Mission Control of AUV for Terrain Survey Using Discrete Event System Theory

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***Abstract*– This paper presents the mission control method of an Autonomous Underwater Vehicle (AUV) to survey terrain of ocean. The motion modes of AUV in the terrain survey mission are analyzed and defined. AUV needs to track a series of points and paths in horizontal plane and keeps depth in vertical plane. The motion control in the two motion modes are introduced briefly. Because of series of paths in the mission for AUV to track, so, there must be a mission control as path changed. When AUV sails from one path to another path or from one point to another point, its state is changed which may be cause poor tracking result. In order to keep optimal terrain survey task, this paper proposes a mission control method using discrete event system (DES) theory by treating the path change as an event transition. Petri net (PN) formalism is used to model and describe the whole mission, specially, when the path changes. At last, simulations in normal and degraded situations are established to verify the method mentioned above. The simulation results indicate that the method is feasibility and effectiveness for AUV.**

Key Words - Autonomous Underwater Vehicle; Terrain Survey; Mission Control; Discrete Event System Theory

I. INTRODUCTION

Unmanned Underwater Vehicle (AUV) has the advantages of long-term voyage, autonomous work mode, small dimension and good concealment. So, AUV is very conformable for ocean survey missions of large, deep, complicated acoustics areas, and ISR (Intelligence, Surveillance and Reconnaissance) of political sensitivity and military blockage areas [1, 2]. Our work in this paper is foucs on autonomous terrain survey using a AUV. There are many AUVs in the word has the ability of terrain survey, and many outstanding survey results are present. Stefan B. Williams, Matthew and Brian[3-5]describes the role of the AUV Sirius on a research cruise to survey drowned reefs using Multibeam sonar along the shelf edge of the Great Barrier Reef in Queensland, Australia. There are many results obtained in their scientific expedition in late 2007, including: Bathymetric maps of the Noggin Pass and Viper Reef study sites, and so on. David W. Caress [6] introduces the high-resolution surveys using MBARI mapping AUV equipped with 200 kHz multi-beam sonar, 110 kHz and 410 kHz side-scan sonar, and a 2-16 kHz sub-bottom profiler. According to the author, the bathymetry surveys of AUV achieve a vertical precision of 0.1 m; surveys from a 50 m altitude achieve 1m lateral resolution and surveys from up to 100 m altitudes achieve lateral resolutions less than 2 m. The famous HUGIN AUV is also a high-resolution survey underwater system which can be used for terrain survey. In literature [7], AUV operations, platform performance, sensor specifications and integration are addressed. current generations of the HUGIN AUVs have been used in a number of Rapid Environmental Assessment missions, including participation in several national and international military exercises and operations are introduced in [8]. Seafloor bathymetric maps in 2D and 3D of different areas surveyed by HUGIN AUV are also present. In literature [9], a deep and long range cruising AUV URASHIMA for surveying deep ocean is described. A mud volcano obtained by side scan sonar and high-precision 3D bathymetry map created by multi-beam echo sounder in sea trials held at the end of February 2005 are present. Stephen McPhail [10] addressed Challenges of using Autosub6000 AUV to find and map hydrothermal vent sites in deep and rugged terrains, In March 2010, in the Cayman trough in Caribbean Sea.

In this paper, the main research is focus on the mission control of AUV when executing the terrain survey mission. The remainder of this paper is organized as follows. In section II, the motion modes of AUV for terrain survey mission are analysed and described. In section III, motion control method of the two motion modes are introduced. Mission control of AUV using discrete event system theory is present in section IV. Results of hardware-in-loop simulation are given in section V. The end is the conclusion.

