Sensor Fault Tolerant Control for AUVs Based on Replace Control

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Abstract: To improve the reliability of the motion control system for an autonomous underwater vehicle (AUV), sensor fault tolerant control based on replace control was talked about. This paper analyzed the decoupling controller and the sensor system firstly, and proposed a fault tolerant control strategy based on the ideas of replacing the fault sensor outputs by the sliding-mode observer outputs (also called replace control). For the irrecoverable sensor faults, the strategy minimized the damage to the AUV. For the jumping faults of sensors, replace control is used during jumping. The simulation results proved the validity of the strategy.

Keywords: Autonomous underwater vehicle (AUV), Decoupling control, Sensor fault tolerant control, Replace control, Sliding-mode observer.

1. Introduction

Autonomous Underwater Vehicle (AUV), because of the importance in business and military and many challenges in technology, more and more scientists and technicians take it seriously, and have carried out a lot of research work.

Fig. 1 shows the whole flow chart of the AUV control system. Planning system produces the AUV location information during the next time, Controller calculates the force and moment by comparing planning information of planning system and information of sensor after measuring, and then obtains the voltage of each thruster by the thrust allocation. Finally, sensors send the AUV message during the next time to the controller, thus forming a complete feedback control system.

Fig. 1. Motion control system of the AUV.

In the control system, sensors provide the actual information for the AUV. If the sensors break down during the use, its outputs will no longer reflect the real value, it may lead to paralysis of the entire
system. In order to guarantee the AUV successfully complete its mission, there is need to build a sensor fault-tolerant control system for monitoring and diagnosis and treatment.

Fault-tolerant control system mainly includes three parts: fault detection, fault location and fault handling (fault-tolerant control). At present, there are many fault processing methods, such as the method based on the analytical model or based on artificial intelligence. In this paper, considering the hardware redundancy of sensors in actual work is not large, output observer is proposed to instead the fault sensor outputs of fault-tolerant control method and fault handling strategy. This strategy doesn’t need to increase additional sensors, it also can be called replace control strategy.

2. Decoupling Control

Decoupling control is of great significance in industrial process control. Industrial processes usually don’t want the change of a setted value to cause big swings in other controlled variables. The system after decoupling is better than the general multivariable systems, no matter from setting or reliability. Therefore, when designing the controller, we should avoid the mutual coupling.

For AUVs, the motion for all degrees of freedom (DOF) is coupled to each other. It is difficult to qualitatively describe and express the coupling. In order to avoid the difficulties of mutual coupling, we consider decoupling for each DOF, and design a controller (the controller for each DOF is the nonlinear function of the deviation and the deviation change rate) on each DOF. Here, we adopt a novel, simple and practical control method – S surface control. The structure of the controller is simple and the quantity of input is little, it is suitable for nonlinear system. The controller combines the ideas of fuzzy control with PID control, and it is not only simplified the controller design, but also can guarantee the effect of control, which has been adopted successfully in real sea test of AUV.

Let’s design a S surface controller on each DOF for the AUV:

\[ u_i = 2.0 / \left(1.0 + e^{(-k_i e_i - k_{i2} \dot{e}_i)}\right) - 1.0 + \Delta u_i \]  
\[ f_i = K_i u_i \quad (i = 1, 2, \ldots, 6), \]

where \( e_i \) and \( \dot{e}_i \) are the input information of \( i \) DOF (deviation and the deviation change rate, normalized processed), \( u_i \) is the control output of \( i \) DOF, \( k_{i1} \) and \( k_{i2} \) corresponding to the control parameters of deviation and rate of change respectively, and the changing velocity of the corresponding DOF can be changed. \( f_i \) is the magnitude of the required force, \( Ki \) is proportion coefficient, \( i=1, 2, \ldots, 6 \), represents six DOF for the AUV motion: surge, sway, heave, yaw, pitch, roll. \( \Delta u_i \) is magnitude of the interference force obtained by the adaptive ways (normalization). Adaptive ways as follows:

a) Determine whether the rate of the AUV motion on DOF \( i \) is less than a set threshold. If it is, turn to (b), if not, to (c).

b) Give the deviation value of this DOF a setted of array, at the same time, add 1 to the setted count value. When the count value reaches a predetermined value, turn to (d).

c) Put the value of array forward one bit, and the count value minus 1, turn to (a).

d) Weighted average the value of the array, use the mean value of the offset to calculate the deviation of control output. The output of adaptive adjustment controller, In order to eliminate the fixed deviation, and set the count value and array to zero, then carry out the next cycle.

Then we have designed a six DOF controller. The controller of each DOF presents the control output, based on the current deviation and the rate of deviation change. But the input of the controller depends on the differences and change rate between the output of planning device and the measurement of sensors.

