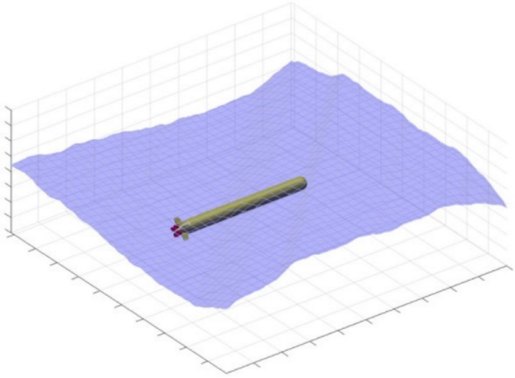
Adaptive Control of Autonomous Unmanned Vehicle in Presence of Environmental Variation



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Autonomous unmanned vehicles operate in a variable environment, often out of reach of the operator, and thus are required to have the ability to automatically adjust parameters in response to disturbances and changes in characteristics. Therefore, Mitsubishi Heavy Industries, Ltd. has been working on the development of an adaptive controller that can add an automatic adjustment function to existing control systems. This report outlines the technology, and describes the results of its verification through simulation using an example case of suppressing the oscillation of an autonomous underwater vehicles moving through an ocean wave environment.

1. Introduction

In recent years, with the increasing need for manpower saving, the development of autonomous unmanned vehicles such as Autonomous Aerial Vehicles (AAVs), Autonomous Underwater Vehicles (AUVs), Autonomous Surface Vehicles (ASVs), and Autonomous Ground Vehicles (AGVs) has been accelerating. The applications of autonomous unmanned vehicles include measuring, exploration, inspection, and logistics, and they are expected to play an active role in a variety of fields.

When operating autonomous unmanned vehicles, disturbances and changes in characteristics can be problematic. These include, for example, change in wind or the weight of the cargo being transported for an AAV, change in ocean waves, seawater temperature, or seawater salinity for an AUV, change in water waves for an ASV, and change in road surface conditions for an AGV. If parameters need to be readjusted for each of these changes, the autonomy and convenience of the product will be limited. In particular, when operating an autonomous unmanned vehicle on a long-duration, long-distance mission, it would be a major setback to have the vehicle return for readjustment. In addition, for AAVs flying in mountainous areas where radio waves cannot reach and AUVs moving underwater, it is difficult for the operator to make adjustments remotely, so a function to automatically deal with disturbances and changes in characteristics is required.

This report describes the development of an adaptive control system that automatically makes adjustments in response to disturbances and changes in characteristics, using an AUV as an example. AUVs can operate autonomously underwater without operation by an operator, and their use is expected to expand to inspection of pipelines and submarine communication cables, deep-sea exploration, and other applications. AUVs can be subject to various disturbances and changes in characteristics during travel, such as differences in seawater salinity, changes in buoyancy balance caused by dropping payloads, ocean waves and rudder failure. Therefore, we are aiming to implement the adaptive control to achieve precise motion control and to apply them to more complex missions.

One of the representative methods of adaptive control is a Model Reference Adaptive Control System (MRACS). Recently, L1 adaptive control[(1)] has been proposed as a method to achieve both robustness and adaptation speed, which were considered to be issues of MRACS. The

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L1 adaptive control incorporates a low-pass filter in an MRACS to decouple the estimation loop from the adaptation loop so that high-frequency adaptation input signals that adversely affect the robustness of the system are not generated even when estimating rapidly changing disturbances or sudden changes in characteristics, and is applied to aircraft, etc(2).

In the study reported in this report, we designed L1 adaptive controllers for longitudinal motion (pitch) and lateral motions (roll and yaw), respectively, to add an adaptive control function to the AUV's attitude control system. These adaptive controllers are installed anteriorly to existing attitude controllers, such as PID (Proportional–Integral–Derivative) controllers, to adjust control inputs in response to disturbances and changes in characteristics. In addition, we verified the performance of the developed adaptive controllers by simulating the oscillation suppression control of an AUV in irregular ocean waves as an example.

2. AUV motion model

This chapter assumes an AUV with a stern thruster and a stern X rudder as shown in **Figure 1**. The 6- Degrees of Freedom (DOF) equations of motion of the AUV can be separated into longitudinal and lateral motions when linearized under appropriate assumptions, such as constant travelling speed and symmetry of the vehicle.

