FAULT-TOLERANT CONTROL FOR A REMOTELY OPERATED VEHICLE (ROV) PROPULSION SYSTEM

MOHD AKMAL BIN MOHD YUSOFF

UNIVERSITI SAINS MALAYSIA

2013

FAULT-TOLERANT CONTROL FOR A REMOTELY OPERATED VEHICLE (ROV) PROPULSION SYSTEM

By

MOHD AKMAL BIN MOHD YUSOFF

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science

July 2013

ACKNOWLEDGEMENT

In the name of Allah S.W.T, the most Beneficent, the most Merciful and peace upon Muhammad S.A.W, the last prophet.

All praise to Allah (S.W.T) who awards me with a precious life and all praise to Him for giving me courage and patience to complete this thesis research.

My deepest appreciation and gratitude goes to my supervisor Assoc. Prof Dr Mohd Rizal Arshad for his valuable advice and patience in guiding me throughout completing this thesis work. My special appreciation goes to my family especially my parents Mohd Yusoff Awang Lah and Zaharah Hassan for their encouragement and prayer.

I would like to extend my gratitude towards my colleagues in Underwater Robotics Research Group (URRG) laboratory especially to Muzammer Zakaria for his consultation in C++ programming, Shahril Rizal Hassan for his companion and assistant during the field test and Alireza Nazeem for helping me to repair and trouble shoot the electronics module.

The last but not least, I would like thank all friends in URRG, staffs in School of Electrical & Electrical Engineering and to all my postgraduates friends for their support and encouragement. This research work is supported by Prototype Research Grant Scheme (PRGS: 6740003).

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LIST OF ABBREVIATIONS

ADC - Analog to Digital converter

ANOVA - Analysis of variance

AUV - Autonomous Underwater Vehicle

BDCM - Brushed direct current motor

BRF - Body-fixed Reference Frame

CG - Centre of gravity

CRD - Control re-design

CRC - Controller reconfiguration

DOF - Degree of freedom

DP - Dynamic positioning

ECEF - Earth-Centered Earth-fixed Frame

ECIF - Earth-Centered Inertial Frame

ECRF - Earth-Centered Reference Frame

FA - Fault accommodation

FDD - Fault detection and diagnosis

FTCS - Fault-tolerant control system

GRF - Geographical Reference Frame

NED - North-East Down

ROV - Remotely Operated Vehicle

SNAME - Society of Naval Architects and Marine Engineers

TAC - Thrust allocation control

TMU	-	Thruster monitoring unit
T-S	-	Takagi-Sugeno
USM	-	Universiti Sains Malaysia
URRG	-	Underwater Robotics Research Group
USBL	-	Ultra Short Base Line
UUV	-	Unmanned Underwater Vehicle

LIST OF SYMBOLS

α^i - Azimuth angle/ thruster angle of attack for i^{th} thruster

$(\tau\beta)_{ij}$ - Effect of interaction between factor A and B

$\dot{\boldsymbol{n}}_{\mathbf{1}}$ - Vector of translational velocity in b-frame expressed in inertial frame

$\dot{\boldsymbol{n}}_{\mathbf{2}}$ - Vector of rotational velocity in b-frame expressed in inertial frame

$\mathcal{B}_0$ - System behavior of faultless system

$\mathcal{B}_f$ - System behavior subject to faults

$F^i_{H,V}$ - Thrust exerts by i^{th} horizontal or vertical thruster

F^i_{Hm} - Maximum thrust exerts by i^{th} horizontal thruster

F^i_{Vm} - Maximum thrust exerts by i^{th} vertical thruster

F_x - Thrust force component in x-axis

F_y - Thrust force component in y-axis

H_1 - Alternate hypothesis

H_o - Null hypothesis

J_m - Rotor moment of inertia and

K_Q - Torque coefficient

K_T - Thrust coefficient

K_m - Motor torque constant

L_a - Armature (motor) inductance,

R_a - Armature (motor) resistance

T_{C_H} - Horizontal thrusters configuration matrix

T_{C_K} - Thrusters configuration matrix associated with roll motion

T_{C_M} - Thrusters configuration matrix associated with pitch motion

T_{C_N} - Thrusters configuration matrix associated with sway motion

T_{C_X} - Thrusters configuration matrix associated with surge motion

T_{C_Y} - Thrusters configuration matrix associated with yaw motion

T_{C_Z} - Thrusters configuration matrix associated with heave motion

T_H^i - i^{th} horizontal thruster *(i=1,2,3,4)*

T_V^i - i^{th} vertical thruster *(i=1,2)*

$V_{a_{act}}$ - Actual (observed) armature voltage

$V_{a_{ref}}$ - Reference armature voltage

V_a - Armature (motor) voltage,

$W_{H,V}^i$ - Weighting matrix for i^{th} horizontal/vertical thruster

e_{V_a} - Armature voltage residual

e_{i_a} - Armature current load residual

e_{res} - Process parameter residual

$i_{a_{act}}$ - Actual (observed) armature current load

$i_{a_{ref}}$ - Reference armature current load

i_a - Armature (motor) current (load)

$\dot{n}$ - Propeller/shaft (rotational) acceleration

$\hat{p}$ - Roll angular velocity

p_{act} - Actual process parameter

p_{ref} - Reference process parameter

$\hat{q}$ - Pitch angular velocity

$\hat{r}$ - Yaw angular velocity

r_H^i - Distance between i^{th} horizontal thruster relative to centre of gravity (CG)

r_V^i - Distance between i^{th}vertical thruster relative to centre of gravity (CG)

$s_{H,V}^i$ - Updated new control input for i^{th} horizontal/vertical thruster

$\hat{u}$ - Surge linear velocity

$u_{H,V}^i$ - Thruster control input for i^{th} horizontal/vertical thruster

u_{Hm}^i - Horizontal maximum thruster control input

u_{Vm}^i - Vertical maximum thruster control input

u_a - Ambient water velocity

$\hat{v}$ - Sway linear velocity

$\hat{w}$ - Heave linear velocity

y'_{act} - Actual output for new controller

y'_{des} - Desired output for new controller

y_A - Output for faultless condition

y_B - Output for faulty condition

y_{act} - Actual output

y_{des} - Desired output

y_{ijk} - Observation of means effect model

$\boldsymbol{B_H}$ - Horizontal thruster control matrix

$\boldsymbol{B_V}$ - Vertical thruster control matrix

$\boldsymbol{g_o}$ - Vector used for pre-trimming (ballast control)

