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Abstract: *This work follows previous works on tracking of targets on Forward Looking Sonar images. A Kalman filter based on a process model of the vehicle was implemented considering two strong assumptions: firstly, the obstacle is fixed in relation to the world reference frame and secondly, it lies proud on the seabed. Consequently, Kalman filtering leads to a biased estimation of successive positions of an obstacle floating in the water column. Starting with this observation a new algorithm has been developed to allow a deferred estimation of the z-coordinate (along the absolute z-axis) of the obstacle related to the vehicle. This is performed offline by minimizing at each step of the sequence the root mean squared deviation (RMSD) between measured sonar positions and predicted positions, i.e. by minimizing the innovation values of the Kalman filtering. Results are given on real data recorded in March 2009 and April 2010 during sea trials organized by GESMA involving the Rapid Environment Assessment (REA) "Daurade" AUV with its BLUEVIEW P450 obstacle avoidance sonar. Tethered mines and other floating obstacles like plastic chains were laid.*

Keywords: *Forward looking sonar images, AUV, Obstacle avoidance*

1. INTRODUCTION

This paper concerns obstacle avoidance issues by processing forward looking sonar (FLS) images and navigation data. In previous works, we first derived a process model in order to predict the motion of a ground target detected in a sonar image [1]. Then a Kalman filter based on this model was implemented in order to track an incoming obstacle by taking navigational data as inputs [2]. According to the assumed condition of a seafloor object, tracking of a tethered object in the water column is not performed especially well. Indeed the obstacle appears to be moving faster than the predicted positions. Here, this defect of the tracking procedure has been used offline to estimate the tether length. This is performed by minimizing the root mean squared deviation (RMSD) between measured sonar positions and positions predicted by means of a new version of our process model. This piece of information is of particular interest for obstacle avoidance but it is generally unavailable because of little or no sampling of the sonar data along the vertical axis.

The paper is organized as follows. Section 2 describes sonar and navigational data used. Our process model and the derived tracking procedure are briefly recalled in section 3. Then the method for a deferred estimation of the vertical position of a floating obstacle is presented in section 4. Some results on real data are showed in section 5.

2. DATA DESCRIPTION

The *Daurade* vehicle is a multi-purpose experimental AUV for Rapid Environment Assessment (REA) applications [3]. It has been developed in the context of a project conducted by SHOM (Service Hydrographique et Océanographique de la Marine) in cooperation with GESMA (Groupe d'Etudes Sous-Marines de l'Atlantique). The obstacle avoidance system is a *Blueview P450* Forward Looking Sonar. The system can obtain a beamformed image over a 15° (vertical) × 45° (horizontal) sector with an across-track sampling rate $\Delta\delta$ equal to 0.18° and an along-track sampling rate Δd equal to 0.17m. The sensor looks straight ahead (see *Fig.1*).

Data used in this paper have been collected by GESMA during two sea trials near Brest (France) in March 2009 and in April 2010.
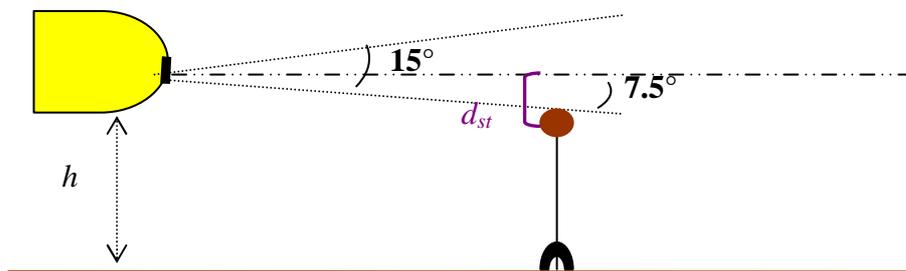

Fig.1: Configuration of the Blueview P450 FLS on DAURADE AUV

The Daurade AUV is built by ECA company and uses the iXSea PHINS Inertial Navigation System that gives the vehicle orientation (roll, pitch and yaw) and its acceleration in relation to the world reference frame, *i.e.* the Euler angles (φ, θ, ψ) and their derivatives. The PHINS system is directly fed by other navigation sensors, namely a 300kHz RDI DVL, a Paroscientific Depth Sensor and a WAAS GPS receiver, and it

computes geographical position and speed of the vehicle using Kalman filtering.

