Scheduling of BSA-AUV Mission Operation: Development, Implementation and Trials

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***Abstract*–This paper presents the development and implementation of a scheduling method that enables the BSA Autonomous Underwater Vehicle (AUV) to perform a mission operation while managing various resources autonomously. The mission is to survey several local areas in a dynamic ocean environment with different survey sensors. When a mission begins, it is assumed that during the execution of the mission, there is no communication between the vehicle and operator, the vehicle is then completely autonomous until the mission finished. So, an on-board scheduling is development to supervise, manage and control the implementation of the mission. It behaves like a soft real-time system and is realized by discrete events driven hierarchical Petri Net (PN). The highest level PN and lower sub-PNs with designed events are introduced detailedly. The feasibility and effectiveness of the mission scheduling is checked by lake trials in nominal and degraded situations.**

Index Terms - autonomous underwater vehicle; ocean survey; mission scheduling; hierarchical petri net; lake trial

I. INTRODUCTION

Autonomous underwater vehicle (AUV) has become an important and popular tool for ocean scientists to learn more about our world's oceans[1]-[4]. We are interested in the problem of collecting data about scalar field, within certain area. In particular, we care about collecting data about inshore areas of the ocean e.g., temperature, salinity, and current profile, seafloor topography and Terrain. Ideally, we would like to have high spatial resolution measurements over the entire area that we care about to modeling, forecast and research. So, an AUV named BSA-AUV (Best Sea Assembly AUV which will be introduced in part II.) equipping some ocean survey sensors is researched

For this paper, we focus on the mission scheduling method of AUV. The mission scheduling is very pivotal for AUV control, because our AUV is a totally autonomous vehicle and no communication between the vehicle and operator when a mission begins. For mission scheduling, there are two issues to solve: mission scheduling architecture and mission scheduling mechanism. The architecture is the basic of the mission scheduling, a good architecture can make an effective and reliably scheduling. Now, most prevalent architectures of current AUV mission scheduling are behavior-based subsumption architecture and hierarchical architecture. Subsumption architecture makes AUV generate rapid responsiveness according to external environment. However, it makes AUV lack abilities of decision-making and planning[5][6]. Hierarchical architecture is a deliberative/act hybrid architecture which overcomes the shortcoming of subsumption architecture. For this architecture, AUV not only has behavior control, but also planning and decision-making[7]-[9]. However, all functions are impossible to be included in the three layer architecture. Other architectures are also proposed, such as: T-REX based deliberative architecture; BDI based neuropsychological architecture, neurocognitive agent architecture, and so on. N, distributed architecture is widely used in complexity system, such as: UAV, space probe, satellite. In this architecture, all function modules are relax-coupling, and both deliberative or act mode according their functions. The advantages of the architecture are logic legible, be prone to integration, easy to maintenance and convenient for extending.

For mission scheduling mechanism, now, differnent AUVs have different methods. HUGIN vehicles use plug-ins running as separate processes and modular design of the system for mission scheduling[10][11]. For MARIUS AUV[12][13], it divide the mission into some certain sub-tasks and use PN to manage and schedule among these tasks. For REMUS AUV, in order to have the vehicle react and alter course to real-time sensor data[14][15], the misison scheduling is divided into three layers: abstraction layer, functional layer and coordination layer. Gary Giger[16] and D.B.MARCO[17] both adopt the hybrid control idea to scheduling AUV mission integrating motion control simultaneously.

In this paper, an on-board scheduling architecture and mechanism is designed to supervise, manage and control the implementation of the mission. It behaves like a soft real-time system and is described by hierarchical Petri Net (PN). Lake trials of survey mission are carried in nominal and degraded situation. The remainder of this paper is organized as follows. In section II, the BSA-AUV platform is described. In section III, agent-based distributed scheduling architecture and mission definition are proposed. Autonomous mission scheduling method using hierarchical PN is introduced in section IV. Results of lake trials are given in section VI. The end is the conclusion.

II. THE BSA-AUV PLATFORM

The BSA-AUV equipping some ocean survey sensors is developed to obtain and research ocean information. It is a

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clipper-built gyroidal style with symmetrical on left-right and anisomerous on up-down and front-back. An elevator, a pair of rudders and two thrusters are fixed on the stern as implements. The form, system architecture and specifications of BSA-AUV are shown in Fig.1 and Tab 1.

