NAGAOKA UNIVERSITY OF TECHNOLOGY

A Study on Utilization of a Restaurant Service Robot by considering a Framework of International Safety Standards

by

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Abstract

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Restaurant Service Robot (RSR) is under research and development (R&D) in the present. RSR can be applied to provide basic restaurant services, e.g., ordering, fetching and bringing food, settlement etc., for customers in a restaurant. In past decade, a RSR has been studied in a real and laboratory environments. For example, a rapid and precise positioning and guidance of the restaurant service mobile robot by using a laser positioning system has been carried out. In addition to such basic studies, more practical studies of RSR is required for its utilization.

Among the main part of a RSR (i.e. mobility, perception, manipulator, and human-robot interaction), a manipulator (robot arm) is always moving when performing a service task, and it becomes a critical part to harm in practice. In order to design the robot arm, we have to take the inherently safe design into account and a pneumatic actuator is suitable due to its inherent compliance. Therefore, in this thesis, the friction compensation using Variable Structure Control (VSC) with an ON/OFF valve has been proposed to control a pneumatic cylinder based on VSC with the proportional one. The experimental results provided the accuracy as same as using a proportional valve.

In general, higher performance is desired for RSR, and this may raise the robots price too high for a particular business application, especially for the ones developed in advanced areas. In addition, robot evaluations in real environment are important for business, but expensive in these areas.

Therefore, this thesis describes about the development of restaurant service robots in Thailand. Our objective is to develop two types of robot for 1) taking orders from customers and 2) delivering an order to the table. This R&D project is carried out in collaboration between Bangkok University and MK Restaurants. A Systematic Approach of Engineering Design and ISO safety standard for service robot in ISO 13482 have been used for design guides and for risk assessment/reduction in developing these robots. To evaluate the robots, five branches of MK in the Bangkok area have been used for six months with 14,280 services and 235,680 customers interested in total from 2009 to 2012. Lessons Learned from this four year project have been summarized.

As for the concluding study, we have re-examined an overall study of RSRs development and real environment evaluation in MK restaurants, and the essential requirements for restaurant service robot utilization have been derived, where safety is the most important for utilization. The proposed Essential Requirements (ER) are verified from the viewpoint of a Framework of International Safety Standards, where the essence of the International Standards related to System Safety are considered. The following standards related System Safety are used for the verification : ISO 13482 of the personal care robot safety in accordance with ISO 12100, ISO 31000 of risk management, IEC 62278 of railway RAMS (Reliability, Availability, Maintainability and Safety). The ER are also verified from the summary of the Lessons Learned. According to the verification, we conclude that the proposed essential requirements for restaurant service robot utilization are adequate from the viewpoint of System Safety.

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I owe my deepest thanks to my family - my mother, my father my sister, my wife and my son who have always stood by me and guided me through my career, and have pulled me through against impossible odds at times. Words cannot express the gratitude I owe them. I would also like to thank Professor Ohkamotoh and his wife. I would like to express my gratitude to them for their support. I would like to acknowledge to Duangporn Ounpanich and Rattana B. who has provided me a merry dinner.

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AKKHARAPHONG EKSIRI
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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ABU	Asia-Pacific Broadcasting Union
ACL	Acrylic
CAD	Computer-Aided Design
D	Demand
DOF	Degrees of Freedom
DSP	Digital Signal Processor
E	Individual Essential Requirement
ER	Essential Requirements
EMC	Electromagnetic Compatibility
F	Factors influencing the RAMS
FBG	Fiber Glass
FDIS	Final Draft International Standards
HACCP	Hazard Analysis Critical Control Point
I	Issue name
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LED	Light-Emitting Diode
MRE	Magnetic Resistance Element
MSR	Mobile Servant Robot
MIL-STD	Military Standard
OS	Operating System

P	Problem
PC	Personal Computer
PM	Preventive Maintenance
PAR	Physical Assistant Robot
PID	Proportional-Integral-Derivative
PIR	Passive Infrared
PWM	Pulse Width Modulation
PACS	Pneumatic Actuator Control System
PCRR	Personal CarRier Robot
PMBOK	Project Management Body of Knowledge
R	Requirement
RA	Risk Assessment
RI	Risk Index
RR	Risk Reduction
RSR	Restaurant Service Robot
RAMS	Reliability, Availability, Maintainability and Safety
RFID	Radio-frequency identification
Robocon	Robot Contest
S	Success
T	Technical specification
TR	Technical Report
UI	User Interface
UML	Unified Modeling Language
VSC	Variable Structure Control
W	Staff?s work to be performed with the robot