II. MOTION MODES OF AUV FOR TERRAIN SURVEY

Terrain survey mission of AUV is that AUV equipped with side scan sonar or multi-beam sonar surveys an ocean area to obtain seafloor topography image or seafloor terrains bathymetry mapping. For the terrain survey mission, there are two motion modes of AUV: way-point tracking and trajectory tracking which can be described as Fig.1. AUV is launched at point S and recovery at E. Given way point set $W=\{W_1\cdots W_i\cdots W_{2n}\}$, then, set $P=\{S,W,E\}$ can form $n+1$ path segments $L=\{L_p,L_1,\cdots L_i\cdots L_{n-1},L_e\}$. Here, $L_p:S\to W_1$ is called prepare task segment; $L_e:W_n\to E$

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is called recovery task segment; $L_i: W_{2i-1} \to W_{2i}$, $i = 1, 2, \cdots n$ are called survey task segments. $L_j: W_{2j} \to W_{2j+1}$, $j = 1, 2, \cdots n-1$ are called transition task segments. AUV sails from launch point S, and reaches the first way-point W_1 (the survey start point) bypass prepare task segment. Then, AUV is tracking the survey task segments L_i to execute the terrain survey. When the task in current survey segment is finished, AUV changes to next survey segment bypass transition segments L_j and continue to survey terrain. At last, AUV reaches the recovery point bypass recovery task segment when all tasks in survey segments are finished. Where, in prepare task segment L_p, recovery task segment L_e and transition task segments L_j, AUV is way-point tracking motion mode; in survey task segments, AUV is trajectory tracking motion mode. Then, definitions of the two motion modes are described.

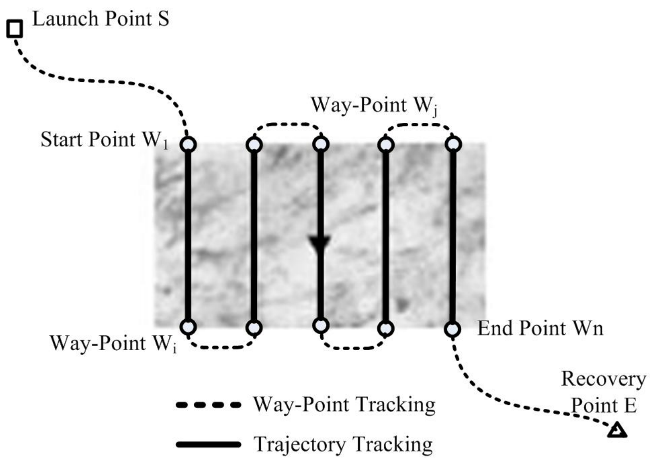

Fig.1 Motion Modes of AUV for Terrain Survey Mission

Definition 1: way-point tracking motion: let AUV sail from one position to another position. The way-point tracking motion can be described as a 4-tuple:

$$STask = \{P, C, \Omega, E\}$$

Where, P is the set of way-points to denote the 3D position of start point W_S and end point W_E 。 C is the set of control parameter, including: velocity, heading, and depth。 Ω is the constraint set，AUV sails from W_S to W_E must satisfy the following constraints:

(1) Position constraint:

$$\lim_{t \to \infty}(X_t - X_E)^2 + (Y_t - Y_E)^2 + (Z_t - Z_E)^2 = 0$$

Where, X_t, Y_t, Z_t is the position of AUV; X_E, Y_E, Z_E is the potion of end point W_E.

(2) Velocity constraint:

$$\lim_{t \to \infty}(V_t - V_d) = 0$$

Where, V_t is the velocity of AUV, V_d is the desired velocity.

E is the terminative condition which may be described in the subsequent section. From the definition of way-point tracking motion, we can find that this motion mode only needs AUV sail from start point to end point, but no strict restrict what path AUV along.

Definition 2: trajectory tracking motion: let AUV accurately follow a planning trajectory. The trajectory tracking motion can be described as a 5-tuple:

$$TTask = < P, S, C, \Omega, E >$$

Where, P is the set of way-points to denote the 3D position of start point W_S and end point W_E 。 S is a predefined straight line trajectory between W_S and W_E. C is the set of control parameter, including: velocity, heading, and depth。 Ω is the constraint set，AUV sails from W_S to W_E along trajectory S must satisfy the following constraints:

(1) Position constraint: for $\forall t$, there is $\varepsilon(t) = 0$. Where, $\varepsilon(t)$ is the distance from current position of AUV to trajectory S. Usually, $\varepsilon(t)$ is called cross-track error.