The control Computer is the core of AUV, including two sub-systems: mission control and motion control computers. They are both the PC104 systems with embedded QNX operation system. The mission control computer is responsible for high level control of AUV and performs path planning, mission scheduling, decision-making and discrete event processing. The motion control computer is responsible for real-time PID control of AUV for speed, depth, height and heading. The mission control computer receives the mission file from the operator on the ground or on the mother ship by RF or WiFi. Then it starts the mission, make global decision for path planning and local decision for obstacle avoidance according to the mission restrictions, environment and self states. At last, it sends the behavior control commands to the motion control computer to control the AUV to execute the mission. During the execution of the mission, the mission control computer must supervise, manage and shceduling the mission perform, process various discrete events and make new decisions to ensure the mission success and the AUV security. BSA-AUV navigation is by global positioning system (GPS) initialized dead reckoning.When on the surface, the vehicle navigation is by GPS position information and, when submerged, navigation is by dead reckoning.

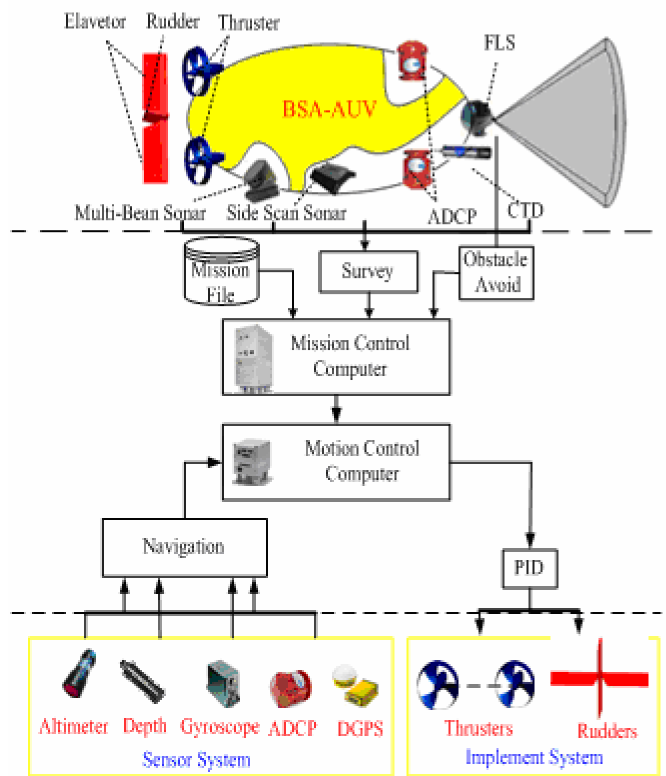

Fig.1 BSA-AUV system architecture

Table 1. Specifications of the BSA-AUV platform.

	Specification	Value	Description
Vehicle	Size	5.0(L)×0.8(D)m	Main Rotor Size
	Weight in air	1000 kg	Positive Buoyan
	Propulsion	(2) 2000 W	2 Horizontal Thrusters
	Horizontal velocity	0-2.5 m/s	Variable
	Energy	37 kWh	Li-Ion batterie pack
	Range	200 km	
	Depth rating	200 m	
Sensor	Depth	±0.01%	Pressure Sensor
	Velocity	±0.2cm/s	DVL
	Altitude	0.1 m	Altimeter Sonar
	Heading	±0.1 deg	IXSEA OCTANS
	Pitch/roll	±0.01 deg	IXSEA OCTANS
	Absolute	<2m	GPS
Acoustic	Forward Looking Sonar (FLS)	250KHz	Detecting Obstacles
	Acoustic Doppler Current Profiler (ADCP)	600 KHz	Providing Current Profiles
	Side Scan Sonar (SSS)	120 or 410 KHz	Mapping Seafloor Topography
	Multi-Beam echo Sounder (MBS)	400 KHz	Mapping Seafloor Terrains
Chemical	Conductivity, temperature, depth (CTD)		
Communication	RF and WiFi		
Computer	Mission and Motion Control Computers		PC104 with QNX OS
Navigation	GPS initialized dead reckoning		
Control	Velocity, heading, depth and height control		PID

III. SCHEDULING ARCHITECTURE AND MISSION DEFINITION

A. Scheduling Architecture

For BSA-AUV, a Multi-Agent-System (MAS) is used to construction the control architecture according to hardware structure and software function. Fig.2 shows the agents division and the flow of information among different agents.

