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Minesniper

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The flight control system of a minehunting ROV-type weapon developed by SIMRAD is presented. The system is separated into lightly interacting subsystems, and autopilots are designed for steering, diving and speed control. The design of the separate controllers is based on PI, forward loop and sliding mode techniques. The diving control system, using the battery-packet as actuator, is specially examined. Results from sea testing show performance and stability for the autopilots.

1. Introduction

SIMRAD (Stjørdal, Norway) has developed a low cost minehunting system. The Minesniper is a light weight low cost mine disposal system utilizing an expendable ROV-type weapon for rapid and efficient mine verification and destruction (Fig. 1).

Minesniper is effective against deep and shallow water moored mines as well as bottom lying devices. Short range location of mines is achieved through the use of a homing sonar fitted to the weapon. The weapon also carries a camera for visual inspection and verification together with a light weight shaped charge for mine detonation.

Several features have been incorporated into the system to achieve rapid mine clearance. Shallow water destruction of a mine in less than 10 minutes from the decision to deploy the weapon is within its capability.

The Minesniper system includes a dedicated short base line acoustic positioning system (APS) and navigation computer. These, together with inputs from the vessel's minehunting sonar, allow automatic guidance of the weapon to the target.

A dedicated navigation display in combination with the camera picture and a model based navigation system enables the operator to accurately manoeuvre the weapon during the final homing operation. Inspection of the target is achieved by manual joystick control.

2. Weapon model

The forces made by thruster revolution and the battery-packet motion are calculated, and dependent on current and vehicle speed, external forces working on the vehicle body are also calculated, together with Coriolis, damping and restoring forces. The equations describing the model are nonlinear and based on the work of Fossen (1994). The dynamic model is

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\xi}) = \boldsymbol{\tau} \tag{1}$$

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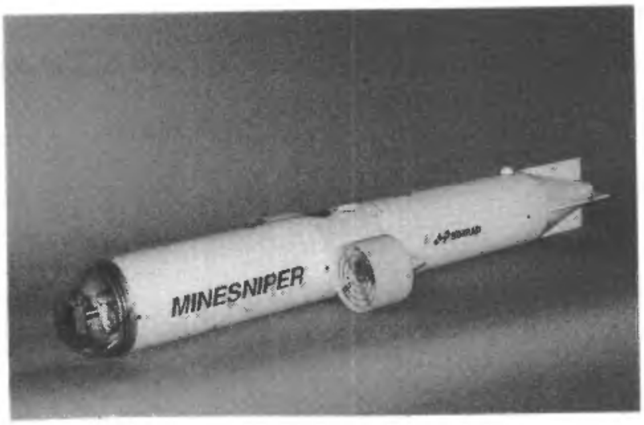

Figure 1. The Minesniper.

and the kinematic model is described by

$$\xi = \boldsymbol{J}(\xi)\boldsymbol{v} \tag{2}$$

where the velocity vector is represented as

$$\boldsymbol{v} = [uvwpqr]^{\mathrm{T}} \tag{3}$$

and the six components of position and attitude in the global reference frame are

$$\xi = [xyz\phi\theta\psi]^{\mathrm{T}} \tag{4}$$

A more detailed set of equations can be found in Smestad (1993).

$$\boldsymbol{u} = \begin{bmatrix} n_p|n_p| \\ n_s|n_s| \\ n_v|n_v| \\ d \end{bmatrix} \tag{5}$$

where n_p, n_s, n_v are rpm (rotations per minute) for port, starboard and vertical thruster and d is the battery-packet position. The actuator matrix can now be expressed as

$$\tau = \boldsymbol{B}(\theta)\boldsymbol{u} \tag{6}$$

where $B(\theta)$ is defined in (7).

$$\boldsymbol{B}(\theta) = \begin{bmatrix} K_p & K_s & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & K_v & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & mg\cos\theta \\ K_p l_y & -K_s l_y & 0 & 0 \end{bmatrix} \tag{7}$$

l_y is the distance between the centre of the weapon and the horizontal thrusters.