3. Sensor System

In this paper, a certain kind of AUV developed by Harbin engineering university led as research object. The installation of the sensors is shown in Table 1 below. The sound and light visual sensors (6012 imaging sonar, 3D imaging sonar and TV) of the AUV mainly are used for the tracking and recognition of underwater target, the impact on AUV motion control is not big. GPS signals are used for positioning correction when the AUV is long-endurance. For this paper, the replace control research of AUV is mainly aimed at the sensors which can affect the robot’s position, such as fiber optic gyro, Doppler velocimeter (DVL), positioning sonar, altimeter sonar and depth gauge.

There are three forms when the AUV sensors break down, that is, (1) the outputs information of sensors remain unchanged; (2) the outputs information of sensors jump within a certain time or period; (3) the outputs information of sensors shock on the timeline. Generally speaking, the first two kinds of failures may happen on fiber optic gyro, Doppler velocimeter, altimeter sonar and depth gauge; all three kinds of failures are likely to happen on positioning sonar. For the third kind of failure of positioning sonar, we adopt linear smoothing method for processing and succeed on sea trials. For the first kind of failure, we monitor it by adopting the method of cumulating the amount of sampling period during which the change rate of data keeps continuously constant; for the second kind of failure, we monitor it...
by adopting the method of extracting of mutations in
the signal through wavelet analysis; Replace control
method is used for troubleshooting.

As can be seen from the table, the AUV is
equipped with all kinds of sensors without hardware
redundancy. Therefore, it is difficult to realize fault
repair by using the method of information fusion.

### Table 1. The configuration of the sensor AUV.

<table>
<thead>
<tr>
<th>Type of sensors</th>
<th>Sensors</th>
<th>State parameters of measuring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia</td>
<td>Fiber optic gyroscope</td>
<td>Heading angle $\psi$, pitch angle $\theta$, rolling angle $\phi$</td>
</tr>
<tr>
<td>Doppler</td>
<td>Velocimeters</td>
<td>Longitudinal velocity $u$, transverse velocity $v$, vertical velocity $w$</td>
</tr>
<tr>
<td>Sonar altimeter</td>
<td></td>
<td>Distance from the bottom of the sea</td>
</tr>
<tr>
<td>Short base</td>
<td>line positioning sonar</td>
<td>Plane coordinates of AUV in the sonar array</td>
</tr>
<tr>
<td>6012 imaging</td>
<td>sonar</td>
<td>The distance $d$ and direction $\Omega$ of underwater targets or obstacle</td>
</tr>
<tr>
<td>3D imaging</td>
<td>sonar</td>
<td>Acoustic image of underwater targets</td>
</tr>
<tr>
<td>Pressure</td>
<td>Depthmeter</td>
<td>Submerged depth</td>
</tr>
<tr>
<td>Radio</td>
<td>GPS</td>
<td>Longitude, latitude</td>
</tr>
<tr>
<td>Optics</td>
<td>TV</td>
<td>Optical image of underwater targets</td>
</tr>
</tbody>
</table>

### 4. Replace Control of Sensors

#### 4.1. The Fault Assumption of Sensors

The replace control of sensors is based on the
following assumptions:

- a) Only one sensor malfunctions;
- b) Thruster does not malfunction;
- c) Replace control is carried out based on which
  kind of fault happened on which sensor that has
  been diagnosed.

#### 4.2. Sliding-mode Observer

When the AUV woks in complicated marine
environment of high pressure and poor visibility,
there are many uncertain factors. Sliding-mode
observer has good robustness for the system
uncertainty. Thus, we introduce the concept of sliding
mode to the fault processing of control system.

### 4.2.1. The Motion Equation of the AUV

In the condition where the gravity and buoyancy
has been balanced and external disturbances have
been ignored, the space motion equation of the AUV
in five DOF can be expressed as:

$$MX = F_m(X) + F,$$  \hspace{1cm} (3)

where $M$ is the mass matrix, including the additional
mass and additional moment of inertia; $X, \dot{X}$ and $\ddot{X}$
represent the displacement matrix, velocity matrix
and (angle) acceleration matrix respectively; $F_m$ is
the force matrix of thruster; $F_v$ is the viscous
hydrodynamic matrix.

For easy analysis, type (3) into the realization
form of corresponding space state. Make $x_1 = X$, $x_2 = \dot{X}$. Then the system can be expressed as
the following space state equation:

$$\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\end{bmatrix} = \begin{bmatrix}
M^{-1} & 0 \\
0 & M^{-1} \\
\end{bmatrix} \begin{bmatrix}
F_m(x_1) + F_v \\
\end{bmatrix} + \begin{bmatrix}
\eta_1 \tanh(x_1 - \hat{x}_1) \\
\eta_2 \tanh(x_2 - \hat{x}_2) \\
\end{bmatrix},$$ \hspace{1cm} (4)

where $M^{-1}$ is the inverse matrix of $M$.