The MAS manage agent: that are in charge of necessary maintenance of the whole system

The perception agent (PA): obtains information about the environment and about the AUV. It collects data from the sensors and adapts them to provide the information requested by the other agents of the system.

The path planning agent (PPA): searches for an optimization global path according to mission demands, AUV constraints, environment information.

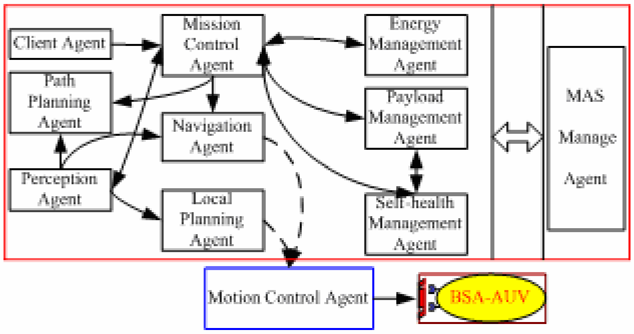

Fig.2 Control architecture based on MAS of the BSA-AUV

The local planning agent (LPA): detects if there are obstacles in the path according the FLS information. It makes AUV avoid obstacles and go to the sub-destination safely.

The energy management agent (EMA): monitors the battery, to prevent it from discharging too much and remaining permanently damaged.

The self-health management agent (SMA): diagnoses faults of all sensors and actuators and tolerate the faults using necessary method. In addition, it also makes leakage, extra-deep, too-shallow (etc) inspection to ensure the AUV safe.

The payload management agent (PMA): makes on-off control of all sensors and actuators according to their fault status, the AUV mission and the energy status.

The mission control agent (MICA): is the core agent who is in charge of mission scheduling and monitoring during whole mission course in nominal mode and in the degraded situations. It may interrupt, adjust or cease a mission according to the information and event of other agents. Here, petri net is developed to realize the autonomous scheduling control which will be detailed in section IV.

The navigation agent (NA) uses dead reckoning method to obtain AUV position and generates real-time navigation control instruction to the motion control agent (MOCA) according to AUV position and the mission schedule instructions from MICA.

The agent designed for BSA-AUV comprises four parts: kernel, switch, input port and output port. The kernel contains specific function library or knowledge base. Input port receives information and events form other agents. Output port reports new procreant information and events to other agents. Switch enable agents make decision based on information and events, choose function and IO port, evaluate the input data and reports the result as information and event to other agents. In our multi-Agent based architecture. AUV carries out its missions through the internal agents' communication and cooperation. Here, information consists of AUV system status, environment information and mission information.

B. Mission Definition

In general, typical tasks included in BSA-AUV mission can be orthogonally enumerated as:

1) *Path following*: Given a set of waypoints, the vehicle tries to reach them in sequence.
2) *Measure tracking:* The vehicle senses a particular measure and tries to track it using a predefined behavior, such as outline following and terrain tracking.
3) *Area survey:* The vehicle moves inside an area describing a particular pattern according to survey sensor. The possible pattern defined in BSA-AUVare shown in Fig.3.

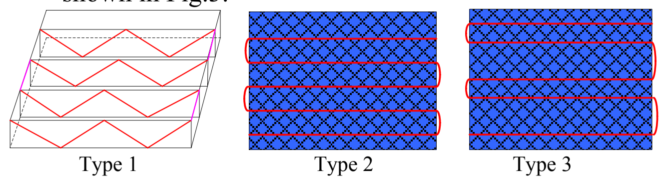

Fig.3 Survey patterns of Area survey: Type1 is CTD Survey Pattern, a zigzag motion in vertical plane; Type2 is ADCP Survey Pattern, an equal interval cropper motion with a fixed depth; Type3 is SSS&MBS Survey Pattern, a unequal interval cropper motion with a fixed height.

