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Active FTC for waterjets propelled ships based on Adaptive Estimator and Sliding Techniques

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***Abstract*— This paper focuses on the design and validation of an active Fault Tolerant Control (FTC) approach dealing with sensor and actuator faults for a ship propelled by two water jets. The proposed FTC relies on an adaptive estimation to reconstruct sensor faults and a second order sliding mode observer based on an adaptive super twisting algorithm to reconstruct the actuator faults. A nonlinear model of the considered ship, issued by a previous work, is used to prove the effectiveness of the proposed FTC in the path following maneuvers, speed regulation, and tracking course. The inputs of this model are the command orders to apply to the water jets including the two engines, the steering and reversing units for each jet. Details of the design process of the faults reconstruction and reconfiguration are given. The stability of the closed-loop system and uniform boundedness of the tracking error are proved based on Lyapunov theory. Simulations with many faults scenario are carried out. Results show that the proposed controller can successfully accommodate faults associated with sensors and actuators.**

Keywords: Water jets, ship nonlinear model, second order sliding mode observer, super twisting algorithm, adaptive estimation, fault reconstruction, reconfiguration, Fault Tolerant Control, sliding mode control.

I. Introduction:

A naval vehicle is a notable example of dynamic systems which are difficult to control due to their complexity, hydrodynamic effects and the harsh environment where they operate. Designing an intelligent vehicle at a high degree of automation is the main ambition in the marine community. Without a fault tolerant controller, it is impossible to guarantee that the system can continue to operate properly in case of faults occurring. Such a controller should tolerate faults automatically and achieve the desired performance under various fault conditions; it becomes more and more imperative in modern autonomous vehicles and presents an attractive research field.

Active FTC needs to detect, isolate and estimate faults and then compensate their effect by reconfiguring the controller [1]. Hence, the FTC proposed in this paper is based firstly on adaptive estimation aiming to reconstruct sensor faults, which will be subtracted from the faulty measures if it exceeds an appropriate threshold [2]. This threshold creates the sensor fault tolerance. Secondly, a second order sliding mode observer is used to estimate the actuator faults. The reconfiguration of the main sliding controller was set up by the injection of the actuator faults information into the equivalent control part of the sliding control law.

The concept of sliding modes appeared in the Soviet Union in the sixties, where introducing discontinuous control action into dynamical systems was explored [3]. Sliding mode techniques are also used for observation and fault detection aims [4]. With a classical Sliding-Mode Observers the disturbance cannot be reconstructed exactly [4]. High order sliding mode approach has been expanded as an intriguing theme for researchers within the last decade for the attractive features found such as the finite-time convergence, the higher accuracy and chattering reduction [5].

A second order sliding mode algorithm called super twisting algorithm has been proposed recently for second-order nonlinear systems [6], [7]. In general, the convergence of this algorithm was proved using complex geometrical conditions [8]. This approach has been successfully used for fault detection and isolation [10] and has been widely applied to real systems see for example [11].

For autonomous vehicles, FTC based on sliding techniques was applied generally for aircraft vehicles [12]. In the marine field, the sliding mode technique was used just as a robust control to steer the ship on a desired course [13], [14], [15] as well as for trajectory planning, tracking control for unmanned surface vessels [16], [17]. No previous work aiming to develop an FTC based on sliding techniques or sensor fault adaptive estimation for a two water jets propelled ship could be found in the literature.

Fig. 1. The considered vessel sailing with 40 knots

The interest in this paper is to propose such a controller for a two water jets boat of 35 meters length Fig.1, with two engines each one having 4200 hp.

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This paper is organized as follows. Section II presents the non linear model of the ship issued by a previous work [18] which meets the general class of surface vessel models given by Fossen [19]. In section III the design of the FTC is explained, details on sensor fault adaptive estimation, high order sliding mode observer as well as the sliding mode controller are given. Finally, in section IV simulations for several faults are carried out to show the efficiency of the proposed FTC.

II. Mathematical Model

The mathematical model of the considered vessel is defined using two coordinate frames: Earth-fixed or NED (North, East, Down) and ship body coordinate system attached to the centre of gravity of the ship.

