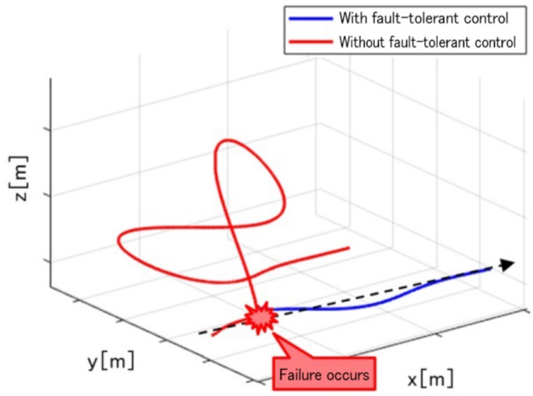
Development of Fault-Tolerant Control for Unmanned Vehicles Using Redundancy Actuators



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Unmanned vehicles are required to have resiliency that enables them to autonomously continue their operation even when actuator failures occur. This report proposes a fault-tolerant control for unmanned vehicles using redundantly arranged actuators to achieve the resiliency. Specifically, we have developed a fault-tolerant control function that allows unmanned vehicles to continue their travel in the event of an actuator failure. This function was realized with a failure detector developed to detect actuator failures by comparison of the rudder angles estimated for each actuator, as well as a fault decoupling controller developed to remove the effect of the failure based on the detected actuator failure information. Furthermore, we conducted a simulative evaluation to verify the effectiveness of the developed fault-tolerant control.

1. Introduction

Against the background where manpower saving and replacement of human work in hazardous environments are demanded, many unmanned vehicles such as automated guided vehicles (AGVs), unmanned aerial vehicles (UAVs), and autonomous underwater vehicles (AUVs) have been developed in recent years. These unmanned vehicles operate in a place without human intervention. Considering such characteristic, they must be resilient enough to continue their travel autonomously even in the event of actuator failures (1).

One of the methods to achieve the resiliency is thought to be fault-tolerant control, which uses redundant actuators arranged in such a way that multiple actuators affect a single action so that even if an actuator fails, the control can be maintained by using other actuators. For example, it has been reported that the AUV "Yumeiruka" equipped with four redundant rudders can maintain the minimum action controllability required for its operation even when some of the rudders fail due to the robust control designed for normal rudder operation, although the control performance deteriorates (2). In addition, for UAVs, robust model predictive control, which takes into account the effects of failures in advance, has been provided so as to enable hovering without loss of stability even when some of the propeller motors fail (3).

On the other hand, methods for detecting actuator failures and proactively using the detected abnormalities to deal with failures have also been studied. For example, the control mixer method (4)(5)(6), which calculates the input distribution by solving simultaneous equations so that the actuator output becomes equal before and after a failure, as well as a method that has multiple controllers designed for predefined failure modes in advance and switches them appropriately when a failure occurs (7) have been proposed. However, when a failure occurs that cannot be detected by sensors, for example, in the case the link mechanism connected to the motor sticks due to external force, it is necessary to build a separate failure detector that detects the failure using signals sensed from the controlled object.

In this report, we introduce a fault-tolerant control that takes advantage of the redundant actuators installed in unmanned vehicles. Specifically, we have developed a fault-tolerant control

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function that allows unmanned vehicles to continue their travel in the event of an actuator failure [8]. To realize this function, we constructed a failure detector that detects an actuator failure by estimating the state of each actuator and comparing the estimated rudder angle values, and a fault-tolerant controller that removes the effect of the failure based on the detected actuator failure information [8].

2. Unmanned vehicle with redundant actuators

Figure 1 and **Figure 2** show an AUV equipped with four rudders as an example of an unmanned vehicle to be controlled by the function described in this report. The vehicle travels in the $x, y,$ and z directions by moving forward while having an attitude motion (roll, pitch, and yaw), which are rotational motion around the three axes of $x, y, and\ z$, respectively, of the vehicle coordinate system. For example, to move upward in the depth direction, the vehicle moves forward with its pitch angle directed upward. The equation (1) represents the simultaneous differential equations for the attitude motion of an unmanned vehicle at a certain equilibrium point.