It is assumed here that the roll angle, pitch angle, and yaw angle of the AUV are controlled by independent 2-DOF PID controllers, respectively. **Figure 2** shows this control schematically. In this report, we designed L1 adaptive controllers using reference models consisting of a closed loop system which includes a longitudinal motion model and a pitch angle controller, and a lateral motion model and roll angle and yaw angle controllers, respectively. This allows for designing adaptive controllers that offset the effects of disturbances and changes in characteristics by adjusting command values to the existing PID controller.

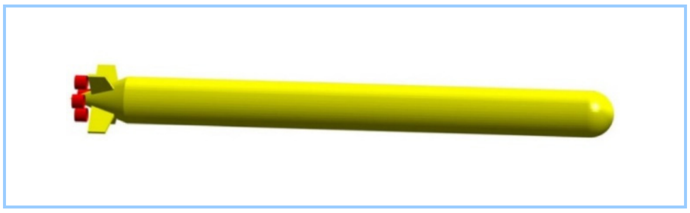

Figure 1 Illustration of AUV

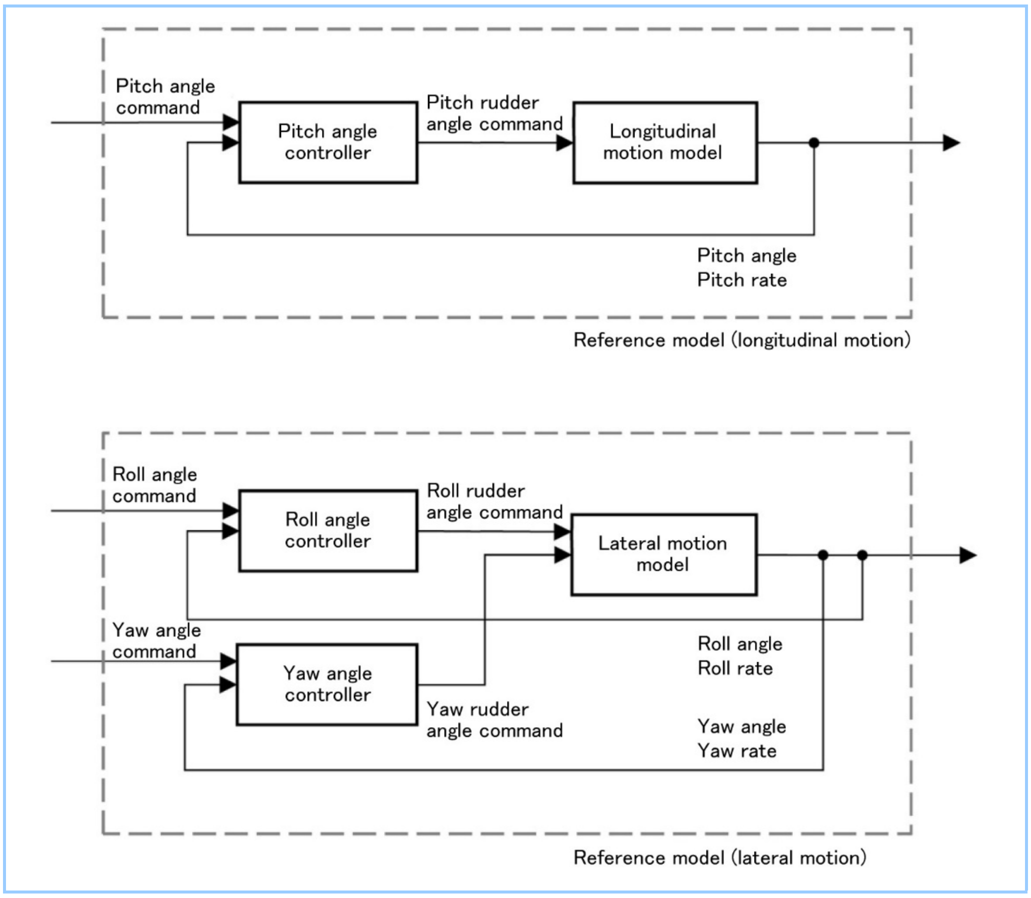

Figure 2 Reference models

3. L1 adaptive control system

The L1 adaptive controller consists of a state predictor, an adaptation law, and a control law, as shown in **Figure 3**. Each component is briefly described below.