Nomenclature

Roman Symbols

A_1	piston effective area [m^2]
A_2	different effective area between A_1 and A_3 [m^2]
A_3	rod effective area [m^2]
A_e	valve effective area [m^2]
a_n	valve constants
C_1, C_2	fluid constant
C_f	a no dimensional, discharge coefficient
C_v	specific heat at constant volume
F_f	static friction force on packing seal [N]
F_P	Pneumatic Cylinder Force
H_{in}	heat transfers entering the chamber
H_{out}	heat transfers leaving the chamber
k	specific heat ratio of gas[-]
L_0	initial displacement [m]
n	air mass [kg]
P	absolute pressure inside the chamber [Pa]
P_a	atmosphere pressure [Pa]
P_{cr}	critical pressure [-]
P_{dn}	downstream absolute pressure [Pa]
P_{up}	upstream absolute pressure [Pa]
Q	air mass flow rate [kg/s]
Q_{in}	air mass flows entering the chamber [kg/s]
Q_{out}	air mass flows leaving the chamber [kg/s]
R	ideal gas constant = 287 [N·m/kg·K]
T	air temperature [K]
T_{in}	temperature of the incoming gas flow [K]
u	control input voltage of valve [V]
u_0	equilibrium voltage of valve [V]
$\dot{U}$	change of internal energy
V	volume of the chamber [m^3]
V_0	dead volume [m^3]
$\dot{W}$	rate of change in the work

Greek Symbols

λ	controller positive constant
ϕ	positive constant of the friction boundary
ρ	air density [kg/m^3]
σ	unit step function
φ	positive constant of the fictitious disturbance
ζ	Fictitious disturbance

Subscripts

i	chamber index 1,2

Chapter 1

Introduction

Recently, service robots have been developed around the world not only for education and research but also for business applications. A report on service robots in 2012 [1] noted that about 2.5 million service robots for personal and domestic use were sold in 2011 and that the sales value increased by 19% to US$636 million. So far, robots for personal and domestic use are employed mainly in the areas of household use, which include floor cleaning, lawn-mowing, and toys. In addition, in the area of public use, some robots have been used for assisting nursing work in hospitals, e.g., [2]. In shopping centers, the "shopping maid" robot of [3] has been implemented at a typical home store for guiding customers to the location of the customer's chosen product.

In research and evaluation, several studies can be referred, for example; the RoboCup at Home is the largest initiative in the world in terms of both the number of teams participating and the number of research issues taken into account where fictitious models of a home [4] and a fictitious Real World [5] also a fictitious one, have been used as the evaluation environments. An environment in which human beings and robots coexist needs advanced techniques. To avoid collisions between robot and human, for example, a reflective collision avoidance technique has been proposed in [6]. An intelligent human-robot interface needed for a service robot and in [7] was provided based on the spatial memory concept. For both studies in [6, 7], evaluations have been carried out in a laboratory environment. While such research and development activities are becoming popular for the service robot, their utilization is still limited.

A service robot is a new applications in non-industrial environments for providing services rather than manufacturing applications in industrial environments. Therefore, the International Organization for Standardization (ISO) has been developed an associated standard ISO 13482 in recognition of the particular hazards presented by newly emerging "robots and robotic devices" [8]. The ISO 13482 focuses on the "safety requirements for personal care robots" in non-medical applications. The personal care applications require close human–robot interaction and collaborations, including physical human–robot contact.

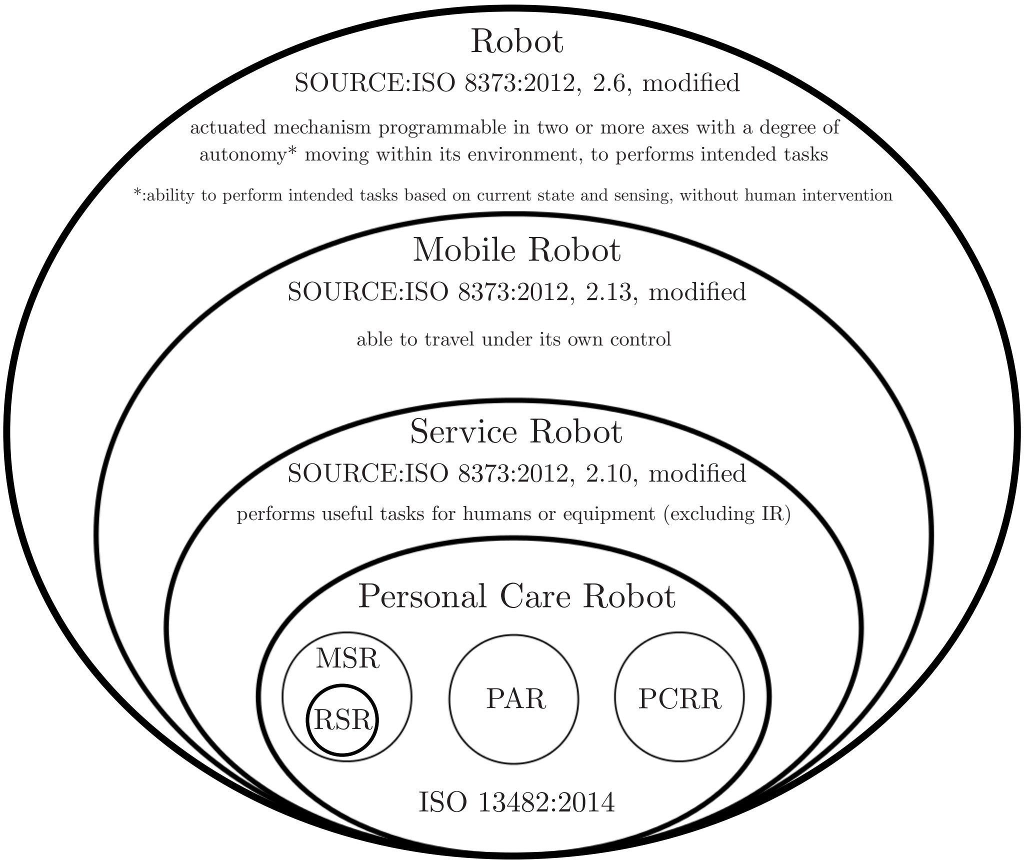
In ISO 13482, the following three types of personal care robots are examined as typical examples (see Fig.1.1):