No matter what missions above, there are two basic tasks designed for AUV: navigation task (NTask) and tracking task (TTask), see Fig.4. The navigation task is used to let AUV navigate from one mission area to another area. The tracking task is used to let AUV survey operation in one mission area.

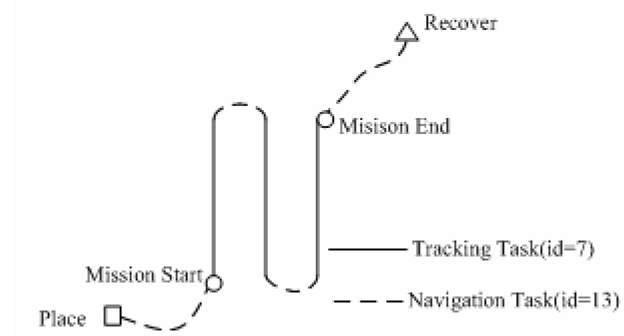

Fig.4 Basic task definition

Definition 1: $NTask = < Id, P, C, R >$

Where $Id = 13$ denotes the task ID; P denotes the information set of all mission points, including: 3D position information; C denotes control parameters set, including: Velocity, heading, depth and height; R denotes restriction set, the restriction of navigation task mainly considers time window, i.e. the earliest and latest start date. The navigation task only request AUV form one point to another point, but not restrict the routes between the two points.

Definition 2: $TTask = < Id, P, L, C, R >$

Where $Id = 7$ denotes the task ID; P denotes the information set of all mission points, including: 3D position information; C denotes control parameters set, including: Velocity, heading, depth and height; R denotes restriction set, the restriction of tracking task mainly considers tracking errors, mission type (showed in Fig.3).The tracking task not only requests AUV form one point to another point, but also requests AUV along given route between the two points.

IV. AUTONOMOUS MISSION SCHEDULING

This section gives the brief description of scheduling method for area survey mission operation. As mentioned early, hierarchical PNs are used to supervise, manage and control the implementation during the whole mission. According to the area survey mission operation process, the whole mission control is divided into three layers: mission layer, task layer and behaviour layer (see Fig.5). The mission layer call global planning according to the mission file. The global planning produce routes accord with the mission requirement, environment restriction and AUV restriction. Then, task list is formed by specifically domain knowledge and specification. The task layer mainly scheduling the mission according to task list, environment information and AUV state information, meanwhile process discrete event during mission executing, sometimes responses the intervenor event also. The mission scheduling will be introduced next particular. The behaviour layer is the bottom control layer. It produces basic behaviour control command according the scheduling command from task layer.

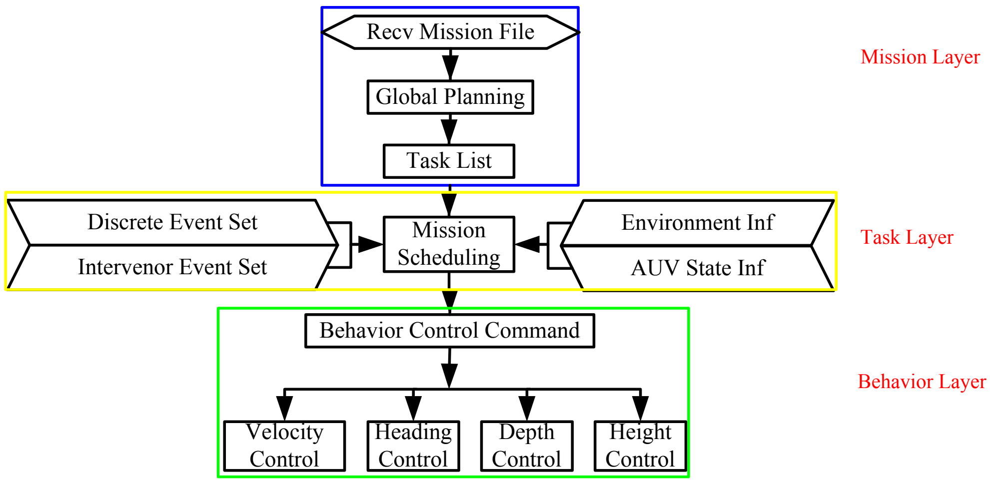

Fig.5 Hierarchical mission control layers

The mission scheduling is realized by a series of PNs. It begins from a main PN which are decomposed to more detailed sub-PNs. All PNs jointly accomplish the whole mission by communication and cooperation. Here, only a main PN named "Mission" for area survey mission is introduced as an example.