3. TRACKING PROCEDURE

3.1.   Process model

The process model provides the sonar coordinates (d,δ) of a detected object given the AUV motion. It is derived from two main sets of equations and their derivatives.

The Euler rotation matrix R_{euler} is composed of three rotations that move the relative reference frame $(O_r, \boldsymbol{x_r}, \boldsymbol{y_r}, \boldsymbol{z_r})$ (O_r: centre of gravity of the vehicle, $\boldsymbol{x_r}$: in the direction of movement of the vehicle, $\boldsymbol{y_r}$: towards its right, $\boldsymbol{z_r}$: down) to the world reference frame $(O_a, \boldsymbol{x_a}, \boldsymbol{y_a}, \boldsymbol{z_a})$ (O_a: centre of gravity of the Earth, $\boldsymbol{x_a}$: geographical North direction, $\boldsymbol{y_a}$: East direction, $\boldsymbol{z_a}$: gravity direction). This allows deriving the first set that gives the relation between target positions (or speeds by differentiation) in the two reference frames:

$$\boldsymbol{p_a} - \boldsymbol{m_a} = -R_{euler}(\varphi,\theta,\psi)\cdot \boldsymbol{m_r} \tag{2}$$

where $\boldsymbol{p_a} = \left(p_a^x, p_a^y, p_a^z\right)$ are the coordinates of the AUV (we assume that its location is coincident with all the other sensors) and $\boldsymbol{m_a} = \left(m_a^x, m_a^y, m_a^z\right)$ are the coordinates of the object in the world reference frame.

The second set gives the localization of a seafloor target in the relative reference frame (see *Fig. 2*):

$$\left(\begin{array}{c} \left(m_r^x\right)^2 + \left(m_r^y\right)^2 + \left(m_r^z\right)^2 = d^2, \\ m_r^y = \sin\delta.d, \\ -\sin\theta.m_r^x + \cos\theta.\sin\varphi.m_r^y + \cos\theta.\cos\varphi.m_r^z = h, \end{array} \right) \tag{1}$$

where $\boldsymbol{m_r} = \left(m_r^x, m_r^y, m_r^z\right)$ are the coordinates of the seafloor target, h is the AUV altitude and (φ,θ,ψ) are the Euler angles that define the attitude of the vehicle.
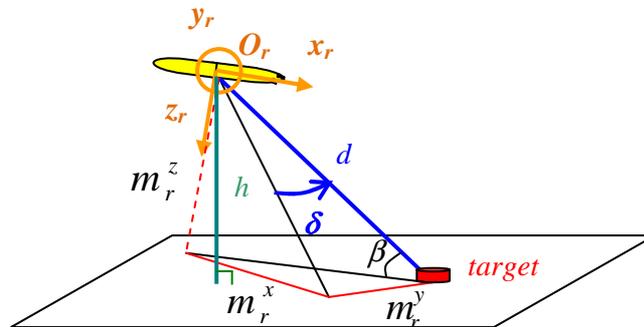

Fig.2: Operational configuration

As explained in [1], the final expression for a moving object is a non linear function of its initial position and navigational data:

$$(\dot{d},\dot{\delta}) = f(d,\delta,\boldsymbol{V}_r,\varphi,\theta,\psi,\dot{\varphi},\dot{\theta},\dot{\psi}) \tag{3}$$

where $\boldsymbol{V}_r = (v_r^x, v_r^y, v_r^z)$ is the speed of the AUV in the relative reference frame.

