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Active Fault Tolerant Control of a Remotely Operated Vehicle Propulsion System

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Abstract

This paper presents an active fault tolerant control of a Remotely Operated Vehicle (ROV) propulsion system. An open frame ROV usually requires multi-thruster system to generate various motions. A general framework of active fault tolerant control contains the fault detection and diagnosis (FDD) subsystem and controller re-design subsystem. The FDD subsystem consists of fault detection, isolation and estimation while fault accommodation is chosen as the controller re-design method. In harsh operating environment, thrusters are liable to fault. Therefore, each thruster is monitored by a sensor module called thruster monitoring unit (TMU). As part of FDD subsystem, this module generates information regarding the status of thruster in form of armature voltage and current load feedback. In the case of thruster failure, it is possible to exploit the excessive number of available thruster by re-allocating the required control input i.e. forces and moments acting on the vehicle. This re-allocation procedure is done by fault accommodation subsystem. A Takagi-Sugeno (T-S) fuzzy method is used to accommodate the thruster faults by penalizing the affected thruster and allowing others to continue the operation. An experimental result is presented by demonstrating the effect a blocked ducting and power supply malfunction. The fault accommodation using T-S fuzzy method is proved to be reliable, fast and efficient in handling and accommodating the thruster fault.

Keywords : ROV; multi thrusters; fault tolerant control; FDD; fault accommodation

1. Introduction

Many UUVs use propeller type thruster as the main actuator. The numbers of thrusters determine the degrees of freedom of motions that are controllable. Thrusters are liable to faults or failure during the mission due to harsh underwater environment and unknown uncertainties [1]. This is due to fact that the electro-mechanical parts of the thrusters e.g. shaft, winding, propeller and etc, have limited life time and are constantly exposed to wear and tear. Thruster faults may lead to abortion of the UUV operation, in which the implication could be costly and time consuming. Therefore it is possible to reconfigure the propulsion system in an optimum way if one or more thrusters are failing in order to maintain at least a minimum maneuverability so that the ROV able to complete the desired mission.

Authors in [2] reviewed the general framework of active fault tolerant control system (AFTCS) including comparison between different approaches, methodologies and applications. There are two components in fault tolerant control which are the fault detection and diagnosis (FDD) and controller re-design. Different (FDD) techniques and approaches are discussed by [3]. There are two concepts in controller re-design which are the control adaptation and controller reconfiguration. The

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systems need to adapt and accommodate to the faulty situation if the faults are tolerable or completely reconfigure the control system if the faults no longer acceptable [4].

Recently more publications are reported on the fault tolerant control in unmanned underwater vehicle system especially on the fault tolerant control of the actuators and propulsion system. A fault diagnosis system for AUV has been proposed using a bank of estimators to evaluate any significant change in the behavior of the AUV. Extended Kalman filters (EKF) is implemented for each actuator fault type including in the no fault case and tested on UUV called Roby 2 [5]. A fault incident experienced in operational ROV called ROMEA initialize the design of fault management system consist of fault detection, isolation and accommodation to deal with experienced fault e.g. flooded thruster and other conventional zero output failures. Further readings on several works fault tolerant control of unmanned underwater vehicle can be referred in [6], [7] and [8]. This paper is organized as following. Section 2 describes the general framework of fault tolerant control including the thruster configuration , thrust allocation and fault detection and dignose. Section 3 describes the fault accommodation using Takagi-Sugeno fuzzy system. Section 4 presents the several test results of the proposed fault accommodation with some conclusion remark at the end of the paper presentation

