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Design and evaluation of a hierarchical control architecture for an autonomous underwater vehicle

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Abstract: This paper researches on a kind of control architecture for autonomous underwater vehicle (AUV). After describing the hybrid property of the AUV control system, we present the hierarchical AUV control architecture. The architecture is organized in three layers: mission layer, task layer and execution layer. State supervisor and task coordinator are two key modules handling discrete events, so we describe these two modules in detail. Finally, we carried out a series of tests to verify this architecture. The test results show that the AUV can perform autonomous missions effectively and safely. We can conclude the control architecture is valid and practical.
Keywords: hierarchical control architecture; AUV; state supervisor; task coordinator; lake tests
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1 Introduction

An autonomous vehicle may be defined as “a vehicle with a sensorial system and an actuator system, managed by control architecture and able to undertake a user specified mission”. Therefore, the architecture is a framework in which the following processes are carried out: sensing, control, errors detection and recovery, path planning, tasks planning and monitoring of events during the execution of a particular mission[1].

This paper presents an overall description of a kind of hierarchical control architecture for AUV and a detailed description of its handling principles for discrete events. In order to test the architecture, a series of tests with real vehicle have been done to validate the architecture.

This paper is organized as follows.

Section 2 presents an overall description of the hybrid system of AUV. Then the hierarchical control architecture with three layers is proposed in section 3. Section 4 describes the state supervisor and task coordinator. Section 5 describes the lake tests carried out to validate the research work, the tests results are also given in this section. Finally, in section 6 conclusions are presented.

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2 Hybrid architecture of the control system for AUV

The control architecture of AUV is a typical hybrid system from an overall point of view[2-3], as shown in Fig.1. The architecture is made up of two main components, autonomous control system and motion control system. These two subsystems are linked by transfer interface.

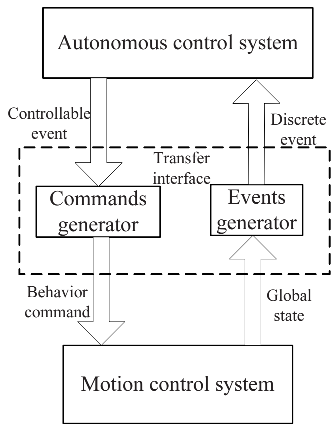


Fig.1 Hybrid architecture of the control system for AUV

The autonomous control system describes the dynamic decision model, which is in charge of the autonomous intelligent control, making decision based on analyzing of the detected discrete events, determining the necessary tasks to complete mission and sending tasks to the motion control system. The motion control system receives decision commands through transfer interface, and performs depth control, velocity control and heading control. The transfer interface is designed to link these two systems and make signal transformation.

3 Hierarchical control architecture for AUV

In order to complete the mission such as long range autonomous navigation and sea bed terrain surveys, AUV should have the abilities of mission planning based on electronic ocean map, coordinating tasks to execute the mission, and mission re-planning when necessary.

So, the autonomous control architecture should have well planning or re-planning ability as well as reactive ability to the changing of the external environment. Conceived as a hybrid system, a kind of hierarchical control architecture for AUV is proposed. The architecture is divided into three layers: mission level, task level and execution level, depicted in Fig.2.