3.2. Kalman filtering

3.2.1. Prediction stage

The state vector is composed of the sonar coordinates, *i.e.* $\boldsymbol{x} = (d \quad \delta)^T$. The state equation (in the discreet domain) is based on the previous model such that:

$$\boldsymbol{x}_k = f(\boldsymbol{x}_{k-1}, \boldsymbol{u}_{k-1}) + \boldsymbol{v}_{k-1}. \tag{4}$$

where $\boldsymbol{x}_k$ is the state vector at the kth filtering step, $\boldsymbol{u}_{k-1}$ is the input vector at step *k-1* which is composed of navigational data and $\boldsymbol{v}_{k-1}$ stands for the white Gaussian state noise.

The prediction stage computes the new state $\hat{\boldsymbol{x}}_{k/k-1}$ given the previous one $\hat{\boldsymbol{x}}_{k-1/k-1}$ thanks to the above equation. Given the strong non linearity of the state function f, the computation of $\hat{\boldsymbol{x}}_{k/k-1}$ is carried out by performing an unscented transform of $\hat{\boldsymbol{x}}_{k-1/k-1}$ [4].

3.2.2. Correction stage

The correction stage is based on the following measurement equation:

$$\boldsymbol{y}_k = H_k \boldsymbol{x}_k + \boldsymbol{w}_{k-1}. \tag{5}$$

where the measurement vector $\boldsymbol{y}_k$ is comprised of obstacle coordinates on the screen at step *k*, $\boldsymbol{w}_{k-1}$ stands for the white Gaussian measurement noise whose covariance matrix is R_{k-1} at step *k-1*, and $[H_k] = [H] = \begin{bmatrix} \dfrac{1}{\Delta d} & 0 \\ 0 & \dfrac{1}{\Delta \delta} \end{bmatrix}$ is the measurement matrix.

This stage corrects the predicted sonar coordinates $\hat{\boldsymbol{x}}_{k/k-1}$ given the new measurement $\boldsymbol{y}_k$. After computing $\hat{\boldsymbol{y}}_{k/k-1} = H\hat{\boldsymbol{x}}_{k/k-1}$ we can correct the state by applying the Kalman equations in the linear case this once:

$$\begin{cases} \hat{\boldsymbol{x}}_{k/k} = \hat{\boldsymbol{x}}_{k/k-1} + K_k(\boldsymbol{y}_k - \hat{\boldsymbol{y}}_{k/k-1}) \\ K_k = P_{k/k-1}H_k^T(H_k P_{k/k-1}H_k^T + R_k)^{-1} = P_{k/k-1}H_k^T(R_k^v)^{-1} \\ P_{k/k} = P_{k/k-1} - K_k R_k^v (K_k)^T \end{cases} \tag{6}$$

The difference $\boldsymbol{v}_k = \boldsymbol{y}_k - \hat{\boldsymbol{y}}_{k/k-1}$ is called innovation term and the associated covariance matrix is R_k^v. The impact of this term is controlled by the Kalman filter gain K_k.

4. LENGTH ESTIMATION OF A MINE TETHER

An estimation of the z-coordinate of the obstacle can be achieved by minimizing at each step of the sequence the root mean squared deviation (RMSD) between measured sonar positions (deduced from measurements y_k) and predicted positions. These predicted points only depend on the first measurement y_0 and prediction given by a new process model derived from the previous one with a new parameter related to the z-coordinate.

This new model is obtained by modifying the third equation of (1) in order to put the distance d_{st} between the sonar and the target along the z-axis in the world reference frame in the place of the altitude h of the sonar. This leads to:

$$- \sin\theta.m_r^x + \cos\theta.\sin\varphi.m_r^y + \cos\theta.\cos\varphi.m_r^z = d_{st} \tag{7}$$

Doing this, the previous f function becomes a new function $\tilde{f}$. For different possible values of $d_{st} \geq 0$, we compute all of the predicted positions as follows:

- In the first step, the predicted sonar position is computed by taking into account the first measurement y_0 such that: $\tilde{x}_0 = \breve{H}y_0$ where $\left[\breve{H}\right] = \begin{bmatrix} \Delta d & 0 \\ 0 & \Delta\delta \end{bmatrix}$.

