Intelligent Guidance and Control Laws for an Autonomous Underwater Vehicle

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Abstract:- In this paper, intelligent guidance and control laws are developed for an autonomous underwater vehicle to engage underwater targets. The engagement of underwater targets is suffered from uncertainties of the complicated underwater environment, short detecting range of the sonar seeker, the low speed ratio between vehicle and target, and longtime operations but no accurate positioning technique. Uncertainties of underwater environment includes temperature-dependent sound propagation path, sound shadow zone, current flowing direction, current flowing noise and self-noise of the vehicle. The first object is to find the target. The second object is to track the target and to re-track the target after the target lost. Seven guidance laws are developed and switched by an intelligent selecting logic for target engaging. Six control modes for yawing and pitching channel are developed. Mode selections are dependent on the guidance laws selected. Those seven guidance laws and six control laws are well tested by digital simulation verifications of four scenarios. Simulation results give the proposed method can cope with the complicated underwater environment to engage the target.

Key-Words: -Guidance and control laws, autonomous underwater vehicle, underwater target.

1 Introduction

Two types of unmanned underwater vehicles are in use: Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). ROVs are teleported through a cable, which supplies power to the vehicle. The drag on the cable and power transmission losses through the cable increase with an increase in the operating range of the vehicle. AUVs do not have such limits, and have a wide scope of operation as they carry their power supply onboard. As there is no external communication for guidance, and power available is limited, mission planning and navigation are extremely critical for successful operation of AUVs. Unmanned underwater vehicles are used to perform exploration, survey, monitoring and data collection tasks that reduce ship cost and human risks [1, 2].

The guidance and control of underwater autonomous vehicles are suffered from vehicle positioning for longtime operation [3-6], sea environment and shorter-detecting range of the passive/active sonar or imaging seeker. It is much more complicated than that of a flight vehicle or missile. Uncertainties of the sea environment includes speed-dependent sound propagation path, seabed, current direction, current noise and self-noise of the underwater vehicle. The diffraction and reflection of the sound propagation paths may give the target detecting shadow area and the “detected” target must be recognized [7, 8].

Sound speed varies with temperature, pressure and salinity, there are considerable variations in sound velocity both spatially (with depth/geographically) and temporally (mooring/afternoon/daily/seasonally). Horizontal variations in sound velocity are usually small due to small gradients in temperature, salinity and pressure. Figs.1a and 1b show the simplified idealized vertical profiles of temperature and sound velocity [7, 8]. This simplified diagram can be divided into three distinct zones. Closest to the surface (Zone 1) there is an isothermal layer created and maintained by mixing due to wind and waves. Within this layer which can be up to 200m deep the sound velocity increases slowly with depth due to the increasing pressure. The middle layer (Zone 2) is the thermocline. Here the sound velocity decreases rapidly with depth due to the decreasing temperature. The base of the permanent thermocline varies greatly with latitude but is typically found at a depth of about a 1000m. Within the deepest region (Zone 3) below the permanent thermocline the temperature change is less dramatic. Here the sound velocity shows a further increase with depth due to increasing pressure.

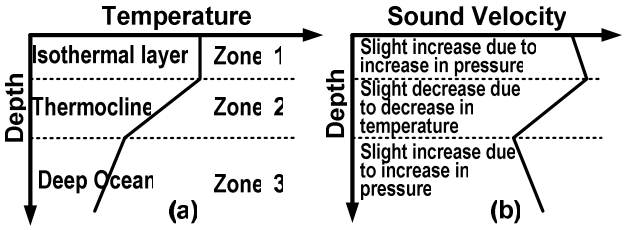

Fig.1. Typical profile of (a)temperature v.s. depth, (b)sound velocity v.s. depth.

The form of the vertical sound profile is extremely important to the propagation of sound in the oceans. Two velocity minima are shown in Fig.1, one at the surface and one between Zone 2 and Zone 3. These areas are also illustrated in Fig.2. These areas effectively trap and focus sound waves and are called 'sound channels'. These are the deep and shallow sound channels. They are shown in Fig.2.

Sound travels very efficiently in sound channels and for this reason they are often utilized for underwater communications. The deep sound channel is often called the **SO**und **F**ixing **A**nd **R**anging (SOFAR) channel. The depth of the SOFAR channel varies considerably geographically. Typically, it is found at around 1500m depth at mid-latitudes, has a depth of about 500m between 50 to 60 degrees north, and reaches the surface in Polar latitudes. The average depth of the deep sound channel is 1000m approximately.

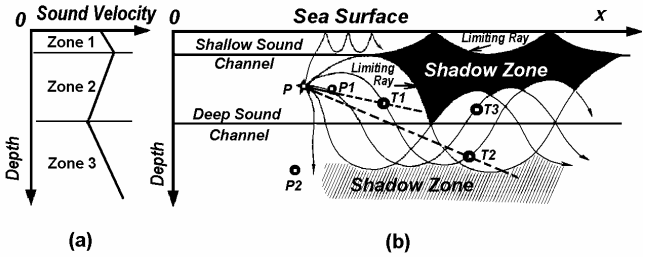

Fig.2. (a)Sound speed, (b) sound propagation and shadow zones.

Fig.2 shows a shadow zone around the shallow sound channel and another shadow zone below the deep sound channel for sound propagation or detection. One can move the detecting point *P* forward (or back) to detect the target in the shadow zone (blank zone of sonar detection). Target at position T_3 for detecting point P will be lost after detecting point be moved to the point P_1. This is due to the position T_3 be fall in the shadow zone for detecting point P_1. It implies the shadow zone is movable according to the detecting point. Furthermore, targets at positions T_1 and T_2 are not distinguishable for passive sonar, and the detected elevation angle is positive while real elevation angles are negative. If the maneuverability of the vehicle is larger than V_m^2/R in which V_m is the vehicle speed and R is the radius of the covertures of the sound curve, then conventional PP or PN guidance laws with maneuverability limitation V_m^2/R can be used to homing target. Otherwise, the detected target will be lost. These imply vehicle speed is limited. Note that the vehicle must be moved to P_2 to engage the target in the shadow zone below the deep sound channel.

Since the sound speed varies with temperature, pressure and salinity, there are considerable variations in sound velocity both spatially (with depth/geographically) and temporally (mooring/ afternoon/daily/seasonally). Therefore, the sound propagation characteristics are difficult to be concluded to get a general rule and conventional guidance laws for flight/navigation vehicles must be modified [9-11]. The large area searching law for target detecting plays a central role than that of terminal homing guidance laws after the target detected. Developing effect guidance and control laws are expected. This is the motivation of this paper.

The first object of guidance and control laws is to find the target. The second object is to track the target. The third object is to re-track the target after the target lost. Seven guidance laws are developed and selected by an intelligent selecting logic for target searching, engaging and intercepting. The speed of the vehicle and the sonar-operating mode are dependent on the guidance mode selected. There are three control modes for yawing channel and pitching channel respectively. Mode selections are dependent on guidance laws selected also. It is a complicated mode switching logic and verified by digital simulations. Four scenarios for target engaging give the proposed method can cope with complicated underwater environment and limits to engage the target.

This paper is organized as follows: Section 2 describes the considered AUV, equations of motion, evaluates the small signal dynamic models and propelling model for 6-DOF simulations and autopilot designs; Section 3 develops the intelligent guidance and control configurations; Section 4 proposes an accurate position navigation technique; Section 5 gives mission planning and guidance laws designs; Section 6 shows simulation verification results.

2 System description and small-signal dynamic models

Fig.3 shows the configuration and coordinates definitions of the considered underwater vehicle. The physical dimension is compatible to that of the MK-48 torpedo (579cm long; 53.3cm diameter; 1545kg weight). The central of gravity (CG) is 5.4cm below the central of buoyancy (OB). Therefore, the rolling axis is inherent stable and major control efforts are paid for pitching/yawing controls. The front propeller has seven leaves and rear propeller has five leaves. They are actuated by two counter direction electric motors for rolling torque balance.