$$\frac{d}{dt}\begin{bmatrix}\Delta p\\ \Delta q\\ \Delta r\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & a_{22} & a_{23}\\ a_{31} & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\Delta p\\ \Delta q\\ \Delta r\end{bmatrix}+\begin{bmatrix}e_{11} & e_{12}\\ e_{21} & e_{22}\\ e_{31} & e_{32}\end{bmatrix}\begin{bmatrix}\Delta\phi\\ \Delta\theta\end{bmatrix}+\begin{bmatrix}b_{11} & b_{12} & b_{13} & b_{14}\\ b_{21} & b_{22} & b_{23} & b_{24}\\ b_{31} & b_{32} & b_{33} & b_{34}\end{bmatrix}\begin{bmatrix}\Delta\delta r_1\\ \Delta\delta r_2\\ \Delta\delta r_3\\ \Delta\delta r_4\end{bmatrix} \quad (1)$$

where $a_{ij}, b_{ij},$ and e_{ij} are the coefficients of the equation of motion and Δ is the amount of change from the equilibrium point. $\theta, \emptyset$ are the attitude angles shown in Figure 1 and Figure 2, $p, q,$ and r are the attitude angular velocities, and δr_i is the rudder angle of rudder #i operated by the controller.

The unmanned vehicle to be controlled in this study has redundant actuators, and the number of actuators that can be used for attitude motion of the three axes is four or more.

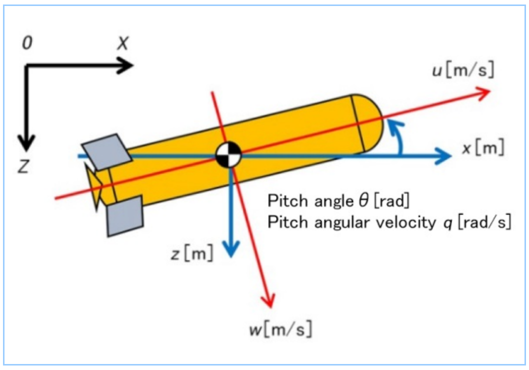

Figure1 X-Z plane view of unmanned vehicle (AUV)

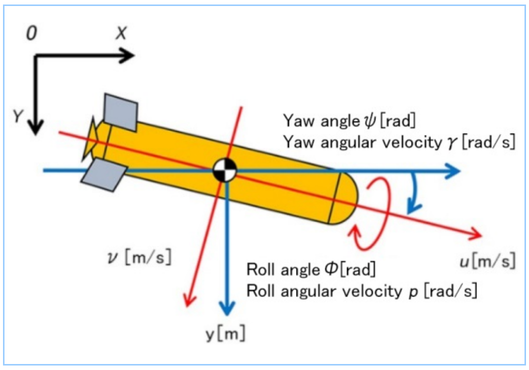

Figure 2 X-Y plane view of unmanned vehicle (AUV)

3. Development of fault-tolerant control

Figure 3 shows a block diagram of the developed fault-tolerant control function. The fault-tolerant control function consists of a failure detector that estimates the location and magnitude of actuator failures and a fault-tolerant controller that uses the fault state quantity output from the failure detector to cancel the effects of failures.

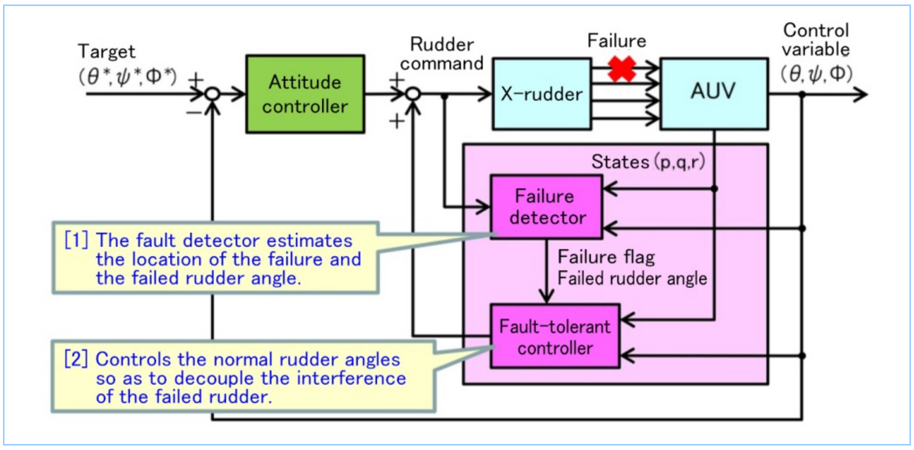

Figure 3 Block diagram of fault-tolerant controller

3.1 Development of failure detector

Figure 4 shows a block diagram of the failure detector. The failure detector estimates the location and magnitude of actuator failures from the inputs and outputs of the unmanned vehicle. It is common to use an observer that can estimate the state using the results of sensing the attitude motion of the unmanned vehicle and the motion model of the vehicle. However, when the actuators are redundantly arranged as shown in Figure 1, the number of actuators to be estimated, 4, is larger than the number of states, 3, so a single observer cannot accurately estimate the operation quantity.