2.1. *Kalman filtering*

The mathematical model is used to filter the sensor data from the compass, pitch and roll sensor, the altimeter, the pressure sensor, the acoustic positioning system and the sonar.

3. Global control

The control system runs in three different modes: direct, manual and automatic. Direct mode means no controllers are running (or in other words, the operator is in control). The commands from the joystick are sent directly to the thrusters and to the battery packet positioning system.

In manual mode the local controllers are running. The operator uses the joystick and sets the desired references for yaw angle (heading), pitch angle, depth, height and speed (surge). The steering control system works in a WYSIWYG[1] manner. The operator turns the weapon with the joystick until the desired heading is reached. The operator then sets the joystick in middle position (the joystick jumps to this position if no force is used on the joystick). The reference heading is set to the present heading and the steering controller will hold this heading. The pitch reference is set directly by a separate handle. The pitch controller moves the battery packet until the desired pitch angle is reached.

In automatic mode the references to the local controllers are set by a global controller. The global controller calculates new references based on the weapon's position, the target position and the desired path. The APS and/or the vessel sonar are used to position the weapon and target. The global controller can work in two different modes: by sight or by path.

3.1. *Transformation*

Weapon positions in the world-fixed coordinate system (x, y, z) are transformed into the path-fixed coordinate system (e_x, e_y, e_z). The transformation matrix is defined in (8).

$$\begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} = \begin{bmatrix} c\psi c\theta & s\psi c\theta & -s\theta \\ -s\psi & c\psi & \theta \\ c\psi s\theta & s\theta s\theta & c\theta \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{8}$$

where c is cos, s is sin and ψ and θ are the direction of the path.

3.2. *By sight*

The heading reference is set to point to the next point on the path (x_k, y_k, z_k) (way-point).

$$\psi_{\text{ref}} = \tan^{-1}\left(\frac{y_k - y}{x_k - x}\right) \tag{9}$$

and by path

$$\theta_{\text{ref}} = \tan^{-1}\left(\frac{z_k - z}{\sqrt{[x_k - x]^2 + [y_k - y]^2}}\right) \tag{10}$$

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[1] What You See Is What You Get.

3.3 *By path*

The *by path* method is finding the position of the weapon relative to the desired path (use transform). The relative error is then used to set references

$$\psi_{\text{ref}} = \psi_{\text{path}} + K_y e_y$$

and

$$\theta_{\text{ref}} = \theta_{\text{path}} + K_z e_z .$$

4. Local control

The local controllers control speed, heading, pitch and depth/height. The controllers are designed to follow a filtered reference. As the weapon passes way-points, the new references from the global controller can make a jump in value. By filtering these references the controllers will work more smoothly.

4.1. *Speed controller*

The speed controller can work in different modes: safe and constant. The default mode safe will continuously consider the error in heading and pitch and slow down when the errors are large, the default max speed in this mode is 1.5 m/s. In constant mode the speed can be set to a fixed value.

There is no sensor that can tell the actual speed of the weapon. The speed is estimated by the mathematical model.

Neglecting the interactions from the other degrees of freedom, the longitudinal rigid-body equation of motion is given by

$$(m - X_{\dot{u}})\dot{u} = X_u u + X_{u|u|} u|u| + K_{\text{thr}} u_{\text{sum}} \tag{13}$$

where

$$u_{\text{sum}} = n_p|n_p| + n_s|n_s| \tag{14}$$

and

$$K_{\text{thr}} = K_p = K_s \tag{15}$$

The two horizontal thrusters are assumed to be equal in performance. The controller used is a sliding mode controller with an integral part given in (22).

The speed reference is filtered by

$$T\dot{u}_d + u_d = u_{\text{ref}} . \tag{16}$$

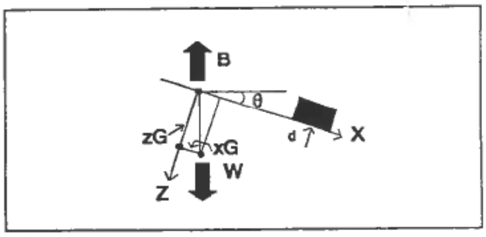

Figure 2. Balance restored.