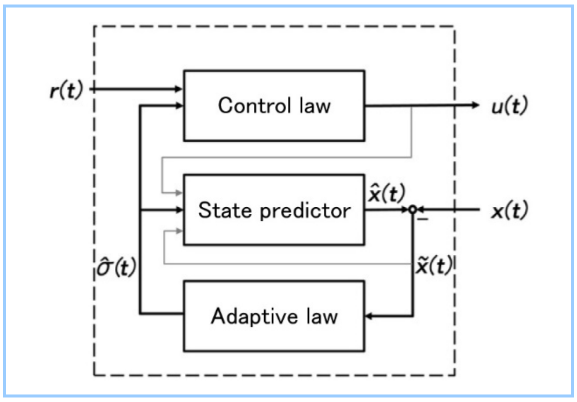

Figure 3 L1 adaptive controller

The state predictor estimates the state of the AUV using the reference models consisting of a closed loop system shown in Figure 2 described in the previous chapter. The state variable to be estimated, $x(t)$ consists of the attitude angle, velocity, angular velocity, and the integral of each PID controller, the estimation equation includes an estimate of the uncertainty $\hat{\sigma}(t)$, caused by disturbances and characteristic changes, in addition to the state variable estimate $\hat{x}(t)$.

The adaptive law calculates $\hat{\sigma}(t)$ based on the estimation error $\tilde{x}(t) = \hat{x}(t) - x(t)$ in the state predictor. $\hat{\sigma}(t)$ is a piecewise constant function with respect to time, which is set to a value that cancels the estimation error $\tilde{x}(t)$ at each update cycle T_s.

The control law processes the command value $r(t)$ by subtracting an uncertainty estimate $\hat{\sigma}(t)$, and blocking high-frequency components through a low-pass filter, and outputs the obtained result as the adaptive input $u(t)$ to offset the effects of disturbances and changes in characteristics acting on the system.

We designed the L1 adaptive controllers described above for the longitudinal and lateral motions of the AUV respectively, and inserted them into the existing feedback control loop to obtain the adaptive control system shown in **Figure 4**. The adaptive controller for longitudinal motion shapes the pitch angle commands and the adaptive controller for lateral motion shapes the roll and yaw commands to automatically make adjustments in response to disturbances and changes in characteristics. The details of the L1 adaptive control design for AUV are described in Reference(3).

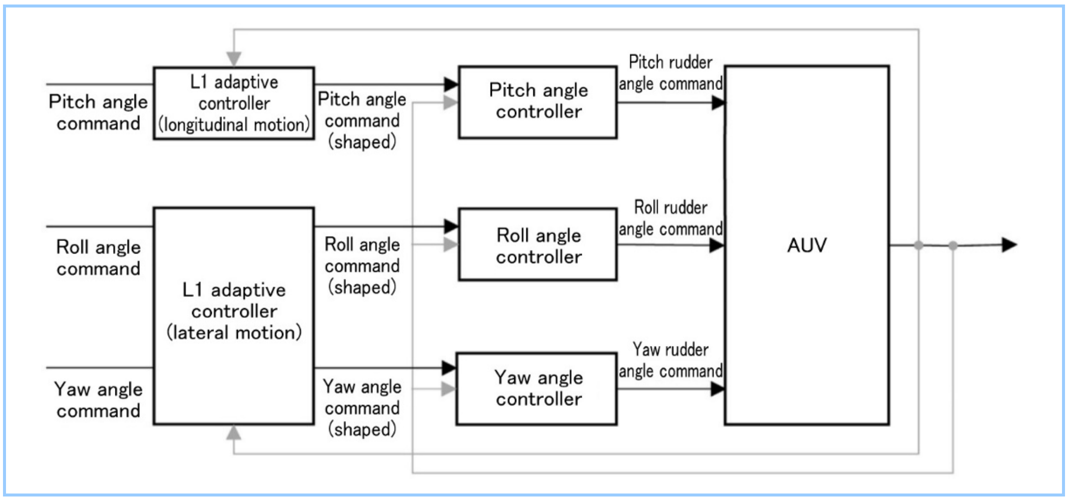

Figure 4 Adaptive control system

4. Verification through simulation

We verified the performance of the designed L1 adaptive controller by using an example case of suppressing the ocean wave-induced oscillation of an AUV travelling near the surface of the water. The simulation reproduced the motion of the AUV travelling in irregular waves using a 6-DOF nonlinear motion model of the AUV and wave spectra that show the ratio of energy possessed by the component waves of each frequency in the irregular waves.