2. Fault Tolerant Control Architecture

2.1 *Open-loop control*

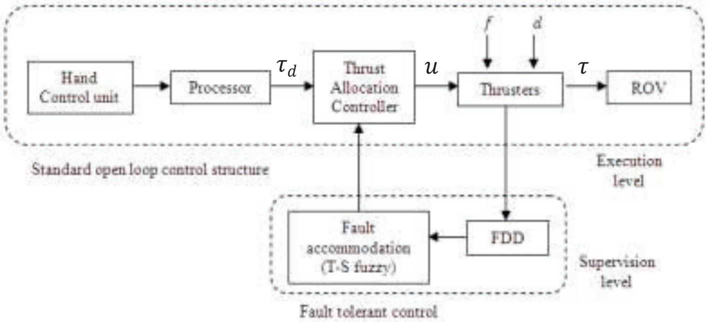

Fig 1: Standard architecture of open-loop ROV control structure with fault tolerant control system with fault accommodation using Takagi-Sugeno fuzzy system.

A standard open-loop or manual control of an ROV is shown in Fig.1. The ROV pilot gives commanded control signal through a hand control unit e.g. joystick to generate control vector τ_d which is the desired forces and moments acting on the ROV. This signal is picked up by the thrust allocation controller i.e. electronic motor controller and converting the desired control input u by activating thrusters required for desired motion of the ROV. This subroutine can be described as the execution level. The fault tolerant control subsystem is represented by fault detection and diagnosis (FDD) and control re-design. This subroutine is also known as the supervision level. For the case of thrusters fault in open loop control, the FDD detects and diagnoses the fault causes by any internal or external disturbance in the thruster. When fault occurs, the magnitude of the fault is estimated to determine the severity of the fault. For the case of partial fault, the activity of affected thruster is reduced while the thruster is completely shut off if the thruster totally failed. This preventive and correction action is done by the thruster allocation controller which is governed by the fault accommodation subsystem. A Takagi-Sugeno (T-S) fuzzy method [9] is used to accommodate the fault. A failure report is sent to the ROV pilot and hence he needs to adjust the desired motion using other available thrusters. For open-loop control, the pilot action in ROV maneuvering defines the closed-loop motion control

2.2 Thruster configuration and thrust allocation

The URRG-ROV [10] is used as the test bed platform to demonstrate the fault tolerant of the propulsion system. This ROV has six electric thrusters, with four unit allocated as the horizontal thrusters and another two units as vertical thrusters. The horizontal thrusters are configured in X-shape configuration as illustrated in Fig.2. In this configuration, each thruster is configured with azimuth angle of 45˚. This configuration allows the ROV to be maneuvered in three DOFs which are the surge, sway and yaw motions. Meanwhile the vertical thrusters are configured in more conventional none azimuth arrangement (not shown in Fig.2). In this work, the active fault tolerant concept is demonstrated on the horizontal thrusters.

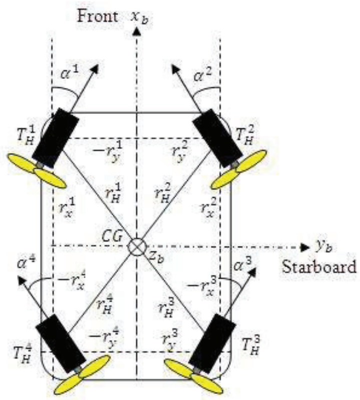

Fig 2: Horizontal thruster configuration

The forces, F^i exerts by i[th] thruster can be written as,

$$F^i = K^i\, u^i \tag{1}$$

where K^i is the thruster force coefficient and u^i is the thruster control input . From Fig 2, the forces and moments, $\boldsymbol{\tau}$ acting on the ROV in the horizontal plane can be written as,

$$\boldsymbol{\tau} = \boldsymbol{B}.\boldsymbol{u} = \begin{bmatrix}\tau_X\\ \tau_Y\\ \tau_N\end{bmatrix} = \begin{bmatrix} K\cos\alpha & K\cos\alpha & K\cos\alpha & K\cos\alpha \\ \sin\alpha & -K\sin\alpha & K\sin\alpha & -K\sin\alpha \\ K(r_x s\alpha_1 - r_y c\alpha_1) & K(r_x s\alpha_2 + r_y c\alpha_2) & K(-r_x s\alpha_3 + r_y c\alpha_4) & K(-r_x s\alpha_4 - r_y c\alpha_4)\end{bmatrix}\begin{bmatrix}u^1\\ u^2\\ u^3\\ u^4\end{bmatrix} \tag{2}$$