α_o - Initial azimuth angle

β_j - Effect of j^{th} level of column factor B

τ_K - Roll moment

τ_M - Pitch moment

τ_N - Yaw moment

τ_{Nm} - Maximum yaw moment

τ_X - Surge force

τ_{Xm} - Maximum surge force

τ_Y - Sway force

τ_{Ym} - Maximum sway force

τ_Z - Heave force

τ_{Zm} - Maximum heave force

τ_i - Effect of i^{th} level of row factor A

ϵ_{ijk} - Random error component

$\boldsymbol{\tau_H}$ - Vector of forces and moments acting on horizontal plane

$\boldsymbol{\tau_V}$ - Vector of forces and moments acting on vertical plane

$\emptyset$ - Euler angle about x-axis in b-frame

d - Disturbance

s - Spin direction coefficient

D - Propeller diameter

K - Motor control matrix

Q - Load (torque) from propeller

F - Thrust force

f - Faults

n - Propeller/shaft (rotational) speed

u - General input / input for nominal controller

u' - Input for new controller

x - Linear position of x-axis in b-frame

y - General output

y - Linear position of y-axis in b-frame

z - Linear position of z-axis in b-frame

$\boldsymbol{C}$ - Coriolis centripetal matrix (including added mass)

$\boldsymbol{D}(\boldsymbol{v})$ - Damping matrix (linear and nonlinear)

$\boldsymbol{M}$ - System inertia matrix (including added mass)

$\boldsymbol{e}$ - Thrust orientation vector

$\boldsymbol{g}(\boldsymbol{\eta})$ - Vector of gravitational/buoyancy forces and moments

$\boldsymbol{v}$ - Vector of translational and rotational velocities in b-frame

$\boldsymbol{w}$ - Vector of environment disturbances (wind, waves and current)

$\mathcal{U}$ - Input set

$\mathcal{Y}$ - Output set

α - Azimuth angle

θ - Euler angle about y-axis in b-frame

μ - Overall means effect

ρ - Density of water

φ - Euler angle about z-axis in b-frame

ω - Wake fraction number

$\boldsymbol{\eta}$ - Vector of position and orientation relative to e-frame

$\boldsymbol{\tau}$ - Vector of forces and moments acting on the vehicle

KAWALAN BOLEH TERIMA KEGAGALAN BAGI SISTEM TUJAHAN KENDERAAN KENDALIAN JAUH (ROV)

ABSTRAK

Sistem tujahan kenderaan kendalian jauh (ROV) selalu terdedah kepada keadaan operasi dan persekitaran dalam air yang teruk. Kegagalan dan keadaan kerja yang tidak diingini menyebabkan kemerosotan prestasi seterusnya memerlukan proses pembaikan. Pemberhentian operasi mengakibatkan kos operasi meningkat. Oleh itu, sistem kawalan boleh terima kegagalan diperkenalkan untuk menangani masalah ini. Kaedah ini adalah untuk memastikan kebolehpercayaan, kemampanan dan keselamatan sesuatu sistem dinamik. Tesis ini mempersembahkan Kawalan Boleh Terima Kegagalan (FTCS) yang direkabentuk khusus untuk sistem tujahan ROV dengan penujah motor berus arus terus. Terdapat dua komponen dalam FTCS iaitu pengesanan dan diagnosis kegagalan (FDD) dan rekabentuk semula pengawal (CRD). FDD dilakukan dengan mengawasi dua parameter proses bagi penujah iaitu voltan gegelung dan beban arus dan membuat perbandingan antara parameter proses sebenar dan rujukan. Melalui kaedah rekabentuk statistik eksperimen, satu eksperimen luar talian telah dijalankan untuk menyelakukan keadaan kegagalan seperti saluran penujah tersumbat dan kegagalan kuasa. Kaedah analisa varians (ANOVA) seperti rekabentuk faktoran dua faktor dan peraturan Tukey's Kramer digunakan untuk menganalisa kegagalan tersebut dan menyediakan model rujukan untuk melaksanakan rekabentuk semula pengawal iaitu pelarasan kegagalan. Kaedah samar Takagi-Sugeno digunakan untuk merekabentuk pelarasan kegagalan dan pengawal gerakan ROV. Keadah FTCS yang dicadangkan telah diuji dalam kolam air tawar dan didapati pantas dalam menangani kegagalan penujah. Hanya 500 ms

diperlukan untuk suatu kegagalan pada penujah dikesan, diasingkan dan arahan kawalan penujah baru dimulakan. Kaedah FTCS ini mengakibatkan darjah kebebasan ROV dikurangkan kepada darjah minima namun ROV masih boleh meneruskan operasi.

FAULT-TOLERANT CONTROL FOR A REMOTELY OPERATED VEHICLE (ROV) PROPULSION SYSTEM

ABSTRACT

Remotely Operated Vehicle (ROV) propulsions system is frequently exposed to harsh operating and underwater environments. Faults and undesired working conditions contribute to performance degradation thus repair actions are required. Stop of operation causes operational cost to increase. Therefore, a Fault-Tolerant Control System (FTCS) is introduced to deal with this situation. This method aims to ensure reliability, sustainability and safety of a dynamical system. This thesis presents a fault-tolerant control specifically designed for ROV electric propulsion system with brushed DC motor thrusters. There are two components in FTCS which are the Fault Detection and Diagnosis (FDD) and Controller Re-Design (CRD). The FDD is done by monitoring two thruster parameters i.e. armature voltage and current load and compare between actual and reference process parameters. Via statistical design of experiment techniques, an offline experiment is performed to simulate possible event of faults. Analysis of variance (ANOVA) methods such as two-factor factorial design and Tukey's Kramer rule are used to analyze the faults and provides the reference model to implement the controller re-design i.e. fault accommodation. A Takagi-Sugeno (T-S) fuzzy system is used to design the fault accommodation and ROV motion controller. The FTCS method has been tested in fresh water pool and proved to be fast in handling the thruster faults. It takes about 500 ms for a fault in a single thruster to be detected, isolated and new thruster command to be initiated. The FTCS method causes the ROV degree of freedom (DOF) to be reduced to a minimum but the ROV still able to continue the operation.

