High-gain observer-based motion control and stability analysis of a towed underwater vehicle

［課程博士・論文博士共通］

博士学位論文内容要旨
Abstract

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論文題目 Title	High-gain observer-based motion control and stability analysis of a towed underwater vehicle （ハイゲインオブザーバを用いた水中曳航体の運動制御と安定性解析）		

Recently, the importance and necessity of underwater vehicles as a remote observatory platform for marine research have been increased and their objectives cover a lot of ground. A towed underwater vehicle (TUV) is one of such vehicles, which is not equipped with a thruster and has to be tugged by a towing ship to travel. Thus the great advantage of TUVs is that they do not require as much cost as other vehicles. On the other hand, most of TUVs in practice are used passively. Although there have been a lot of efforts for motion control of TUVs, it still has some problems to be solved. In particular, some highly nonlinear dynamics have to be handled, e.g., originating from the flexible towing cable and hydrodynamic forces, but there are few works which address the system nonlinearity directly. Moreover, a control system for TUVs needs to be robust against model uncertainties and to be able to change its operating depth. Hence, the objectives of this study are to develop a motion control method for TUVs by considering its nonlinearity in a direct manner and to confirm the stability of the control system and its robustness in the case of depth tracking control.

This dissertation presents a high-gain observer-based motion control method and stability analysis of a TUV, having two pairs of movable wings at the center and rear (the main and tail wing) to control its depth and attitude actively. A high-gain observer is one of the nonlinear design techniques, which is able to estimate the state considering fully the nonlinearity of the system and to recover the performance of the state-feedback controller.

This dissertation addresses the viewpoint of the order of the control system which varies depending on how many rigid cable segments are applied to model the flexible towing cable. It is desirable that the high-order systems are controlled by the low-order controller. Therefore, the lowest-order model of the TUV is employed to construct the control systems in this work. The stability of the proposed method is analyzed theoretically and simulations are performed to evaluate the control system. According to these results, the robustness of the controller is reinforced by modifying the control approach and performance evaluations by simulations are conducted emphasizing robustness evaluation.

The content of each chapter is as follows.

Chapter 1 explains the background with previous works on motion control of TUVs and the objectives of the dissertation in detail.

Chapter 2 gives the problem setting containing some prerequisite assumptions and the TUV models with different lengths of the towing cable, on which this study will be based. In addition to formulating the dynamical model and its explicit state-space representation, a coordinate-transformed system to design a high-gain observer is derived.

Chapter 3 designs the state-feedback and output-feedback controllers for the lowest-order models consisting of an LQ-control-based method and the high-gain observer in accordance with the coordinate-transformed system in Chapter 2.

Chapter 4 presents stability analyses of the closed-loop control system based on the singular perturbation method. Not only the asymptotic stability of the system is proved but also the region of attraction is estimated. Further, a state-space scaling method to improve the conservativeness of the estimate is proposed. The

comparison to the conventional estimates demonstrates the efficacy of the scaling method and a perspective on a depth tracking control is obtained.

Chapter 5 evaluates the controllers by two types of control simulations. The one is a regulation with initial deviations of the state variables from an equilibrium, where the simulation results are compared to the results of the estimation in Chapter 4. It can be concluded that the original region of attraction may be larger than even the scaled estimation and the LQ-control-based system regulates both the depth and attitude of the vehicle without model uncertainties. The other simulations are the depth tracking control by switching multiple controllers corresponding to different-depth equilibria, where the full operating range of the control system for the model with 100 m cable is investigated as a representative case and is obtained as the depth range from 5 m to 85 m.

The simulation results reveal in Chapter 5 that the controller based on the LQ-control framework with the high-gain observer is effective; however, the control system is not enough robust against model uncertainties, which implies that it is not available for the control of the higher-order systems. Therefore, focusing on the model with 100 m cable, Chapter 6 presents enhancement of robustness of the controller by expanding the control method from the LQ-control-based approach to an LQI-control-based one. Additionally, a linear Kalman filter-based output-feedback controller as a model of the conventional control design is prepared to be compared with the high-gain observer-based controller.

Chapter 7 evaluates the controllers designed in Chapter 6 by three types of control simulations; regulation simulations with initial deviations from an equilibrium similar to the one in Chapter 5, and with some model uncertainties such as a towing velocity change, and a depth tracking ones. It is also investigated whether the controllers can be applied to the higher-order systems or not. The simulation results indicate that on the whole the proposed control system demonstrates better results than those of the linear Kalman filter-based one and has feasibility for the higher-order systems. Besides, the depth tracking control via switching several controllers as in Chapter 5 fails for the LQI-control-based approach. Accordingly, another tracking control method is examined, where the reference depth signal in the control system is altered by degrees. Under some parametric variations, the full operating range of the LQI-based controller for the model with 100 m cable is obtained, which is almost the same range as that with LQ-based controller without model uncertainties.

Chapter 8 summarizes and concludes this work.

Consequently, this dissertation has confirmed the importance of the direct consideration of nonlinear dynamics and has clarified the effectiveness of the high-gain observer-based approach in the control system design of TUVs with the well-known conventional scheme LQ control. The stability analysis in detail is the most unique contributions of this research; particularly the estimation of the region of attraction and the improvement of the conventional estimates by devising a state-space scaling method have high originalities. This scaling method is extensively available not only for problems of underwater vehicles but also other control systems. Meanwhile, as demonstrated by the simulations, the proposed control method has a potential for better control of TUVs and therefore will improve TUVs as more accurate and reliable ocean observatories.