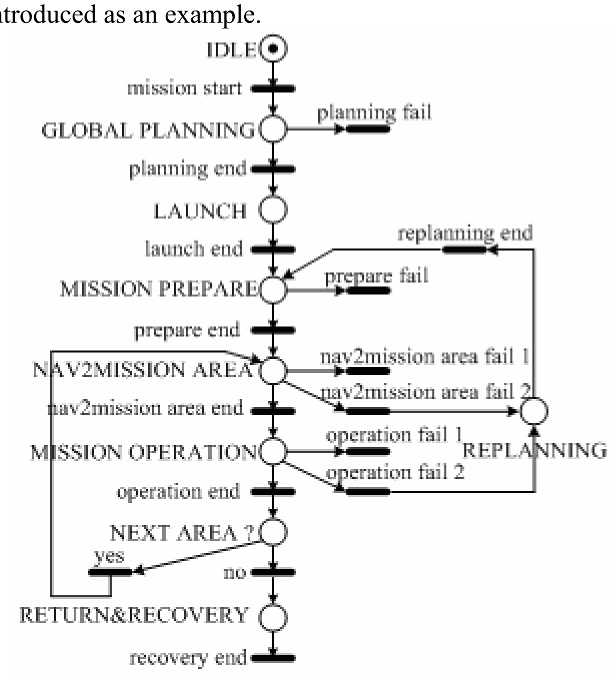

Fig.6 Main petri net "*Mission*"

"*Mission*" PN describes the general phases of the vehicle from its launch until its recovery. It also defines the sequence of mission that will be executed depending on unpredictable situations that may occur. The place marked in this PN indicates the phase in which the vehicle is or the high level action in progress to activate its sub-PN. This PN also indicates the ability of events supervising and control. Fig.6 shows the "*Mission*" PN:

1) Four places symbolise the four phases of navigation;

2) A set of places details the following of the plan with the loop navigation to the next mission area and operation until the exhaustion of the mission areas;

3) The other places detail the behaviour of the vehicle during planning and replanning;

4) Specific transitions and the associated Petri nets control the possible failures.

At the beginning of the mission, the activation of global planning place describes the process of using path planning algorithm for out-line planning. The place launch describes the launch operation in the launch area including floating-state adjustment, attitude adjustment, and so on. The place mission prepare describes system initializing, self checking, loading mission, sensors configuration. It enables directing the vehicle towards the first mission area according to the last plan. The place navigate to mission area describes the sail from one point to another point on the path. The place mission operation describes the survey operation in the objective area and activates the PN corresponding to the type of the operation. In the event of failure during navigation towards the next mission area or during the execution of an operation, the place re-planning describes the on-line decision to activate the secondary Petri net "Replanning" which sends a request of calculation for a new plan. The place recovery describes the end of the mission. The transitions navigation to mission area fail 1 and operation fail 1 indicates fatal events to stop mission and corresponding control to protect the AUV security. The transitions navigation to mission area fail 2 and operation fail 2 indicates other events to adjust the mission and activate a re-planning to execute.

V. LAKE TRIAL

This section presents the lake trial results at Thousand Islands Lake, Chekiang province, China, in April, 2010. At first, a simple point-to-point mission without using planning algorithm was carried out to test the AUV mission scheduling. In this test, all survey sensors were present at its survey routes. The designed routes and trial scenes of mother ship and BSA-AUV are showed in Fig.7. The total voyage of the mission is about 2km. AUV was launched near the mother ship, run the mission from a start point S, prepared at mission prepare routes S-L1-L2, then, executed CTD survey at L2-L3, ADCP survey at L3-L10, SSS&MBS survey at L10-E in turn, returned to end point E finally.