CHAPTER 1

INTRODUCTION

1.0 Overview

This introductory chapter presents the research motivation, problem statement and thesis objectives. The scope and limitation of research and research contribution are included. The thesis organization is briefly presented at the end of the chapter.

1.1 Research motivation

Unmanned underwater vehicles (UUV) such as Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV) have been widely used in many applications such as in commercial e.g. ocean mining, oil industry and other ocean engineering work services, in military e.g. mine sweeping and port safety, in academic institution e.g. scientific exploration and other oceanography study, and many more (Yuh, 2000). The key technology advances in the relevant area of UUV such as battery technology, alternative energy source like fuel cells, underwater communication, propulsion system and sensor fusion that enable the UUV to be used to an extent that can be comparable with manned underwater vehicle (Budiyono, 2009).

The UUV system is physically composed of various equipments, payloads and subsystems that were not designed to necessarily work together (Podder *et al.*, 2004). The hardware components of UUV system can be affected by product liability issues such as limited life cycle, maintainability, wearing, saturation, corrosion, humidity, temperature, high pressure of undersea environment and etc. The uncertainties during performing underwater mission are always inevitable and unpredictable thus leaving the UUV system vulnerable to various external and internal faults. For this reason, the status of several critical components such as actuators, sensors, battery and etc need to be monitored continuously. However, it is impossible to monitor the components without proper feedback signal in order to alert to the operator about the status of the components during the mission. In most scenarios, the operator can only assumes and hopes that the initial setting and configuration are working according to plan. Furthermore, with increasing mission hours for underwater mission, the chances of components failure are getting higher.

In most UUVs, electro-mechanical actuators such as electric motor and hydraulic motor are mainly used as the propulsion system. Electric thruster (see Figure 1.1) can be found in many small and medium class UUVs since it is convenient to control. Compare to mechanical actuated thruster such as hydraulic thruster, electric thruster is more reliable, more efficient, smaller in size and easy to maintain and repair (Abu Sharkh *et al.*, 1995). It also produces zero waster and contaminants compare to hydraulic type. However, this type of actuator consumes the most electrical energy compare to other components in order to convert sufficient amount of electrical energy into desired output such as thrust and torque. The energy conversion produces heat and vibration which results in wear and tear in the components especially the mechanical parts.

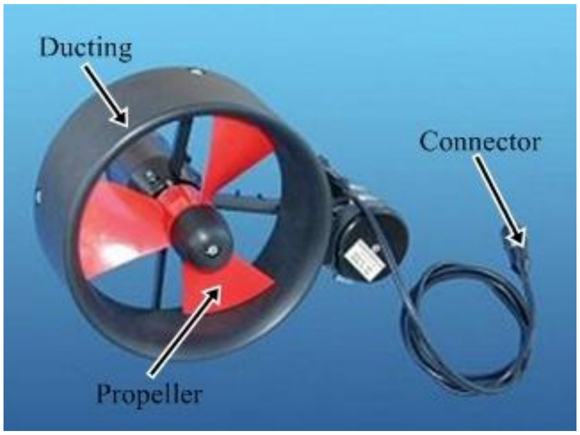

Figure 1.1: Example of electric thruster (SAAB Seaeye, 2012)

A failure in any part of the propulsion system can cause irregularity in the electrical power consumption. This irregularity can be treated as harmless or harmful to the system depending on the severity level of the faults. As example, a UUV which uses two rear thrusters can deviate from its initial course if one thruster produces less thrust than the other, or an ROV becomes under actuated because one or more of its thruster failed. This thesis work is also motivated by experiences in dealing with unknown thruster issues during development and testing of USM-URRG ROV (see Figure 1.2).

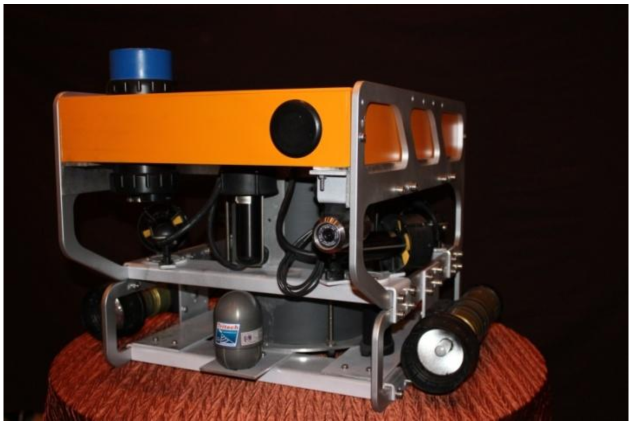

Figure 1.2: URRG-USM ROV

To overcome this issue, the conventional control system need be associated with an additional subsystem that can detect and diagnose the occurrence of faults and automatically re-design the nominal controller so that the UUV can maintain its operation and continue the assigned task. This method is also known as redundant control system. A conventional dynamical system treats the faults by implementing physical redundancy. This means that important components e.g. actuator is replicated and implemented more than one and connecting in parallel. During an event of fault, the fault component can be shut down and replaced by a standby component. This method however, causes additional cost but is proven very efficient. Such method usually found in a very critical system such as in nuclear reactor and air craft systems. As an alternative to physical redundancy, analytical redundancy is introduced. Through this method, an explicit mathematical model is used to analyze the existing fault hence try to find a solution to overcome such fault conditions. Such addition of physical or analytical redundancy into a dynamical system makes the system fault-tolerant (Blanke *et al.*, 2004). For this reason, analytical redundancy is used as the basic guideline in development of fault tolerant control system for ROV propulsion system.

1.2 Problem statement

In harsh underwater environment, unmanned underwater vehicles are liable to various faults and undesired working conditions. Thrusters can be regarded as one of the most common and most importance sources of faults (Omerdic and Roberts, 2004). The major problems encountered by UUV such as ROV is whether to continue or abort the mission if one or more of the thrusters failed. Unlike AUV, an ROV usually has more thrusters to provide sufficient thrust to generate various motions in localized area. It is common to see an ROV is equipped with multiple thrusters which is larger than its controllable DOF, making the vehicle over actuated. As example, in ROV with X-shaped thruster configuration like the Sea Eye Falcon ROV (see Figure 1.3), the surge motion can be produced by combination of maximum thrust vector of its four horizontal thrusters. However, the surge motion also can be produced by three, two or even one thruster providing that the deviation from its initial course is still acceptable. Therefore, it is possible to re-design the controller in an optimal manner so that maneuverability of the ROV can still be performed by accepting the performance degradation.