Equations of motion are generally derived in the body coordinate frame. In this work, the mass, added mass and damping matrices are assumed be diagonal. Equations of motion of an underwater vehicle in six degree of freedom (6DOF) can be written as [9]

$$\begin{aligned}
&\dot{\eta}_1 = J_1(\eta_2)v_1 \\
&\dot{\eta}_2 = J_2(\eta_2)v_2 \\
&M_1\dot{v}_1 = -C_1(v_1)v_2 - D_1(v_1)v_1 + \tau_1 \\
&M_2\dot{v}_2 = -C_1(v_1)v_1 - C_2(v_2)v_2 - D_2(v_2)v_2 - g_2(\eta_2) + \tau_2
\end{aligned} \tag{1}$$

where

$\eta_1 = [x \quad y \quad z]^T$, $\eta_2 = [\phi \quad \theta \quad \psi]^T$, $v_1 = [u \quad v \quad w]^T$, $v_2 = [p \quad q \quad r]^T$. The symbols ϕ, θ, ψ p, q and r denote the roll, pitch and yaw angles and angular rates while *x, y, z, u,* v and *w* are the surge, sway and heave displacements and velocities; respectively. The terms $J_1(\eta_2)$, $J_2(\eta_2)$, M_1 , $C_1(v_1)$, $D_1(v_1)$, M_2 , $C_2(v_2)$, $D_2(v_2)$ and $g_2(\eta_2)$ denote the kinematical transformation, mass, Coriolis, damping matrices including the added mass effect, and the restoring vector, respectively. The kinematical transformation matrices in roll, pitch, and yaw are defined as

$$J_1(\eta_2) \equiv \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & c\phi c\psi + s\phi s\theta s\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi s\theta & c\phi c\theta \end{bmatrix} \tag{2}$$

$$J_2(\eta_2) \equiv \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi / c\theta & c\phi / c\theta \end{bmatrix} \tag{3}$$

where $c\bullet = \cos(\bullet)$, $s\bullet = \sin(\bullet)$ and $t\bullet = \tan(\bullet)$. The mass matrices are

$$\begin{aligned}
&M_1 = diag(m_{11}, m_{22}, m_{33}). \\
&M_2 = diag(m_{44}, m_{55}, m_{66}).
\end{aligned} \tag{4}$$

where the positive constant terms $m_{jj}, 1 \le j \le 6$, denote the vehicle mass including added mass in surge(x), sway(y), heave(z), pitch and yaw. The Coriolis matrices are

$$C_1(v_1) \equiv \begin{bmatrix} 0 & m_{33}w & -m_{22}v \\ -m_{33}w & 0 & m_{11}u \\ m_{22}v & -m_{11}u & 0 \end{bmatrix} \tag{5}$$

$$C_2(v_2) \equiv \begin{bmatrix} 0 & m_{66}r & -m_{55}q \\ -m_{66}r & 0 & m_{44}p \\ m_{55}q & -m_{44}p & 0 \end{bmatrix} \tag{6}$$

The damping matrices are

$$D_1(v_1) = diag\left(d_{11} + \sum_{i=2}^{3} d_{ui} \mid u \mid^{i-1}, d_{22} + \sum_{i=2}^{3} d_{vi} \mid v \mid^{i-1}, d_{33} + \sum_{i=2}^{3} d_{wi} \mid w \mid^{i-1} \right) \tag{7}$$

$$D_2(v_2) = diag\left(d_{44} + \sum_{i=2}^{3} d_{pi} \mid p \mid^{i-1}, d_{55} + \sum_{i=2}^{3} d_{qi} \mid q \mid^{i-1}, d_{66} + \sum_{i=2}^{3} d_{ri} \mid r \mid^{i-1} \right) \tag{8}$$

where $d_{jj}, d_{ui}, d_{vi}, d_{wi}, d_{pi}, d_{qi}, d_{ri}$ and $1 \le j \le 6, i = 2,3$, represent the hydraulic-dynamic damping in surge, sway, heave, roll, pitch and yaw. The restoring force vector is

$$g_2(\eta_2) = [\rho g \nabla GM_T \sin(\phi) \quad \rho g \nabla GM_L \sin(\theta) \quad 0]^T \tag{9}$$

where ρ, g, ∇, GM_T *and* GM_L are the water density, gravity acceleration, displaced volume of water, transverse metacentric height and longitudinal met centric height; respectively. The available inputs are

$$\tau_1 = [\tau_u \quad 0 \quad 0]^T , \quad \tau_2 = [\tau_p \quad \tau_q \quad \tau_r]^T \tag{10}$$

where τ_u, τ_p, τ_q *and* τ_r are the control force in surge and torques in roll, pitch and yaw; respectively. They are applied from two counter direction propellers actuated by electric motors and four cruciform tail fins($\delta_1, \delta_2, \delta_3, \delta_4$) at 0°, 90°, 180°, 270°.

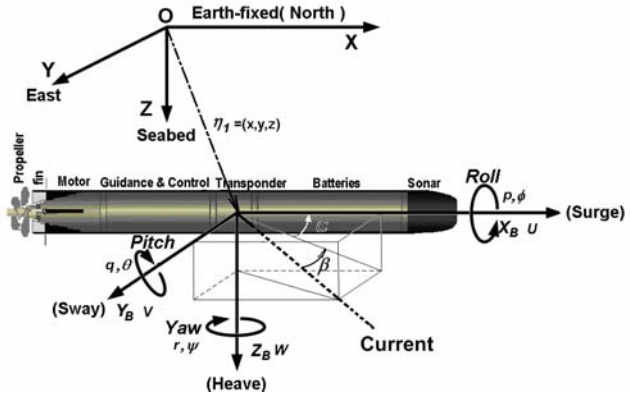

Fig.3. Coordinate system of the underwater vehicle.

The relationship between rolling/pitching/ yawing channel actuating angles ($\delta p, \delta q, \delta r$) and four fin angles ($\delta_1, \delta_2, \delta_3, \delta_4$) is

$$\begin{bmatrix} \delta p \\ \delta q \\ \delta r \end{bmatrix} = \begin{bmatrix} 1/2 & 0 & 1/2 & 0 \\ 0 & 1/2 & 0 & -1/2 \\ -1/2 & 0 & 1/2 & 0 \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix} ; \quad \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \delta p \\ \delta q \\ \delta r \end{bmatrix} \tag{11}$$

The small-signal perturbation models [12] of three

angular rates (p,q,r) and two accelerations ($\dot{w},\dot{v}$) from control efforts ($\delta p,\delta q,\delta r$) for different operating speed ($V_m=\sqrt{u^2+v^2+w^2}$ in m/s) around trims $(\alpha,\beta)=(0°,0°)$ are given below:

$$\frac{p}{\delta p}=\frac{p_n V_m^2}{s+p_d V_m};$$
$$\frac{q}{\delta q}=\frac{q_{n1}V_m^2 s-q_{n0}V_m^3}{s^2+q_{d1}V_m s-q_{d0}V_m^2};\quad \frac{r}{\delta r}=\frac{-r_{n1}V_m^2 s-r_{n0}V_m^3}{s^2+r_{d1}V_m s-r_{d0}V_m^2};$$
$$\frac{\dot{w}}{\delta q}=\frac{-w_{n2}V_m^2 s^2+w_{n1}V_m^3 s+w_{n0}V_m^4}{s^2+w_{d1}V_m s-w_{d0}V_m^2};$$
$$\frac{\dot{v}}{\delta q}=\frac{+v_{n2}V_m^2 s^2-v_{n1}V_m^3 s-v_{n0}V_m^4}{s^2+v_{d1}V_m s-v_{d0}V_m^2} \qquad (12)$$

All coefficients given in Eq.(12) are positive values. They give the considered system is an unstable open-loop system in pitching and yawing channels. Therefore, they need stable compensation and gain adaptation for autopilot according to the vehicle speed (V_m).