where,

$$A = \begin{cases} r_x s\alpha_1 - r_y c\alpha_1, & for T_H^1 \\ r_x s\alpha_2 + r_y c\alpha_2, & for\ T_H^2 \\ -r_x s\alpha_3 + r_y c\alpha_4, & for\ T_H^3 \\ -r_x s\alpha_4 - r_y c\alpha_4, & for\ T_H^4 \end{cases} \tag{3}$$

The surge, sway and yaw motions are represented by $= [\tau_X \quad \tau_Y \quad \tau_N]^T$. Each component of the control input vector is limited by constraint,

$$-u_m^i \le u^i \le u_m^i \qquad i = 1,2,3,4 \tag{4}$$

where u_m^i is the thruster maximum control velocity. Constraint described in (4) shows the thruster velocity saturation where thruster unable to rotate faster than its maximum velocity. The maximum forces and moments for surge, sway and heave motions can be written as the accumulation of maximum forces $\boldsymbol{F_m^i}$ exerted by each thrusters**,**

$$\boldsymbol{\tau_{Xm}} = \textstyle\sum_{i=1}^{4} \boldsymbol{F_m^i}\cos\alpha \tag{5}$$
$$\boldsymbol{\tau_{Ym}} = \textstyle\sum_{i=1}^{4} \boldsymbol{F_m^i}\sin\alpha \tag{6}$$
$$\boldsymbol{\tau_{Ym}} = \textstyle\sum_{i=1}^{4} \boldsymbol{F_m^i}\, A \tag{7}$$

Let the forces and moments exerted by each thrusters are assumed to be identical such that $F^i = F^1 = F^2 = F^3 = F^4$. Thus the maximum forces and moments can be written as,

$$\tau_{Xm} = 4F_m\cos\alpha = 4Ku_m\cos\alpha \implies K\cos\alpha = \frac{\tau_{Xm}}{4u_m} \tag{8}$$
$$\tau_{Ym} = 4F_m\sin\alpha = 4Ku_m\sin\alpha \implies K\sin\alpha = \frac{\tau_{Ym}}{4u_m} \tag{9}$$
$$\tau_{Nm} = 4F_m A = 4Ku_m A \implies KA = \frac{\tau_{Xm}}{4u_m} \tag{10}$$

Equations (8), (9) and (10) can be written in normalised form as Equation (11) which for a given normalised $\underline{\boldsymbol{\tau}}$, the feasible control input $\underline{\boldsymbol{u}}$ can be determined such that $\underline{\boldsymbol{\tau}} = \underline{\boldsymbol{B}}.\underline{\boldsymbol{u}}$

$$\begin{bmatrix} \frac{\tau_X}{\tau_{Xm}} \\ \frac{\tau_Y}{\tau_{Ym}} \\ \frac{\tau_N}{\tau_{Nm}} \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & \frac{1}{4} \end{bmatrix} \begin{bmatrix} \frac{u^1}{u_m^1} \\ \frac{u^2}{u_m^2} \\ \frac{u^3}{u_m^3} \\ \frac{u^4}{u_m^4} \end{bmatrix} \Leftrightarrow \underline{\boldsymbol{\tau}} = \underline{\boldsymbol{B}}.\underline{\boldsymbol{u}} \tag{11}$$

For fault free case, the motor control input $\boldsymbol{u}$ produces the corresponding propeller rotational speed $\boldsymbol{n}$ to generate the corresponding forces and moments $\boldsymbol{\tau}$. However, during the thrusters fault situation, the thrusters unable to produce the same nominal rotational propeller speed $\boldsymbol{n}$ thus changing the corresponding forces and moments. Therefore a new formulation as shown by Eq.(12) can be written to replace Eq.(11). During thrusters fault, Eq.(12) is written based on actual rotational propeller speed to calculate the propulsion forces and moments.