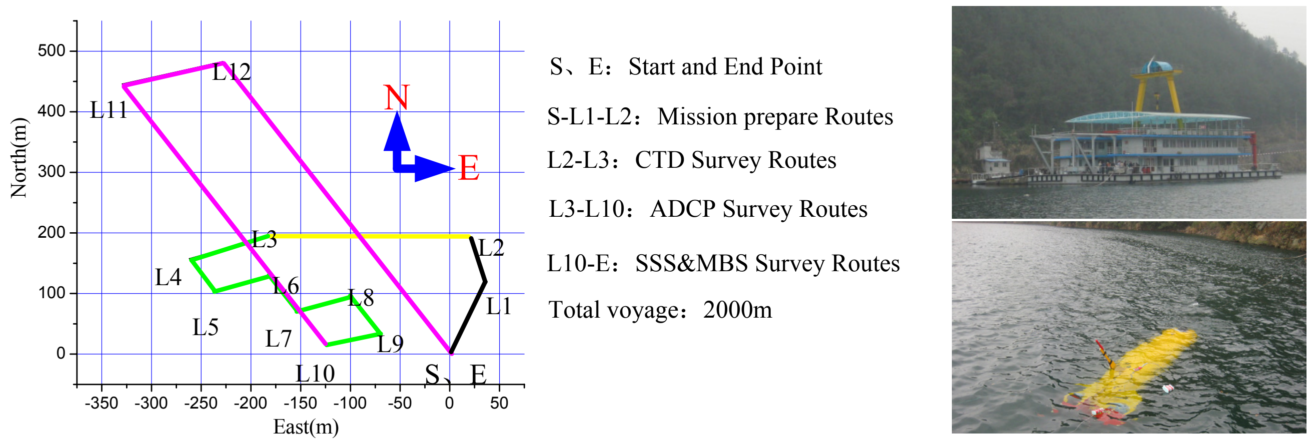

Fig.7 A simple point-to-point misison design and trial scenes

In the whole mission, the velocity of AUV is required at 2kn and a maximum depth 1.3m which lets AUV sailed near surface for assuring communication with mother ship. Fig.8 gives the trial result of this mission that AUV correctly accomplish. The whole process of this successful mission proved that the mission scheduling is feasibility in nominal situation. Fig.9 shows segments of ADCP, SSS and MBS survey outcomes. Because there are almost not change for conductivity and temperature, so the CTD survey outcomes is not present here.

