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Energy-based motion control of a slender hull unmanned underwater vehicle ☆

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ABSTRACT

This paper presents a motion control system for tracking of attitude and speed of an underactuated slender-hull unmanned underwater vehicle. The feedback control strategy is developed using the Port-Hamiltonian theory. By shaping of the target dynamics (desired dynamic response in closed loop) with particular attention to the target mass matrix, the influence of the unactuated dynamics on the controlled system is suppressed. This results in achievable dynamics independent of stable uncontrolled states. Throughout the design, the insight of the physical phenomena involved is used to propose the desired target dynamics. Integral action is added to the system for robustness and to reject steady disturbances. This is achieved via a change of coordinates that result in input-to-state stable (ISS) target dynamics. As a final step in the design, an anti-windup scheme is implemented to account for limited actuator capacity, namely saturation. The performance of the design is demonstrated through simulation with a high-fidelity model.

1. Introduction

Mathematical models of underwater platforms often present a significant degree of uncertainty. This is because their dynamic response involves complex fluid-body and environmental interactions that are challenging to model over an extensive envelope of operating conditions. The dynamic response to a given excitation can change depending on the platform forward velocity and the proximity of boundaries like the free surface, the sea floor, or other vehicles. In this paper, energy-based control design principles are applied as a means of controlling a vehicle in the presence of such uncertainty.

Motion control designs based on energy-related properties like passivity and dissipativity have been very successful due to their inherent robustness; see, for example, Astolfi et al. (2002) and Fossen (2011) and references therein. A controller designed so that stability depends only on dissipativity properties can result in closed-loop stability under parametric uncertainty; even changes in model structure may be tolerated provided that dissipativity properties remain unchanged (Brogliato et al., 2007). In this paper, we adopt this approach and present a tracking controller for forward speed, roll, pitch and yaw based on the Port-Hamiltonian Theory (van der Schaft, 2000; Ortega et al., 2002).

There have been a number of nonlinear motion control designs for marine craft presented in the literature. A good overview can be found in Woolsey and Techy (2009). Of these, an example of an energy-based design for which passivity is not demonstrated is presented in Woolsey and Techy (2009). In Donaire et al. (2011), the authors present the design of a passive control system for a fully actuated ROV in three degrees of freedom. The present work extends this previous design. In particular, this paper presents the design of a control system for an underactuated UUV for which the centre of buoyancy and gravity is not coincident. The vehicle model used in this work is much more sophisticated, and challenging to control, in that both the restoring forces are considered and the hydrodynamic modeling is more realistic.

The design proposed is based on the Port-Hamiltonian System (PHS) theory. PHS models have a particular structure that incorporates explicitly a scalar function that can represent the total energy stored in the system as well as other functions that describe the structure of the system in terms of energy distribution and dissipation. As its name indicates, the input and output variables of a PHS constitute a port. Through this, the system exchanges energy with its environment.

PHS models are an extension of the canonical equations of motion in classical mechanics developed by Hamilton (Lanczos, 1960). The fundamental feature of PHS models is that they readily show physical

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properties which enable energy-based control design with a physical interpretation of the control law (van der Schaft, 2000; Ortega et al., 2002). In such designs, the control forces are used firstly to shape the potential energy such that its minimum is attained at the desired configuration of the closed-loop system, and secondly to inject damping.

In the rest of the paper, we write the classical dynamic model of a slender-hull underwater vehicle—see Gertler and Hagen (1967) and Fossen (2011)—into a PHS form. This extends the work of Donaire and Perez (2012), which considers open-frame underwater vehicles. We then consider a control design for both forward speed and attitude tracking based on energy shaping and damping assignment such that the closed-loop system retains a PHS form.

