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Reduction of the dynamic coupling in an underwater vehicle-manipulator system using an inverse dynamic model approach

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Abstract: This paper proposes a control strategy for station keeping of an underwater vehicle-manipulator system when the manipulator is asked to perform a certain task. The control structure consists of an inverse dynamic feedforward controller, the interaction forces between subsystems and a PILIM feedback controller for pitch control of the vehicle. The UVMS includes a 6-DOF vehicle and a 3-link manipulator, where the manipulator has a significant mass compared to the vehicle. The equations of motion are based on a tree representation of the UVMS and are described with the Newton-Euler algorithm. Hydrodynamic effects and friction considerations are taken into account in the forward dynamic model, while in the inverse dynamic model they are ignored. Simulation results show the validity of the inverse dynamic model approach without perfect knowledge of the system for station keeping of the vehicle. A key contribution of the study is that it is based on a lightweight underwater system. The main problem addressed in this paper is the station keeping of an underwater vehicle when the attached manipulator is moving. It is demonstrated that an inverse dynamic model used as a feedforward controller is a viable solution in the presence of system uncertainties.

Keywords: underwater vehicles, manipulators, modeling, dynamic coupling, inverse dynamics, PILIM control.

1. INTRODUCTION

The interest in underwater vehicle-manipulator systems has increased over the past years due to the need for interaction in underwater environments. More recently, robots have been deployed to inspect and collect information for the oil and gas industry, military purposes and biological/geological studies. Manipulation in underwater environments is the next step that allows faster and safer development of oil and gas sites, disposal of mines or geological data collection. Technological development has led to lighter and more compact underwater robots. Integrating a manipulator on such a robot may perturb the system if appropriate control methods are not developed. These types of systems are referred to as lightweight underwater-vehicle manipulator systems (UVMS).

To reduce time and cost for analyzing the lightweight UVMS, the system can be defined through the equations of motion. The UVMS can be described through a single chain representation as presented by Antonelli and Chiaverini (1998b) or as two independent systems, Kim et al. (2003). The equations of motion have to represent as closely as possible the real system. Fossen (1991) considered the UVMS as a macro-micro manipulator and developed the equations of motion based on the Newton-Euler algorithm. A similar approach was used by Antonelli and Chiaverini (1998b) to represent the UVMS. The goal of the paper was to develop a control architecture for redundant systems based on the inverse kinematics. The Euler-Lagrange method for system representation has also been used extensively. Olguin-Diaz et al. (2013) used this method to develop a force/position control scheme for a UVMS. A modified version of the Euler-Lagrange algorithm, the Quasi-Lagrange algorithm was used by Sarkar and Podder (2001) to obtain the trajectories of the manipulator and vehicle using a minimum hydrodynamic drag. In the Quasi-Lagrange approach the equations of motion are presented in the body-fixed frame. This representation is considered advantageous due to the fact that it matches the information from the on-board sensors.

Using the model of the system, studies of the interaction of the manipulator on the position keeping of the vehicle was performed by Dunnigan and Russell (1998). The study established the most affected DOF and proposed a control method for this specific DOF. McLain et al. (1996) analyzed the coupling effects based on a real system consisting of the OTTER AUV and a single link manipulator attached to the vehicle. The paper presented a coordinated control scheme for the vehicle-arm system and investigated the hydrodynamic effects of the UVMS. Studies on underwater vehicle-manipulator systems have been conducted previously e.g. Antonelli and Chiaverini (1998a); Antonelli et al. (1999, 2001). However, in all the cases the dry mass of the vehicle is considerably larger than the mass of the manipulator and no conclusions about the interaction between subsystems are stated. The inverse dynamic model is considered as an inverse problem where the model of the robot is known and can be used to

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determine the joint torques and vehicle forces when the desired position, velocity and acceleration are known. The model can be used either as a linearizaion technique for nonlinear systems or as part of the controller for motion control. The model based controller can improve the performances of the classical control strategies by reducing the tracking error. Morales and Carelli (2003) and Piltan et al. (2012) used the inverse dynamic model to linearize a second order system. To control the motion of the manipulator a feedback controller was used. Simulation results with a 3-link manipulator showed reliable results for the motion tracking. Boerlage et al. (2003) presented the inverse dynamic model as a feedforward controller. The authors proposed an analysis technique that relates the inverse dynamic model with a second order filter. Korkmaz et al. (2013) present a control method for the UVMS based on inverse dynamics. The interaction forces between the vehicle and manipulator are computed and used in the control law that aims to linearise the system. Simulation results show an improvement in the behavior of the system when the inverse dynamic model is used. The progress is due to a perfect knowledge of the system. Abdessemed (2012), Pott et al. (2011) stated that the inverse dynamic model is useful for performance improvement only in the case when full knowledge of the system is known.