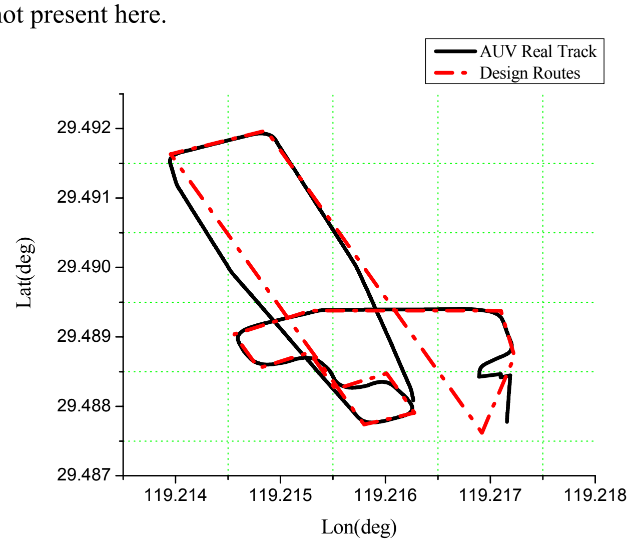

Fig.8 Point-to-point misison result

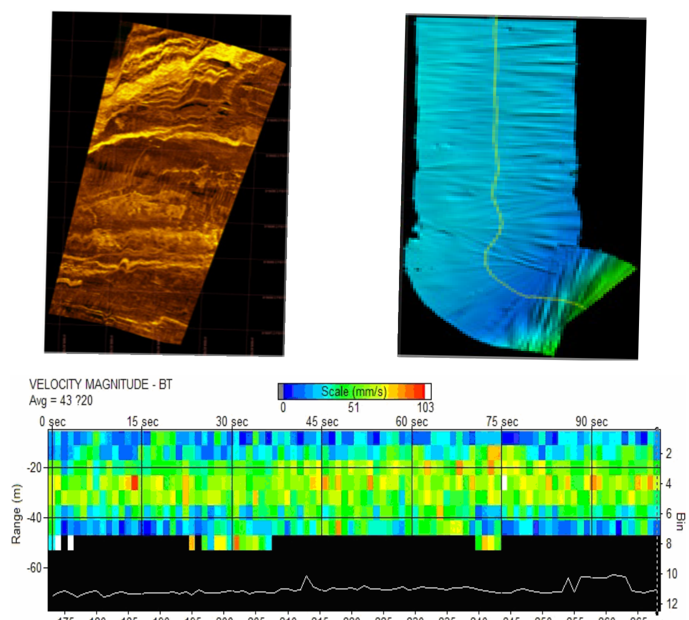

Fig.9 Segments of ADCP, SSS and MBS survey outcomes. The up-left is SSS image, the up-right is MBS image, the bottom is current profile obtaind by downward ADCP.

In order to evaluate the re-planning and the adaptability of our mission scheduling, other trials in various degraded situations were carried out. Here, we give a trial of in degraded situation of energy shortage as an example. This trial is a area survey mission which is different with the mission mentioned above. There were three objective areas of CTD, ADCP, and SSS&MBS to survey. First, global planning is called by mission scheduling to obtain survey routes according to survey type of each area. Fig.10 shows the planning and trial result. An energy shortage event was set factitiously when AUV navigated from SSS&MBS area to CTD area. The result shows that AUV terminates navigation to CTD area and drop the last operation to execute a re-planning process. The new plan was calculated directly to the end point and AUV executed the new plan and reached the end point. This and other trials (not present here) proved that the mission scheduling of BSA-AUV is feasibility for various degraded situations. The BSA-AUV has the online re-planning ability and the adaptability according to discrete events during mission.

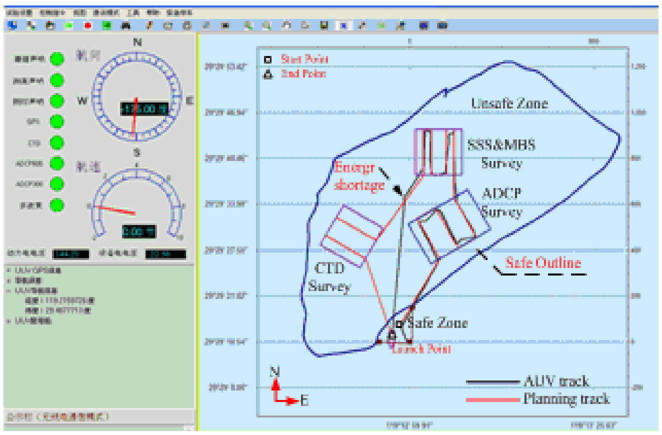

Fig.10 Survey mission in degraded situation of energy shortage

VI. Conclusion and Future Work

This paper presented the partial results of an ongoing research project which aims at ocean survey of BSA-AUV. The main work of this paper focus on the development, implementation of mission scheduling of AUV, meanwhile lake trials also be present. For mission scheduling, there are two issues to solve: mission scheduling architecture and mission scheduling mechanism. Using for reference of UAV, space probe, satellite etc. complexity system, distributed architecture is adopt here. For construct this distributed architecture, multi-agent system is used according to hardware structure and software function of the vehicle. This makes the architecture logic legible, be prone to integration, easy to maintenance and convenient for extending. After architecture introduction, the proposed mission scheduling mechanism is presented. In the approach presented in the paper, hierarchical petri nets are used to safely model the mission and the control structures. All these PN building blocks have been designed free of deadlocks and reusable. It has been shown that it is possible to compose PN building blocks to generate and scheduling the whole mission. For an example, the main PN "mission" is introduced in detail. It describes the general phases of the vehicle from its launch until its recovery. At last, the feasibility and effectiveness of the mission scheduling is checked by lake trial result in nominal and degraded situations. Future work will involve adding multiple vehicle coordination capabilities in the architecture and PNs allowing the scheduling of missions involving several vehicles.

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