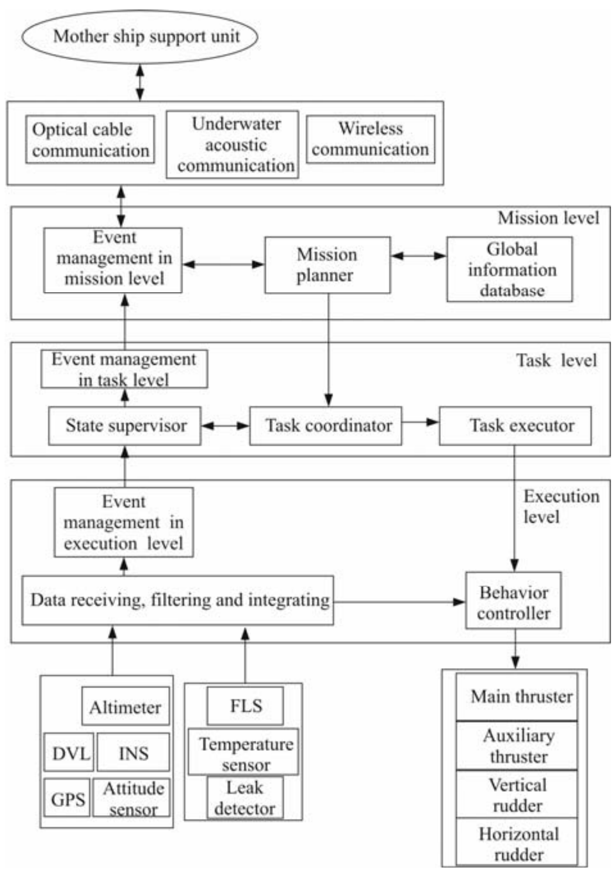


Fig. 2 Hierarchical control architecture for AUV

3.1 Mission level

The function of this level is to make decisions for the whole mission. It is of the highest intelligence. Mission level should have some basic functions such as mission planning or re-planning based on electronic ocean map, mission requirements and current situation of AUV[4]. Take an example of the mission for terrain survey, the mission level performs mission planning and produces a series of navigation courses and terrain survey courses. These courses contribute to tasks sequence.

3.2 Task level

This level is in charge of task coordination, producing behavior control commands[5-6]. This level should also detect faults of sub-systems, configure resources, reason about the environment and make responses to the changes of environment. This level should send re-planning requirement signal to mission level if it can not handle the situation.

3.3 Execution level

This level is of the lowest intelligence but of the highest accuracy and real-time property[7]. The execution level is in charge of vehicle stabilization and keeps direct contact with actuators and sensors. This level operates on behavior commands issued by the task level and outputs the motor commands.

4 Principle of discrete events handling in task level of AUV

4.1 Supervisor theory of discrete events

The principle of state supervisor is a mapping function from L to Γ. Formally, a state supervisor is expressed as follows:

$$f: L \rightarrow \Gamma,$$

where L is the set of events; Γ is the set of property values of events in L. Suppose that $\Gamma = \{0,1\}$.

The supervisor specifies a control strategy for each possible events sequence. Use $f(\sigma)=1$ to express supervisor f that allows the event $\sigma \in L$ to happen; and $f(\sigma)=0$ means that supervisor f forbids the event σ to happen. The intention for designing a supervisor is to make system behaviors satisfy some criterion, in other words, the system should allow the expected events while forbidding the unexpected events.

The state supervisor monitors the execution of mission by monitoring system states, and obtains the events sequence. Usually, the control rules are expressed as an automation machine, whose transition is driven by some events. $S=(R,\phi)$, where R is the set of rules and ϕ is the output feedback.

If w is a sequence of events, $w=\sigma_1\sigma_2\cdots\sigma_n$, the value of $f(w)$ can also be thought as the state of automation machine S transited from initial state M_0 driven by events sequence w. The supervisor returns to its initial state after triggering the event with the highest priority.

4.2 Design of state supervisor

Being different from classical RW theory, the monitored events $\sigma_1,\sigma_2,...,\sigma_n$ are of priorities. The priority of event can be determined by operator $MP(\sigma_i)$. The relation $MP(\sigma_1)>MP(\sigma_2)$ means the priority of event σ_1 is higher than event σ_2.

In a monitoring period, the events are ranked by their priorities, only the event with the highest priority can be allowed to happen, and all the others are forbidden. For example, if $MP(\sigma_1)>MP(\sigma_2)>\cdots>MP(\sigma_n)$, then $f(\sigma_1)=1,\ f(\sigma_2)=\cdots=f(\sigma_n)=0$.

After this monitoring period, the supervisor returns to initial state with no event being detected.

Taking the navigation task as an example, during the navigation task, the possible discrete events include timing GPS calibration, obstacle avoidance, task overtime, heading adjustment, task termination, faults of hardware, etc. These events are defined in Table 1. In the priority column, smaller value means higher priority.

Table 1 Observable events in navigation task

Event	Definition	Priority
AUV faults	Defined by the type of fault.	1
Task termination	If $\sqrt{(X-X_0)^2+(Y-Y_0)^2}\le R_0$, where, (X_0,Y_0) is the end point of navigation course; (X, Y) is the current position of AUV; R_0 is the radius of end area.	2
Obstacle avoidance	The obstacle has been detected by forward looking sonar (FLS).	3
Heading adjustment	Timing checking, if $\psi-\psi_0\ge\psi_T$, where, ψ is the current heading of AUV; ψ_0 is the heading of the navigation course; ψ_T is the limitation to the error of heading.	4
GPS calibration	Triggered every 3 hours, AUV floats above the water and calibrates the INS.	5
Task overtime	Timing checking, if $t>1.5\times l/v$, where t,l,v are the execution time of navigation task, the length of navigation course and AUV velocity respectively.	6

4.3 Design of task coordinator

In order to handle the discrete events, response rules are designed. Responding rules for events during navigation task are shown in Table 2.

