Research on Multi-AUV system for Deep-Sea Hydrothermal Exploration*

Hongli Xu1, Xiaodong Kang1,2, Xisheng Feng1

1Robotics State Key Laboratory, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, Liaoning, China
2Graduate School of the Chinese Academy of Sciences, Beijing, China

ABSTRACT
This paper proposes a new method using multiple autonomous underwater vehicles (multi-AUV) in deep-sea hydrothermal exploration that will provide a rapid improvement of the quality of collected data. Firstly the development of underwater vehicles and search strategies for hydrothermal exploration are introduced. Then the proposed method is presented in detail and its advantages are given. Thirdly we debate major challenges and questions facing the method and conclude the key technologies for multi-AUV system, including formation control, autonomous hydrothermal plume tracing and coordinated collision avoidance. At last we present our views on the emphases for research on multi-AUV system for deep-sea hydrothermal exploration.

Keywords
Multi-AUV system; Deep-sea hydrothermal exploration; Key technologies; Cooperative control

1 INTRODUCTION
Thirty years have past since the first discovery of hot springs on the Galapagos Spreading Centre. Now it is widely recognized that hydrothermal activity has very important research significance in geochemistry, marine geology and marine biology. Hydrothermal vent fields are typically located along mid-ocean ridges, at volcanic centers, and in back-arc basins. Rugged seafloor terrain and irregular plume dispersion make deep-sea hydrothermal exploration very difficult. No more than 10% of the 55-60,000km of global ridge crest has been investigated systematically up to now.

Conventional hydrothermal exploration relied upon towed vehicles, human occupied vehicles (HOV) and tethered remotely operated vehicles (ROV). But CTD tow-yos could resolve the sites of seafloor venting to length scales of less than a kilometer but rarely to better than a few hundreds of meters. HOVs and ROVs remain the only option for manipulation tasks such as sampling, deploying and recovering subsea instruments, and close range observation. With the development of AUV technology, AUV started to play an important role in hydrothermal exploration from the middle 1990s. But it is necessary to estimate the depth of the non-buoyant plume and infer the approximate location of the plume center before AUV survey by conventional methods. Furthermore all of the existing methods acquire only time-series datasets of hydrothermal fluids.

This paper proposes a new method based on multi-AUV system that will provide a rapid improvement of the quality of collected data. It is organized as follows. Section 2 summarizes semi-autonomous and autonomous search strategies for deep-sea hydrothermal exploration and introduces some typical AUVs around the world. A strong emphasis is laid on Section 3, in which the proposed method is presented in detail. In Section 4 we debate major challenges and questions facing the method and conclude the key technologies for multi-AUV system, including formation control, autonomous hydrothermal plume tracing and coordinated collision avoidance. At last we present our views on the emphases for research on multi-AUV system for deep-sea hydrothermal exploration.

2 THE DEVELOPMENT OF SEARCH STRATEGIES AND AUVS FOR HYDROTHERMAL EXPLORATION
Traditionally, deep-sea hydrothermal exploration can be divided into three conjoint steps (shown as figure 1). Step 1 is mainly to search for a hydrothermal plume in an unknown area. In this step a pattern called "tow-yo" is generally used to detect several hot and chemical springs, that may represent plumes from several different vents. Once the depth of the non-buoyant plume has been estimated and the approximate location of the plume core inferred, Step 2 can be undertaken. Then AUV will be launched to locate, map and photograph the determined abnormal field. The precise location of the plume core can be declared by the detailed sampling including chemical and physical tracers. If oceanographers are interesting in the hydrothermal vent, we can use HOVs or ROVs to observe the vent in short distance and place some long-

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term observation instruments around the vent in Step 3. The further research may focus on the resource evaluation by these long-term continuous data.

AUV belongs to a basic tool used in Step 2. Firstly we introduce two current search strategies, semi-autonomous and autonomous, and some typical AUVs in service around the world.

![Figure 1 Steps of the deep-sea hydrothermal exploration](image)

2.1 Semi-autonomous Search Strategy
The semi-autonomous search strategy means that AUV is pre-programmed for the whole exploration process by domain expert. The mission of each dive is based on the information acquired in the preceding dive and expert’s experiences. The most typical examples using this strategy include ABE and r2D4 (shown in Figure 2).

