

FAULT TOLERANT CONTROL OF THE ELECTRIC PROPULSION FOR AUTONOMOUS SURFACE VEHICLES

Hakan Akyıldız, Erhan Türkmen
Department of Ship Building and Ocean Engineering, Istanbul Technical University

ABSTRACT

The application of a simple design of fault tolerant control (FTC) methodology to the electric propulsion of autonomous surface vehicle is presented. The existing approaches to fault detection and isolation and fault tolerant control in a general framework of a active fault tolerant control are considered according to design methodologies and applications. FMEA (Failure Mode and Effects Analysis) is carried out as a fault analysis, precarious parts of propulsion system are found and offered a solutions to risky applications.

Keywords: Fault Tolerant, Autonomous Surface Vessel, FMEA, Electric Boat, FTC, Risk Analysis

1. Introduction

A customary risk analysis methods for a modern autonomous vessel systems may cause an overall system instability and safety deficiency. To reach increased performance and safety requirements, new approaches to control system design have been developed. For safety-critical systems, the consequences of a minor fault in a system part can be disaster. For the purpose of improve the reliability, safety, economically and fault tolerance, it is necessary to design control systems which are capable of tolerating potential faults, namely, fault tolerant control.

Fault detection and diagnosis are systems of great importance for modern electric vehicles. Fault is an unpermitted deviation of a parameters of the system from the acceptable condition.

Defects in sensors or in controllers can cause undesired reactions and consequences. When a fault occur in a system, the main problem to be addressed is to raise an alarm, ideally diagnose what fault has occurred, and then decide how to deal with it. The problem of detecting a fault, finding the source/location and then taking appropriate action is the basis of fault tolerant control in safety critical systems such as aircraft, robots, space systems and underwater autonomous vehicles. In other wards, by designing a dynamical system, an approach of the fault detection and isolation is processing input/output data, which is able to detect the presence of an incipient fault and eventually to precisely isolate it. Then, the design of a reconfiguration unit, namely a fault tolerant control, performs control reconfiguration for the faulty system.

The paper presents first a brief description of the overall benchmark, then the analysis of the possible faults acting on the system on the basis of the failure mode and effects analysis (FMEA). Afterwards, a simple FDI strategy is described, which allows perfect isolation of the three possible faults proposed in the benchmark. Finally, the information provided by the FDI unit are used to develop a control reconfiguration structure in order to achieve a fault tolerant system.

2. Fault Diagnosis and Fault Tolerant Control

All real systems in nature (physical, biological and engineering systems) can malfunction and fail due to faults in their components. The chances for failures are increasing with the system's

complexity. The complexity of engineering systems is permanently growing due to the growing system size and degree of automation, and accordingly increasing are the chances for faults and at the same time, aggravating the consequences of system failures for engineer and environment. Therefore, increased attention has to be paid to reliability, safety and fault tolerance in the design and operation of technical systems in industrial automation. But obviously, compared to the high standard of perfection that nature has developed with the ‘self-healing’ and ‘self-repairing’ mechanisms in complex biological organisms, the fault management in engineering systems is far behind their technological capabilities and is still in its infancy.

In technical automatic control systems, defects may happen in sensors, actuators, the components of the product itself, or within the hardware or software of the control equipment. Component faults can develop into a failure of the whole system. This effect can easily be amplified by the closed loop. The closed loop may also hide an incipient fault from being observed until a situation is reached in which a failing of the whole system is unavoidable. Even making the closed loop robust or reliable by robust or reliable control, respectively, can not solve the problem in full. It may ensure to retain stability of the closed loop and continue its mission with desired or tolerable degraded performance in the presence of faults, but when the faulty part continues to malfunction, it may cause damage to engineer and environment due to the impact of the faults. So, robust and reliable control using available hard or software redundancy may be efficient ways to maintain the functionality of the control process, but it can not guaranty environmental compatibility or safety of the whole system.

A realistic fault management has to provide dependability which includes both reliability and safety. Dependability is a fundamental requirement in industrial automation, and a cost-effective way to provide dependability is fault tolerant control (FTC). The key issue of FTC is that local faults are prevented from developing into a system failure that can end the mission of the system, and/or cause safety hazards by the faulty devices or the whole system for engineers and environment. Because of its increasing importance in industrial automation, FTC has become an emerging topic in control theory.