- For steps k greater than 0, we compute predicted sonar positions $\tilde{x}_k = \tilde{f}\left(\tilde{x}_{k-1}, u_{k-1}, d_{st}\right)$ given the previous one $\tilde{x}_{k-1}$.

Finally, we estimate the vertical distance from the sonar to the target as:

$$\hat{d}_{st} = \arg\min_{d_{st} \in [0, 1.2 \times h]} \sqrt{\sum_{k=0}^{N} \left\| x_k - \tilde{x}_k\left(d_{st}\right) \right\|^2 \Big/ (N+1)},$$

where $N+1$ is the number of pings used, and $x_k = \breve{H}y_k$ for $k>0$.

By noticing that $x_k - \tilde{x}_k = \breve{H}\left(y_k - \tilde{y}_k\right) = \breve{H}\tilde{v}_k$, we can therefore say that the estimation consists in finding $\hat{d}_{st}$ that minimizes the new innovation term $\tilde{v}_k$ of a Kalman filter based on the new model.

5. EXPERIMENTAL RESULTS

In the following, we will call the experimental measurements those given by a detection algorithm based on a goodness-of-fit test and described in [2], and the theoretical measurements those we estimated visually.

The Daurade sea trials in April 2010 were designed to assess the performance of the present method for estimating the length of the tether of a moored mine. Two tethered spherical targets were deployed: the rubber one with a tether of 15m and the steel one with a tether of 12m. Fig. 3 shows results concerning the first target. The top part of Fig. 3 shows a sonar altitude about 15m and the RMSD minimisation that gives an estimated distance $\hat{d}_{st}$ of 0.5m. That was exactly the case: GESMA was testing avoidance capability in the case of an obstacle in the direction of travel of the vehicle. In this case, the estimation was as good on experimental measurements as on theoretical measurements. Predicted points and measurements points are plotted in the bottom part of Fig. 3 in case of $d_{st}=0.5$ that is to say when these two sets of points are close from each other.

This task was more difficult for data gathered in March 2009 on a large obstacle shown in Fig. 4. Indeed, the estimated value $\hat{d}_{st}$ (11m) based on experimental measurements