Figure 5 schematically shows the sailing scenario used for the verification, in which the AUV travels at a speed of 4 kt and a depth of around 2 m targeted for the roll, pitch, and yaw angles of 0°. For the ocean waves in the simulation, two-dimensional irregular waves were reproduced by superposing elementary waves based on the ISSC spectrum proposed by the International Ship and Offshore Structures Congress (ISSC), which is suitable for simulating waves in the open sea. The direction of the ocean waves was set at 45 degrees against the direction of the travelling line, the significant wave height was set to 3.72 m, and the significant wave period was set to 12.5 seconds.

Figure 6 shows the attitude angle response of the AUV when the simulation under the conditions described above was conducted. The solid and dashed lines represent the results with and without shaping of the command values using the L1 adaptive control, respectively. These results indicate that the vibration was suppressed in terms of all of roll, pitch, and yaw by the shaping. Comparing the peak values of the attitude angle vibration, oscillation suppression effects of 41% for the pitch angle, 32% for the roll angle, and 46% for the yaw angle were confirmed.

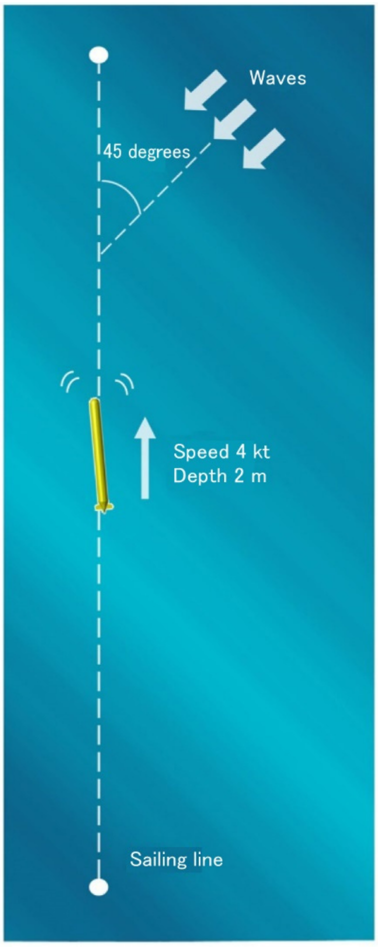

Figure 5 Sailing scenario

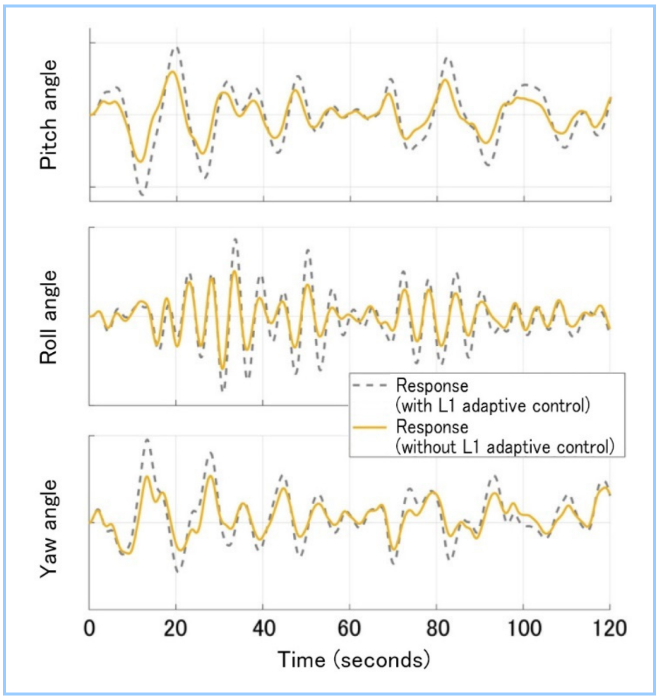

Figure 6 Simulation results

5. Conclusion

In the study reported in this report, we designed L1 adaptive controllers for a 2-DOF PID control system that independently controls roll, pitch, and yaw to deal with disturbance and changes in dynamic characteristics by shaping the target signals. In addition, we verified that the designed L1 adaptive controllers are effective in suppressing wave oscillation through a travelling simulation using a 6-DOF nonlinear motion model in which two-dimensional irregular waves were reproduced by spectral decomposition.

We believe that the results presented in this report will contribute to improving the performance of autonomous unmanned vehicles such as AAVs, AUVs, ASVs, and AGVs, and we will promote the application of this technology to our products.

References

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