Figure 1.3: Example of horizontal thrusters configuration on Seaeye Falcon ROV (SAAB Seaeye, 2012)

To allow controller re-design in case of thruster faults, the operational thrusters need to be continuously monitored to detect any abnormal process parameters. The affected thruster can be allowed to operate if the faults are conciliatory or will be completed shut down if the faults are no longer tolerable. To adapt to faulty condition, a fault tolerant control system need to be developed tailored to the ROV that is under observation so that any event of fault can be handled properly. The control system must have the ability to adapt to the faults or reconfigure the controller. This technique is known as Fault-tolerant Control System (FTCS). The proposed method has been performed and tested on electric based propulsion system of USM-URRG ROV.

1.3 Objectives

The objectives of this thesis work are determined as follows.

1. To develop a method to monitor the process parameters of electric thruster and to detect and isolate the faulty thrusters.
2. To study the relationship between faulty and faultless thruster process parameters and to provide the controller with reference or trained data.
3. To develop a control strategy to enable fault accommodation towards thruster faults and to demonstrate the application of fault-tolerant control in manual and autopilot maneuvering.

1.4 Scope and limitation of research

This research works focus on the practical implementation of fault-tolerant control system (FTCS) in ROV that used multiple BDCM thrusters as propulsion system. Therefore, FTCS for other type of ROV actuators or subsystems e.g. sensors are not considered in this research. The proposed FTCS method has not been fully tested in real faulty situation. Therefore, the proposed method in this thesis is mutually based on approximation and simulated event of faults. The architecture of the proposed FTCS is developed with blocks of several modules. Therefore delay between modules is unavoidable. The delay also caused by machine delay. A delay can be found during fault detection and isolation. As example, the delay may come from the Thruster Monitoring Unit (TMU), where it needs to monitor all thrusters by scanning each thruster one unit at a time. A delay also exists during the re-design process in order the controller to react to the faults. Due to limitation in testing facility, the experiment to study the hydrodynamics of the ROV and thrusters has not been conducted. Instead, the models are based on several assumptions and approximations as suggested by the literatures.

To perform a full scale performance evaluation of the FTCS is not practical due to limitation of hardware and testing facilities. All experiments are conducted either in a water tank or swimming pool. The ROV is not equipped with high end localization modules such as Ultra Short Base Line (USBL) system. Therefore the relation between body-fixed reference frame (b-frame) and earth-fixed reference frame (e-frame) is very limited. The ROV only has the depth sensor, echo sounder and gyro-compass in order to measure the relative distance between the b-frame and e-frame. The ROV has been tested in a 9 x 15 meter square swimming pool with maximum depth of 2.5 meter. Thus the ROV is yet to be tested at greater depth. The experiment is conducted based on assumption that external disturbances such as underwater current and waves is minimum. The auto-pilot stability is only achievable for a limited period of time due to ROV buoyancy configuration. The ROV is configured with passive buoyancy where the buoyancy adjustment is made by manually adding and removing mass based on try and error. This method also used to determine the stability of the vehicle. In this work, the ROV is configured slightly positive buoyant. Therefore, during the auto-pilot test i.e. auto-depth, the buoyancy force will gradually push the ROV upward slowly. The umbilical also affects the motions because the drag effect.

1.5 Research contribution

The research contribution of this thesis aims to implement a specific fault-tolerant control technique into propulsion system of an ROV. There are three major contributions in this thesis. First is the development of Thruster Monitoring Unit (TMU). This sensor module can monitor multiple thruster status up to six units. The TMU takes about 300ms to scan a single thruster and provides information on thruster status i.e. armature voltage and current load. Theses parameters are the essentials information in order to perform the Fault Detection and Diagnosis (FDD) of any faulty thrusters. Next contribution is the usage of statistical Design of Experiment (DOE) in analyzing the thruster’s parameters relationship both in faultless and faulty conditions. The DOE method allows the experimental results to be presented conclusively. This method provides the reference data for the implementation of the fault accommodation controller. Next contribution is the practical implementation of Takagi-Sugeno (T-S) fuzzy system in the development of the fault controller i.e. fault accommodation and motion controller i.e. auto-pilot control of the ROV. T-S fuzzy system is known for fast handling; therefore it allows the fault controller to switch from faulty thrusters to healthy thrusters and achieve the closed-loop motion control in auto-pilot with less computational times

1.6 Thesis Organization

This thesis dissertation presentation is organized as the follows:

- **Chapter One** presents the introduction of the proposed fault tolerant control methods for a remotely operated vehicle propulsion system. This chapter contains discussion on the research motivation and the problem statement. The research objectives, approach, scope and limitations are also discussed.
- **Chapter Two** presents the literature review of the topics that are related to the general structure fault tolerant control methods and its implementation in unmanned underwater vehicle (UUV). Some literatures on UUV subsystem, statistical design of experiment and Takagi-Sugeno (T-S) fuzzy system are also being reviewed.
- **Chapter Three** presents the theoretical background of fault-tolerant control and ROV. In this chapter, the theory and basic principles of fault-tolerant control system and the theory of ROV such as modeling and mathematical formulations are presented.
- **Chapter Four** presents the methodology and implementation of the proposed fault-tolerant control for a remotely operated vehicle propulsion system including the design and experimental setup.
- **Chapter Five** presents the overall result, analysis and discussion of the proposed fault tolerant control of ROV propulsion system.
- **Chapter Six** concludes the thesis presentation with recommendation for future works.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents the literature review regarding the historical background, general framework of fault-tolerant control and its applications. Some preliminaries about the unmanned underwater vehicle are briefly discussed. A comparative literature on early works and recent researches of different techniques and implementation of fault-tolerant control on the unmanned underwater vehicle are reviewed. The literature for fuzzy logic control and its approach in fault-tolerant control is reviewed. The statistical design of experiment and its basic structures is also reviewed.