$$\begin{bmatrix} \frac{\tau_X}{\tau_{Xm}} \\ \frac{\tau_Y}{\tau_{Ym}} \\ \frac{\tau_N}{\tau_{Nm}} \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & \frac{1}{4} \end{bmatrix} \begin{bmatrix} \frac{n^1}{n_m^1} \\ \frac{n^2}{n_m^2} \\ \frac{n^3}{n_m^3} \\ \frac{n^4}{n_m^4} \end{bmatrix} \Leftrightarrow \underline{\boldsymbol{\tau}} = \underline{\boldsymbol{B}}.\underline{\boldsymbol{n}} \tag{12}$$

Components of the vector $\underline{\boldsymbol{\tau}}$ and $\underline{\boldsymbol{n}}$ are dimensionless number, restricted to the standard interval [-1,1]. This enables better understanding and easier visualization of the problem. Since in this work the DC brush motor thrusters are used as the main propulsion system in which does not have the ability to provide the feedback of propeller rotational speed, other approach is used by utilizing the feedback of armature voltage and current load of the thrusters. In principle of electric motor, the current load rises and fluctuates according to load i.e. torque and forces. At the same time, change in armature voltage changes the current load. During the fault free case, the current load fluctuates within the nominal range. However, the current load will rise and fluctuates out of nominal range when there is abnormal load. Let consider the following shaft speed dynamics,

$$0 = -R_a i_m - K_m n + v_m \tag{13}$$

$$J_m \dot{n} = K_m i_m - Q \tag{14}$$

where v_m is the armature voltage, i_m is the armature current, n is the propeller rotational speed, R_a is the armature resistance, K_m is the motor torque constant, J_m is rotor moment of inertia and Q is the load from the propeller. Equations (13) and (14) show that, for fixed constants (R_a, K_m, v_m and J_m), the propeller load Q is proportional to the armature current i_m and propeller rotational speed n. Change in propeller load changes the current load. This information is used for fault detection of faulty thrusters. By changing the armature voltage input v_m, new constraint bound as in Eq.(15) is created.

$$-s_m^i \leq s^i \leq s_m^i, \qquad i = 1,2,3,4 \tag{15}$$

$$0 \leq s^i < 1 \tag{16}$$

The numerical value of s^i depends on the type of fault and usually selected in advance for each particular fault type. In this work, s^i is selected from an experiment which demonstrating a thrusters fault due to blocking ducting and power supply malfunction. For $s_i \to 0$, the thruster has total fault and need to be permanently shut down while $s^i = 1$ indicates that the thrusters has no fault. The value of s^i represents the output of Takagi-Sugeno fuzzy system that have been selected in advance to accommodate the thrusters fault.

2.3 Fault detection and diagnosis (FDD)

The fault detection and diagnosis (FDD) subsystem are represented by three components; the fault detection, fault isolation and fault identification. The task of fault detection is to decide whether a fault has occurred while the fault isolation is to find which component, or in this case which thruster is having a fault. According to [3], a fault is defined as an unpermitted deviation of at least one characteristics property of a variable from an acceptable behaviour. In this work, the properties being observed are the armature voltage v_m and current load i_m. These measured process parameters are continuously monitored during the ROV operation. The monitoring process is handled by a sensor module called thruster monitoring unit (TMU). The measured process parameters of each ith thruster (${v_m}^i_{act}, {i_m}^i_{act}$) are compared with the reference process parameters ($v^i_{ref}, {i_m}^i_{ref}$) which have been identified during an offline experiment. Comparing between reference process parameters and actual process parameters yields an error value called residuals. The residuals or differences between actual and reference process parameters are given as,

$$\text{Armature voltage residual:} \quad e^i_{v_m} = {v_m}^i_{ref} - {v_m}^i_{act} \tag{17}$$

$$\text{Current load residual:} \quad e_{i_m} = {i_m}^i_{ref} - {i_m}^i_{act} \tag{18}$$

2.4 Type of fault

It is difficult to determine the exact cause of the thrusters fault. The fault could be cause by external and internal causes. Author in [4] suggested three types of time dependant fault; abrupt, incipient and intermittent fault. To verify the finding and performance of the proposed fault tolerant control of propulsion system, a list of possible internal and external fault causes (Table 1) is identified and simulated through experiments.