4.2. *Retardation and positioning*

A controller takes care of retardation and positioning. The position reference is set to a distance (r) from the target (0.5–5 m). Heading and pitch must point in the direction of the target. If the current (C) is estimated, the controller can compensate for the current directly. The controller equation is given in (23).

The range weapon–target is filtered by

$$\dot{u}_d + 2\xi\omega_0 u_d - \omega_0^2 r_d = -\omega_0^2 r_{\mathrm{ref}} \tag{17}$$

It is important to use the initial conditions

$$r_d(0) = r(t_0), \quad u_d(0) = u(t_0) \tag{18}$$

as the retardation controller takes (over) control at t_0.

A compass is located at the back of the Minesniper. Due to long updating rate the steering controller was designed to be placed in the weapon itself. A simple P-controller does the work

$$u_{\mathrm{diff}} = K_p(\psi_d - \psi) \tag{19}$$

where u_{diff} is the difference revolution between the two horizontal thrusters

$$u_{\mathrm{diff}} = n_p|n_p| - n_s|n_s| \tag{20}$$

the heading reference is filtered at the central unit and passed to the local controller inside the weapon. The filtering is done by

$$\dot{r}_d + 2\xi\omega_0 r_d + \omega_0^2\psi_d = \omega_0^2\psi_{\mathrm{ref}} \tag{21}$$

$$\begin{aligned} u_{\mathrm{sum}} = {} & K_i \int_0^t [u_d(\tau) - u(\tau)]d\tau + \frac{1}{K_{\mathrm{thr}}}\Big(- X_u u - X_{u|u|}u|u| \\ & + (m - X_u)\Big[\dot{u}_d - \eta \tanh\Big(\frac{u - u_d}{\phi}\Big)\Big]\Big) \end{aligned} \tag{22}$$

$$\begin{aligned} u_{\mathrm{sum}} = {} & K_0 C + K_i \int_0^t [r(\tau) - r_d(\tau)]\mathrm{d}\tau + \frac{1}{K_{\mathrm{thr}}}\Big(X_u u + X_{u|u|}u|u| \\ & - (m - X_{\dot{u}})\Big[- \dot{u}_d - \lambda(u_d - u) - \eta \tanh\Big(\frac{u_d - u + \lambda(r - r_d)}{\phi}\Big)\Big]\Big) \end{aligned} \tag{23}$$

By combining u_{diff} and u_{sum} the rpm references to the horizontal thrusters are calculated by

$$\begin{aligned} n_s &= \mathrm{sign}\,(u_{\mathrm{sum}} - u_{\mathrm{diff}})\sqrt{\frac{\mathrm{abs}(u_{\mathrm{sum}} - u_{\mathrm{diff}})}{2}} \\ n_p &= \mathrm{sign}\,(u_{\mathrm{sum}} + u_{\mathrm{diff}})\sqrt{\frac{\mathrm{abs}(u_{\mathrm{sum}} + u_{\mathrm{diff}})}{2}} \end{aligned} \tag{24}$$

Revolution control is implemented on the horizontal thrusters.

4.4. *Pitch controller*

The effect of moving the weight (battery-packet) is easy to analyse. Moving the battery pack means moving the x-coordinate of the centre of gravity (x_G). This is given by

$$x_G = \frac{md}{M} \tag{25}$$

where M is the total mass of the weapon, m and d are the mass and the position of the battery pack. The buoyancy and weight force (B and W) will pull in opposite directions and the weapon enters a new state of equilibrium. The new pitch angle is found by

$$\theta = -\tan^{-1}\left(\frac{x_G}{z_G}\right). \tag{26}$$

z_G is the metacentre height. See Fig. 2.

