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Exploiting Redundancy in Underwater Vehicle-Manipulator Systems

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The current work focuses on the development of a comprehensive scheme for the coordinated control of remotely operated vehicle–manipulator (ROVM) systems, and it proposes a novel mode for their operation. The proposed scheme consists of 2 main stages: redundancy resolution, and and robust model based 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 (DOF) 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 control of the system, a dynamic model is derived using the energy-based quasi–Lagrange approach. As opposed to a classic Lagrangian derivation, the quasi–Lagrange approach generates the equations in terms of body-fixed frames. As well, an adaptive sliding mode controller is implemented that constantly compensates for unknown dynamics throughout the vehicle-manipulator system. To demonstrate the efficacy of the scheme, a numerical case study is performed. Results illustrate that a complex end-effector spatial maneuver defined by a single 6-DOF pilot input can be accomplished with a 4-DOF manipulator mounted on a small ROV.

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 remotely 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 it decouples the manipulator and ROV degrees of freedom (DOF). In most cases, pilots attempt to eliminate any ROV motion by lodging the ROV against an immovable object using thrusters or by 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 DOF, the ROV itself contributes 6 active DOF.) Further, for smaller ROVs, the serial manipulator is usually underactuated for 6 DOF tasks, and so the elimination of the ROV DOF results in a very constrained end-effector workspace. If the ROV DOF are used during an end-effector task, then there are many possible ways to achieve a desired end-effector motion. A redundancy resolver determines the optimal combination of ROV and arm motions that yields the required end-effector motion while also realizing the additional secondary objectives.

The implementation of redundancy resolution methods within ROVM systems has been documented in only a few existing works. A singularity robust task-priority redundancy resolution was shown to be useful for an 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 was shown that fuzzy logic is an effective means for handling multiple kinematic constraints. A fault-tolerant redundancy resolution method was proposed by Soylu et al. (2007). In that work, the Gradient Projection Method (GPM) was used to blend a series of secondary objectives using a fuzzy weighting scheme with a fault-tolerant property. The current study follows Soylu et al. (2007).

While the redundancy resolution scheme translates the pilot's intent into desired ROVM joint rates, it falls on a robust control strategy to realize these joint rates. Robust control methods generally depend on dynamic models of the system. Existing dynamics models of ROVM 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 an ROVM system. Tarn et al. (1996) developed a dynamic model of an ROVM based on Kane's method.

For 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 any model-based controller. A drawback of the Lagrange approach is that it yields the equations of motion in terms of generalized coordinates specific to an inertial frame. However, for ROVM dynamics modeling, it is convenient to work in the body-fixed frames. To this end, the quasi-Lagrange approach is used to model the system dynamics in the current work. The differences between the classic Lagrangian and the quasi-Lagrangian will be elaborated in the dynamic modeling section.

Controller development has been largely applied to ROVs, and it is rare that the manipulator DOF are considered. The unified control of ROVM systems has been addressed by Antonelli and Chiaverini (1998), who designed an adaptive controller for an

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