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

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Summary of Doctoral Dissertation

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

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Introduction

In recent years, the importance of exploration of underwater environments has increased due to some environmental problems or the necessity of ocean development. Therefore, underwater vehicles, which can be equipped with various kinds of instruments, have become essential tools for marine investigations. Among such vehicles, towed underwater vehicles (TUVs) are towed by the mothership to travel since they do not have any thrusters inherently, so that the cost for the development can be reduced and the apprehension for the power supply is not necessary.

A lot of efforts have been devoted to motion control problems of TUVs to make the platform more reliable. However, only few previous works have addressed control problems of TUVs by considering their nonlinearities directly. Nonlinear dynamics resulting from hydrodynamic forces and a flexible towing cable seem to be a key to better motion control of TUVs and hence, our laboratory has been working on improving the control systems of TUVs by considering the nonlinear dynamics.

This dissertation presents a high-gain observer-based motion control method and a singular perturbation-based 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. A high-gain observer is a sort of nonlinear design technique and can allow the full consideration of the nonlinearity to estimate the state of the system. The other important viewpoint of the research is the relationship between the orders of the system and controller; generally, the system order is likely to be high for a realistic model while the controller order is required to be lower. Hence, this study adopted the lowest-order model of the TUV to design control systems and its robustness, i.e., whether the controller can be applied to higher-order models or not was evaluated via simulations.

Methodology

Based on a previous theoretic analysis of a control system structure of TUVs, Chapter 2 presents the problem definition for simplicity and dynamical model formulation of the TUV system. This study focused on TUV motions in the vertical plane, and ignored environmental water current and the dynamics of the mothership and wing actuators. The towing speed was assumed to be constant and was set as 4 m/s for the nominal case. The models in accordance with different lengths of the towing cable were considered and the cables were approximated by the lumped-mass method. This means that the order of the system depends on the number of the cable segments, and the maximum number of the segments was set to five. In particular, the model with the cable length 100 m was the main and standard case throughout this research. The measured outputs were set as the depth and attitude of the vehicle, which were the control objectives.

In this work, an LQ-control scheme was employed first to be combined with the high-gain observer in Chapter 3. An equilibrium point was calculated corresponding to each model, so that the depth was the half length of each cable and the vehicle attitude was horizontal. The linearized system around each equilibrium was obtained, and an LQ state-feedback controller was designed by solving the Riccati equation. Chapter 3 also describes the specification of the high-gain observer with respect to the transformed system based on the input-output linearization scheme.

Next, a detailed stability analysis of the LQ-based closed-loop control systems was performed in Chapter 4. The singular perturbation method was used to show an asymptotic stability of the system and to obtain estimate of the region of attraction. The singularly perturbed system and Lyapunov function of the whole system were derived by introducing the scaled estimation error. Applying the conventional approach, the region of attraction was estimated. Moreover, in order to improve the conservativeness of the estimation results, a “state-space scaling method” was devised, which alleviates an impeding effect due to the unbalance of the eigenvalues of a positive-definite matrix in the Lyapunov function.

On the other hand, Chapter 5 evaluates the LQ-based controllers by regulation simulations with initial deviations of the state variables from each equilibrium. An initial deviation was increased gradually and its maximum allowable value was searched for both state-feedback and output-feedback controllers. These results were able to be regarded as a kind of the region of attraction, therefore, were compared with the estimate in Chapter 4. Depth tracking of the system with the cable length 100 m was also investigated by switching multiple controllers with different depth equilibria. Calculating multiple equilibrium points, the LQ feedback gain with respect to each equilibrium was obtained and each state-feedback was connected with the high-gain observer. Thus, the controllers were switched to change the depth of the vehicle. The initial depth was set at 50.205 m to explore the descending and ascending limitations, and then the direct change between the deepest and shallowest depths was attempted.

Finally, an LQI-control scheme was introduced in order to enhance the robustness of the control system in Chapter 6. Using a reference signal of the output, the linear augmented system was derived and the LQI state-feedback controller was constructed. As in Chapter 3, the LQI state-feedback was combined with the high-gain observer. In addition, a linear Kalman filter-based controller was designed as a representative of a conventional LQI-based output-feedback controller. Chapter 7 compares these two controllers by three types of control simulations. First, regulation simulations with initial deviations from an equilibrium were performed similar to the one in Chapter 5. Second, regulations with some model uncertainties as follows were carried out; a towing velocity was changed to faster and slower, hydrodynamic parameters were perturbed ±20% from their nominal values and a payload was +50% increased. Third, depth tracking via mainly the reference signal change was examined with model uncertainties. Further, the LQI-based controllers were applied to the higher-order systems and evaluated similarly by the same simulations.