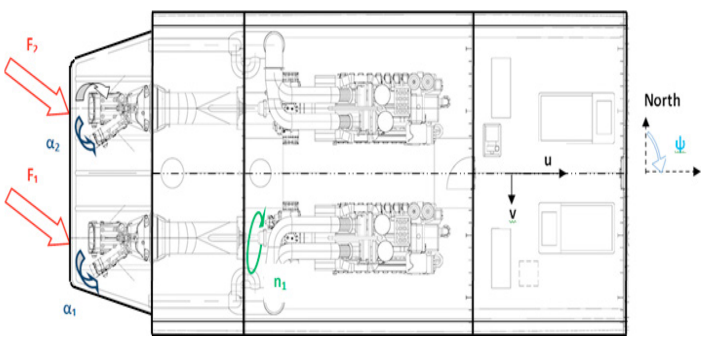

Fig. 2. Main parameters for the mathematical model of the boat: Astern top view

The mathematical model of the patrol boat is described with an assumption that the platform is moving only in the horizontal plane.
The ship speeds surge u and sway v are defined in the body-fixed coordinate frame, and the yaw speed r is the ship rotation around the vertical axis. The positions x_{pos} and y_{pos} and the course ψ are defined in the earth-fixed frame. The command to be applied are the water jets orders including the two engines, the steering and reversing unit for each jet. A previous work [18] aiming to model and identify the system led to the following model:

$$\begin{cases} m_1\dot{u} = \tau_1 + m_0 rv - a_{11}u - a_{12}|u|.u - a_{13}u^3 \\ m_2\dot{r} = \tau_2 - a_{21}r - a_{22}|r|r - a_{23}r^3 \\ m_3\dot{v} = \tau_3 - m_0 ru - a_{31}v - a_{32}|v|v - a_{33}v^3 \\ \dot{\psi} = r \\ \dot{x}_{pos} = \cos\psi.u - \sin\psi.v \\ \dot{y}_{pos} = \sin\psi.u + \cos\psi.v \end{cases} \quad (1)$$

With

$$\begin{cases} \tau_1 = F_1'\cos\alpha_1 + F_2'\cos\alpha_2 \\ \tau_2 = F_1' sin(\alpha_1 - \alpha_0) + F_2' sin(\alpha_2 + \alpha_0) \\ \tau_3 = -F_1'\sin\alpha_1 - F_2'\sin\alpha_2 \end{cases} \quad (2)$$

Where m_0 is the normalised mass of the ship. m_1 , m_3 are the sum of the former mass and the added mass, m_2 is the normalised inertia moment. α_1 and α_2 are the deviation angles.The normalization factor considered is the maximum value of the force given by each thruster F_{max}. This choice is done to make the thrusters commands $F'_{i/i=1..2}$ lie between -1 and 1. $F'_{i/i=1..2}$ characterize the engine rpm $n_{i/i=1..2}$ and the bucket position $e_{i/i=1..2}$ according to the diagram in Fig3 [20].

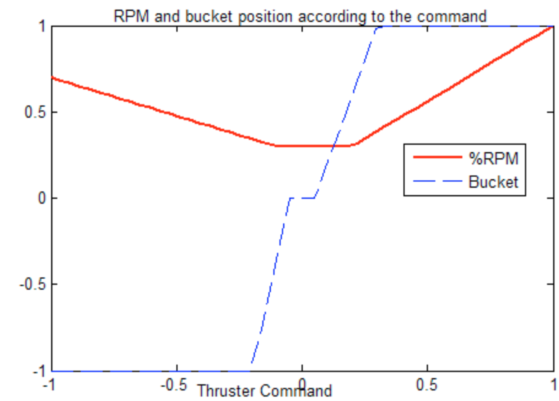

Fig. 3. Engine RPM and Bucket Position according to the command

III. FTC scheme

The proposed FTC scheme is as given in the Fig.4.

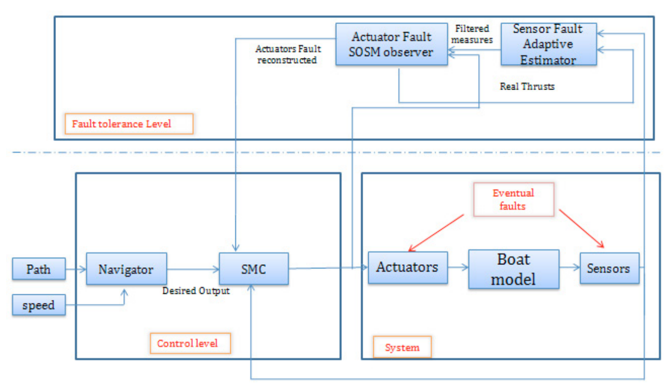

Fig. 4. Diagram of the proposed control topology

The main controller uses sliding mode. The supervision level is based on adaptive fault sensor estimator and on second order sliding mode observer by the adaptive super twisting algorithm. Details of these blocks are given in this section.

A. sliding mode controller

The main goal of the controller is to provide the thrusters and steering angles command orders needed for the ship to follow the desired values of course and surge velocity. It is assumed that the higher order derivatives of these variables exist and are bounded.

1) Step 1: Speed control: The objective is to regulate the surge velocity u to a desired reference u_c. u is governed by the following equation:

$$\dot{u} = \phi_1(u,r,v) + g_1.\tau_1 \quad (3)$$