This knowledge is used in a forward loop. If the weapon is not in motion it is enough to move the weight to a pre-calculated position to get the desired pitch angle. But when the weapon is in motion, it is necessary to use feedback from the pitch sensor. The error is also integrated so the weight is moved until the desired pitch angle is reached. The controller equation is

$$d = \frac{M}{m}\tan(\theta_d)z_G + K_i\int_0^t [\theta_d(\tau) - \theta(\tau)]\,\mathrm{d}\tau \tag{27}$$

where M is the mass of the weapon, m is the mass of the battery packet and z_G is the centre of gravity, d is the position reference for the battery-packet controller.

The pitch reference is filtered by

$$\dot{q}_d + 2\zeta\omega_0 q_d + \omega_0^2\theta_d = \omega_0^2\theta_{\mathrm{ref}} \tag{28}$$

4.4. *Depth/height controller*

Two different depth/height controllers are used. One controller calculates a new pitch reference, the other uses the vertical thruster. The vertical thruster is meant to be used only when the weapon is not in motion or in emergency situations. A pressure sensor gives the depth z.

When in motion the depth controller can specify a pitch reference simply by

$$\theta_{\mathrm{ref}} = K_p(z_{\mathrm{ref}} - z) \tag{29}$$

Depth control with the vertical thruster is done by a PI-controller:

$$n_v = K_i\int_0^t [z(\tau)_{\mathrm{ref}} - z(\tau)]\,\mathrm{d}\tau \tag{30}$$

An altimeter gives the height h above seabed. The same controllers are used to control height. a new depth reference is calculated simply by

$$z_{\mathrm{ref}} = z + h - h_{\mathrm{ref}}. \tag{31}$$

5. Test results

The Minesniper has been tested and demonstrated several times. Successful runs against dummy targets have proved the functionality of the system. The results from one test are presented here. The weapon was run automatically from launching to target.

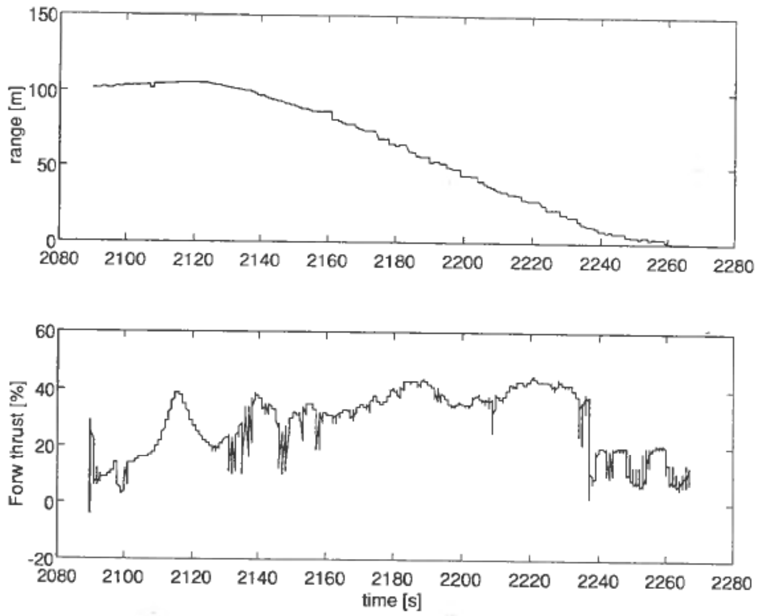

Figure 3. Range and thrust.

