Exploiting Redundancy in Underwater Vehicle-Manipulator Systems

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ABSTRACT: The current work focuses on the development of a comprehensive scheme for the coordinated control of underwater vehicle–manipulator systems (ROVMs). The proposed scheme consists of two main stages: Redundancy resolution, and dynamic modeling and robust control. In the redundancy resolution stage, the end-effector input commanded by a human pilot is distributed over the vehicle and manipulator. The redundant degrees of freedom (DOFs) are used to accomplish secondary objectives. To this end, the Gradient Projection Method (GPM) is merged with a fuzzy logic based weighting scheme. Regarding the dynamics-and-control stage, the dynamic modeling is carried out using the energy-based quasi–Lagrange approach. As opposed to a classic Lagrangian derivation, the quasi–Lagrange approach generates the equations in terms of the body-fixed frame. As for the ROVM system controller, a novel sliding mode controller is proposed. The proposed controller contains a continuous adaptive term that constantly compensates for unknown dynamics. Unlike conventional sliding-mode controllers, the proposed controller is chattering-free. To demonstrate the efficacy of the scheme, several numerical simulations are performed. Results illustrate that a complex spatial maneuver can be accomplished with a 4-DOF manipulator mounted on a small ROV using a single 6-DOF pilot input.

KEY WORDS: *Underwater vehicle-manipulator systems; Redundancy resolution; Quasi-Lagrangian dynamic modeling; Sliding-mode control.*

INTRODUCTION

Underwater remotely operated vehicles (**ROVs**) equipped with robotic manipulators are used in a variety of underwater applications such as oil and gas extraction, installation of underwater telecommunication cables and inspections and maintenance of offshore structures. The combined system is referred to as an underwater remote operated vehicle-manipulator (**ROVM**). To date, the motions of the ROV and the manipulator are guided independently by a human pilot on a surface support vessel through a long slender tether that provides power and telemetry. In current practice, the desired manipulator joint motions are created using a teleoperated master-slave arm configuration. This mode of operation depends on the ability of the ROV to hold station and decouples the manipulator and ROV degrees of freedom. In most cases, pilots attempt to eliminate any ROV motion by lodging the ROV against an immovable object using thrusters or an additional arm. This simplifies the pilot's task, but it eliminates the redundancy inherent in the ROVM system (In addition to the manipulator's degrees of freedom, the ROV itself contributes six active degrees of freedom.)

Furthermore, for smaller ROVs the serial manipulator is usually underactuated for six degree of freedom tasks, and so the elimination of the ROV degrees of freedom results in a very constrained end-effector workspace If the ROV DOF's are used during an end-effector task, then there are many possible ways to achieve a single- end-effector motion. A redundancy resolver determines the optimal combination of ROV and arm motions. The optimal solutions yield the required end-effector motion while realizing the additional secondary objectives.

The implementation of redundancy resolution methods within ROVM systems has been documented in only a few existing works. The singularity robust task-priority redundancy resolution was shown to be useful for a ROVM by Chiaverini (1997) due to its multitask capabilities. In Sarkar and Podder (2001), the kinematic redundancy is utilized to minimize the total hydrodynamic drag forces experienced by a ROVM system in an effort to reduce the energy consumption. In Antonelli and Chiaverini (2003), the singularity robust task-priority redundancy resolution is merged with a fuzzy technique to resolve the ROV-manipulator coordination. It is shown that fuzzy logic is an effective means to handle multiple kinematic constraints. However, since the task-priority approach requires predefined secondary task values, it may not be suitable for on-line underwater tasks in which the predefined task values are not always available. A fault-tolerant redundancy resolution method that does not require predefined secondary values was proposed by Soylu et al., (2007). In Soylu et al., (2007), the Gradient Projection Method (**GPM**) was merged with the fuzzy logic. In the current study, the work of Soylu et al., (2007) is followed since it gives a more flexible framework for complex on-line underwater missions in comparison to the other multi-task accommodating resolution methods.

While the redundancy resolution scheme translates the pilot's intent into ROVM joint rates and provides reference values, it falls on a robust control strategy to realize these reference joint rates. Robust control methods generally depend on dynamic models of the system. Existing dynamics models of ROVMs include that of Ioi and Itoh (1990) who extended the Newton-Euler formulation to include the requisite hydrodynamics terms. Sagatun and Fossen (1991) derived the equations of motion for an ROVM system using the Lagrange method. McMillan et al. (1995) extended the articulated-body formulation to develop a computationally efficient dynamic simulation of a ROVM system. Tarn et al. (1996) developed a dynamic model of a ROVM based on Kane's method.

For the multi-body systems such as ROVMs, the Lagrange approach is preferred since it provides the equations of motion in an analytical form- a requirement for the model-based controller. A drawback of the Lagrange approach is that it yields the equations of motion in terms of