(2) Heading constraint: for $\forall t$, there is $|\psi(t) - \psi_{trk}| = 0$. Where, $\psi(t)$ is the current heading of AUV; ψ_{trk} is the direction of trajectory S.

(3) Velocity constraint:

$$\lim_{t \to \infty}(V_t - V_d) = 0$$

Where, V_t is the velocity of AUV, V_d is the desired velocity.

E is the terminative condition which may be described in the subsequent section. From the definition of trajectory tracking motion, we can find that this motion mode not only needs AUV sail from start point to end point, but also need AUV sail along trajectory S.

III. Motion Control of AUV

A. Motion Control System

Motion control is the basic ability of AUV. According to section II, there are two motion control of AUV in terrain survey mission: way-point tracking control and trajectory tracking control. The motion control system of the two motion modes of AUV is showed in Fig.2. It can be find that the motion control of AUV can be divided into three parts: velocity control, heading control in horizontal plane and depth control in vertical plane. This decomposing can consumedly reduce the difficulty of control and also can meet the motion in terrain survey mission. In Fig.2, the real position of AUV is obtained by GPS when on surface and obtained by dead reckoning when underwater. The real heading, depth and velocity, rudder and elevator of AUV are respectively obtained by a compass, pressure sensor, DVL and coder.

The difference between way-point tracking control and trajectory tracking control is the heading control part, especially the heading guide method. For heading guide of trajectory tracking control is described in literature [11] and our previous job in literature [12], which is not present here. In this section, the heading guide method and depth control method will be introduced in detail.

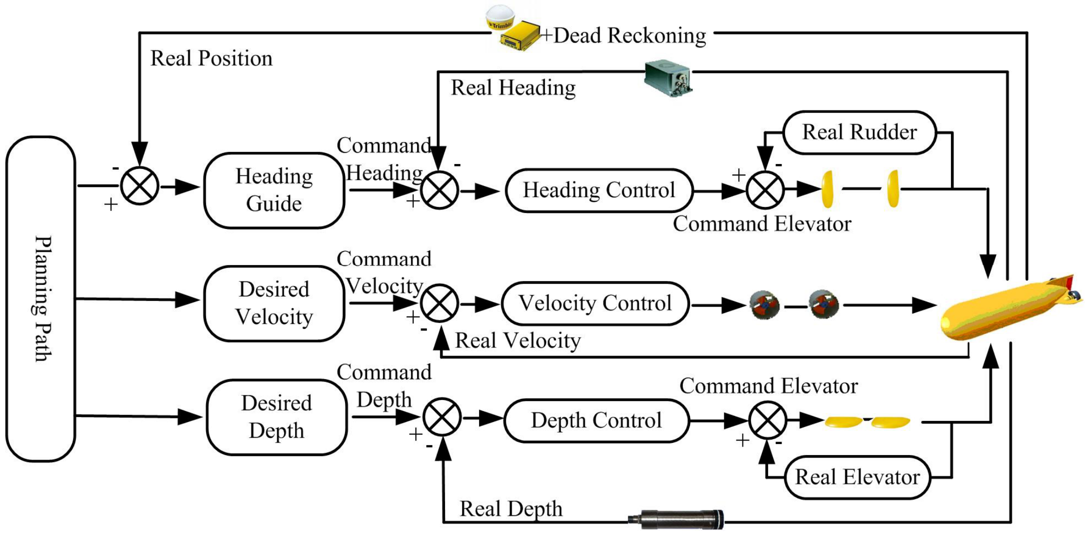

Fig.2 Motion Control System of AUV

B. Heading Guide for Way-point Tracking

For way-point tracking, the only need is let AUV sail to the aim point. So, the heading guide method is simple. Pure Pursuit (PP) guidance method can be used to obtain the command heading of AUV:

$$\psi_{cmd}(t) = \tan^{-1}\left(\frac{Y(f)-Y(t)}{X(f)-X(t)}\right) \tag{1}$$

Where, $\psi_{cmd}(t)$ is the command heading of AUV at moment t ; $X(f)$ and $Y(f)$ are the position of aim point; $X(t)$ and $Y(t)$ are the position of AUV at moment t .