The vehicle will approach to a steady-state speed (V_{ms}) after the propelling force and drag are balanced. That is, a rolling speed of propelling motor (M_{spd}) corresponding to a steady-state vehicle speed (V_{ms}). The steady- state speed (V_{ms}) must be modified by amplitudes of pitching and yawing angular rates for lager drag will be get for large angle of attack and sideslip(α,β). It is in the form of

$$V_{ms}=a_0+a_1|r'|+a_2|r'^2|+a_3|r'^3|\,(\text{m/s}) \qquad (13)$$

where $r'\equiv\sqrt{r^2+q^2}$ and a_i are functions of M_{spd}. They are evaluated from theoretical calculations, 6-DOF simulations and corrected by real navigation experiments. Fig. 4 shows relationships between M_{Spd}, V_{ms} and *r'* of the considered system. It shows the larger value of *r'*, the less value of vehicle speed. Eq.(13) gives the steady-state conditions and can be used to formulate the completely propelling dynamic model of vehicle speed form motor speed command (M_{TCmd}). Two dynamic models will be added to describe the motor speed response and the water compressibility. They are represented by two first-order models:

$$\frac{M_{spd}}{M_{TCmd}}(s)=\frac{1}{1+1.353s};\quad \frac{V_m}{V_{ms}}(s)=\frac{1}{1+1.175s} \qquad (14)$$

Time constants (1.353, 1.175) given in Eq. (14) are all evaluated and verified by post data processing of navigation experiments. Eqs. (13)- (14) describe the open-loop speed response from motor speed command. In this work, open-loop speed control will be used for there is no speedometer in AUV.

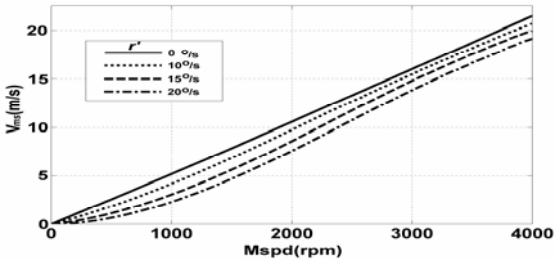

Fig. 4. Steady-state relationships between V_{ms}, M_{Spd} and total angular rate *r'*.

3 Guidance and Control Configuration

A general guidance and control configuration of the autonomous underwater vehicle is shown in Fig.5. It includes mission planning, homing seeker(sonar), guidance and control laws, inertial navigation system (INS), depthmeter. Mission planning gives the predicted target position(PTP) and the vehicle will be here. Homing seeker insures the contact between target and vehicle. Guidance laws provide the way to the target. Control laws provide a stable controlled vehicle to be guided. INS and depthmeter give the datum for guidance and control.

In this work, three rolling/pitching/yawing two-loop attitude controllers with angular rates (*p*,*q*,*r*) in the inner loop for stabilizing the unstable vehicle and attitude angles(ϕ,θ,ψ) in the outer loop for tracking. Base upon them, guidance laws can be applied to the controlled system. Guidance laws may include depth control, lateral control, rate control, mid-course (cruise), mid-course(search), PP homing, PN homing, Re-attack process, vehicle/target position estimations, ..etc. They can be divided into two catalogues: (1)lateral guidance and control laws, and (2) vertical guidance and control laws.

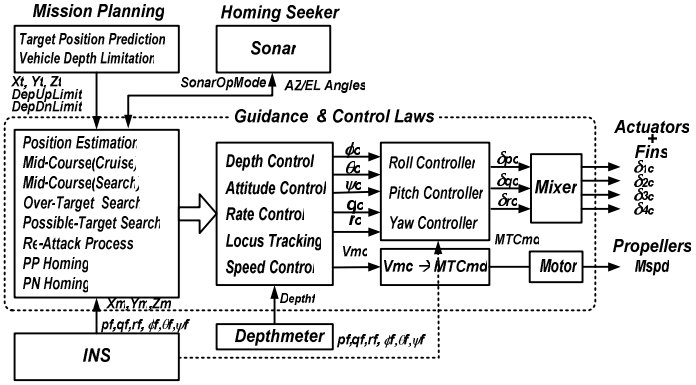

Fig.5. The guidance and control configuration of the considered system.

Figs. 6 and 7 show lateral and vertical guidance

and control configurations. They include many conditional switches to select guidance and control laws. They are selected by *Yawmode* and *Pitchmode* and given in Table 1. Mode selections of different guidance laws are given in Table 2.

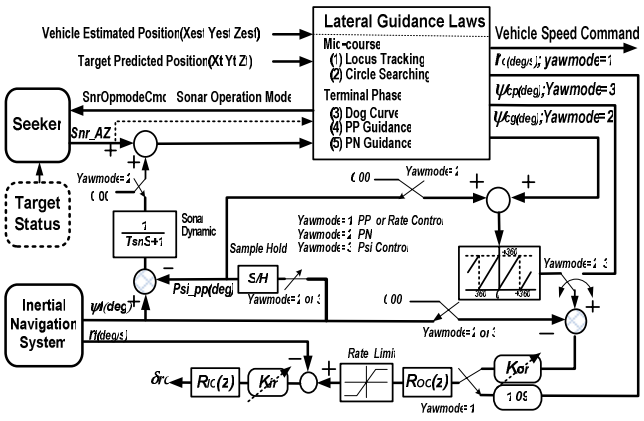

Fig.6. Lateral guidance configuration.

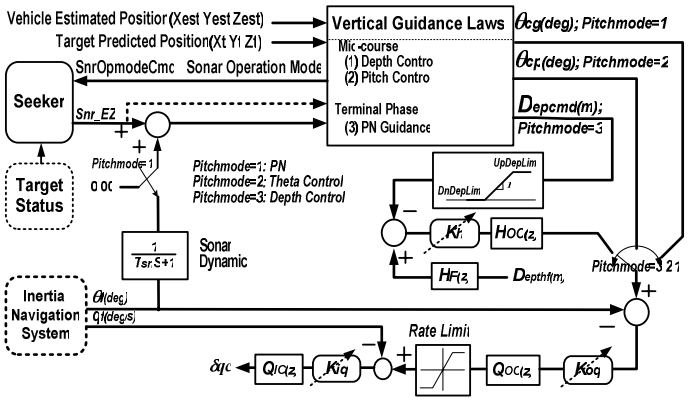

Fig.7. Vertical guidance configuration.

Table 1. Classification of control modes.

Yawmode	**Purpose**	*Pitchmode*	**Purpose**
1	**PP Guidance (Rate Control)**	**1**	**PN Guidance**
2	**PN Control**	**2**	**Angular Control**
3	**Angular Control**	**3**	**Depth Control**

Table 2. Mode selection for different guidance laws.

Items	**Guidance Laws**	***Yawmode***	***Pitchmode***
1	**Mid-Course(Cruise)**	**3**	**3**
2	**Mid-Course(Search)**	**1→3→1→**	**3**
3	**Over-Target Search**	**1→3→1→**	**3**
4	**Possible Target Search**	**1→3→1→**	**3**
5	**Re-attack Process**	**1,2**	**1**
6	**PP Homing**	**1**	**1**
7	**PN Homing**	**2**	**1**
8	**Locus Tracking**	**3**	**3**

The compensators [12, 13] and adaptive gains shown in Figs.6 and 7 are found and given below:

(a) Yawing Channel gain and compensators

$$R_{oc}(z)=\frac{0.5z-0.4391}{z-0.9391};$$

$$R_{ic}(z)=\frac{18.444z^2-32.9206z+14.7356}{z^2-1.2899z+0.3279};$$

$$K_{or}=+0.0021V_m^{\ 2}+0.0512V_m+0.4271;$$

$$K_{ir}=+0.0107V_m^{\ 2}-0.3932V_m+3.9541;$$

$$r_{\lim}=0.972V_m+5.000\,.$$

(b) Depth/Pitching Channel gains and compensators

$$H_c(z)=\frac{0.8422z-0.8343}{z^2-1.7823z+0.7902};$$

$$H_f(z)=\frac{0.0582}{z-0.9418};$$

$$Q_{oc}(z)=\frac{0.5z-0.4391}{z-0.9391};$$

$$Q_{ic}(z)=\frac{18.444z^2-32.9206z+14.7356}{z^2-1.2899z+0.3279};$$

$$K_h=-0.0003V_m^{\ 2}-0.0324V_m+1.8775;$$

$$\theta_{\lim}=+0.0333V_m^{\ 2}-2.841V_m+58.775;$$

$$K_{oq}=+0.0021V_m^{\ 2}+0.0512V_m+0.4271;$$

$$K_{iq}=+0.0107V_m^{\ 2}-0.3932V_m+3.9541;$$

$$q_{\lim}=0.972V_m+5.000$$

(c)Rolling Channel gains and compensators

$$P_{oc}(z)=\frac{0.3333z-0.2065}{z-0.8732};$$

$$P_{ic}(z)=\frac{5.00z-4.2331}{z-0.2231};$$

$$K_{op}=-0.0039V_m^{\ 2}+0.1523V_m+2.7188;$$

$$K_{ip}=+0.0110V_m^{\ 2}-0.3999V_m+3.9268;\quad p_{\lim}=45°/s\,.$$

Note that the control configuration is similar to that of pitching or yawing channel. $P_{oc}(z)$ and $P_{ic}(z)$ are outer and inner compensators, K_{op} and K_{ip} are outer and inner gains and $p_{\lim}$ is the rolling rate control limit.