Table 1. Fault simulation

Type of fault	Method of simulation	Preliminary result
External - Propeller load increases	The thrust is disturbed by blocking the ducting	Current load increases
Internal – Power supply malfunction	The supply voltage to the motor controller is increased/decreased intermittently	Current load and armature voltage increases/decreases
Internal – Motor controller malfunction	The supply voltage to the motor controller is not connected	Zero output in current load and armature voltage

Blocked ducting is a common issue for small thrusters. The thrusters could suck other nearby physical elements e.g. leaf and sea weed into the water flow. Blocked ducting causes propeller load i.e. torque to increase because the water flow is compromised. Increase in load causes abrupt changes in the current load. For a thrusters which operating at maximum input i.e. voltage, blocked ducting causes the current load to rise exceeding the maximum operating value thus risking damaging the thrusters. However, blocked ducting could be temporary thus the affected thrusters may not be permanently shut off. Fig.6 shows two possible blocked ducting, partial and full. Partially blocked ducting may cause the thrust to decrease while fully blocked ducting may cause the thrust to reduce to almost zero. A fault code table (Table 2) is introduced to visualize the possible fault into several categories. The table shows the relationship between thruster states, fault types and correction action that will be taken to accommodate the fault.

Table 2: Fault code table

Thruster state	Class	Type	Constraint bound s_i
Normal (fault free)	-	-	1.0
Partially blocked ducting	External	Partial	0.8
Fully blocked ducting	External	Total	0
Voltage increase	Internal	Partial	0.7
Voltage drop	Internal	Partial	0.9
Voltage total loss	Internal	Total	0
Unknown	Internal	Total	0

2.5 Fault accommodation using Takagi-Sugeno fuzzy system

The Takagi-Sugeno fuzzy system is used to accommodate faulty thrusters. Its task is to penalize faulty thruster and re-organize all available and active thrusters to be used in manoeuvring. The general representation of T-S fuzzy rule can be written as,

$$\text{IF } x_1 \text{ is } A_{i1} \text{ AND } x_2 \text{ is } A_{i2} \dots \text{AND} \dots x_n \text{ is } A_{in} \text{ THEN } u = f(x_1, x_2, \dots x_n) \tag{19}$$

This multiple dual input single output T-S fuzzy system used the residuals of each i^{th} thruster i.e. $e^i_{i_m}$ and $e^i_{v_m}$ as the inputs with new constraint s^i as the output. For zero order T-S model, the following fuzzy rules are applied for each ith thruster.

RULE 1: IF $e^i_{i_m}$ is ZERO AND $e^i_{v_m}$ is ZERO THEN $s^i = 1.0$

RULE 2: IF $e^i_{i_m}$ is NEGATIVE SMALL AND $e^i_{v_m}$ is ZERO THEN $s^i = 0.8$

RULE 3: IF $e^{i}_{i_m}$ is NEGATIVE LARGE AND $e^{i}_{v_m}$ is ZERO THEN $s^i = 0$
RULE 4: IF $e^{i}_{i_m}$ is NEGATIVE SMALL AND $e^{i}_{v_m}$ is NEGATIVE SMALL THEN $s^i = 0.7$
RULE 5: IF $e^{i}_{i_m}$ is NEGATIVE LARGE AND $e^{i}_{v_m}$ is NEGATIVE LARGE THEN$s^i = 0$
RULE 6: IF $e^{i}_{i_m}$ is POSITIVE SMALL AND $e^{i}_{v_m}$ is POSITIVE SMALL THEN $s^i = 0.9$
RULE 7: IF $e^{i}_{i_m}$ is POSITIVE LARGE AND $e^{i}_{v_m}$ is POSITIVE LARGE THEN $s^i = 0$