Results

To begin with, stability analysis in Chapter 4 proved that the equilibrium of the closed-loop system was asymptotically stable. The conventional estimate of the region of attraction resulted in a very conservative value of the state variables due to the unbalance of the eigenvalues of a matrix in the Lyapunov function. In contrast, utilizing the state-space scaling method, the scaled results became at least more than tenfold compared to that with conventional method. Hence somewhat practical estimates were obtained and the efficacy of the scaling method was demonstrated obviously. What is more, regions of attraction for other equilibriums were estimated to extract a perspective on a depth tracking control, where the local regions of attraction indicated overlap and subsumed the neighbor equilibriums each other. Although these estimates of the region of attraction were still conservative, this analysis indicated the correlation between the local regions of attraction and the reachable operating range by switching multiple controllers.

The first half of Chapter 5 reveals the regulation performances of the LQ-based controllers designed in Chapter 3. The results comparison between the simulation and analysis was made as follows.

- For the state-feedback controller the simulation result and the analytical estimate showed the reasonable consistency, although there were some initial conditions under which regulations were successful in the simulation but which were not included in the analytical result.

- For the output-feedback controller, the analytical estimate was smaller than the result of simulations even if the scaled method was employed. The state estimation errors were investigated in detail to ascertain the good estimation performance of the high-gain observer.

- Comparing the limits of the allowable initial deviation and the trajectories of the output, it was concluded that the output-feedback controller recovered the performance of the state-feedback controller.

Thus the LQ-control-based system without model uncertainties was able to regulate both the depth and attitude of the vehicle. By contrast, the robust performance of the LQ-based control system were poor. For instance, even without initial deviations the regulation was failed with the towing speed 6 m/s, which is faster than the nominal value. Therefore, the robustness of the controller had to be increased in order to apply the control system to the higher-order systems.

Meanwhile, depth tracking control simulations in the second half of Chapter 5 disclosed that the full operating range of the LQ-based switching control system for the model with 100 m cable was from 5.205 m to 85.205 m, which was covered by a few controllers. The control system also succeeded in keeping the attitude of the vehicle horizontal. The direct change of the depth between 5.205 m and 85.205 m was successful with the trajectory 85.205 m → 5.205 m, but not with 5.205 m → 85.205 m. In other words, the region of attraction of the controller with the depth 85.205 m did not contain the equilibrium of 5.205 m. Consequently, the connecting controllers were necessary to change the vehicle depth as 5.205 m → 85.205 m.

According to the simulation results reported in Chapter 7, the demonstrated performance of the LQI-based controllers designed in Chapter 6 were summarized as follows.

- In the regulations, the proposed control system showed better results than the Kalman filter-based conventional one with respect to not only the range of the maximum initial deviation but also the transient response.
- In the robust performance evaluations, the results with the conventional controller indicated the unfavorable oscillatory loci with -20% hydrodynamic parameters. This seemed to originate from the performance of the linear Kalman observer. While the proposed controller maintained almost the same steady performance with all the parameter combinations.
- The depth tracking control via switching several controllers as in Chapter 5 was not able to apply to the LQI-control-based approach directly. Instead of the method, the reference depth signal was changed in a step manner. The final obtained operating range for the proposed controller was from 5.205 m to 84.205 m, which was almost as large as that of LQ-based controller without model uncertainties.
- These observations were basically the same or rather conspicuous with the higher-order systems. In particular, some perturbed parameters prevented the conventional controller from regulating the highest-order system. Contrary to this, the proposed controller showed the smooth convergence regardless of the order of the model.

Hence, the proposed control system demonstrates more desirable results than those of the linear Kalman filter-based one through the whole. The LQI-based controller with the high-gain observer had a feasibility for the higher-order systems and its full operating range could be extended almost the same as that with the LQ-based controller, even with some model variations.

Conclusions

The high-gain observer-based motion control method of a TUV presented in this dissertation revealed the importance of the direct consideration of nonlinearity of the system. The most unique contribution of this research was a state-space scaling method in the stability analysis in Chapter 4, which was devised to improve a conventional conservative estimate of a region of attraction. This method can be extensively available for other control systems. The effectiveness of the proposed control approach was evaluated via simulations including depth change as well. The LQI-based controller was successfully applied to the higher-order systems and showed better performance with some model uncertainties compared to the conventional controller.

These results imply that the proposed controller has a potential for better control of TUVs although the controller is based on the lowest-order model; however, there are some remaining works to apply this method to practical applications. For example, environmental water current and other external disturbance factors must be taken into consideration, and the experimental evaluation will need to be performed to ensure the validity of the study. Hence, further investigations will make the presented method more practical and will advance TUVs as more reliable ocean observation platforms.