ABE (Autonomous Benthic Explorer), a 4500 m AUV built in Woods Hole Oceanographic Institution in 1993, has surveyed a distance of over 2500 km in over 1300 h of bottom-time. It is a three-body, open-frame vehicle that utilizes glass balls as flotation in two free-floated upper pods while the single, lower housing is host to the batteries that power the vehicle and all of its electronics (Christopher 2008). It is equipped with geophysical, oceanographic and project-specific sensors like multibeam sonar, scanning sonar, magnetometer, camera, redox sensor and so on.

![Figure 2 Two typical AUVs using semi-autonomous search strategy](image)

2.2 Autonomous Search Strategy
Autonomous search strategy means that AUV has the capability of online mission planning and can execute the whole exploration process without human interaction. It includes two operation modes: using single vehicle or multiple vehicles.

Shuo Pang (Shuo & Jay 2006) presented an algorithm of chemical plume tracing based on olfactory mechanisms for single AUV. The basic principle of this algorithm is that male moths always track females along pheromone
emitted by them. He conducted experiments with REMUS AUV using a plume of Rhodamine dye developed in a turbulent fluid flow in November 2002 at San Clemente Island. This set of tests included 8 formal runs and the source location was successfully declared 7 times.

We can search many research results about chemical plume tracing using single vehicle like Shuo & Jay (2006) but autonomous hydrothermal exploration using single AUV has not been realized up to now. Because of the limitation in single AUV’s capability it may be a promising operation mode using multiple AUVs in the future.

Sandia National Laboratory presented a multi-agent collaborative plume localization algorithm and tested by multiple Ranger AUVs, shown as Figure 4(a). The field results showed that three Range AUVs sometimes can approach the plume source and get closer in depth but sometimes can’t reach the plume source because of the limitation of maneuverability. So this algorithm should be made further improvement (Bryan et al 2003).

Martins in Portugal presented an innovative integrated acoustic navigation system and coordination control maneuver for a formation of multiple AUVs and surface crafts for the search of underwater plumes (shown as Figure 4(b)). However, his research results still stay on the level of theoretical schema and remain to the further experiment demonstration (Martins et al 2003).

(a) Ranger AUV  
(b) Multi-AUV Configuration  
Figure 4 Two typical multi-AUV systems using autonomous search strategy

The conventional towed system and single AUV can only acquire the time-series sampling of hydrothermal fluids. Multiple AUVs using autonomous search strategy may dramatically increase the quality of the gathered data. It can implement the four-dimensional adaptive sampling and acquire high-resolution datasets that is necessary to develop predictive models of both the distribution and temporal variability of hydrothermal systems.

Autonomous search strategy with multi-AUV system may be one of the mainstream development orientations for hydrothermal exploration in the near future. Nowadays there have been many research institutions paid close attention to this domain and acquired some periodical achievements. But the key problems need to be discussed and researched thoroughly.

3 THE PRESENTED HYDROTHERMAL EXPLORATION PROCESS WITH MULTI-AUV SYSTEM

This section mainly discusses that how to use multiple AUVs to perform autonomous adaptive sampling tasks in the second hydrothermal exploration step. We plot the hydrothermal exploration process with multi-AUV system into three successive phases as shown in Figure 5. When mission starts, in the first, a group of AUVs search for the hydrothermal plume in the form of 3D formation in a large-scale area. There are two searching results. One is that mission time has depleted or the defined area has been scanned completely, so the mission of multi-AUV system will be ended. The other is that the plume has been identified by multiple sensors and the depth of the non-buoyant plume also has been established. And then multi-AUV system goes into the tracing phase.

In the following tracing phase multiple AUVs will go against the plume until the approximate location of the plume core is inferred. The main problem is that the behavior strategies of tracing under the conditions of turbulence and tides. Once the plume has been lost by all the AUVs, multi-AUV system has to return to the searching phase and search for the plume again.

While the plume core is declared, multiple coordinated AUVs will form a certain formation and mapping the plume source from multiple views and multiple directions simultaneously. Therefore not only the precise site of the vent core can be determined but also the images, its detailed geologic setting and chemosynthetic communities are all obtained.

Figure 5 The presented hydrothermal exploration process with multi-AUV system

The above three phases complement each other. The most important behaviors are to search for, trace and locate the plume. In the searching phase, main requirement is to improve search efficiency, and primary difficulty is how to make multiple AUVs adapt to complex marine environment. In the tracing phase each AUV must make a decision continuously for optimization between keeping formation and tracing targets by sensor data from itself and other AUVs. Its main requirement is that AUV can’t
fall into any local extremum. Its main difficulties include that how to integrate various sensor information with different characteristics and how to avoid influence of turbulence and vortex. When multi-AUV system is in the locating phase, obstacle avoidance is mainly required because of high temperature and unknown ridge. But it is a very difficult problem to choose obstacle avoidance behavior in harmony while the mutual communication is limited and the seafloor terrain is unknown and extreme complex.