(d)Fin actuating limits

$$\delta_{1c\lim}=16°,\ \delta_{2c\lim}=25°,\ \delta_{3c\lim}=16°,\ \delta_{4c\lim}=25°$$

They are evaluated from the small-signal dynamic model described by Eq.(12) and verified by 6-DOF simulations and navigation experiments.

4 Navigation techniques

A generally navigation requirements for survey AUV[1] are (1) mission programming to follow a pre-determined survey area load to the AUV; (2) mission positioning accuracy of 10 to 40 meters; (3) data positioning accuracy of 5 to 20 meters; Fig.8 shows the positioning scheme used. It is discussed detail in Reference14. Requirement(1) is performed with on-board computer in AUV; Requirement(2) is accomplished by GPS correction on the surface

before AUV is launched; Requirement(3) is accomplished by a positioning technique shown in Fig.8[14]. There is no correction from GPS above the sea surface and LBL system undersea.

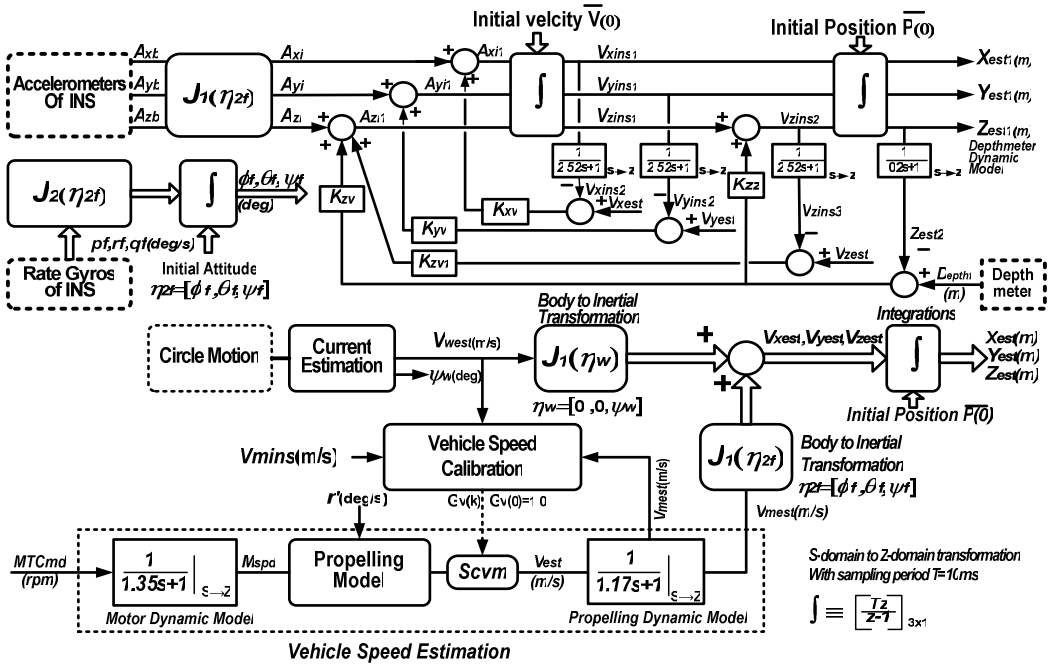

Fig. 8. The proposed positioning Technique

The rolling speed of the propelling motor(M_{spd}), depth measurement(*depthm*) of depth meter, estimated current information (V_{west}, ψ_w) and low-cost rate gyros (p_f, q_f, r_f) and accelerometers (A_{xb}, A_{yb}, A_{zb}) with state observers are used to estimate the vehicle position (X_{est1}, Y_{est1}). The positioning techniques are verified by a navigation experiment in coast area of Taiwan with a long-baseline acoustic positioning system(LBL).

Fig.9 shows position deviation between them. It gives average deviation 11.8m and maximal deviation 25.6m for 1176 sec operation. This deviation is less than detecting range of the active/ passive sonar. Therefore, navigation performance of the AUV satisfies the requirement(3). The guidance and control problem is reduced to cope with the sound shadow zone and possible position of the target.

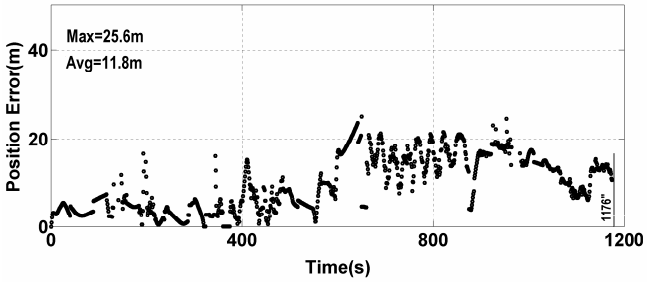

Fig.9. Position deviation between estimated and LBL results.

5 Mission planning and guidance laws

5.1. Target Engaging Concept

Fig.10 shows the target engaging concept, in which LOS is the line of sight to target, LOF is line of fire of the vehicle, predicted target position (PTP) is the target information get from vessel sonar target acquisition system(TAS), residual distance is the distance between vehicle position (*Xm*,*Ym*) and PTP, dashed-area is the target possible position area after the vehicle reaching. Two target searching processes must be performed: (1)before-PTP target searching and (2)over-PTP target searching. They are used to cope with the target moving and sound shadow zone with short-range sonar. In general, target course information is more reliable than position for diffraction and reflection of sound propagation in the vertical plane.

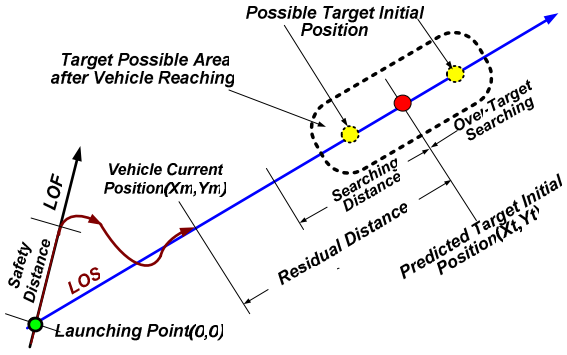

Fig.10. The target engaging concept.

5.2. System Software functional signal flow

The system functional flow is shown in Fig.11. The vehicle is initialized, tested and launched from the vehicle fire control system (FCS). A leaved checking and a safety distance with launching course and depth are used to insure the safety of the launching vessel. A current estimation process is performed after safety distance run through. And then go to internal guidance process, UAV position estimation and target position estimation.

The flow chart of the internal guidance law is shown in Fig.12. The condition of target acquisition is classified as (1) target never contact($\overline{TC}$), (2)target contact(*TC*), (3) target detected(*TD*), and (4) target lost(*TL*). Five sustaining target contact(*TC*) is defined as target detected(*TD*); i.e., the target is recognized. Definitions of them are given in Table 3. The number of target contact for target detected is dependent on the target engagibility of the sonar.