- **Mobile Servant Robot (MSR)** : a personal care robot that is capable of traveling to perform serving tasks in interaction with humans, such as handling objects or exchanging information.
- **Physical Assistant Robot (PAR)** : a personal care robot that physically assist a user[1] to perform required tasks by providing supplementation or augmentation of personal capabilities.
- **Personal CarRier Robot (PCRR)** : a personal care robot with the purpose of transporting humans to an intended destination.

These robots typically perform tasks to improve the quality of life of intended users, irrespective of age or capability.

A Restaurant Service Robot (RSR) is also a kind of service robot which is under research and development at present. RSR can be applied to provide basic restaurant services, e.g., ordering, fetching and bringing food, settlement etc., for customers in a restaurant. In the past decade, a RSR have been studied in a real and laboratory environments. For example, a rapid and precise positioning and guidance of the restaurant service mobile robot by using a "laser positioning system" has been carried out in [9, 10]. Using a three landmarks positioning and landmark-based localization algorithms to localize the mobile robot with rough precision by using a camera has been proposed in [11]. And RFID-based localization algorithm have also been used to localization of the mobile

[1] either the operator of the personal care robot or the beneficiary of the service provided by the personal care robot



ISO 8373:2012, Robots and robotic devices – Vocabulary
ISO 13482:2014, Robots and robotic devices – Safety requirements for personal care robots
MSR: Mobile Servant Robot, PAR: Personal Assistant Robot, PCRR: Personal Carrier Robot, IR: Industrial Robot
RSR: Restaurant Service Robot

FIGURE 1.1: Definition overview of a personal care robot in accordance with ISO 13482:2014

robot with high precision when it was close to the designated destination. The service tasks of RSRs are not limited to the above. A RSR could be applied to providing an entertainment for customers. In [12] a "social service robots in wellness and restaurant applications" have been developed only for short–term evaluation.

Those RSRs as mentioned above typically consist of 4 main parts as follows:

- **Mobility** : a leg/wheel to bring itself to a designated destination.
- **Perception** : an ear(s) and/or eye(s) to understand what is around the robot, where the robot is, how the robot can safely interaction with the environment and people, etc.

- **Manipulator** : an arm(s) to pick and place an objects.
- **Human-robot interaction** : a device to communicate to people (including a light, signal, display, etc.).

As a definition of a service robot in accordance with ISO 13482 and considering the features of the restaurant service robots as mentioned above, a restaurant service robot here is identified as a mobile servant robot in ISO 13482.

Among the main parts of a RSR, a manipulator (robot arm) is always moving when performing a service task, and it becomes a critical part to harm. Therefore, in order to design the robot arm, we have to take the inherently safe design into account. Typically, an electric motor is widely used as an actuator for a robot arm joint. Nevertheless, from the viewpoint of safety, a motor joint with a gearbox is not preferable for this issue because it is a non-compliant control system inherently. Thus, here we focus on a pneumatic actuator.

Compared to conventional electric and hydraulic actuators, pneumatic actuators have natural compliance due to the compressibility of air. In addition, they are waterproof, robust in changes to the environment and have low electrical noise. In other words, for manipulations of RSR in which compliance is required, pneumatic actuators are preferable. With growth and development of the research, pneumatic actuators have been used in many fields, such as robot manipulators [13, 14], a robot for a disability assistance [15, 16], air braking [17], clutch control, packaging, pick and place, air suspension. Also for development of manipulators with robot characteristics needed in rehabilitation and prosthetic applications, pneumatic actuators are a natural choice. However, the position control of pneumatic actuators is difficult due to nonlinearities of the compressed air, external disturbances due to friction on packing seals (for a pneumatic cylinder), and parameters variations.