During the navigation task, if the supervisor has detected two events σ_1 GPS calibration and σ_2 obstacle avoidance simultaneously, where $MP(\sigma_1)<MP(\sigma_2)$, the priority will rank events sequence $\sigma_2\sigma_1$. The supervisor triggers obstacle avoidance event, that is, $f(\sigma_2)=1$, $f(\sigma_1)=0$. To ensure the real-time property of the task coordination, only a single event can be triggered during a coordination period. The state monitor module sends obstacle avoidance event to the task coordination module. According to the coordination rules, the current navigation task is suspended, while the obstacle avoidance task is performed. The obstacle avoidance algorithm guides AUV to steer clear of obstacles.

Table 2 Tasks coordination rules during navigation task

Event	Response	Meaning
Obstacle avoidance	Obstacle avoidance	Suspend current navigation task, perform obstacle avoidance.
Task overtime	Next task	Cancel current navigation task, perform the next task.
Heading adjustment	Navigation task	Adjust heading during navigation task.
Navigation task termination	Next task	Cancel current navigation task, perform next task.
AUV faults	Fault tolerance	Suspend current navigation task, perform fault recovery process.
GPS calibration	GPS calibration	Suspend current navigation task, perform GPS calibration.

5 Lake tests

In order to verify the hierarchical control system, a series of lake tests have been carried out with real test platform. The main objective of these tests is to verify whether the autonomous control system could have the ability of autonomous planning and autonomous control. Another objective is to verify the reactive ability of the control system, such as avoiding obstacles in real time according to information obtained from forward looking sonar (FLS)[8-9].

5.1 Test for autonomous planning

AUV was carried by mother ship to the starting area. After releasing AUV into water, firstly, used the remote operator to manipulate AUV to the starting point *A*, and adjusted its heading to almost parallel to course *A*-*B*, then sent mission text to AUV by underwater acoustic communication. Mission text designated the starting point, end point and survey task area defined by four points. The global mission planning algorithm was running according to the received mission text. The planned trajectory is shown in Fig.3, *A-B-C-D-E-F-G-H-I-J*, where the length of each course *A-B,C-D*, *E-F,G-H*, *I-J* is 500 m, and the length of each course *B-C*, *D-E*, *F-G*, *H-I* is 2 000 m, respectively; the length of the whole mission courses is 10 500 m. During execution of the mission, the monitoring computer of mother ship monitored the states of AUV through optical cable. AUV could navigate to the end point *J* at the designated velocity and depth.

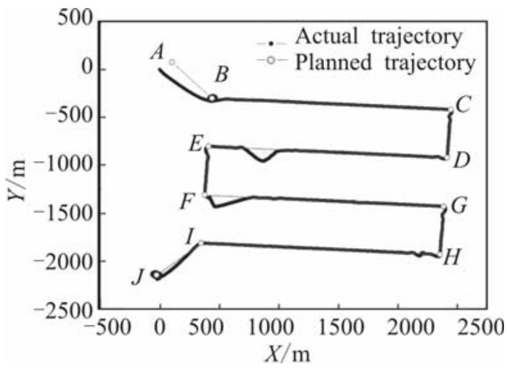


Fig.3 Test results of autonomous mission planning and execution

The reasons for departures at courses *D*-*E* and *F*-*G* are partially due to the crosswind disturbance of nearly 10m/s, and the disturbance of optical cable. State supervisor detected the heading adjustment event and made correct response, the heading was adjusted.

From the test results, it can be found that AUV could achieve mission text correctly; the mission planner could plan the sequential paths moving from the starting point to the survey task area and ending at the end point. The heading and positions of AUV were adhering to the planned navigation course. The mission was completed perfectly.

5.2 Test for autonomous re-planning

During the execution of mission, mother ship sent another mission text through underwater acoustic signals to inform AUV to navigate to a new end point. AUV then underwent mission planning again with new mission text, and produced a new sequence of paths to the new designated end point.

The first mission text was the same as the first test. The first planned trajectory was *A-B-C-D-E-F-G-H-I-J*, as shown in Fig.4. When AUV navigated to point *K* at course *D*-*E*, the mother ship sent a new mission text to change the endpoint to *M*, the mission planning algorithm planned a new course *K*-*M*, and navigated following the new course. When navigating to point *L*, the mother ship sent another mission text again to change the end point to *M* but with a different velocity and depth. Because the course *L*-*M* was on the surface of water and disturbance was strong, so, the execution of mission was ended at point *N* without completion of the whole mission.