Therefore, assuming that one actuator is normal, we constructed observers that estimate other actuator operation quantities for each actuator. This allows the reduction in the number of actuator operation quantities to be estimated by the observer, so that the number of actuator operation quantities to be estimated is the same as the number of states. For actuators assumed to be normal, the input quantity from the controller is regarded as the actuator operation quantity.

As an example, equation (2) shows the system to be estimated assuming rudder #1 is normal. In this equation, δr_i^{cmd} represents the control input of rudder #i.

$$\frac{d}{dt}\begin{bmatrix}\Delta p\\ \Delta q\\ \Delta r\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & a_{22} & a_{23}\\ a_{31} & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\Delta p\\ \Delta q\\ \Delta r\end{bmatrix}+\begin{bmatrix}e_{11} & e_{12}\\ e_{21} & e_{22}\\ e_{31} & e_{32}\end{bmatrix}\begin{bmatrix}\Delta\phi\\ \Delta\theta\end{bmatrix}+\begin{bmatrix}b_{12} & b_{13} & b_{14}\\ b_{22} & b_{23} & b_{24}\\ b_{32} & b_{33} & b_{34}\end{bmatrix}\begin{bmatrix}\Delta\delta r_2\\ \Delta\delta r_3\\ \Delta\delta r_4\end{bmatrix}$$

$$+\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}\Delta\delta r_1^{cmd} \qquad (2)$$

In equation (2), the rank of the coefficients of the three items on the right-hand side pertaining to rudders #2, #3, and #4 is 3, so the amount of rudder operation can be estimated using the pseudo-inverse matrix.

As shown in Figure 4, the actuator that has failed is determined by comparing multiple operation quantities estimated for the same actuator among the operation quantities estimated by the configured observer. For example, the estimated values for rudder #1 are $\widetilde{\delta r}_1^2$ estimated assuming rudder #2 is normal, $\widetilde{\delta r}_1^3$ estimated assuming rudder #3 is normal, and $\widetilde{\delta r}_1^4$ estimated assuming rudder #4 is normal. If either of rudder #2, #3, or #4 fails, there will be a difference between the control input and the rudder operation quantity, so the operation quantity estimated assuming the failed rudder is normal will have a deviation from the other estimated values.

Therefore, the failure judgment logic for each actuator determines the actuator with the largest deviation from the average value of the estimated operation quantity output from the three observers as a failure candidate. As an example, **Figure 5** shows a flowchart of the failure judgment logic for rudder #1.

Finally, actuator failure is determined with unanimity of the failure candidate flags output from the three failure determination logics. The failure estimation value is the average value of the estimated operation quantities, taking into account the estimation error of the observers.