In fact, it is not necessary to calculate command heading according equation (1) and adjust in each control moment, because there is not need AUV to track a trajectory. So, the guide method is improvement: only the heading error between AUV and $\psi_{cmd}(t)$ is larger than a limen, the heading adjust will be done. Then, the guide method can be described as:

$$\begin{aligned} &\psi_c(t) = \tan^{-1}\left(\frac{Y(f)-Y(t)}{X(f)-X(t)}\right) \\ &\psi_{cmd}(t) = \begin{cases} \psi_c(t) & if \;\; abs(\psi_c(t)-\psi(t)) > \sigma \\ \psi_{cmd}(t-1) & if \;\; abs(\psi_c(t)-\psi(t)) \le \sigma \end{cases} \end{aligned} \tag{2}$$

Where, $\psi(t)$ is the real heading of AUV at moment t ; $\sigma = 5^{\circ}$ is the heading error limen.

C. Depth Control Method

Depth control of AUV is relative difficult and has biggish risk in the complicated ocean environment. So, for depth control, nonlinear cascade control is adopted in this paper to realize a small overshoot and quickly control result. The control principle of depth control is showed in Fig.3. Depth control is the main control loop; pith control is the assistant control loop; the depth control of AUV is realized by controlling the pith of AUV. Between the depth control and pitch control, a nonlinear function is used to switch the depth command to a pitch command, which can realize quickly and steady depth adjusting.

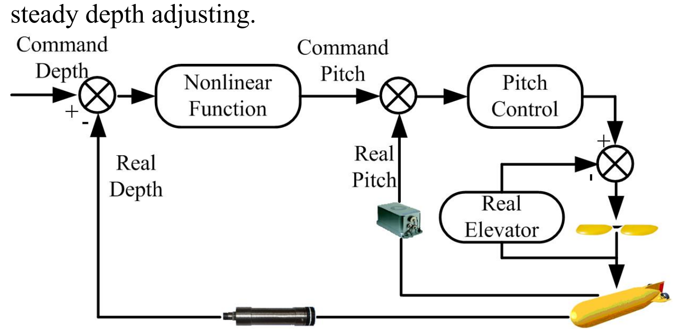

Fig.3 Depth Control of AUV Using Nonlinear Cascade Control

The nonlinear function adopted is:

$$\theta_{cmd}(t) = k\frac{e^{-a\tilde{\zeta}(t)} - e^{a\tilde{\zeta}(t)}}{e^{-a\tilde{\zeta}(t)} + e^{a\tilde{\zeta}(t)}} \tag{3}$$

Where, $\theta_{cmd}(t)$ is the command pitch at moment t ; $\tilde{\zeta}(t)$ is the depth error at moment t ; k is a proportion coefficient to limit the max pitch; a is zooming to adjust the gradient of the nonlinear curve. In practice, $k = 30$ ， $a = 0.02$ .that is to say, the max command pitch of AUV is limited to $\pm 30^{\circ}$. According to the nonlinear function, the command pitch is large (always exceeds 20°) when the depth error is large. Then, the command pitch reduce with the depth error reduce, at last reduce to zero. So, quickly and steady depth adjusting of AUV is realized.

IV. Mission Control of AUV

A. Petri Net Theory

For mission control of AUV in terrain survey, it is modelled by discrete events driven Petri net (PN) formalism in this paper. First, basic Petri net theory will be introduced.

