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# A study on hovering motion of the underwater vehicle with umbilical cable

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ABSTRACT

The paper presents a new modeling of the behavior of an underwater vehicle (UV) operating in the littoral sea, including the umbilical cable (UC) effect, where we derive a new simulation method of the full equations of the combined rigid body motion of a UV and flexible motion of the UC.

In the modeling of flexible UC dynamics, we establish the governing equations of the UC dynamics based on the catenary equation method, and apply the shooting method to solve the two-point boundary value problem of the catenary equation. Using this, we propose a new formulation and solution of the governing equations to estimate the space position and forces of the UC end point under the action of concentrated and distributed forces due to underwater currents.

We propose a new mathematical model on the hydrodynamics of a UV affected by the UC dynamics. For this, we map the applied forces of the UC to the dynamics of the UV through rotation matrices, and perform computer simulations to analyze the derived modeling of the UV affected by the UC dynamics. We perform simulations on the UV motion, including surge, heave, sway, and turning motions, for the cases with the UC and without the UC effect, and discuss their results.

## 1. Introduction

Underwater exploration is becoming more and more important, since a vast range of unknown resources in the deep ocean remain undeveloped. The UV can help us better understand marine and other environmental issues, protect Earth's ocean resources from the pollution, and efficiently utilize these resources for human welfare. There have been many types of research worldwide into the design and development of the UV. For example, Deam and Given (1983) summarized the vast research on the ROV, and proposed five steps to develop ROV. Stewart and Auster (1989) submitted a low-cost technology for developing the ROV, which is helpful to designers in related fields. Prestero (2001) described common configurations of torpedo-AUVs, including a fixed propeller installed at the aft end, and control planes (fins) of rudder and elevator located aft. Panish (2009) devised a different configuration for Bluefin, in which all control planes were removed and as a result, the propeller was actuated in the horizontal and vertical directions based on a double gimbal arrangement, acting as both a rudder and an elevator.

Fig. 1 shows that in general, the deep-sea-operated vehicle systems typically consist of a support vessel, winch, UC, and UV. The UC is widely used in the ocean environment, and plays an important role in supplying power and communications between the UV and the support vessel. However, the management and attachment of the UC and the drag relative to the current cause some restrictions on the maneuverability of the UV. Therefore, while analyzing the UV's maneuvering behaviors, estimation of the corresponding effect caused by the UC and the current will be helpful. However, most researchers neglect the effect of the UC, because the UC effect will cause the numerical model to become very complicated and difficult to solve. Therefore, only a few authors deal with this kind of problem by including the effects due to the UC. Several methods with different properties exist for this purpose: Experimental study, Finite Element Methods (FEM), Finite Difference Methods (FDM), Catenary Equations, Lump-Mass-Spring Formulations (LMS), and Finite Segment Approaches (FSA). While all of these methods are based on a particular and generalized mathematical formulation of the problem, experimental study will remain the most reliable method to predict the dynamic behavior of the UC systems. Yoerger et al. (1991) and Hover and Yoerger (1992) measured the motion of a deep UV system. However, the experimental study was time-consuming, costly, and the experiment faced some limitations and difficulties. Buckham et al. (2000) applied the FEM to calculate the

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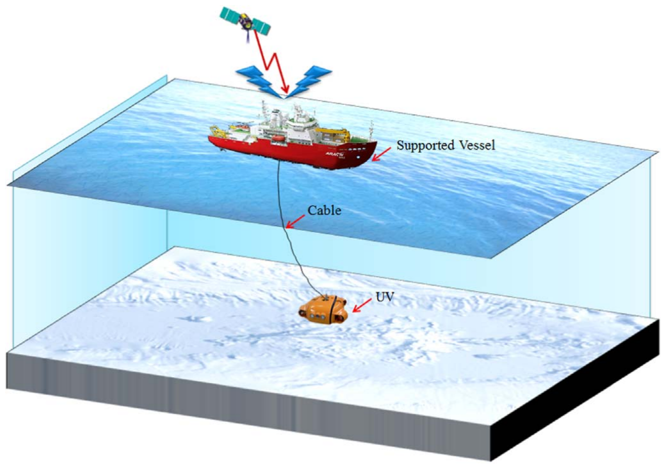