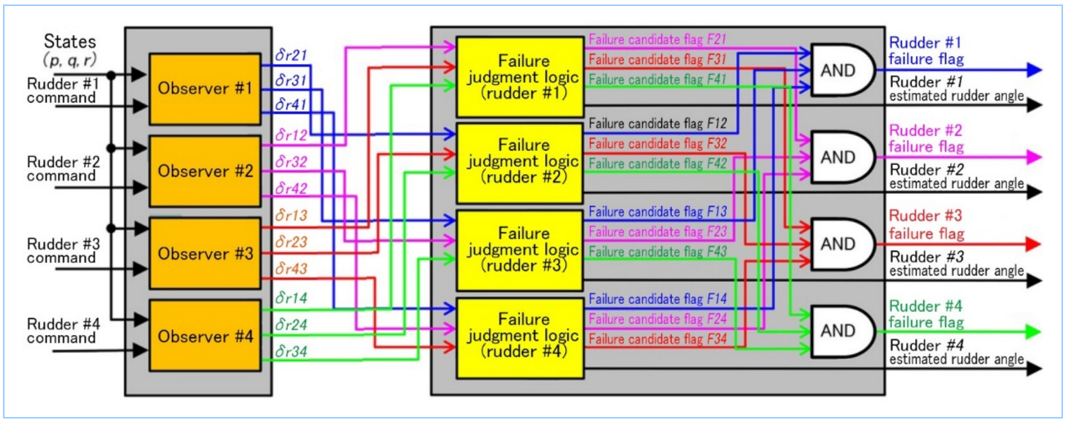

Figure 4 Block diagram of failure detector

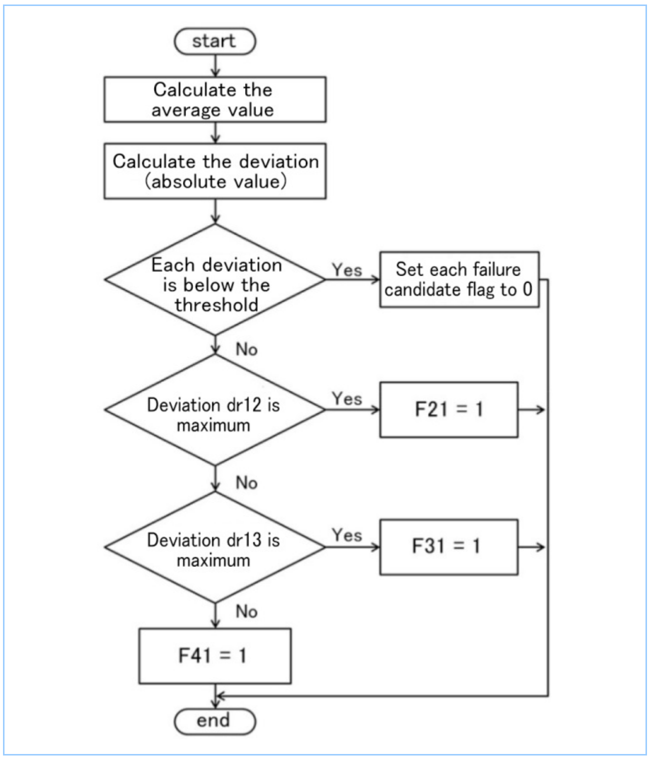

Figure 5 Flowchart of failure judgment logic (Rudder #1 failure for example)

3.2 Development of fault-tolerant controller

The decoupling controller is based on a decoupling control law that cancels the effect of a failed actuator on the vehicle by correcting the command values of the remaining actuators based on the estimated results of the failed actuator output from the failure detector.

For example, equation (3) shows the AUV state equation in the case of a rudder #1 failure. The failed rudder becomes uncontrollable and acts as a disturbance force on each motion axis. The number of controllable actuators becomes three, and the coefficients of the three items are degenerated.

$$\frac{d}{dt}\begin{bmatrix}\Delta p\\ \Delta q\\ \Delta r\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & a_{22} & a_{23}\\ a_{31} & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\Delta p\\ \Delta q\\ \Delta r\end{bmatrix}+\begin{bmatrix}e_{11} & e_{12}\\ e_{21} & e_{22}\\ e_{31} & e_{32}\end{bmatrix}\begin{bmatrix}\Delta\phi\\ \Delta\theta\end{bmatrix}+\begin{bmatrix}b_{12} & b_{13} & b_{14}\\ b_{22} & b_{23} & b_{24}\\ b_{32} & b_{33} & b_{34}\end{bmatrix}\begin{bmatrix}\Delta\delta r_2\\ \Delta\delta r_3\\ \Delta\delta r_4\end{bmatrix}$$

$$+\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}\Delta\delta r_1^{failed} \tag{3}$$

In order to decouple the failed actuator, by transforming equation (3) so that the accelerated angular velocity of the axes of motion (roll angle, pitch angle, and yaw angle) becomes zero and solving with respect to the normal actuator, the rudder angle correction amount can be obtained.

4. Verification with simulation

4.1 Simulation condition

Using an AUV as an example, the effectiveness of the developed fault-tolerant control was verified. As the simulation condition, a case in which a rudder fails while the AUV is travelling straight ahead was considered. The assumed actuator failure used for this verification was the sticking of one of the X rudders of the AUV that occurred due to external forces while travelling straight ahead.

4.2 Simulation result

Figure 6 shows the 3D vehicle track simulation result. The result indicates that when the fault-tolerant control was not applied (red line), the vehicle moved up significantly due to the actuator failure, resulting in the track that deviated significantly from the target track. When the fault-tolerant control was applied (blue line), the effect of the failure was suppressed and the vehicle was able to follow the target track even after the failure occurred.

