the manipulator