Table 3. Target Status Definition

Status	Description
$\overline{TC}$	Target never contact from launching
1TC	Target Contact for $\overline{TC}$; Target contact gain from *TL* Target lost from *2TC*
2TC	Target Contact again from *1TC*; Target lost from *3TC*
3TC	Target Contact again form *2TC*; Target lost from *4TC*
4TC	Target Contact again form *3TC* Target lost from *TD*
TD	Target Contract again from *4TC*
TL	Target lost from *1TC*

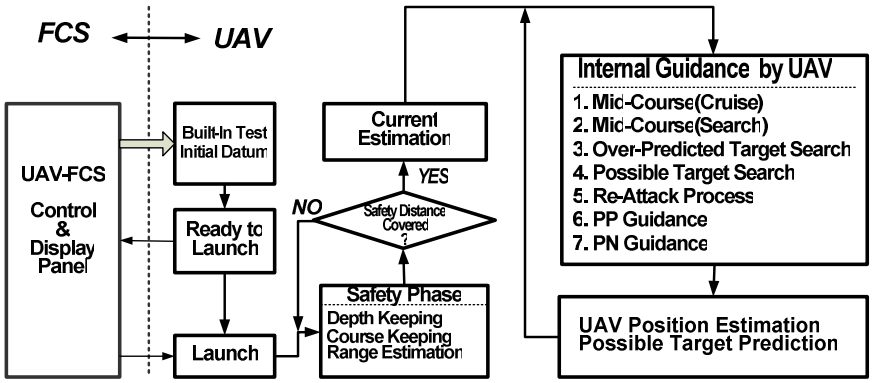

Fig.11. The software flow chart of the AUV.

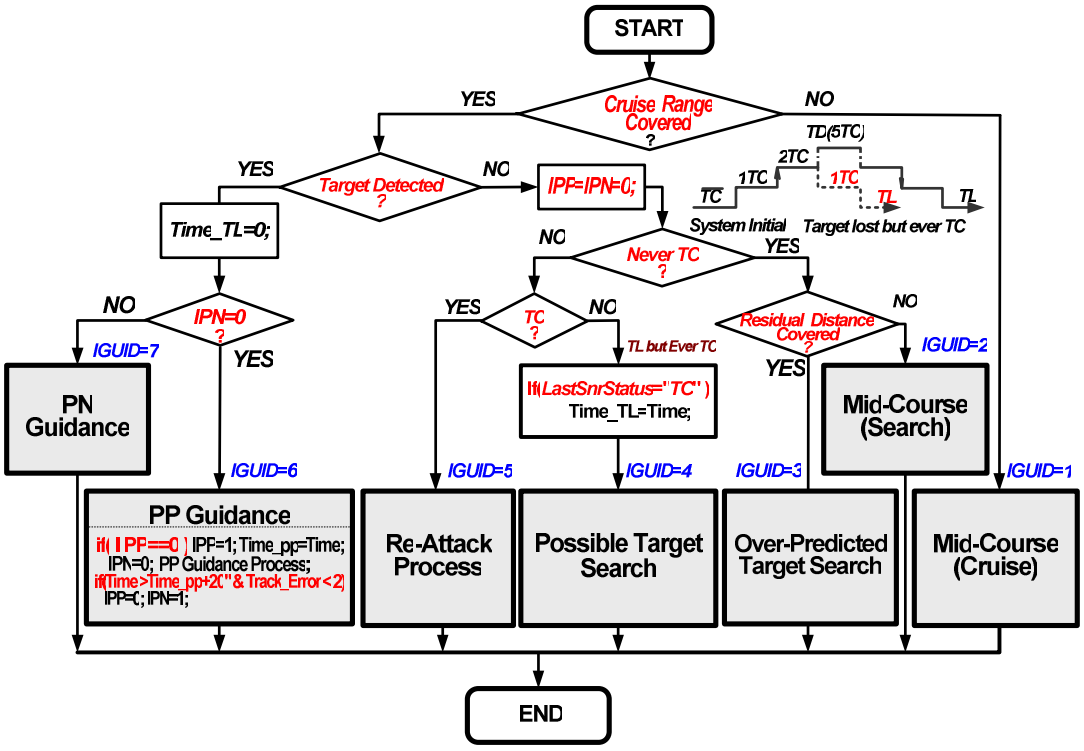

Fig.12. The system flow chart of the internal guidance law.

5.3. Seven guidance Laws

(1)Mid-course(Cruise)

Guiding the vehicle to the front of the Predicted Target Position (PTP) along the Line of Sight (LOS); i.e., the tracking locus which is defined by the launching point and the PTP. The Cruise Range(***CR***) is determined by PTP, the Maximal Target Motion Range(***MTMR***) and the Sonar Detecting Range(***SDR***):

$$CR = dis\tan ce(PTP) - \max(MTMR, SDR) \qquad (15)$$

The locus tracking law is given in Appendix A. Medium speed is used for approaching the predicted target position as soon as possible for saving power consumption. Maximal speed is used for terminal homing phase only. The depth is selected between upper depth limit and lower depth limit. The control modes used are *Pitchmode*=3 and *Yawmode*=3.

(2)Mid-course(Search)

Three dimensional target searching forward with circular and depth changing motion for eliminating the shadow zone(see Fig.2) and enlarging the searching area. The circular motion is one clockwise motion plus one counter clockwise motion; depth of the vehicle is changed up and down periodically; and the sonar operation mode is in active mode for clockwise motion and in passive mode for counter clockwise motion and linear motion; the vehicle speed is medium speed for moving forward and low speed for circular motion.

The programming logic of above statements is shown in Fig.12. Note that control modes shown in Figs.6 and 7 are given in Table 2. The simulation results of the mid-course target search is shown in Fig.14.

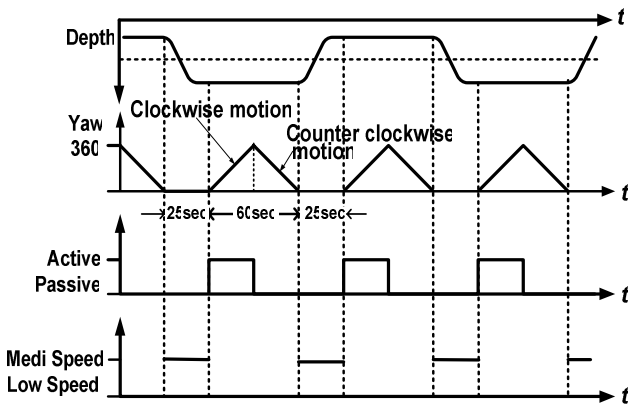

Fig.13. Parameters adaptation in the Mid-course search process.

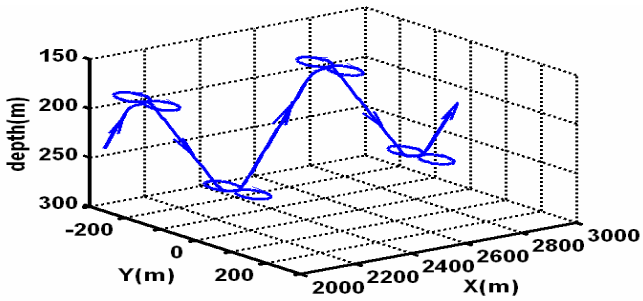

Fig.14. Simulation results of the Mid-course(Search) process.

(3)Over-predicted target search

Enlarging the searching area after the vehicle reaching the PTP and the target is not ever contacted($\overline{TC}$). Fig.15(a) shows the planning of vehicle motion. The vehicle motion loci are from **Wp1, WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP9,..** Each section is constructed by the searching process shown in Figs.13 and 14. Fig.15(b) shows the simulation results for the searching process.

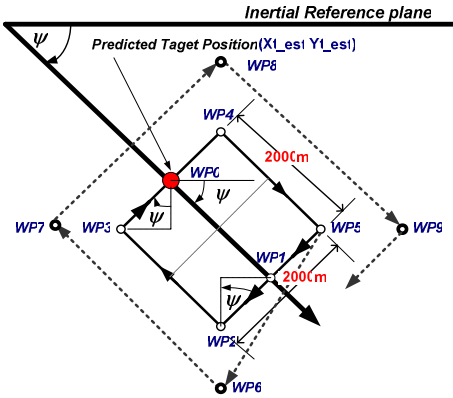

Fig.15(a). Searching loci of the over-predicted target search.