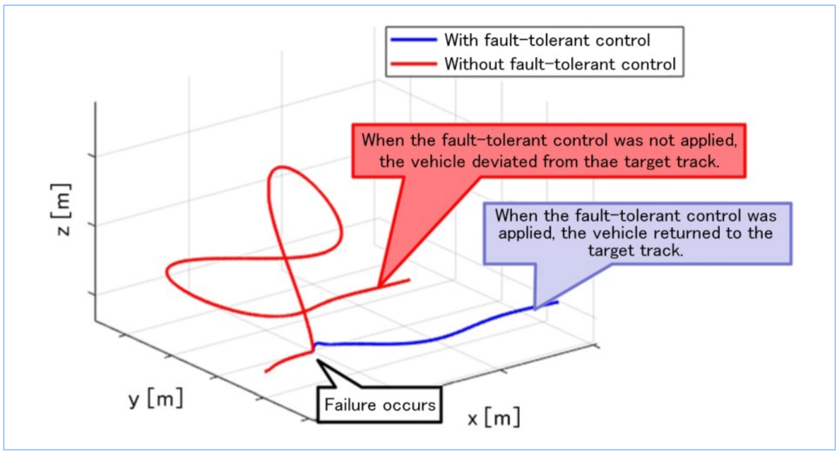

Figure 6 Simulation result (3D vehicle track)

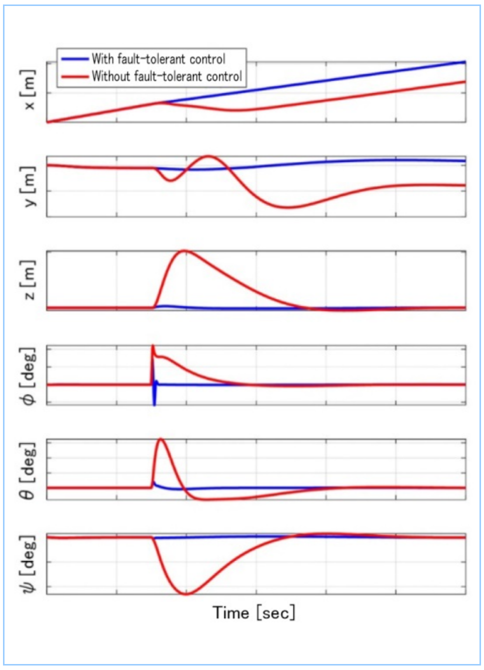

Figure 7 Simulation result (position and attitude angle)

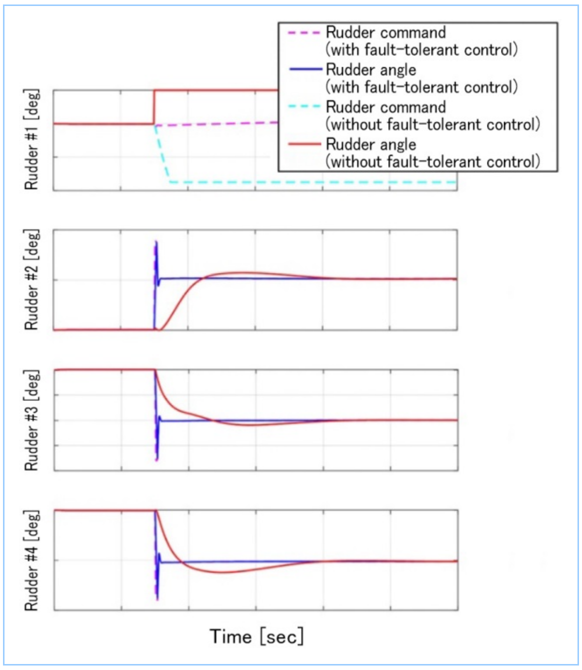

Figure 8 Simulation result (rudder angle)

Figure 7 shows the AUV positions and AUV attitude angles simulation results. Without the fault-tolerant control, the AUV deviated from the target track significantly in both the y-axis and z-axis directions due to the effects of the failure. On the other hand, it can be confirmed that applying the fault-tolerant control reduced the deviation from the target.

Figure 8 shows the rudder operation quantity simulation results. It can be seen that the failure of rudder #1 was immediately detected by the failure detector, and the effect of the failure was canceled by the normal rudders using the fault-tolerant controller.

5. Conclusion

We have developed, for unmanned vehicles with redundant actuators, a fault detector which consists of observers constructed for each actuator, and a fault-tolerant controller that reduces the effect of an actuator failure by canceling the effect of the failed actuator with normal actuators.

As a result of the simulation of a rudder sticking failure using an AUV as an example, it was confirmed that the control deviation at the time of a failure could be reduced by applying the fault-tolerant control, and that the developed fault-tolerant control was effective against actuator failures.

We believe that the result described in this report will contribute to improving the resiliency of vehicle products (AGVs, UAVs, and AUVs) that have redundant actuators, and we will promote its application to our products.

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