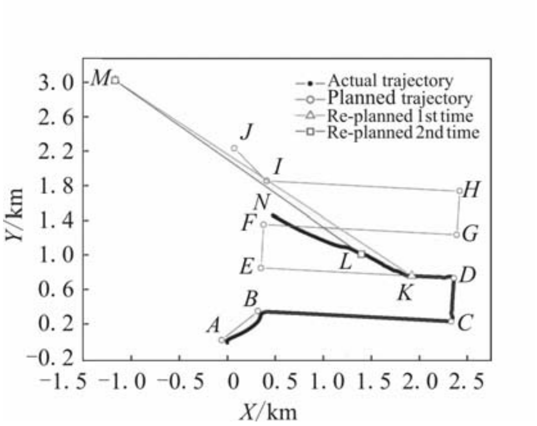


Fig. 4 Test results of mission re-planning

5.3 Test for autonomous obstacle avoidance

The intention of this test is to verify the reactivity of the autonomous control system and obstacle avoidance algorithm based on forward looking sonar.

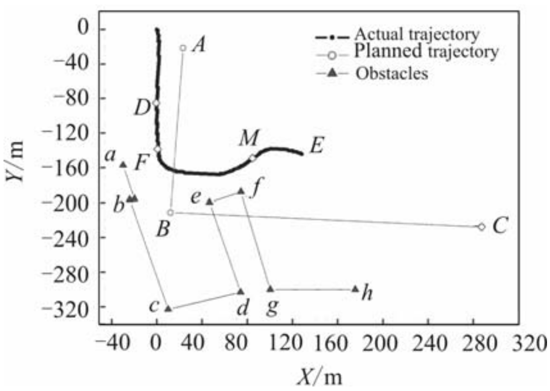
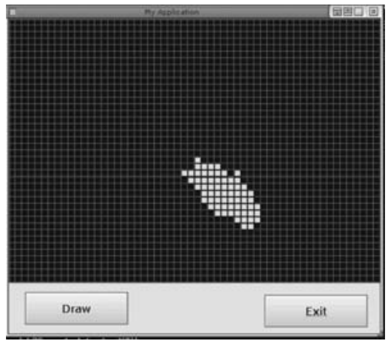
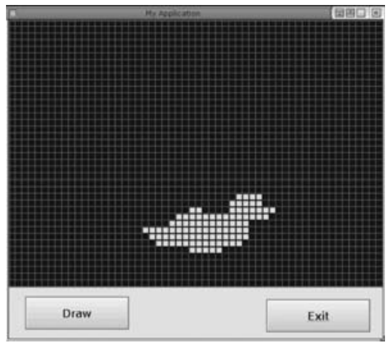


Fig.5 Test results of obstacle avoidance

This test was done nearby the dock. Designated the trajectory *A*-*B*-*C*, as shown in Fig.5, where the lengths of course *A*-*B* and *B*-*C* were 200m and 270m respectively. AUV navigated at the depth of 5m and at the speed of 1m/s. Firstly, manipulated AUV to the starting point *A* by remote operator, and adjusted the heading to 180°, then AUV executed the mission autonomously. At the starting point *S*, the forward looking sonar didn't find any obstacle signals, so AUV followed the course *A*-*B*. At point *D*, the FLS detected obstacle signals. The image of sonar is shown in Fig.6(a). The obstacle avoidance algorithm computed the avoiding heading was 196.7°. When navigating to point *F*, the heading command was adjusted to 176.2°. The image of FLS is shown in Fig.6(b). When AUV was at point *M*, the obstacle was completely avoided. AUV then adjusted its heading to the end point *C*.



(a) Sonar image at point *D*



(b) Sonar image at point *F*
Fig.6 Sonar image display

6 Conclusions

In this paper, a kind of hierarchical control architecture for AUV has been surveyed. This architecture is of three main layers, mission layer is in charge of decision-making such as mission planning and re-planning; execution layer is in charge of the stability of AUV; exceptions are handled by state supervisor and task coordinator, which are in task layer. The lake tests have been carried out to validate the autonomous ability and reactivity. From the tests results, it can be concluded that the control architecture has abilities of mission planning, re-planning and execution; the control architecture can handle discrete events，such as heading adjustment and avoiding the obstacles correctly and effectively.

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