3. Result and Discussion

To verify the performance of the proposed fault accommodation using T-S fuzzy system, the ROV is put at stationary in water tank. Two thrusters T_H^1 and T_H^2 of the horizontal thrusters are chosen as the faulty thrusters. T_H^1 is simulated with partially blocked ducting while T_H^2 is simulated with power supply malfunction i.e. increased voltage input. The normal current load and armature voltage are bounded within $-4 \leq i_m \leq 4$ and $-20 \leq v_m \leq 20$. At this point, the nominal constraint bound is $-1 \leq s^i \leq 1$. Fault is considered if the current load and armature voltage are exceeding the nominal boundary. These scenarios are meant to test the fuzzy rule 1, 2 and 4. To simulate ducting blocking, thruster T_H^1 is partially blocked with a rigid body e.g. plastic. For the case of power supply malfunction, the supply voltage to thruster T_H^2 is increased by 25% of its nominal voltage. The thruster monitoring unit (TMU) scan each thruster and provide the thruster feedback i.e. armature voltage and current load at interval time of 2 second

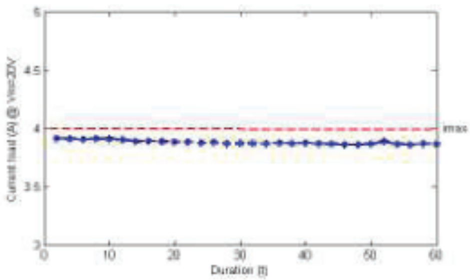

Fig 3. Average normal current load $|i_m|$ for horizontal thruster $T_H = [T_H^1, T_H^2, T_H^3, T_H^4]$ at $|v_m|$ = 20V (90% PWM)

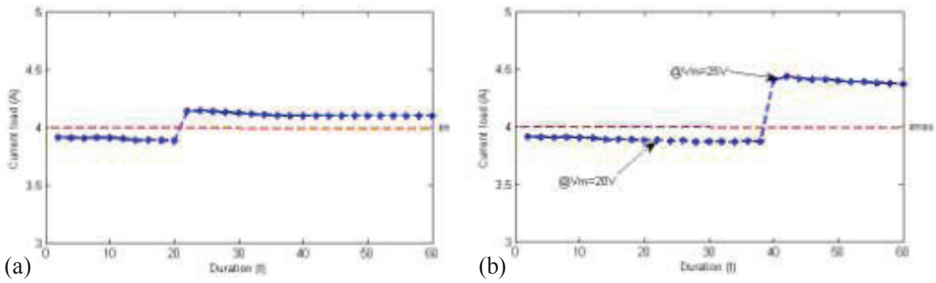

Fig 4. Current load for (a) T_H^1 due to partially blocked ducting and (b) power supply malfunction (increased voltage) without fault accommodation

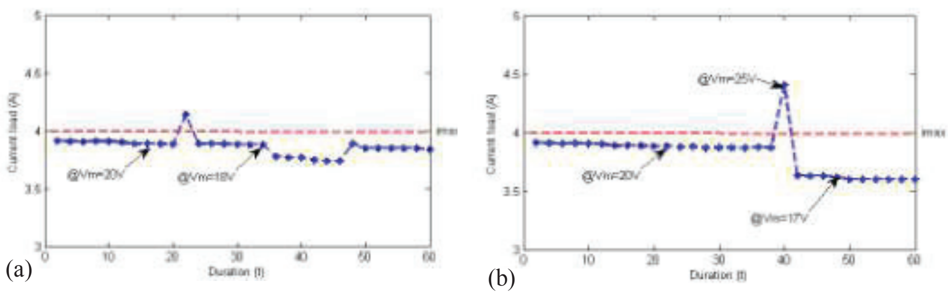

Fig 5. Correction action by T-S fuzzy fault accommodation (a) partially blocked ducting and (b) power supply malfunction (increased voltage)