Slender-hull underwater vehicles are typically underactuated.[1] These vehicles are controlled by means of tail fins that are used to affect attitude and simultaneously the velocities perpendicular to the direction of travel. When a control surface is deflected a force is generated at the aft of the vehicle. This force is at a distance to the moment reference point, hence it results in a moment. In effect, a deflection causes both a force (in either the sway or heave direction) and a moment resulting in a rotation. Because of this, it is impossible with a vehicle of this kind to control attitude without affecting a linear velocity, or a linear velocity without affecting attitude.

In our controller design, we choose not to control the unactuated vehicle behaviour and demonstrate how a supression-of-dynamics approach can be used to completely remove the uncontrolled behaviour from the target dynamics. This is essential to ensure that the control action does not affect the behaviour of the part of the system being controlled. As a part of this, we highlight the importance of the target mass matrix. We further show how integral action can be added and exploit the PHS form to provide a procedure for control design that ensures stability and robustness to slowly varying disturbances. The addition of integral action can lead to loss of performance when operational conditions result in the saturation of the actuators (thruster and tail fins). We therefore address the issue of actuator saturation using an anti-wind-up control scheme. Finally, we present a numerical case study to illustrate the performance of the proposed control design.

2. Port-Hamiltonian systems

An input-state–output *Port-Hamiltonian system* (PHS) has the following form (van der Schaft, 2006):

$$\dot{\mathbf{x}} = \left(\hat{\mathbf{J}}(\mathbf{x}) - \hat{\mathbf{R}}(\mathbf{x})\right)\frac{\partial \mathcal{H}(\mathbf{x})}{\partial \mathbf{x}} + \hat{\mathbf{G}}(\mathbf{x})\mathbf{u}, \tag{1}$$

$$\mathbf{y} = \hat{\mathbf{G}}^T(\mathbf{x})\frac{\partial \mathcal{H}(\mathbf{x})}{\partial \mathbf{x}}, \tag{2}$$

where $\mathbf{x} \in \mathbb{R}^n$ is the state vector and $\mathcal{H}: \mathbb{R}^n \to \mathbb{R}$ is known as the Hamiltonian. This function can represent the total energy stored in the system. The pair $\mathbf{u}, \mathbf{y} \in \mathbb{R}^m$ are the input and output variables. These are conjugate variables, namely, their inner product represents the power exchanged between the system and the environment. The function $\hat{\mathbf{J}}(\mathbf{x})$ is skew-symmetric and describes the power conserving interconnection structure through which the components of the system exchange energy. The function $\hat{\mathbf{R}}(\mathbf{x}) \geq 0$ is symmetric and captures dissipative phenomena in the system. The matrix $\hat{\mathbf{G}}(\mathbf{x})$ weighs the action of the input on the system and defines the output. From (1) and (2), it follows that

$$\frac{d\mathcal{H}}{dt} = \mathbf{y}^T\mathbf{u} - \frac{\partial \mathcal{H}^T(\mathbf{x})}{\partial \mathbf{x}}\hat{\mathbf{R}}(\mathbf{x})\frac{\partial \mathcal{H}(\mathbf{x})}{\partial \mathbf{x}} \leq \mathbf{y}^T\mathbf{u}, \tag{3}$$

which exhibits the passivity of the PHS model (van der Schaft, 2000).

If one can design the controller such that the resulting closed-loop system takes a PHS form, then the closed-loop system, under certain conditions,[2] is passive and thus stable, and the energy function $\mathcal{H}$ can be used as a Lyapunov candidate. Conditions of symmetry, positiveness, and boundedness on the various functions lead to stability of the state at which the energy attains its minimum. This is a very attractive feature for control design, if we can design a controller such that the closed-loop system can be put into a PHS form and the desired equilibrium point is the point that minimises the closed-loop energy, then we can guarantee stability of the equilibrium point. Moreover, the control system will be stable even if there is model uncertainty (parameters or even model structure) provided that the closed loop PCH form is preserved. This gives robustness to model uncertainty.