In this work a method for reducing the coupling effects between the vehicle and manipulator is proposed. Using the Newton-Euler principle for modeling the system, the interactions between the manipulator and vehicle are highlited. A new control methodology is proposed for station keeping of the vehicle. The control incorporates the "inexact" inverse model as a feedforward controller and takes into account the coupling effects. The feedback part is present only for the DOFs that are significantly affected by the interactions.

The rest of the paper is structured as follows. In Section 2 the methodology to develop the simulation platform is presented. In Section 3 the control architecture for the vehicle is presented. In Section 4 results of the proposed controller are analysed. Section 5 presents the conclusions and future work for this research.

2. SYSTEM REPRESENTATION AND EQUATIONS OF MOTION

A simulation model for the UVMS is used to study the effects of the inverse dynamic model incorporated in the control strategy. The simulation model is composed of two parts: the kinematic representation and the equations of motion of the system. A single chain representation of the UVMS has been chosen. This means that the vehicle is considered as an extension of the manipulator. The links of the manipulator have a cylindrical shape, similar to the shape of the vehicle. Choosing a single chain representation of the UVMS is advantageous for producing a general model of the system: if any part of the system is changed, the equations do not have to be rewritten, they are recomputed automatically. Furthermore, the chain representation is useful for highlighting the interaction effects between subsystems. This chain representation, also called a "tree-representation" consists of nodes (the links) and arcs (the joints) of the system. The reference frame for each part of the system is placed at the center of mass. In Fig. 1 a sketch of the system is presented. The

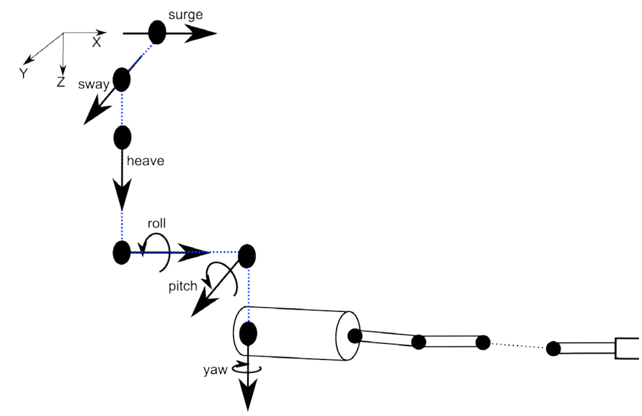

Fig. 1. Generic UVMS graph

vehicle is considered as a virtual 6-DOF joint, having the three translational movements of the real vehicle (surge, sway, heave) and the three rotational movements (roll, pitch, yaw). For simplification of the kinematic problem, the virtual 6-DOF joint can be decomposed into six independent joints with zero mass. The connection between the first joint of the manipulator and last DOF of the vehicle is represented through a node that preserves the characteristics of the vehicle: mass, length, radius. These assumptions lead to the representation of the UVMS as a manipulator.

The dynamic model of the UVMS is described through a matrix representation shown in 1.

$$M(q)\dot{\zeta} + C(\zeta, q)\zeta + D(\zeta, q) + g(\eta) = \tau \qquad (1)$$

where M is the inertia matrix, C is the Coriolis and Centripetal matrix, both consisting of rigid body terms and added mass terms, D is the damping matrix and g represents the restoring forces. τ are the forces applied to the overall system. The hydrodynamic terms are modeled based on the research of McLain et al. (1996) with a few other characteristics taken into account. The added mass terms can be related to the distance travelled by the links of the manipulator and by the shape of the body. By studying these effects a spline model can be used to develop these hydrodynamic effects. The moment integral along the length of the rigid body has to be performed to compute the hydrodynamic drag. For calculating the drag coefficients, the shape of the body, the Reynolds number and the distance traveled by the body are considered. Furthermore, it was observed by Leabourne and Rock (1998) that the position of the consecutive rigid bodies alters the effects of the underwater environment. The effect produced on the system is called the "shadowing-effect" and it was considered in the hydrodynamic model. A detailed description of the dynamic and hydrodynamic model can be found in Barbălată et al. (2014).

3. CONTROL STRATEGY

The movement of the manipulator has a significant effect on the position keeping ability of the lightweight vehicle. Developing a control strategy for reducing the coupling effects is of interest in this paper. The control method