2.1 Preliminaries on Unmanned Underwater Vehicle

Unmanned Underwater Vehicle or UUV technology has been a very popular underwater robotics platform among marine industries, military and academic communities. According to Yuh (2000), there are many potential applications of underwater robotics such as seafloor mapping, geological sampling, underwater inspection, underwater construction, underwater entertainment, fisheries and etc. There are two most common types of UUVs which are the tethered and autonomous UUV as shown in Figure 2.1. The tethered UUV has an umbilical cable connecting the vehicle with surface control station.

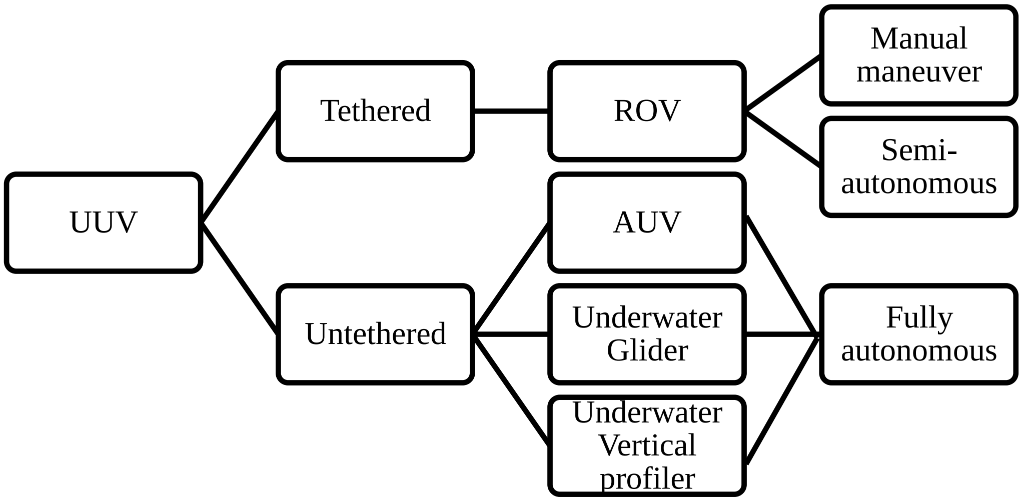

Figure 2.1: Different types of unmanned underwater vehicles

The umbilical usually carries the information signals, commands signal and electrical power supply. The operator or pilot manually supervises UUV operation from the surface. This type of UUV is commonly known as the Remotely Operated Vehicle (ROV). The ROV has a confined range of operation due to physical limitation of umbilical length. Thus, it is usually being localized at the onset within the range of work area. Some ROVs are able to perform semi-autonomous or auto-pilot motions such as auto-depth, auto-attitude and auto-heading when they are required to perform station-keeping at a localized area. Example and description of different types of ROV is shown in Figure 2.2 and Table 2.1.

Figure 2.2: Example of different types ROV (a) micro ROV (GNOM, 2012), (b) mini ROV (Seabotix, 2012), (c) general ROV (SAAB Seaeye, 2012) and (d) work class ROV (Nautic Expo, 2012)

Table 2.1: Description of different types of ROV (Marine Technology Society, 2012)

Types	**Description**
Micro	• Weight less than 3kg. • Alternative to diver for shallow water application • Observation type/eyeball class (with camera)
Mini	• Weight less than 15kg. • Alternative to diver for shallow water application • Observation type/ eyeball class (with camera)
General	• Typical propulsion less than 5HP • Carry small manipulator (1 DOF) and sonar unit • Maximum working depth 1000 meter
Light/heavy work class	• Typical propulsion up to 50-220HP • Carry several manipulators, complete sonar and other measurement equipments • Maximum working depth 2000-3500 meter
Trenching/Burial class	• Extended version of heavy work class type • Typical propulsion up to 500 HP • Perform cable laying and other underwater construction on seafloor • Maximum working depth up to 6000 meter

The other type is the non-tethered, autonomous UUV. Recently there are many different platforms with different names that possess the autonomous capability. The conventional autonomous UUV is known as the Autonomous Underwater Vehicle (AUV). The AUV does not attach to umbilical; therefore it is able to move freely with minimum supervision from the operator. The operator can track the AUV and upload the command script acoustically when the AUV operates underwater or by using conventional radio frequency when the AUV resurfaces. The AUV has its on-board power supply and pre-computed or adaptive controller that allows the vehicle to move autonomously. High capacity power supply e.g. battery allows the AUV to be used for certain types of mission where the use of ROV seems impractical such as long-range mission i.e. oceanographic data collection (Budiyono, 2009).

There are also other types of autonomous UUV such as underwater glider and autonomous vertical profiler (see Figure 2.3). An underwater glider is a new generation of autonomous UUV. This type of UUV is known for using less energy due to its capability to glide in saw-tooth profile and maneuver without using external propulsion. It uses small changes in buoyancy and centre of gravity to produce the surge and pitch motion and allows the gravity and buoyancy force to take over its maneuver. Due to its large cost saving-potential, underwater glider is sustainable for a long period of time for collection of real-time ocean measurements and sampling (Bachmayer *et al*., 2004).

Meanwhile vertical profiler is an autonomous UUV designed for underwater mission through a water column. It only has vertical motion and cannot be maneuvered in horizontal motion. Like underwater glider, vertical profiler makes use of buoyancy changes and gravity to produce the vertical motion. Therefore it uses less energy and able to perform long hour of operation. Vertical profiler usually carries sensor modules such as conductivity-temperature-depth (CTD), dissolve oxygen (DO), turbidity, backscatter and etc to allow repetitive measurements and samplings over a period of time (Afzulpurkar *et al.,* 2012). Different examples of autonomous UUVs are shown in Figure 2.3