The objective is to use the control action $\mathbf{u}$ to achieve a *desired closed-loop system* or *target dynamics* of the form

$$\dot{\mathbf{x}} = \left(\hat{\mathbf{J}}_d(\mathbf{x}) - \hat{\mathbf{R}}_d(\mathbf{x})\right)\frac{\partial \mathcal{H}_d}{\partial \mathbf{x}}, \tag{4}$$

where $\hat{\mathbf{J}}_d(\mathbf{x}) = -\hat{\mathbf{J}}_d^T(\mathbf{x})$, $\hat{\mathbf{R}}_d(\mathbf{x}) \geq 0$, and the desired equilibrium point $\mathbf{x}^*$ minimises $\mathcal{H}_d(\mathbf{x})$. Ortega et al. (2002) provide a general methodology to design a feedback control law $\mathbf{u} = \boldsymbol{\beta}(\mathbf{x})$ that renders the open-loop PHS (1) into the closed loop system (4). This technique is known as *Interconnection and Damping Assignment Passivity-based Control* (IDA-PBC). In such design, the controller modifies the interconnection of the system ($\hat{\mathbf{J}} \to \hat{\mathbf{J}}_d$), assigns damping ($\hat{\mathbf{R}} \to \hat{\mathbf{R}}_d$), and the passivity-based control refers to the fact that the controller re-shapes the energy ($\mathcal{H} \to \mathcal{H}_d$) so that the desired equilibrium point $\mathbf{x}^*$ minimises $\mathcal{H}_d$.

The IDA-PBC design reduces to finding the feedback control law $\mathbf{u} = \boldsymbol{\beta}(\mathbf{x})$ that forces a matching of the dynamics of the open loop system (1) to that of the desired closed-loop system (4), in which $\mathbf{x}^*$ is a stable equilibrium point that minimises $\mathcal{H}_d$. That is, IDA-PBC seeks the control law that solves the following *Matching Problem*:

$$\boldsymbol{\beta}(\mathbf{x}): \quad \left(\hat{\mathbf{J}}_d(\mathbf{x}) - \hat{\mathbf{R}}_d(\mathbf{x})\right)\frac{\partial \hat{\mathbf{H}}_d}{\partial \mathbf{x}} = \left(\hat{\mathbf{J}}(\mathbf{x}) - \hat{\mathbf{R}}(\mathbf{x})\right)\frac{\partial \mathcal{H}}{\partial \mathbf{x}} + \hat{\mathbf{G}}(\mathbf{x})\boldsymbol{\beta}(\mathbf{x}), \tag{5}$$

with the constraint that

$$\mathbf{x}^* = \arg\min_{\mathbf{x}} \mathcal{H}_d(\mathbf{x}). \tag{6}$$

There are different ways of solving the matching problem (5)–(6) depending on the type of system we have and the desired closed-loop system functions, $\hat{\mathbf{J}}_d(\mathbf{x})$, $\hat{\mathbf{R}}_d(\mathbf{x})$, and $\mathcal{H}_d(\mathbf{x})$.

If the system is fully actuated, then one can adopt the desired Hamiltonian $\mathcal{H}_d(\mathbf{x})$ and solve (5) algebraically for the controller. In such cases the easiest control strategy is that which keeps the kinetic energy unmodified and reshapes only the potential energy and damping. If a system is underactuated, and features coupling between the unactuated and actuated states, one has less freedom to chose the potential energy and damping. In this case, it is necessary to modify the kinetic energy and the interconnection. In theory, this can be achieved through a solution of the PDE (5), but for many systems it can be very difficult to find a suitable solution. Alternatively, a method such as Immersion and Invariance (Astolfi et al., 2008) can be used to immerse the system into coordinates where the system is fully actuated. Doing this, however, requires some intuition about a suitable structure and response for the actuated target dynamics. For a system such as the one considered

[1] There are some exceptions to this. Some vehicles in this class are equipped with additional fins at the bow or tunnel thrusters. In both of these cases, independent control in lateral and longitudinal speed is possible. These configurations are not, however, typical.

[2] The Hamiltonian must be bounded from below (van der Schaft, 2000).