Compared with towed system and single AUV, the multi-AUV system has many unique advantages: simultaneous location and mapping of a dispersing non-buoyant hydrothermal plume, cooperative operation in and around any new hydrothermal vent site to characterize its geologic setting and reveal the nature of any chemosynthetic ecosystem it may host, and adaptive sampling in situ. So we believe that multi-AUV system can provide a more effective and more efficient method for hydrothermal exploration in the future.

4 THE CORRELATIVE KEY TECHNOLOGIES
From the above hydrothermal exploration process with multi-AUV system it can be seen that there are three key technologies for multi-AUV system to be solved urgently, including formation control, hydrothermal plume tracing and coordinated collision avoidance.

4.1 Formation Control
Formation control is needed to keep multiple AUVs in a required spatial formation under the limitations of both environment and mission during the whole mission process from sailing, operating to returning. The special particularities of multi-AUV formation control include 3D formation, weak communication and maneuverability constraint.

The formation of multi-AUV system is distinguished from that of multiple unmanned ground vehicles (UGV). It belongs to 3D formation with 3D non-linear movement in 3D workspace and is a main difficulty to be solved. Because of this many traditional formation control methods can't be directly applied to multi-AUV system and need to be improved in some aspects.

Weak communication means that channel is time-varying, space-varying, and has serious attenuation and multi-path reflection. Communication quality is severely affected by multi-path propagation in water due to reflection and refraction. So it has larger time delay and higher error-code quotient in data transmission compared with radio communication in the atmosphere.

Acoustic communication, commonly used by multi-AUV formation, belongs to a typical weak communication. The information transmitted among AUVs is limited to a defined quantity under the condition of the acoustic communication. Some cooperative control methods of multiple UGVs may not be applied to multi-AUVs system because of the requirement of real-time communication.

Maneuverability constraint means that the outputs of formation control is restricted by AUV's kinematics and dynamics. Generally AUV possesses four DOFs or even more. Strong coupling exists between different DOFs.

During the horizontal turning for example, not only yaw, forward displacement and lateral displacement but also pitch, roll and heave motion are occurred simultaneously. But not all DOFs can be controlled, such that the rotation about the main axis of symmetry is uncontrollable for most cruising AUVs. This requires that the 3D formation control don't exceed AUV's capability and must consider the response ability of AUV control system.

4.2 Hydrothermal Plume Tracing
The difficulties of hydrothermal plume tracing originate from the discontinuity of plume traces and the irregularity of their distributions. Typical hydrothermal plume tracers comprise of temperature, salinity, pH, Fe, CH₄, Mn, H₂ and turbidity etc many variables. Each variable has its own independent distribution characteristics. It is very hard to select suitable plume-detection methods at first. This involves the selection of the plume tracers and AUV's sensors. Moreover it is harder to navigate multiple AUVs to approach the hydrothermal vent by multiple sensors information fusion, especially in the environment with turbulent flow.

Additionally multiple AUVs must keep original formation as possible at the same time of tracing the plume.

4.3 Coordinated Collision Avoidance
The coordinated collision avoidance is a behavior strategy of multi-AUV formation for avoiding unknown obstacles through sharing information and coordinating actions of each other. This definition suggests that there are two factors in multi-AUV obstacle avoidance: communication and coordination, which are just its difficulties.

Above all, information-sharing strategy based on explicit communication can't be used in multi-AUV formation because of the characteristics of acoustic communication. Each AUV can acquire a little information from the other AUV and must make decision mainly depending on its own sensors. In addition, obstacles may be another AUV, unknown seafloor ridge, or big marine animals. It is still an unsolved problem to avoid those movable obstacles.

If multiple AUVs detect the same obstacle at the same time, they must adopt some measures to avoid confliction with each other. So another difficulties is just how to ensure consistent behavior for collision avoidance.

5 CONCLUSIONS AND DISCUSSIONS
Now AUVs have been accepted in deep-sea hydrothermal exploration tasks where they have been shown to be more effective than previous technology. Multi-AUV system can perform autonomous adaptive sampling that is difficult to the existing systems and improve the data quality greatly. We consider that it will play an important role in deep-sea hydrothermal exploration in future years.
The study of this paper is still relatively young, and there are many fundamental technologies that need to be researched thoroughly in the upcoming years.

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REFERENCES