Definition 3: basic PN is a 3-tuple $N = \{S, T; F\}$, where, S is called place set of net N, T is called transition set of net N, F is called flow relation of net N. PN is a directed net and must satisfy conditions below:

(1) $S \bigcup T \neq \varnothing$;

(2) $S \bigcap T \neq \varnothing$;

(3) $F \subseteq S \times T \bigcup T \times S$

(4) $dom(F) \bigcup cod(F) = S \bigcup T$

Where, "$\varnothing$" denotes the empty set; "$\times$" denotes the Descartes product of two sets; F is a ordinal even set compose by element S and element T. The denotations of $dom(F)$ and $cod(F)$ is:

$$dom(F) = \{x \mid \exists y : (x, y) \in F\}$$

$$cod(F) = \{x \mid \exists y : (y, x) \in F\}$$

In the definition, $S \bigcup T \neq \varnothing$ denotes that net N at least has one element; $S \bigcap T \neq \varnothing$ denotes that places and transitions are different elements. $dom(F) \bigcup cod(F) = S \bigcup T$ denotes that there is not isolated elements in net N, that is to say, S, T and F are not "$\varnothing$". In the Petri net, S is usually showed by "○". T is usually showed by "｜". F is usually showed by a directional arrowhead "→".

Net N defined above is only the structure of Petri net. Petri net also has another element: token which can reflect the state of the discrete system.

Definition 4: suppose a net $N = \{S, T; F\}$, mapping: $M : S \to N_0$ (where $N_0 = \{0\} \bigcup N^+$) is called a token of net N. Then 4-tuple $N = \{S, T; F, M\}$ is called a token net.

Token is usually showed by k black point in the place showed by "○", which denotes there are k tokens in one place. There is an initial token M_0 in a net, which describes the initial state of the event system. Start by initial token M_0, there may be several transitions happen. For any a transition, there is a new token M_1 obtained. Then, start by M_1, there may be other transitions happen, in turn, the tokens continually change which is the working of event system.

B. Mission Control Using Petri Net

Petri net is a very great tool for modelling and analysing a discrete event system, and now is widely used in the mission control of AUV [13-15]. The control system of AUV for terrain survey mission is a typical hybrid system including continuous system control and discrete system control [16]. Fig.4 gives the Petri net of AUV mission control designed in this paper. The significations of places and transitions in Fig.4 are described in Table 1. From Fig .4, we can find that there are a main net; a lateral net and two sub-nets. The two sub-nets are used to model the two motion control modes: way-point tracking control and trajectory tracking control. The lateral net is used to model the initial process of the mission. It is to guide AUV sail to the first survey point if AUV is not at that point at the beginning.