differs from estimated value (8m) based on theoretical measurements as shown in Fig. 5. This is probably due to noisy experimental measurements. Moreover, as the three Nokalon floats are not clearly visible, we can assume that the obstacle was pushed down by current forces. Under this assumption, the echo area does not represent the Nokalon floats nor the chains nor the bar but probably a mix of them that leads to a value of 8m between obstacle and sonar along the z-axis.
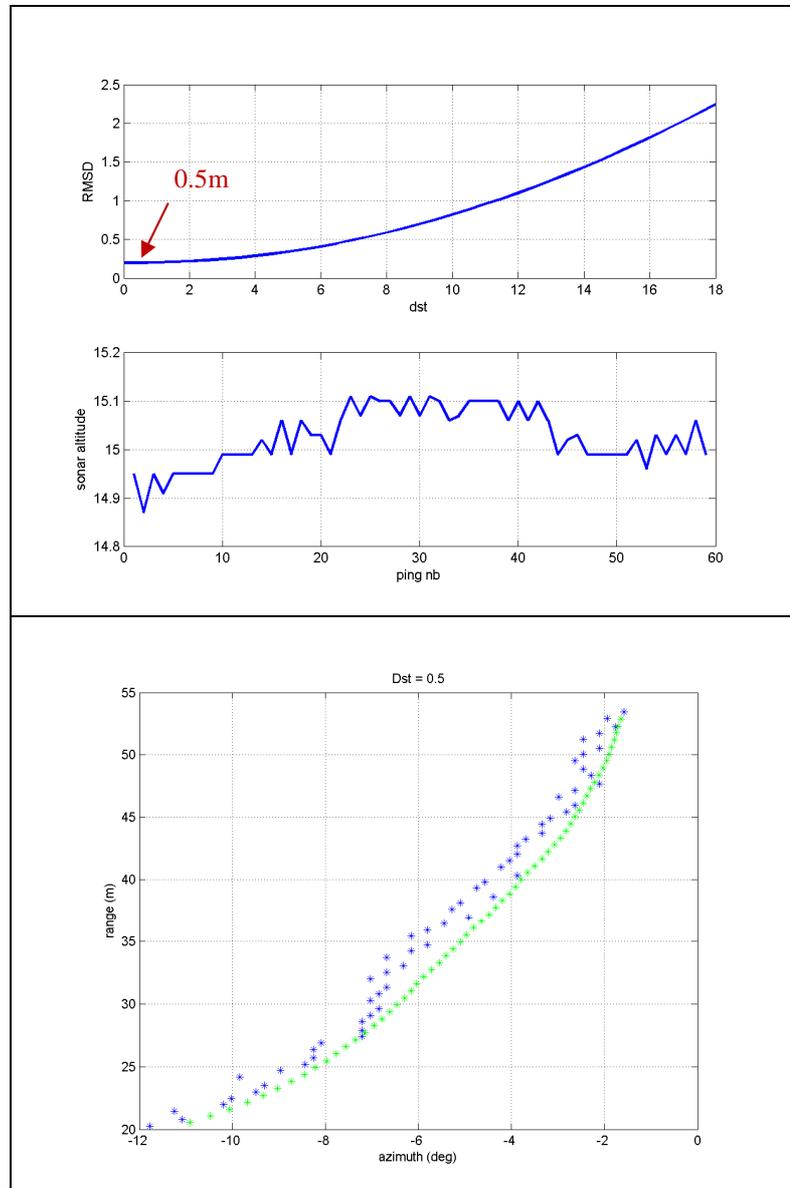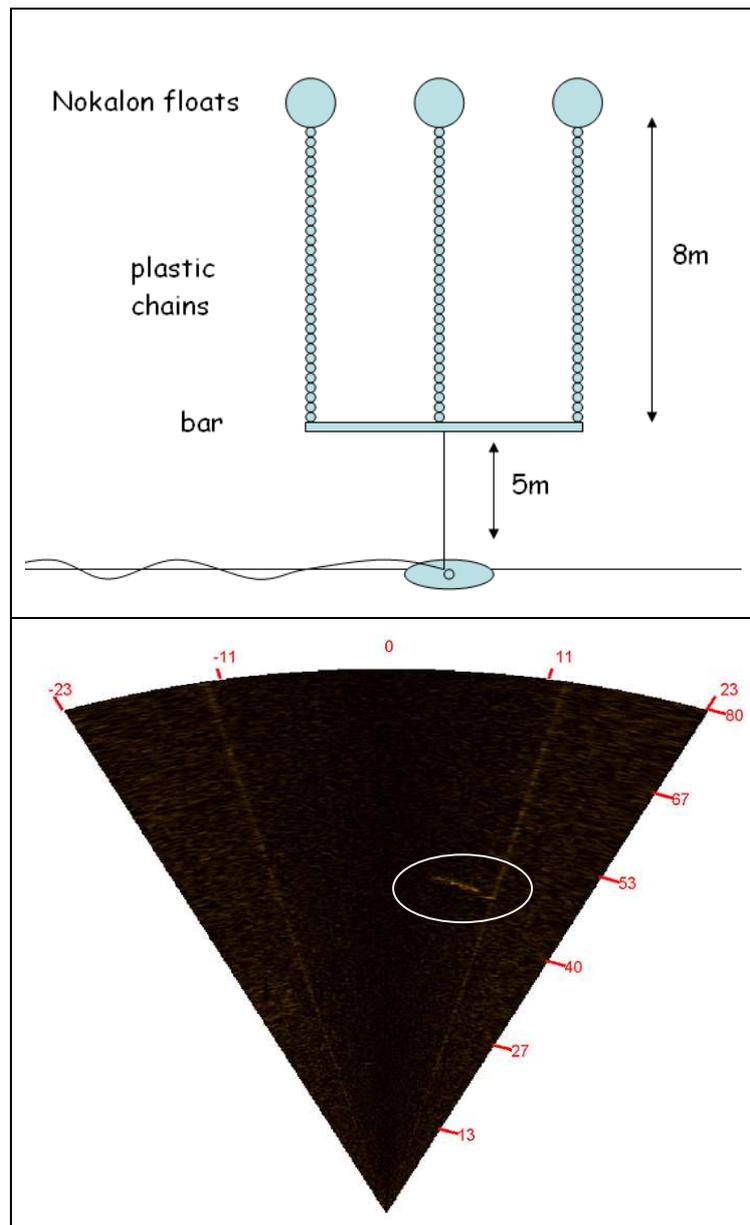