#### 4.2.2. The Design of Sliding-Mode Observer

To the state space equations of the AUV
represented in (4), we design a nonlinear sliding
mode observer as follows:

$$\begin{bmatrix}
\hat{x}_1 \\
\hat{x}_2 \\
\end{bmatrix} = \begin{bmatrix}
\dot{x}_1 + \eta_1 \tanh(x_1 - \hat{x}_1) \\
\dot{x}_2 + \eta_2 \tanh(x_2 - \hat{x}_2) \\
\end{bmatrix},$$ \hspace{1cm} (5)

where, $\hat{x}_1$ and $\hat{x}_2$ respectively represent the estimates of state vector $x_1$ and $x_2$, that is the AUV
velocity and the estimates of the acceleration;
$\eta_1 = \text{diag}(\lambda_1, \lambda_2, \ldots, \lambda_{15})$ is positively steady
opposite angle gain matrix that to be designed;
$\eta_2 = \text{diag}(\lambda_{21}, \lambda_{22}, \ldots, \lambda_{23})$ is positively steady
feedback gain matrix that to be designed.

In (5), we use tangent function $\tanh(*)$ instead
of symbolic function $\text{sgn}(*)$ that used in
conventional sliding mode observer. The purpose of
doing this is to eliminate the chattering of sliding
mode observer.

Define the error vector of observer:

$$\begin{bmatrix}
e_1 \\
e_2 \\
\end{bmatrix} = \begin{bmatrix}
x_1 - \hat{x}_1 \\
x_2 - \hat{x}_2 \\
\end{bmatrix}$$ \hspace{1cm} (6)

According to the equation (2) and (3), we can calculate the error output equation of observer:
\[
\begin{align*}
\dot{e}_1 &= e_2 - \eta_1 \tanh(e_1) \\
\dot{e}_2 &= -\eta_2 \tanh(e_1)
\end{align*}
\]  \quad (7)

We can know that by reasonable selection of gain matrix \(\eta_1\) and \(\eta_2\), it can make \(\dot{e}_1 \dot{e}_1 < 0\), that is sliding mode observer meets the attractive conditions. This means that the sliding residual error \(e_1\) can converge to the vicinity of sliding surface and has zero mean value. Thus \(e_1 \rightarrow 0, \dot{e}_1 \rightarrow 0\).

There are 10 outputs for the sliding mode observer. \(\dot{u}, \dot{v}, \dot{w}, \dot{\theta}, \dot{\phi}\) can be obtained directly from the observer. The other 5 observed quantities \((\dot{x}, \dot{y}, \dot{z}, \dot{\theta}, \dot{\phi})\) can be obtained through the time integral of velocity gained by observer. The acceleration required in the study is obtained through velocity difference. Thus, we set up an sliding mode observer for the AUV. Then we can achieve the replace control about Doppler velocimeter, fiber-optic gyro (DVL), sonar altimeter, positioning sonar and depthometer.

### 4.3. Replace Control

The first kind of fault of sensors is a kind of fault that can't be repaired for the actual configuration of the AUV. If the outputs are used in feedback control, it can lead to the control out of the AUV and even paralysis of the system. The second kind of fault of sensors can lead to instability of AUV motion. But when both kinds of faults happened, the outputs of the observer are still valid in a certain time. Therefore, we can replace the outputs of sensors in the feedback control. The principle of replace control is shown in Fig. 2 below.

As shown in Fig. 3, the fault monitoring module checks whether the sensor malfunctions, the module of level analysis of fault judges the type of fault, the extent of the fault and the handling measures. For the third type of fault of positioning sonar, we perform a single process. If the position sensor has jump fault in a certain time in the second type of fault, then we need to use replace control during the period of jump fault, in order to maintain the stability of control system. If the position sensor has the first type of fault, the module of level analysis of fault will assess the current task. We can know whether completion time of automatic buoyancy task is in the range of tolerance (it depends on the maximum time that the error accumulation determined by test can withstand) of replace control. If within the range, we can use replace control, then take appropriate task; if not. We can judge that the AUV has serious fault that is unable to resist. At this point, the module of level analysis of fault will assess the risk level of current task. if the risk level is high, it will take buffer tasks within the range of tolerance of replace control. For example, keep away from obstacles task, then the AUV can discards excess load and starts the buoyancy device (Referred to as “the task of saving itself”). If the risk level is low, it will execute the task of saving itself directly.