**Fig. 1.** A typical deep-sea-operated vehicle system.

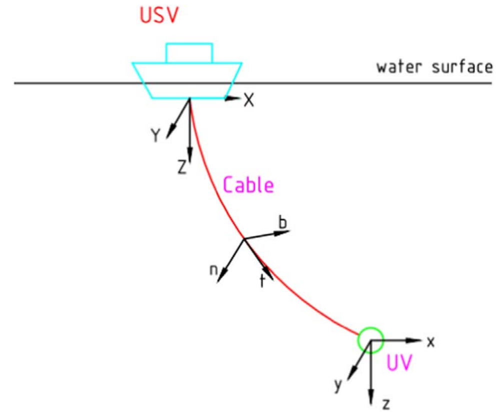


**Fig. 2.** The three coordinates of the system.

tension and bending force on the slack tether attached to the ROV. However, the computational load of this approach is heavy, and it is difficult to incorporate such packages into control system designs. Ablow and Schechter (1983) proposed an implicit FDM to simulate a UC, which has frequently been referenced in the relevant literature. However, if the tension in the UC is lost, their algorithm will become singular. The LMS formulation has a clear physical interpretation, and does not require a large amount of computing. Chai and Varyani (2002) presented a general LMS formulation that allowed static and dynamic analysis of a variety of slender structures. Wingnet and Huston (1976) discussed the FSA for cable dynamics. They modeled the cable as a series of links connected to each other by ball-and-sockets joints. Although some researches on the hydrodynamics of a UC system have been conducted, they have various limitations. Most of them are one- or two-dimensional, and usually they do not discuss the kinematic properties of the UV in detail. Many of these studies require much computer effort, and are certainly not capable of solving the equations in real time, as is required in model-based estimation and control. In fact, existing researches commonly do not consider hydrodynamic loading on the main body of a UV caused by ocean disturbing effects, such as current agitation and motion velocity of the UV itself during UC operation.

Clearly, the UC motion is very complex, but addition of non-linear motion of the UV makes the system more complex. There are many researchers work on modeling and simulating dynamic behavior of UC. However, until now, almost previous studies still exist a knotty problem that how to implement the dynamic analysis of the complete UV and UC system, since the dynamic interaction between UV and the UC is uncertain, complex and difficult to describe; unfortunately, it is not fully studied and carefully analyzed. So, new efficient and reliable modeling methods for the UC and further for the complete UV and UC system should be considered and developed. Thus, in this paper, we present the governing dynamic equation on combined motions of the UV and the UC based on the catenary equation, and apply the shooting method to solve the two-point boundary value problem of the catenary equation.

Catenary equations provide a static representation of cables (Irvine, 1981). It is easier to gain insight into the mechanisms that govern the solution than to understand the FEM representation. Also, catenary equations provide a simple representation of the forces acting on the supports where the cable is attached. The equations are solved faster than FEM equations, and the result is exact. Therefore, this paper proposes a new method that combines catenary equations and the shooting method, which is based on the search method developed by Sagatun (2001) for simulation of the UC in space. The basic theory of catenaries is well established, and the catenary equations provide a simple representation of the forces acting on the supports where the cable is attached. We apply the shooting method to solve the two-point boundary value problem. The shooting method is a mathematical procedure applied to boundary value problems with unknown initial states. Another advantage of the proposed method is that we obtain the dynamic model as a function of physical variables such as positions and forces, and this allows greater ease of interaction with other dynamics, such as a UV at the free end of the UC.

The hydrodynamic numerical model for simulating the UV maneuvering behavior is very important. A general non-linear model for the dynamics of the UV can be derived either using a Newtonian or a Lagrangian method. In order to understand the behavior of the UV maneuvering in an ocean current, we formulate the mathematical model with the UC effect based on the formulae with 6 degrees of freedom (6 DOF) motions formulated in the paper with hydrodynamic coefficients of the UV that we obtained through experiments, and from the literature. We use the catenary equation method to calculate the configuration simulation of the UC connecting to the UV, and solve the corresponding two-end boundary-value problem by using the shooting method. We also apply the 4th Runge–Kutta method to solve the 6 DOF motions of the UV with the UC effect. We describe the compact hydrodynamic model with 6 DOF motions and the numerical solution technique in this paper.

## 2. Mathematical model of system

For a dynamical system, modeling of the system dynamics using

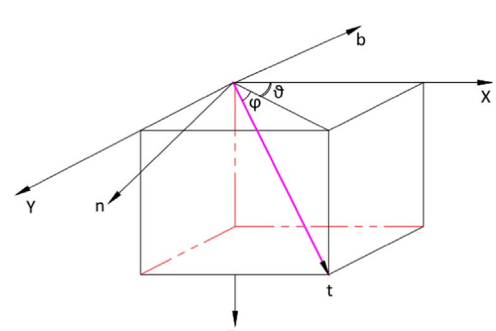


**Fig. 3.** The relative position of two coordinate systems.