Fig. 3 Relative obstacle altitude estimation
Up: RMSD vs. d_{st} and sonar altitude vs. ping number
Down: Predicted points (green) and measurements (blue) for d_{st}=0.5

Fig. 4 Large obstacle in sight
Up: Diagram of the obstacle
Down: FLS image of this obstacle

6. CONCLUSION

This paper proposes an original mean for estimating the vertical position of an obstacle in the vertical axis. The estimation is achieved offline by minimizing, along the sonar image sequence, the innovation term of a Kalman filtering of the successive obstacle positions. This is an important piece of information to help the vehicle to revise its trajectory and to induce a good avoidance strategy.

The method has been tested on real data supplied by the French organisation GESMA, a division of the French Ministry of Defense (DGA).

Future work concerns the modification of the process model so as to make this estimation at the same time as the tracking.
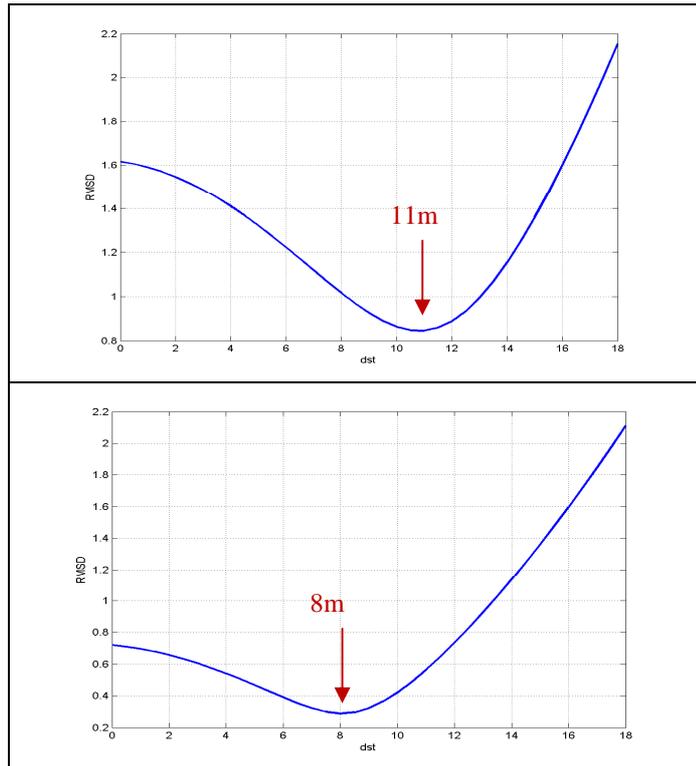
Fig. 5 Relative obstacle altitude estimation for track shown on Fig. 4
Up: RMSD vs. d_{st} based on experimental measurements
Down: RMSD vs. d_{st} based on theoretical measurements

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