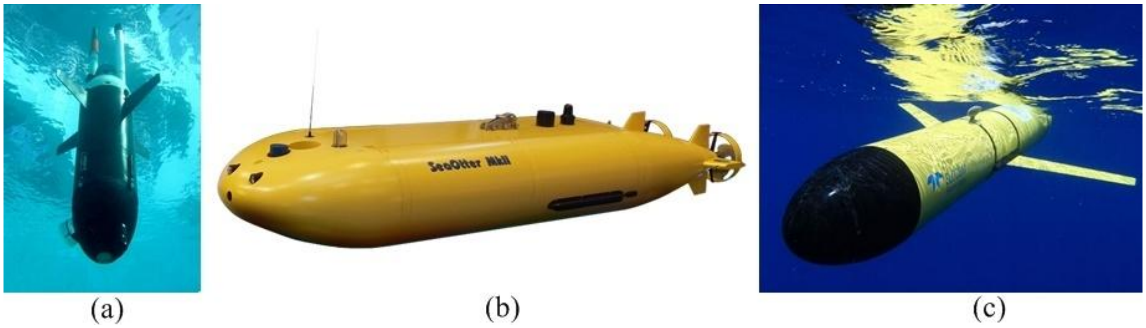

Figure 2.3: Example of different type autonomous UUV (a) NIO autonomous vertical profiler (NIO, 2012), (b) Sea Otter AUV (AUVAC, 2012) and (c) Slocum Coastal Electric Glider (WHOI, 2012)

2.2 Unmanned underwater vehicle subsystems

Both tethered and autonomous UUV usually have similar subsystems and standard components. Different UUV may be equipped with different payload to support the underwater mission. Yuh (2000) has highlighted key subsystems of an unmanned underwater robotics and its recent development (see Figure 2.4). To understand the dynamics of UUV, it is important to realize that the dynamics, including the hydrodynamics parameter uncertainties are highly nonlinear, coupled and time-varying. The dynamics effect of the payloads i.e. sensors, manipulator and etc, and thruster dynamics also need to be considered. Control system is another challenging area in UUV research due to the facts that it is difficult to control a highly nonlinear dynamical system with hydrodynamics uncertainties. Many works on various advance UUV control system has been proposed such as sliding control, nonlinear control, adaptive control, fuzzy control, neural network control and many more. The literature also presented coordinated motion control, where the subject of interest is to study the coupled effect between the manipulator and the vehicle control. A remark on fault tolerant control has been highlighted as an important aspect in UUV control system. By implementing the fault tolerant control, for tolerable failures, the UUV should be able to adjust for the failure and complete the assigned task. Other key subsystems in UUV are the navigation and sensors, communication, power system, pressure hull and mechanical manipulator.

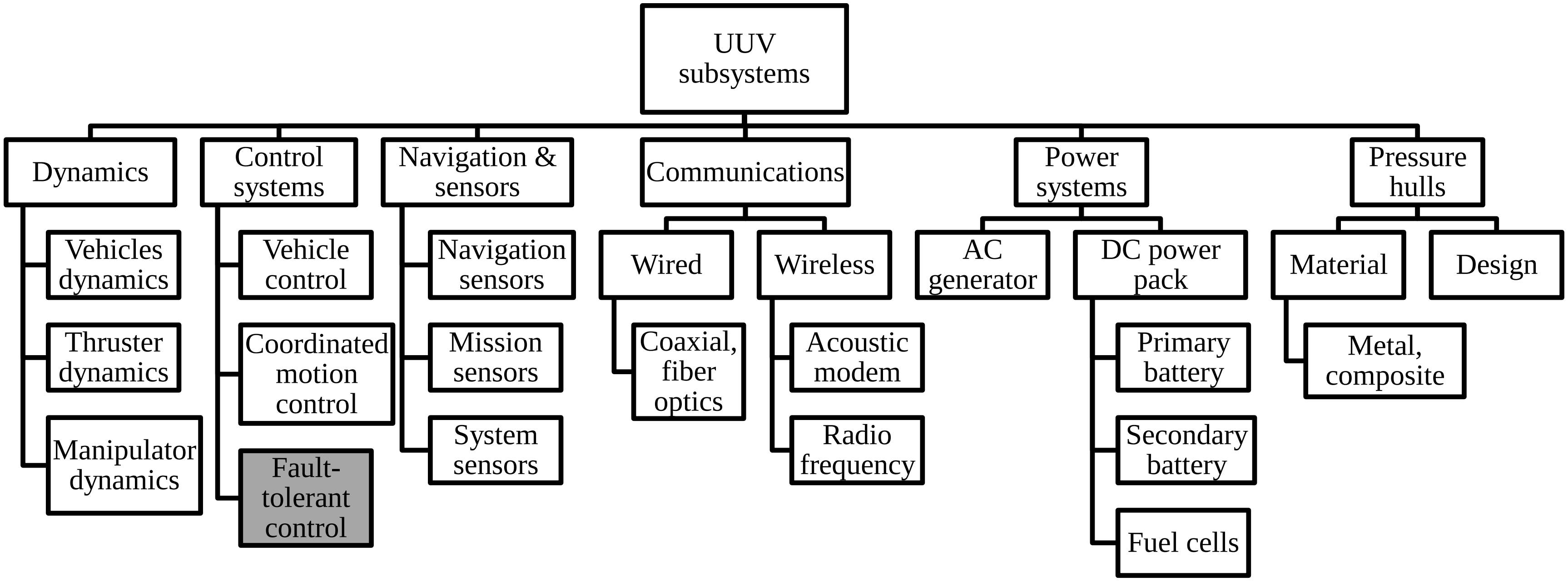

Figure 2.4: Key subsystems of unmanned underwater vehicle

2.3 Fault-tolerant control: Background and methods

The following literatures discussed the historical background of fault-tolerant control and its general concept and methods.

2.3.1 Historical background

In modern days, control system has been the pivotal factor in determining the success rate, performance and safety of a technical system or process. To cope with the increased demand in process output and system performance, the process itself needs to be enhanced in term of performance, reliability and safety. As result, the process system is becoming more sophisticated and requires a sturdy control system. This scenario has encouraged many efforts in developing new method and approach in the control system. One unique approach is to introduce fault tolerance components in the control system to tolerate components failures while maintaining desirable stability and acceptable output performance (Zhang and Jiang, 2008).

Historically, the increased amount of researches on fault-tolerant control was motivated by air flight control designs (Steinberg, 2005). The first approach of fault tolerant control system in the flight control is to provide better indication of fault event and further provide self repairing in order to assist the pilot and ensure safe landing of the aircraft. Nowadays, automatic fault accommodation is an essential system inside both commercial and military aircrafts. Aside from being applied extensively in the flight control system, FTCS had continuously drawn increase amount of attention in wider range of applications; from industries to the academic communities.