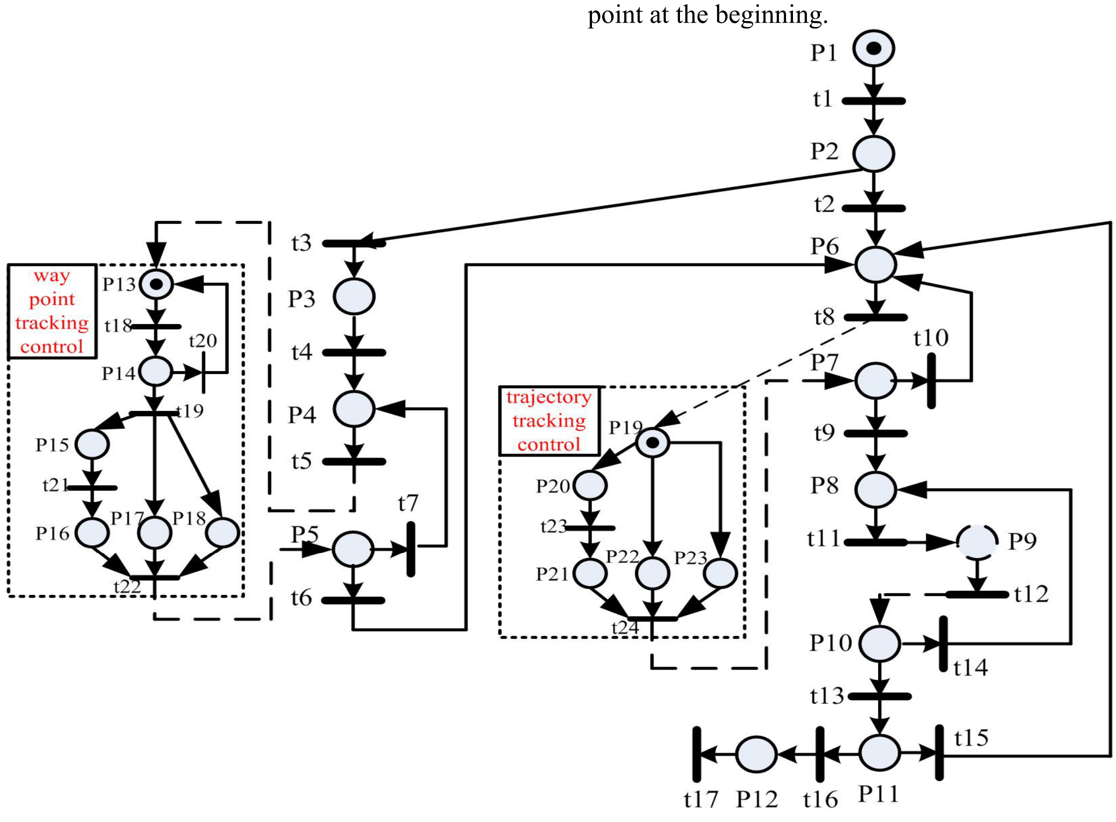

Fig.4 Petri Net of AUV Mission Control for Terrain Survey

Table 1 Signification of Places and Transitions in Fig.4

Place	Signification	Transition	Signification
P1	Idle	t1	Mission start
P2	At W1?	t2	Yes
P3	Insert a task sailing to W1	t3	No
P4	Sail to W1	t4	Insert task ok
P5	Reach W1?	t5	Way-point tracking
P6	Survey task	t6	Yes
P7	Reach way-point?	t7	No
P8	Transition task	t8	Trajectory tracking
P9	way-point tracking control	t9	Yes
P10	Reach way-point?	t10	No
P11	Next survey task?	t11	Way-point tracking
P12	Sail to recovery point	t12	Control ok
P13	Idel	t13	Yes
P14	Error < limen	t14	No
P15	Heading guide	t15	Yes
P16	Heading control	t16	No
P17	Velocity control	t17	Mission over
P18	Depth control	t18	Calculate Heading error
P19	Idel	t19	Yes
P20	Heading guide	T20	No
P21	Heading control	T21	Command heading
P22	Velocity control	T22	Control ok
P23	Depth control	T23	Command heading
		T24	Control ok

The mission control showed in Fig.4 is only the normal process. In addition, degraded situation of AUV fault also must be considered. In this paper, three kinds of AUV faults are considered: survey sensor fault, leak and energy shortage. When these three faults occurs, AUV need to cancel the mission and replan to the recovery point as a way-point tracking motion.

V. SIMULATION

This section will present the simulation result of mission and motion control for terrain survey of AUV. Fig.5 shows the simulation result in normal situation. AUV launches from launch point, surveys via the routes ①-②-③-④-⑤-⑥-⑦-⑧ seriatim and recovery at the recovery point at last. Where, routes ①, ③, ⑤, ⑦ are the survey path, so, AUV executes trajectory tracking motion. Routes ②, ④, ⑥ are transition paths; ⑧ is the recovery path, so, AUV executes way-point tracking motion. From the figure, we can find that the tracking effects of way-point tracking and trajectory tracking are different. The initial velocity of AUV is 0 and command velocity is 2 m/s. The initial heading of AUV is 90°and command heading is changed according to the heading guide method. Fig.6 shows the velocity and heading control results of AUV.

Fig.7 shows the simulation results in degraded situation. At simulation time 650s when AUV sails at route ③, a energy shortage fault is set to the AUV. The simulation result shows that AUV terminates the mission and AUV replan directly to the recovery point via route ⑨.