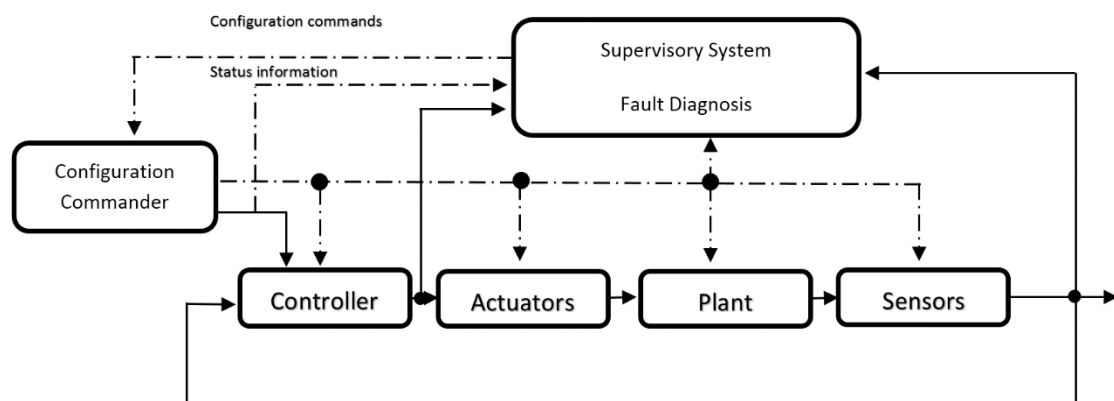


Figure 1. Basic scheme of a fault tolerant control system

3. General Introduction about ASVs

ASVs can range in complexity but must include four main elements: a body (hull), a propulsion system, a navigation system, and a data collection and transmission system. There is no standard

that regulates autonomous surface vehicles and these vessels differ greatly in appearance and functionality depending on the production of the unit and its intended function.



Figure 2. Rendering view of ASV developed by ASV Global

ASVs are a relatively new technology and have a brief history. Early ASVs were designed mostly for educational use. Further advancement of ASVs has been due to the rapid progression of technology. For example, Global Positioning System Receivers (GPSR) have become more compact, affordable, and easily available. Today, most ASVs exist as prototypes being developed by private interest groups and are not being applied to perform routine or standardized tasks. There exists at least one company, Liquid Robotics, which markets its ASVs to the commercial market.

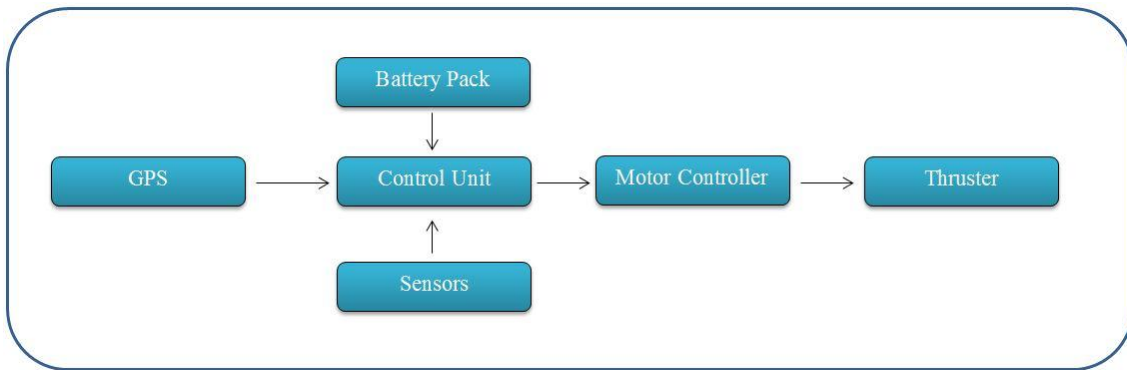


Figure 3. General Electrical Propulsion System of ASV

4. Fault Diagram of the ASV's Propulsion System

This system composed by the control unit, GPS and propulsion system. Above those components, a controller calculates set-points for shaft speed n_{ref} , referenced current for cruising speed I_{ref} and referenced location X_{ref} setted up previously proper to operation area. The objective of the propulsion system is to maintain the boat's ability to propel itself and to maneuver, varying shaft speed and location.