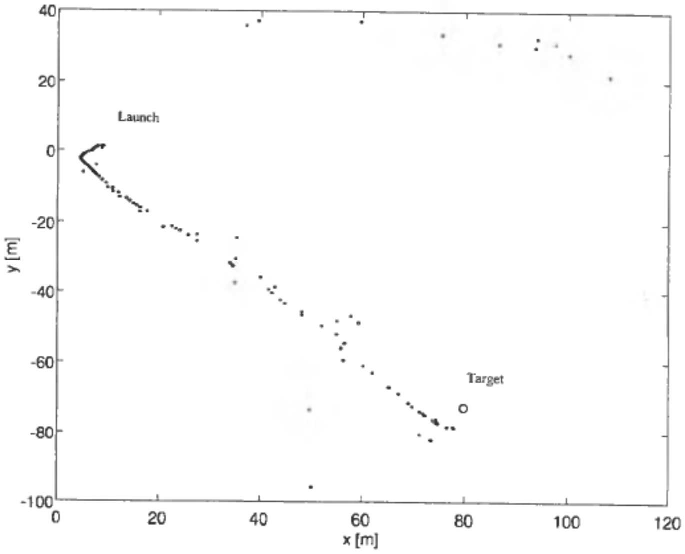

Figure 4. Horizontal-plot. From launching to target.

5.1. *Global positioning*

A dummy target, a responder positioned by the APS, was placed 110 m out. The target was observed on the camera 2–3 minutes after launching. The data presented in the *xy*-plot (Fig. 4) shows the raw data from the APS. Some error positions are detected, but these are filtered out by Kalman filtering. Figure 3 shows the range and forward thrust. A speed of 1 m/s during transportation is observed.

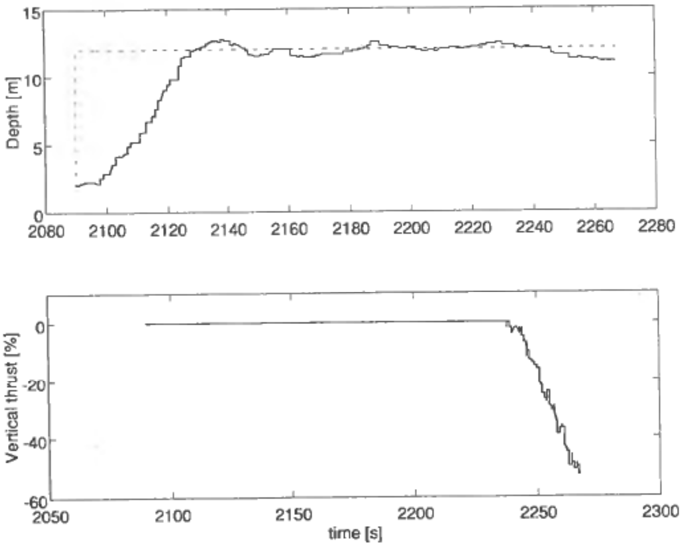

Figure 5. Depth and vertical thrust.

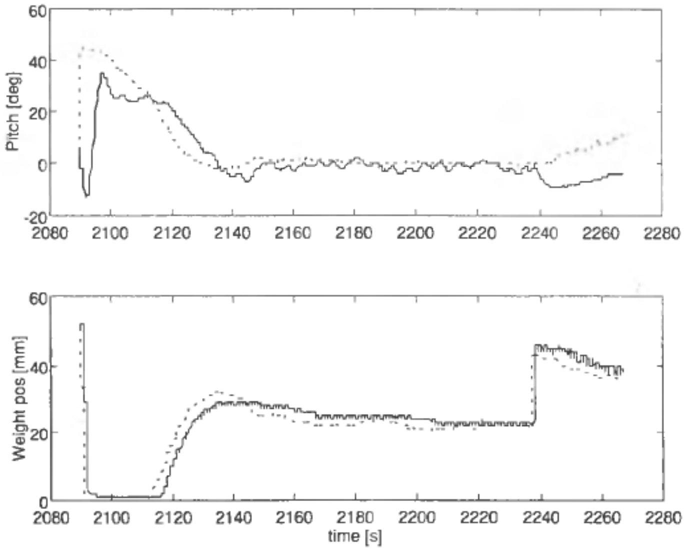

Figure 6. Pitch and weight-position.

5.2. *Depth and pitch*

The target was placed at a depth of 12 m. This depth was achieved rather quickly as shown in Fig. 5. Notice that the vertical thruster is first used when placed at the target.

As observed in Fig. 6, the integral part of the pitch controller was set to zero when the positioning controller took over.

6. Conclusion

Test results show acceptable performance for the autopilot system.

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