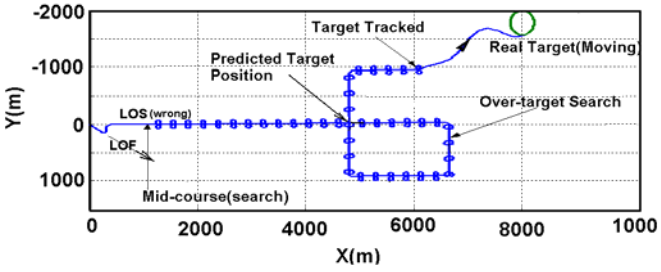

Fig.15(b). Simulation results of over-target search(From PTP to Target Tracked).

(4)Possible-target search

Used for the target lost (*TL*), the last tracked target position replacing the predicted target position (PTP) stated in (3) and performing the searching process stated in (3).

(5)Re-attack process

Re-attack process is used for target just lost track (TD→TC); i.e., from PP or PN homing process to

the Re-attack process. This process is keeping vehicle speed, course and depth 50sec after the target lost. Performing the possible-target search process stated in (4) after 50sec. The purpose of keeping speed, course and depth is used to eliminate the possible shadow zone.

(6)Pure Pursuits (PP) Guidance

Pure pursuit guidance is used for target just detected(*TD*). The vehicle speed and sonar operation mode are kept at the time of the target just detected. The purpose of maintaining speed and operation mode is to reduce possible disturbance for target tracking. The vehicle will be heading to the target. Since the Proportional Navigation (PN) guidance is faster than the PP guidance. Therefore, it will be changed to the PN process after the vehicle has headed to the target. The target homing with full PP guidance is shown in Fig.16 for different target moving course.

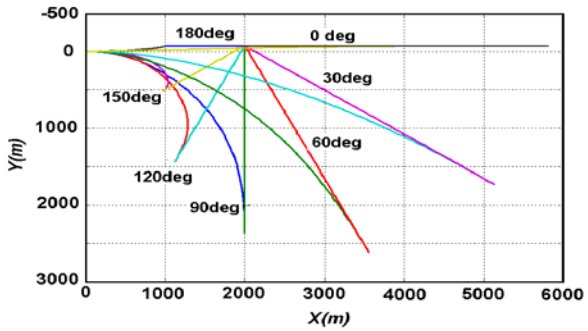

Fig.16. Target homing with the PP guidance.

(7) Proportional Navigation (PN) Guidance

The time(*Time_pn*) for performing Proportional Navigation (PN) guidance is after the PP guidance has performed 20" and the heading error less than 2°(shown in Fig.13). Fig.17 shows the homing process for different target escaping course.

In the PN process, the vehicle speed and sonar mode are adaptive according to the PN process proceeded the time after *Time_pn*. The basic concept of the adaptive algorithm is increasing the value of PN process time represents decreasing the distance between vehicle and target. It implies that target noise level is stronger for detecting. Speed up the vehicle is to engage the target as soon as possible.

Note that speeds up the vehicle is also increasing the self-noise and degrading the target detection. Therefore, speed up is performed when the distance between target and vehicle is shorter enough. High speed ratio between vehicle and target is usually expected for high kill probability. The speed ratio between underwater vehicle is usually less than 1.5. Low speed ratio usually makes the target move out of the field-of-view (FOV) of the sonar; i.e., target will be lost(*TL*), for PN guidance with larger navigation constant (*NC*). In this work, a sonar tracking angle dependent *NC* is used for coping with a low speed ratio between UAV and Target. It reduces the value of NC for large value of sonar tracking angle for preventing the target lost. Low *NC* implies vehicle turning rate is slowing down to prevent the target move out of the field-of-view (FOV) of the sonar. It is formulated as

$$NC = -2.5 \times (|Snr\_AZ| - 30)/(||Snr\_AZ| - 30| + 15) + 2.5 \quad (16)$$

where *Snr_AZ* is the azimuth tracking angle of sonar. Note that Eq.(16) is used only for horizontal plane.

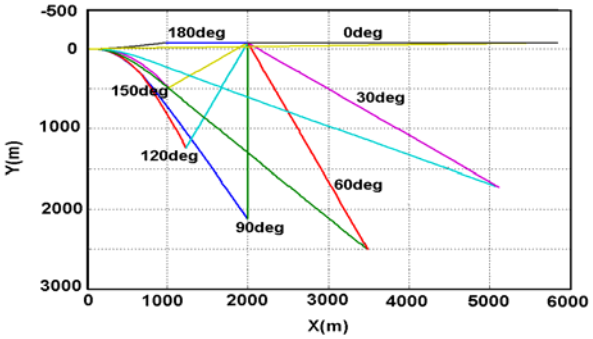

Fig.17. Simulation results for constant direction moving target.

Seven guidance laws have been discussed. They are connected by the system flow chart shown in Fig.12. The first object of the proposed intelligent guidance laws is to find the underwater target in the complicated environment, and then intercept it with adaptive homing guidance laws.

6. Simulation Verifications

In this section, digital simulations of four scenarios are used to verify the proposed intelligent guidance and control laws. Simulation results for four scenarios are given below:

6.1. Scenario #1

(a)Target initial position and Maneuver

Target Initial Position : X_T = 5Km;Y_T =-0.5Km; Z_T = 0.1Km;

Velocity : V_T =10m/s;

Acceleration : A_T= – 0.2m/s² in the horizontal plane;

Initial direction: 180deg.

Target Prediction position X_T=5Km, Y_T=0m;

(b)Sonar specifications

Detection Range: 2Km in passive mode; 1Km in active mode;

Horizontal FOV: 60deg;

Vertical FOV: 20deg

This scenario is used to illustrate the target engage concept shown in Figs.10, 11 and 12.

The target detection error is 500m in Y-axis. Simulation results are shown in Fig.18, in which gives (a)Mid-course(cruise) phase; (b)Mid-course (search); (c)PP/PN homing process. Note that the programming depth control can eliminate the shadow zone shown in Fig.2.

Fig.19 shows (a)Vehicle speed(Vm); (b)Sonar tracking angle (Snr_AZ) in the horizontal plane; (c)Sonar tracking angle(Snr_EL) in the vertical plane; (d)Miss distance (Miss) between the AUV and target; (e)Navigation constant (NC). Fig19(a) shows the vehicle speed changed from low speed to high speed. The changing logic is dependent on the range between vehicle and target. This changing is used to reduce the effect self-noise of the vehicle for the target detecting. Fig.19(e) shows the varying NC represented by Eq.(16) to prevent the target lost.

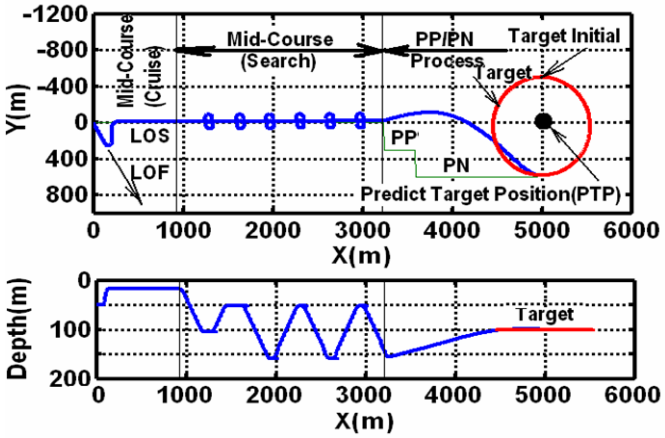

Fig.18. Target Engaging in the horizontal and vertical planes.