**Fig. 3. Sensor fault diagnosis and fault tolerant control system.**

It should be noted that buffer task is a short-time moving task which is carried out when the fault unable to resist is detected. It can lead the state of AUV motion to the stop, even to be far away from the danger. In this way, it can avoid loss caused by sudden failure of sensors when the AUV is in dangerous environment. At the same time, for the risk level and execution time of task, the mission planning module will allocate task in real-time when the AUV is moving underwater. It will also estimate the execution time of current task according to the state of the current task and information of path planner and set up risk level for the current task. For example, for the long-endurance mission of AUV, if it met obstacles, then the path planner will divide the
long-endurance mission into task of before avoiding obstacles, task of avoiding obstacles and task of after avoiding obstacles. It will also estimate the execution time of current task and set the risk level of task of avoiding obstacles to be the highest.

Particularly, for local task of avoiding obstacles, because we can't accurately estimate the time it takes, once sensors have the first type of fault, we need to take the buffer operation that is performing replace control while timing. If keeping away from the obstacles is realized within the scope of permissible time of replace control, AUV will carry out save itself task in the safest situation. If the AUV is stopped when it is not away from obstacles within the time scope, at this time, the state of AUV motion has nearly stopped and it is also a relatively safe time to save itself.

6. Simulation Results

6.1. Handling Simulation of the First Type of Fault

The simulation is divided into two parts. We take an example that the AUV completes the task of avoiding obstacles met in the long-endurance mission by using Doppler velocimeter and optical fiber gyro control, and Doppler velocimeter has the first type of card fault (the outputs of Doppler velocimeter are suddenly constant in a certain point).

Simulation one is to determine the maximum withstanding time of error accumulation of replace control in simulation test. Simulation two is the processing strategy of fault when the AUV is doing the task of avoiding obstacles. Simulation one is shown in Fig. 4, set the AUV to be from starting point (0,0,0) passing point (5,5,π/4), point (10,5,π/2), point (10,0,π), to the target point (0,0,3π/2) (Three coordinates respectively is the x coordinate, y coordinate and heading angle ψ). The simulation time is nearly 10 minutes. The simulation is in 0.5 s for a beat and the fault happened in the 320th beat. The time detected is 325 beats and replace control lasted for nearly 7 minutes. Judging from the results of simulation, the effects of replace control are better in this period of time. Judging from the results of simulation, the effects of replace control are better in this period of time. We have done many times simulation tests to determine the during time of replace control. Here the time limit we use is 5 minutes.

Simulation two is shown in Fig. 5. The execution time of task of avoiding obstacles sets for 5 minutes in replace control. The 6021 collision avoidance sonar is installed in front of the AUV and the scanning range only can be 90 degrees. Therefore, buffer task is setted to stop after the task of avoiding obstacles is carried for 5 minutes under replace control.

In Fig. 5, point A is the place where fault happened; point G1 is the terminal point of local planning when there are no faults; point G2 is the place where the AUV stopped after buffer task when faults happened; point G3 is the place where the AUV hit obstacles without buffer task; point O is starting point.

As can be seen, if we ordered the AUV to stop controlling and save itself instead of taking replace control when the Doppler velocimeter had the first type of fault, the AUV will hit the obstacles due to the AUV large inertia. However, if we took replace control, the AUV would stop after taking buffer task to avoid obstacles for 5 minutes. After the buffer task, the AUV state was nearly static, and now the AUV can save itself safely. In addition, for the settings of buffer task, if the scan range of the AUV sonar installed is wide, the methods of buffer task can be more and more reasonable.
6.2. Handling Simulation of the Second Type of Fault

Wavelet analysis technology can detect the singularity and irregular jump of signal, and replace control mainly processes the random jump parts of sensor faults. We analyse the effects of replace control according to the data of fiber optic gyroscope in a sea test. From Fig. 6, we can see that outputs of heading angle of fiber optic gyroscope jumps in several beats. However, during the time of jump fault, we replaced the jump data of heading angle by the outputs of observer in order to maintain the stability of the AUV motion.

Fig. 6. Handling simulation of the second type of fault.

7. Conclusions

For the first type of fault of sensors, because of the AUV sensor configuration, we are unable to repair the deadly fault. But we can minimize the dangers of the fatal fault by taking the strategy of replace control, and even can guarantee that the AUV completes the tasks successfully. For the irregular jump fault in a period of the second type of fault, we can take replace control within the time of jump fault. Therefore, when the existing AUV sensor configuration is not under the redundant situation, we don’t need additional sensors. We can take some fault-tolerant control strategies, in order to guarantee that the AUV can complete the tasks successfully or securely save itself when the sensors malfunction.

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