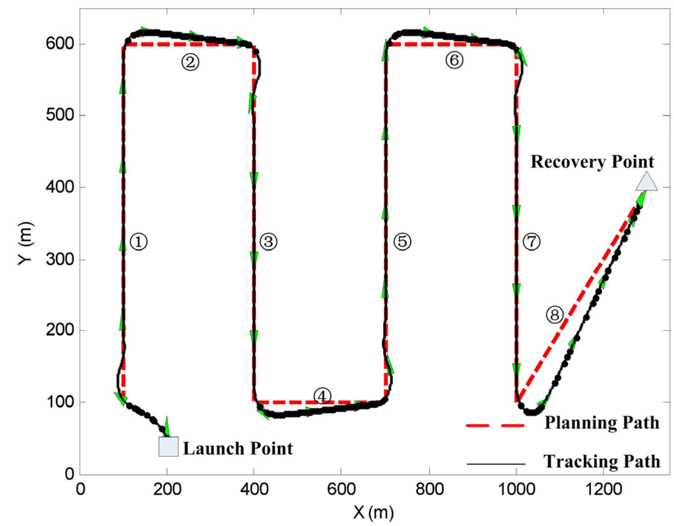

Fig.5 Simulation Result in Normal Situation

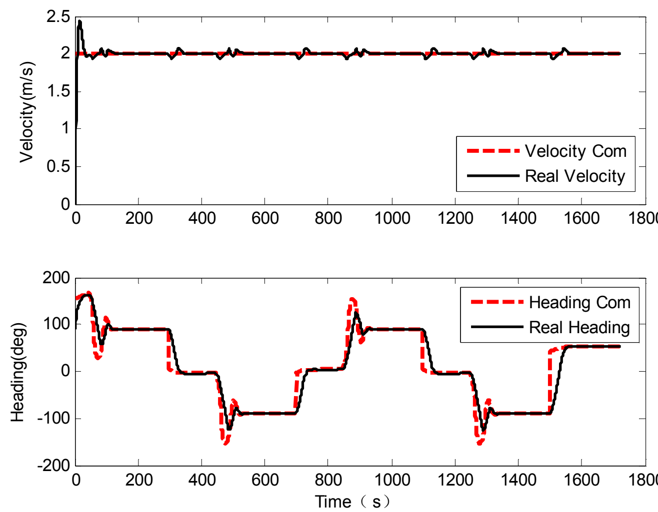

Fig.6 Velocity and Heading Control Results of AUV

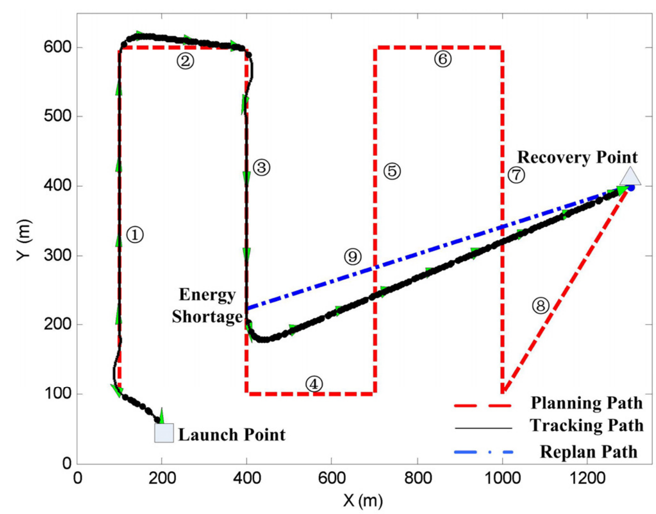

Fig.7 Simulation Result in Degraded Situation

VI. CONCLUSION

Terrain survey mission is an important application for AUV both in military and civil aspects. This paper addresses the AUV mission control problem for terrain survey using Petri net of discrete event system theory. In this paper, the motions of AUV for terrain survey are divided into two aspects: way-point tracking motion and trajectory tracking motion. The definition of each motion mode is described. Where, trajectory tracking motion is used to execute the survey task; way-point tracking motion is mainly used to the transition among survey task. The motion control system of the two modes, the heading guide and depth control methods are introduced. For mission control of AUV, Based on discrete event system theory, Petri net formalism is used to model and describe the whole mission. The Petri net designed includes a main net; a lateral net and two sub-nets. At last, simulation results show the feasibility and validity of AUV mission control. Specially, when degraded situations of AUV are occurred, the method proposed can cope with these degraded situations.

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