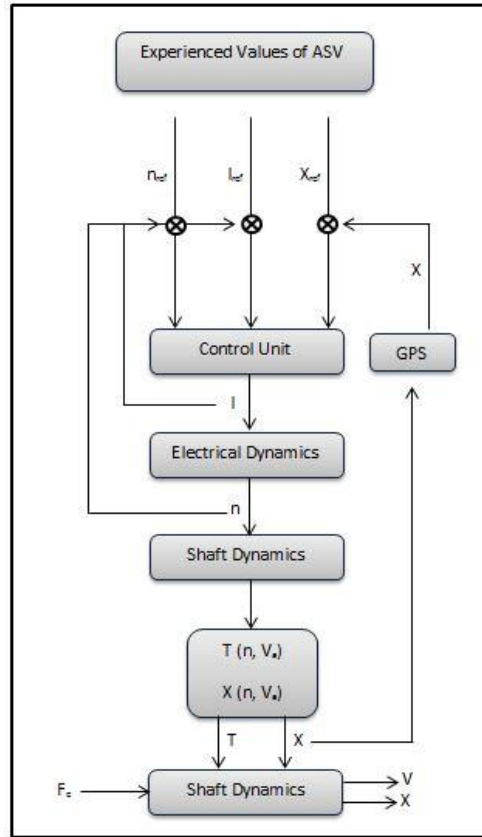


Figure 4. Fault Diagram of the ASV's Propulsion System

4.1 Experienced Values of ASV

Experienced Values of ASV is (n) and (I) values related the each other. These values observed from previous test or computational analysis. On the other hand, (X) value could be changed according to operation area. By comparing the Experienced values obtained from previous test or computational analysis to values measured during operation time, fault could be found.

4.2 Control Unit

The structure of the control unit mainly consist of mini-computer such as Sb-Rio, Raspberry Pi or Arduino, communication component such as Radio Frekans (RF), Wi-Fi or X-Bee and other electronic equipments suchs as cables, IMU, GPS module and motor controller.

4.3 Electrical Dynamics and Shaft Dynamics

The electrical dynamics are electrical engines that producing a torque QB needed to turn the shaft and rotational shaft speed nB linked to propeller.

The shaft dynamics is generating thrust (T) and location (X) needed for propulsion.

5. Fault Scenarios

The faults of interest that can occur in an autonomous surface vessel propulsion system may be classified in three major categories. Shaft speed faults, Current faults and Location faults.

5.1 FMEA Methodology

In this section, the adopted failure modes and effect analysis (FMEA) methodology is used to improve design. In other words, a FMEA procedure is used to present the causes and the effects of the faults in a hierarchical model of a system.

It is far less expensive to prevent problems early than fix problems after launch. Therefore, FMEA can identify and address safety issues on the system or end users before a potential risk. Then, it can identify can carry out corrective actions assessing the risk associated with the identified failure modes, effects and causes. A FMEA is an engineering analysis that performed finding and correcting weaknesses before the product gets into the hands of the customer.

The first step in any risk assessment is to define the goal of the risk assessment.

Components of the FMEA methodology are:

- a) Severity : Severity assesses how serious the effects would be should the potential risk occur.
- b) Probability of Occurrence : The probability of occurrence evaluates the frequency that potential risks will occur for a given system. The probability score is rated against the probability that the effect occurs as a result of failure mode.
- c) Detectability : Detectability is the probability of the failure being detected before the impact of failure to the system being evaluated is detected. The detectability score is rated against the ability to detect the effect of the failure mode or the ability to detect the failure mode itself.

5.1.1 Risk Score Matrix

The risk score is the product of its three individual component ratings : severity, probability and detectability. This composite risk is called a risk priority number (RPN).

$$RPN = S \times P \times D$$

The RPN provides a relative priority for taking action. The bigger one, the more important to address the corresponding failure being assessed.

5.2 Description of the benchmark

Three kinds of faults have been considered:

Table 1. Risk Analysis of ASV by adopting FMEA methodology

<i>Fault</i>	<i>End Effect</i>	<i>Consequences</i>	<i>Severity Level</i>
$\Delta n > 0$	Decreased boat speed	Maneuvering risk, high energy consumption, operation cancel	Very High
$\Delta n < 0$	Acceleration	Maneuvering risk, high energy consumption, operation cancel, collision risk	Very High
$\Delta X > 0$	Decreased or reversed boat speed	Maneuvering risk, high energy consumption, operation cancel	High
$\Delta X < 0$	Increased boat speed	Maneuvering risk, high energy consumption, operation cancel, collision risk	High
$\Delta l > 0$	Decreased or reversed boat speed	Maneuvering risk, high energy consumption, operation cancel	Very High
$\Delta l < 0$	Increased boat speed	Maneuvering risk, high energy consumption, operation cancel, collision risk	Very High

- A first class faults are regards to shaft speed measurement which is performed by tachometer.

$$\Delta n = n_{ref} - n \text{ (rpm)}$$

If Δn is positive, it means there could be some problems at motor controller, the control system or the thruster. It leads to decrease of boat speed. If problem is at the thrusters there is not so much solution to repair because the mechanical system fault. On the other hand, if problem at the motor controller or the control system some solutions could found such as filtering software or the auxiliary systems against a fault. However, if Δn is negative, it means that there could be some problems at motor controller or control system. It leads to increase of boat speed.