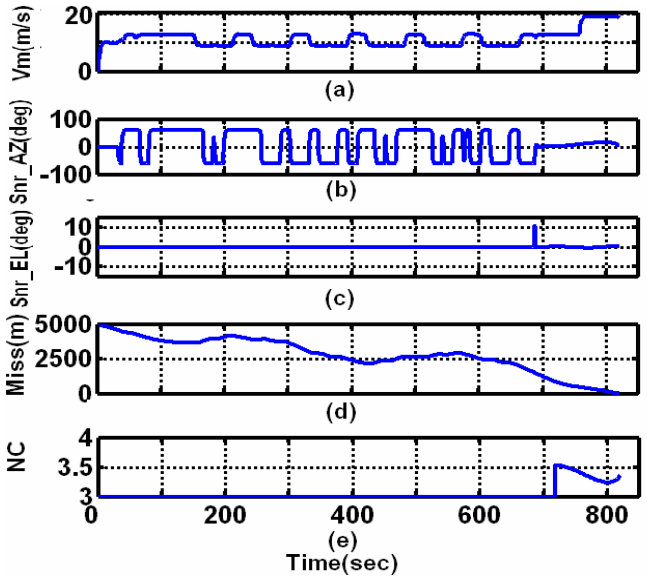

Fig.19. (a)Vehicle speed; (b)Sonar tracking angle in the horizontal; (c)Sonar tracking angel in the vertical; (d)Miss distance; (e) Navigation constant.

6.2. Scenario #2

(a)Target initial position and Maneuver

Target Initial Position : X_T = 7Km;Y_T =-3Km; Z_T = 0.1Km;

Velocity : V_T =10m/s;

Acceleration : $A_T = -0.1 m/s^2$ in the horizontal plane;

Initial direction: 180deg.

Target Prediction position X_T=4.5Km, Y_T=0m;

(b)Sonar specifications

Detection Range: 2Km in passive mode; 1Km in active mode;

Horizontal FOV: 60deg;

Vertical FOV: 20deg

This scenario is used to illustrate the long range target engaging with large target position prediction error. Guidance laws used are: (a)Mid-course (cruise) process; (b)Mid-course (search) process; (c)Over-predicted target search process; (d) Re-attack process; (e)Possible-target search process; (f)PP/PN homing process.

Fig.20(a) shows the target engaging in the horizontal and vertical planes. Fig.20(b) shows the re-attack process after the target lost(*TL*). The target lost is resulted from target outsiding the field of view(FOV) of the sonar in the horizontal plane or target is in the shadows zone. The re-attack process is keeping vehicle speed, course and depth 50sec after the target lost. And then performing the possible-target search process. The purpose of keeping speed, course and depth is to eliminate the possible shadow zone shown in Fig.2. The he possible-target search process can enlarge the detecting area of the sonar.

Fig.20(c) shows the target engaging loci in three-dimensional space. Fig.20 shows that the AUV and target are intercepted after multiple guidance and control modes switching.

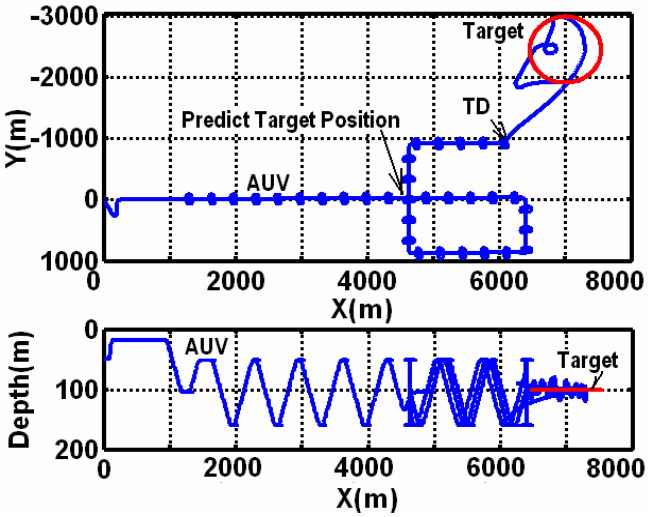

Fig.20(a).Target Engaging in the horizontal and vertical planes.

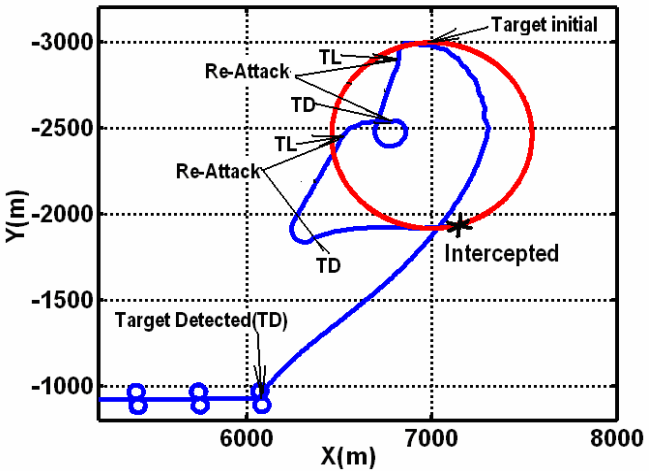

Fig.20(b). Target homing in the horizontal plane.

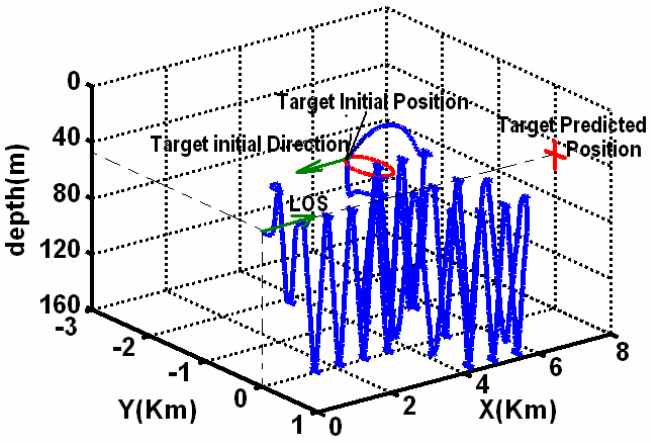

Fig.20(c). Target Engaging Loci in 3D-space.

6.3. Scenario #3

(a)Target initial position and Maneuver

Target Initial Position : X_T = 2Km;Y_T =-0.5Km; Z_T = 0.1Km;

Velocity : V_T =12.5m/s;

Acceleration : A_T= $-0.2m/s^2$ in the horizontal plane;

Initial direction: 180deg.

Target Prediction position X_T=2Km, Y_T=0m;

(b)Sonar specifications

Detection Range: 2Km in passive mode; 1Km in active mode;

Horizontal FOV: 60deg;

Vertical FOV: 20deg

This scenario is used to illustrate the short-range target engage concept. The target initial position is in the detecting area of the sonar. Therefore, only PP and PN processes are used. Fig.21 shows target engaging loci in the 3D-space. Fig.22 shows (a)Vehicle speed(*Vm*); (b)Sonar tracking angle (Snr_AZ) in the horizontal plane; (c)Sonar tracking angle(Snr_EL) in the vertical plane; (d)Miss distance(Miss) between AUV and target; (e)Navigation constant(NC).

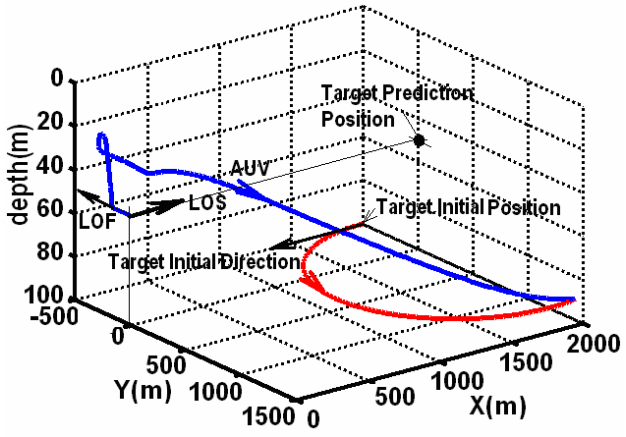

Fig.21.Target Engaging Loci in 3D-space.