Fig 4(a) shows that T_H^1 blocked ducting after t=20. This scenario causes the propeller load to increase. The current load i_m increases proportional to the propeller load. The mathematical relation between current load and propeller load is shown in (13). Sudden voltage increase at t=40s as shown in Fig 4(b) causes the current load for T_H^2 to increase drastically. Fig 5(a) and (b) show the correction action taken by the T-S fuzzy fault accommodation. The correction action is done by penalizing the faulty thrusters and creating new constraint bound for T_H^1 and T_H^2. These thrusters are allowed to operate but under usage restriction. For T_H^1, the new constraint bound is reduced to $-0.8 \leq s^1 \leq 0.8$ where the PWM is reduced from maximum 90% to 80% so that the current load can be brought back within the nominal $-4 \leq i_m^1 \leq 4$. Meanwhile for for T_H^2, the 25% increased in the supply voltage ($v_m = 25V$) is considered small, thus the thruster is allowed to continue its operation by limiting the PWM. The thruster is now restricted under new constraint of $-0.7 \leq s^2 \leq 0.7$. This means that the PWM is reduced to 70% of 25V so that the current load can be brought back to its nominal boundary.

4. Conclusion

A simple but efficient fault tolerant control is proposed for a remotely operated vehicle with multiple thrusters. This concept is applied on the open loop control of the URRG-ROV. Thruster fault can be managed by exploiting the excessive number of thruster to re-allocate the required control input i.e. forces and moments acting on the vehicle. Faulty thrusters are penalized by restricting its usage and priority. This is done by creating the new constraint bound and updating the weighting matrix. A fault accommodation subsystem is performed using the Takagi-Sugeno fuzzy system with several fault scenarios has been successfully tested.

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References

[1] E.Omerdic and G.Roberts, Thruster fault diagnosis and accommodation for open frame underwater vehicles, *Control Engineering Practice 12*, Elsevier ,2004, 1575-1598.

[2] Y. Zhang, and J.Jiang, Bibliography review on reconfigurable fault-tolerant control systems, *Annual Reviews in Control 32 Elsevier* 2008, p229-252.

[3] Isermann,R Model-based fault detection and diagnosis – status and applications, *Annual Reviews in Control 29,* Elsevier,2005 p71-85.

[4] M.Blanke, M.Kinnaert, et al, Diagnosis and Fault-tolerant Control . 2006 Springer-Verlag Berlin-Heidelberg Second edition.

[5] A.Alessandri, M.Caccia, et al. Fault detection of actuator faults in unmanned underwater vehicles. *Control Engineering Practice* 1999, 357-368.

[6] Podder, T. K., G. Antonelli, et al, Fault tolerant control of an autonomous underwater vehicle under thruster redundancy: simulations and experiments, 2000 IEEE.

[7] Wang, Y., M. Zhang, et al, Condition monitoring system for sensors and thrusters of AUV." *Jixie Gongcheng Xuebao/Chinese Journal of Mechanical Engineering 42*,2006, p214-218.

[8] Hanai, A. M., S. K. Choi, et al, Experimental validation of model-based thruster fault detection for underwater vehicles,*IEEE International Conference on Robotics and Automation,* 2009

[9] M. Reza Emami, Andrew A. Goldenberg, et al, Systematic design and analysis of fuzzy logic control and applications to robotics Part 1 Modeling, *Robotics and Autonomous Systems 33,* Elsevier 2000 p 65–88

[10] Yusoff, M. A. M. and M. R. Arshad , Development of a Remotely Operated Vehicle (ROV) for underwater inspection, *JURUTERA, The Monthly Bulletin of The Institution of Engineers, Malaysia 2(February 2012)*, p10-13.