- The second class faults are related the position values which is performed by the GPS.

$$\Delta x = x_{ref} - x \text{ (u,v,w)}$$

If Δx is positive, it means there could be some problems at a control unit, motor controller, the thruster or the GPS. It leads to decrease of boat speed. Although, probability of occurrence of obtaining faults at GPS, if some faults occurs on this part, repairing of part will be impossible

because of autonomously. If Δx is negative, it means there could be some problems at a control unit or motor controller or GPS. It leads to increase of boat speed.

- The third class faults are regards to energy consumption which is performed by a current sensor or amperemeter.

$$\Delta I = I_{\text{ref}} - I \text{ (amps)}$$

Reasons of the energy consumption faults may be very different. These faults could be derived from batteries, current sensors, motor controller, telemetry system or thruster faults. If problem is derived from current sensors or telemetry system, correct values of current couldn't be known. On the other hand, if problem doesn't take it's source from the measuring parts, measurement could be right and some solutions may be found.

6. Fault Detection and Isolation Methodology

The basic assumption used in developing the FDI (Fault Detection and Isolation) scheme, is that the faults can occur independently and just when the reference signals n_{ref} , x_{ref} , and I_{ref} are constants and the system has reached the steady state.

7. Conclusion

As an emerging and active area of research in automatic control, fault-tolerant control has recently attracted more and more attention. A brief technical review and bibliography listing on the historical and new development in active faulttolerant control systems (AFTCS) have been presented in this paper.

In this paper, a simple design of a fault tolerant control system applied to a Autonomous Surface Vehicle's electric propulsion system has been described. After a brief description of the system a fault and risk analysis has been carried out and a set of possible remedial actions has been found. In order to prevent faults on fully autonomous surface vehicles during operation, there is not so much alternative solution. Especially faults derived from electronic equipments such as GPS, sensors and other connection equipments, even action could be changed, generally operation is canceled depending on the severity of fault. In order to faults for mechanical systems and water proofing, several preventive solutions may be found. However, if faults on mechanical systems occur on the operation time, vessel should send emergency signal to land and protect its position. On the other hand, in order to decrease the risk priority number, control system algorithm should be tempered to all fault probabilities. Since there is not casualty on the ASVs, most important risk on the autonomous boats is economical. As a result, control system algorithm of the autonomous vehicle should be tempered to described fault probabilities. To prevent other faults derived from electroic equipments, economical situation should be considered.

Table 2. FMEA Application of ASV

Failure Mode	Effects of Failure	SEV	Causes of Failure	OCC	Process Controls	DET	RPN	Recommended Solution(s)
Low shaft speed	Maneuvering risk, high energy consumption, operation cancel	8	Jammed materials to thruster	4	Reinforced control system and motor controller against probable faults Protection to thruster against jammed materials	3	96	If energy consumption high from definite value, ASV should go back to port.
High shaft speed	Maneuvering risk, high energy consumption, operation cancel, collision risk	7	Control Unit works wrong Motor controller works wrong	4	Reinforced control system and motor controller against probable faults	2	56	If control unit or motor controller continue works wrong, ASV Should go back to port.
Further on estimated location	Maneuvering risk, high energy consumption, operation cancel	5	Wrong data collection, wrong data reading, motor controller works wrong	4	Reinforced control system and motor controller against probable faults	2	40	If control unit or motor controller continue works wrong, ASV Should go back to port.
Behind of estimated location	Maneuvering risk, high energy consumption, operation cancel, collision risk	5	Wrong data collection, wrong data reading, motor controller works wrong, defect on thruster	4	Reinforced control system and motor controller against probable faults	2	40	If control unit or motor controller continue works wrong, ASV Should go back to port.
High energy consumption considering estimated energy	Maneuvering risk, high energy consumption, operation cancel	7	Jammed materials to thruster, external forces have high values	4	Reinforced control system and motor controller against probable faults Protection to thruster against jammed materials	2	56	If energy consumption high from definite value, ASV should go back to port.
Low energy consumption considering estimated energy	Maneuvering risk, operation cancel, collision risk	8	Battery defets	6	Regularly battery voltage control	1	48	ASV should go back immediately at low speeds

References

- [1] Akyıldız H, Üstün Ö. (2015). Fault-tolerant control of the electric propulsion system for a boat, İstanbul.
- [2] Dailly, C. (1990). Fault monitoring and diagnosis. Computing and Control Engineering Journal, 1(2), 57–62.
- [3] Frank, M. P. & Blanke, M., Fault diagnosis and fault tolerant control. CONTROL SYSTEMS, ROBOTICS AND AUTOMATION – Vol. XVI
- [4] Liu, Q., & Zhu, D., Fault tolerant control of unmanned underwater vehicles with continuous faults : Simulations and experiments. International Journal of Advanced Robotic Systems, Vol. 6, No.4 (2009)