2.3.2 General framework of fault-tolerant control system

Conventional controller usually designed for faultless plant or ideal plant. Hence, the closed loop meets given performance specification and satisfies its function. However, in the event of fault, the result may become unsatisfactory. An ideal fault-tolerant control system (FTCS) has the ability to identify faults and tolerate components failures by accommodating them automatically while at the same time, the process stability can be maintained by accepting some degree of performance degradations due to event of failures (Blanke *et al*., 2006). There are several components that reassemble an FTCS i.e. fault detection, fault diagnosis, fault identification, fault isolation and controller reconfiguration.

It is appeared that usage of terms maybe used interchangeably in various FTCS literatures, therefore several authors have suggested commonly accepted terms in the field of supervision, fault detection and diagnosis. Based on a report by Isermann and Balle (1997), these terms have been jointly discussed by IFAC SAFEPROCESS (Fault detection, supervision and safety for technical processes) technical committee. Nevertheless, most of FTCS researches agreed on two major components, which are the fault detection and diagnosis (FDD) and controller re-design (CRD). The general overview of the fault-tolerant control concept is shown in Figure 2.5.

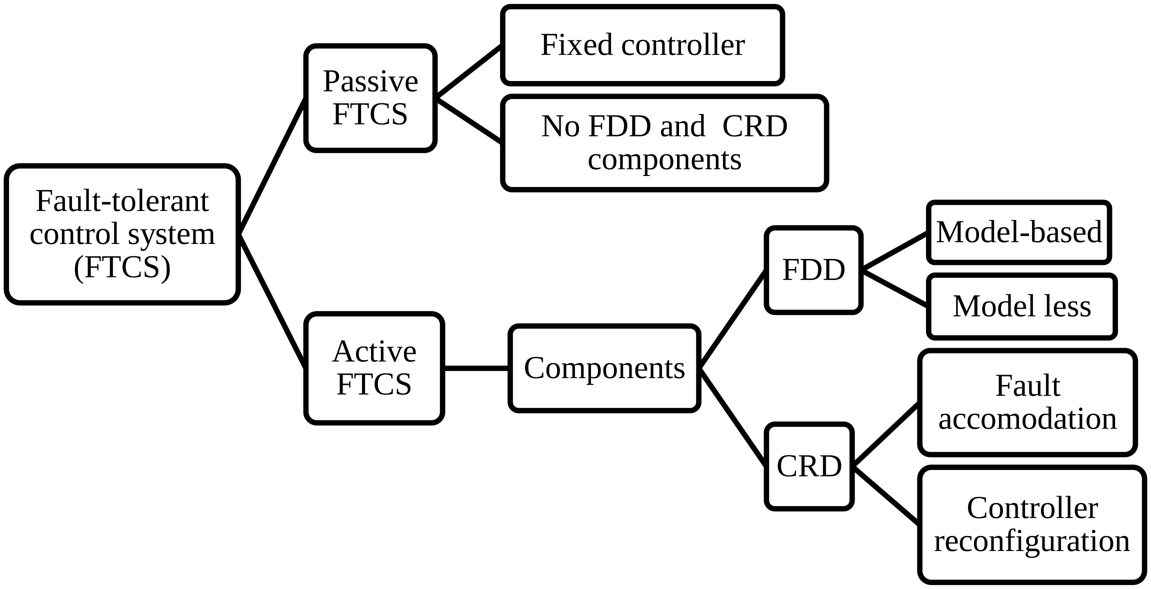

Figure 2.5: General overview of fault-tolerant control system

Figure 2.6 shows the general architecture of fault-tolerant control in a closed loop system. A complete fault-tolerant control system is defined as a closed loop control system which can tolerate component malfunctions while maintaining desirable performance and stability properties (Zhang and Jiang, 2008). The addition of fault tolerant components can be decomposed as in the supervision level while the nominal controller can be decomposed as is in the execution level.

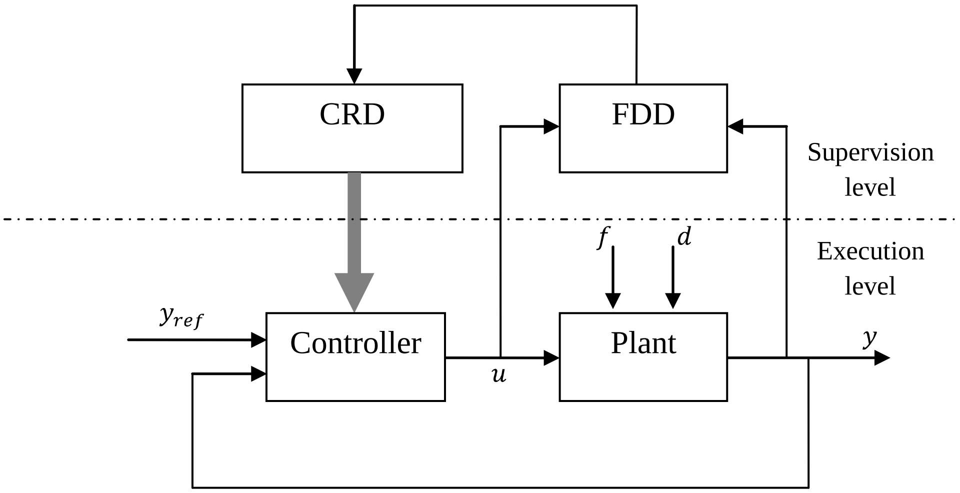

Figure 2.6: General architecture of fault tolerant control of closed loop system (Blanke *et al*., 2006)

2.3.3 Passive and active fault-tolerant control system

According to Zhang and Jiang (2008), there are two categories in fault tolerant control systems; the passive fault tolerant control system (PFTCS) and active fault tolerant control system (AFTCS). By definition, the PFTCS can be regarded as the classical approach in fault tolerant control system. In PFTCS, the controllers are designed tailored to a class of presumed faults. These types of controllers are usually fixed but designed to be robust against the prefixed information. Nonetheless, due to fact that the controllers are fixed, neither FDD nor RCD is required (Eterno *et al.*, 1985). Contradictory to passive FTCS, active FTCS by its name, reacts actively to components failures by sending reconfiguration command to current controller to compensate performance degradation causes by emergence of fault.