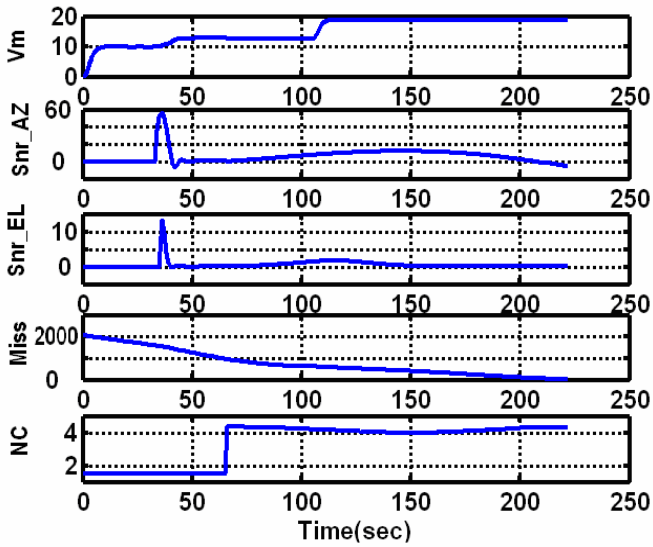

Fig.22. (a)Vehicle speed; (b)Sonar tracking angle in horizontal; (c)Sonar tracking angel in vertical; (d)Miss distance; (e)Navigation constant.

6.4.Scenario #4

(a)Target initial position and Maneuver

Target Initial Position : X_T =3Km;Y_T =-0.5Km; Z_T =50m;

Velocity : V_T =12m/s;

Acceleration : A_T=-0.2m/s/s in horizontal plane

A_T=0.05m/s/s in vertical Plane;

Initial direction: 180deg.

Target Prediction position X_T=3Km, Y_T=0m;

(b)Sonar specifications

Detection Range: 2Km in passive mode; 1Km in active mode;

Horizontal FOV: 60deg;

Vertical FOV: 20deg

This scenario is used to illustrate the short-range target engage concept. The target initial position is in the detecting range of the sonar. The target is escaping with two-axis acceleration. Fig.23 shows target engaging in the 3D-space. Fig.24 shows (a)Vehicle speed(*Vm*); (b)Sonar tracking angle

(Snr_AZ) in the horizontal plane; (c)Sonar tracking angle(Snr_EL) in vertical plane; (d)Miss distance (Miss) between AUV and target; (e) Navigation constant(NC).

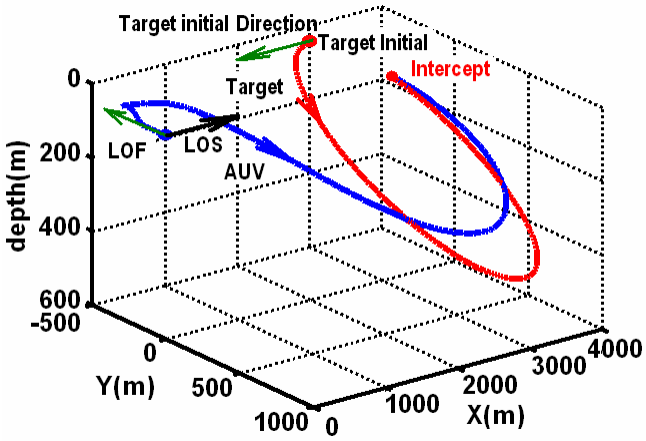

Fig.23.Target Engaging Loci in 3D-space.

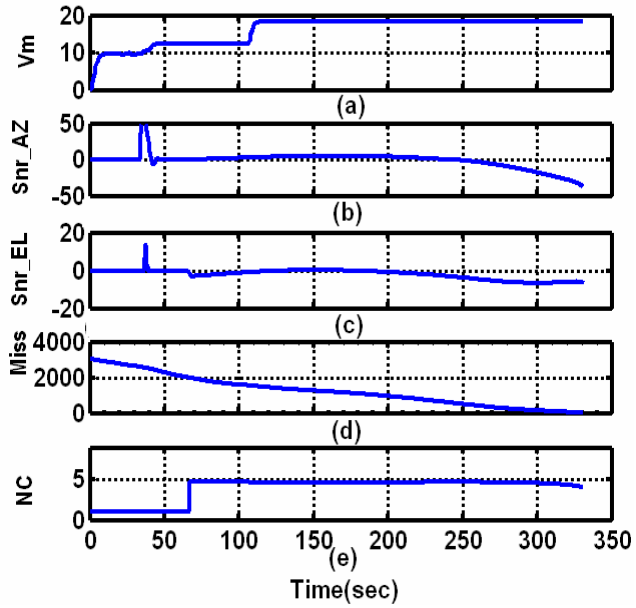

Fig.24. (a)Vehicle speed; (b)Sonar tracking angle in horizontal; (c)Sonar tracking angel in vertical; (d)Miss distance; (e) Navigation constant.

7. Conclusions

In this paper, intelligent guidance and control laws have been developed for an autonomous underwater vehicle. Seven guidance laws and six control modes are programmed automatically by the target engaging status. Those were well tested by digital simulation verification of four scenarios. Simulation verification results give the proposed guidance and control laws can cope with the complicated underwater environment to engage the target.

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Appendix A: Locus Tracking Law

The tracking locus connected with point # i (X_i, Y_i) and point # i+1 (X_{i+1}, Y_{i+1}) and tracking definition is formulated as following equations. The tracking locus is defined as

$$a_{i+1}X + b_{i+1}Y + c_{i+1} = 0 \qquad \text{(A1)}$$

with
$a_{i+1} = Y_{i+1} - Y_i, b_{i+1} = X_{i+1} - X_i$ *and* $c_{i+1} = X_i Y_{i+1} + X_{i+1} Y_i$, the normal displacement between vehicle(X_M, Y_M) and the tracking locus is

$$LH = -(a_{i+1} X_M - b_{i+1} Y_M + c_{i+1}) / \sqrt{a_{i+1}^2 + b_{i+1}^2} \qquad \text{(A2)}$$

Positive value of *LH* represents the vehicle is on the right-hand side of the tracking locus; negative value of *LH* represents the vehicle is on the left-hand side of the tracking locus. The purpose of locus tracking is to keep *LH* be a wanted value (*LHc*); and moving from point #i toward point # i+1. *LHc*=0 represents the vehicle will moving on the tracking locus. The direction of the vehicle will move always from way point #i to way point # i+1 for controlled parameters are *LH*=*LHc* and $\psi_c = \psi_{c1}$; which is shown in Fig.A1. It shows the geometry relation of the vehicle and the tracking locus. For faster locus tracking purpose, variable structure control scheme is switched according to amplitude of LH. The vehicle will be guided toward to tracking locus orthogonally for |LH| > *R*, and toward to way point #i+1 for |LH| < R. The selection of R is the minimal turning radius capability of the vehicle at high speed maneuvering. It will perform smoothing tracking performance and low water flowing noise. The guidance law is formulated as

$$\psi_{c1} = 57.296 \times atan2(a_{i+1}, b_{i+1}) \qquad \text{(A3)}$$
$$\psi_{c2} = \psi_{c1} + 90 \times sign(LH) \qquad \text{(A4)}$$
$$\psi_c = \psi_{c1} + 2(LHc - LH) \ldots\ldots \text{for } LH < R + LHc \qquad \text{(A5)}$$
$$\psi_c = \psi_{c2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{for } LH > R + LHc \qquad \text{(A6)}$$

where *R* represents the minimal turning radius of the vehicle.

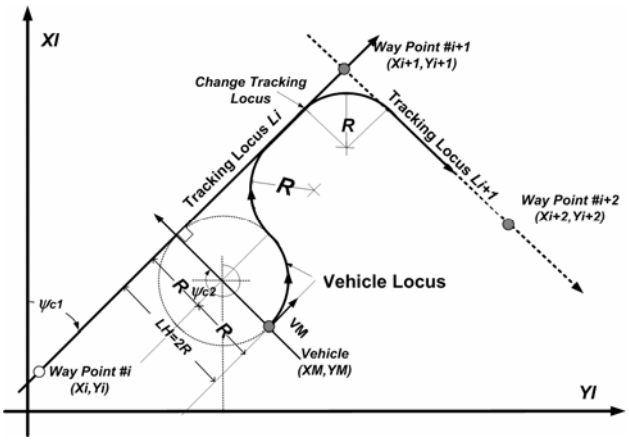

Figure A1. The fastest loci tracking concept with turning radius R.