The aim of reconfigurable control is to maintain stability and acceptable performance without unnecessary shut off the whole process or system operation if the faults can be tolerated. The reconfigurable controller receives a live signal from FDD. Therefore an FDD must be functional in real-time to provide most recent and up-to-date information regarding the exact status of the system or process. FDD update time, sensitivity and robustness are among key issues in AFTCS. Not to mention that when a controller receives a reconfiguration command, it needs time to re-adjust and replace the initial control with a new control or make a control adaptation that follows the prescription ordered by FDD (Zhang and Jiang, 2008).

2.3.4 Analytical and physical redundancy

Redundancy can be represented as analytical and physical types as shown in Figure 2.7. Analytical redundancy is another way to represent the concept of active fault-tolerant control. Here, an explicit mathematical model is used to perform the two steps of fault-tolerant control. The existing fault is diagnosed and evaluated by using the information that is provided by the model as the reference or trained data and in the online measurement signals. Next, the model is adapted or reconfigured to the faulty situation to allow the closed-loop system to achieve its desirable output. The opposite of analytical redundancy is the hardware or physical redundancy. This type of redundancy system is a conventional and more direct forward method which is done by replicating and implementing important components more than one in parallel configuration (Blanke *et al*., 2006)

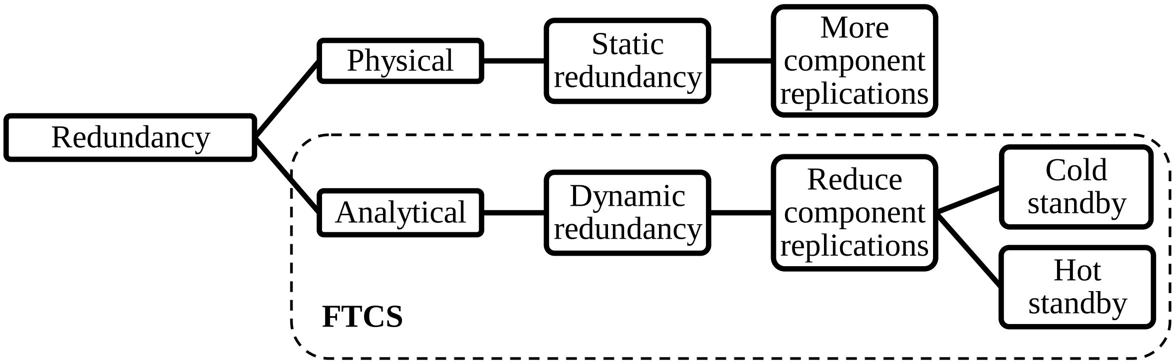

Figure 2.7: Physical and analytical redundancy

According to Muencfhof *et al.* (2009), the physical redundancy is also known as static redundancies (see Figure 2.8) while the analytical redundancy is known as dynamics redundancy. The number of parallel components can be reduced if the dynamic redundancy concept is used.

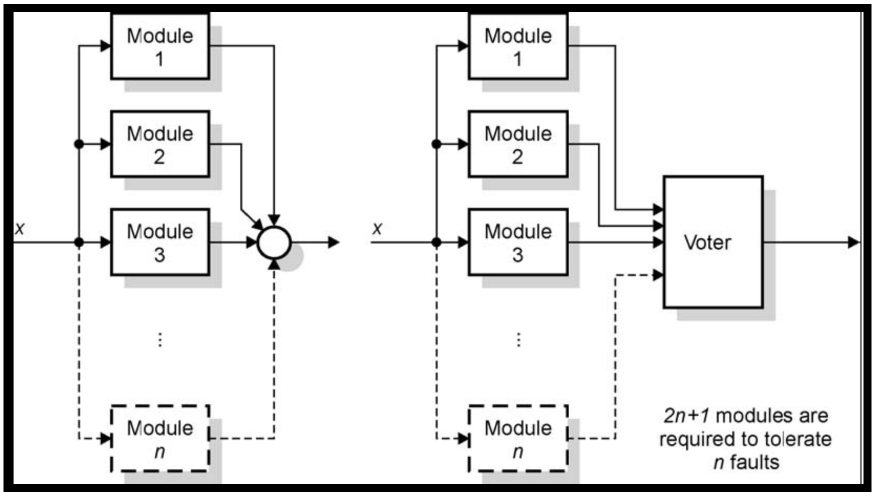

Figure 2.8: Static redundancy (Muenchhof *et al*., 2009)

In dynamics redundancy, standby component maybe active or inactive thus can be differentiated as cold standby (see Figure 2.9) and hot standby (see Figure 2.10). In cold standby, the redundant component is only operating when the fault occurs by replacing the affected component whereas in hot standby, the redundant component is also a part of active component during faultless situation. If only the fault comes into existence, then whichever components that are still active will become the redundant components with the overall system have to accept some degree of performance degradation.

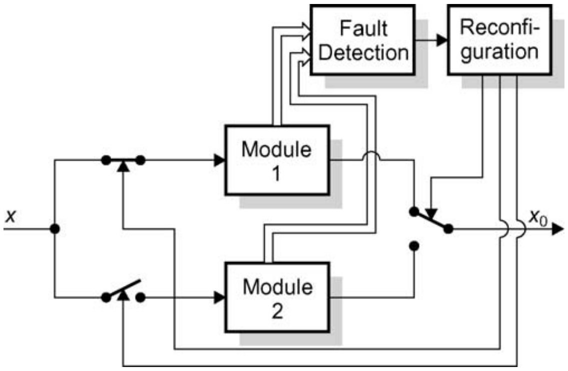

Figure 2.9: Dynamic redundancy with cold-standby (Muenchhof *et al.*, 2009)

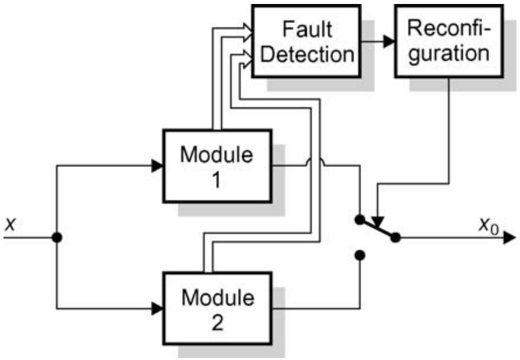

Figure 2.10: Dynamic redundancy with hot-standby (Muenchhof *et al.*, 2009)