Nevertheless, the advantages have been driving researchers to seek the solutions for making pneumatic actuators to be competitive servo systems [18]. Many advanced techniques and modern controllers have been applied to control the position of the pneumatic actuator system such as adaptive control [19], block-oriented approximation feedback linearlization [18], Feedback Linearization [20], Variable Structure Control (VSC) [21–24].

A pneumatic cylinder control using proportion valves (or continuous valves) has been proposed in these researches. In order to control a pneumatic cylinder, we need a couple of proportional valves and servo amplifiers. Such a system with proportional valves is more complex when using a pneumatic cylinder as a robot arm actuator. On the other hand, ON/OFF valves are mainly used in industrial applications because they are low cost, simple, and more robust in change to the environment. From the viewpoint of inherently safe design, a pneumatic actuator using an ON/OFF valve is important to reduce the risk of the overall system (less number of device implies more Reliability, or less risk).

However, VSC with ON/OFF valves have not been extensively investigated so far. For example, the approximation of control laws using Variable Structure Methods in hydraulic servo systems control [21] have been evaluated, position control of a pneumatic actuator using ON/OFF solenoid valves by using PID control technique with novel PWM had been proposed for a servo system, and the results had an overshoot when the mass was changed [25]. Therefore, in this thesis, a simplified equation of a pneumatic cylinder chamber pressure for both cases when the piston extends and retracts is proposed at first. Based on the model, we design the VSC controller with full state feedback using an ON/OFF valve based on a proportional valve design method. Closed-loop stability was analyzed by Lyapunov's stability method. Chattering phenomenon reduction was shown experimentally. The effectiveness of the proposed method was examined experimentally.

In addition to the actuator issues, for RSR utilization, overall performance/cost ratios should be considered. In general, higher performance, e.g., autonomy, is desired for restaurant service robots, and this may raise the robot's price too high for a particular business application, especially for the ones developed in advanced areas, e.g., Japan, the US, and the EU. In addition, robot evaluations in real environments are important for business, but expensive in these areas. In Thailand, a developing country, the ABU robot contest (Robocon) [26] is very popular, where many students have been enthusiastically involved in Robocon since 2002. Due to this, Thailand has become a strong Robocon country, improving Thailand university robots have enough basic performance for real applications. Since the R&D cost of a robot in Thailand is one half to a tenth of that of Japan and other "advanced" countries due to mainly to staff costs, a robot made in Thailand and satisfying a business requirement will extend the service robot market at a fair price while providing reasonable performance. As a first step in extending the service robot industry, the real-environment evaluation of the robot is very important. However, few research evaluations have been reported in research in Thailand so far.

Therefore, this thesis describes our restaurant service robot development and evaluation whether its design requirements *R1* − *R14* in Section 3.3.2 are satisfied or not in the real environment. These have been carried out through the collaboration between Bangkok University and MK Restaurants Group Public Company Limited (MK Company). The author was involved as the project manager and the robot system designer from 2009 to 2012. The developed robots are expected to go to a customer's table by using simple Robocon technology to provide the services of taking orders and serving foods. The first and second robots we developed take orders from a special menu. The third, fourth, and fifth robots are designed to deliver a specified menu to a customer's table. These five robots work at five separate branches of the restaurant. A Systematic Approach of Engineering Design [27] and ISO safety standards for service robots in ISO/FDIS 13482 [28] have been used for design guides and for Risk Assessment/Reduction in developing these robots. To evaluate the robots, five branches of MK restaurant in the Bangkok area of Thailand have been used for six months with 14,280 services and 235,680 customers interested in total. Lessons Learned in [29] have been used to summarize the evaluation results.

As for the concluding study, we have re-examined an overall study of restaurant service robot development and real environment evaluation in MK restaurants, and the essential requirements for restaurant service robot utilization have been derived, where safety is the most important for utilization. Therefore, the proposed Essential Requirements (ER) are verified from the viewpoint of a Framework of International Safety Standards, where the essence of the International Standards related to System Safety are considered. The following standards related to System Safety are used for the verification : ISO 13482 of the personal care robot safety in accordance with ISO 12100, ISO 31000 of risk management, IEC 62278 of railway RAMS (Reliability, Availability, Maintainability and Safety). The ER are also verified from the summary of the Lessons Learned.

According to the verification, we conclude that the proposed essential requirements for restaurant service robot utilization are adequate from the viewpoint of System Safety.

This thesis is divided into six chapters and organized as follows:

Chapter 2: Pneumatic Control System Development toward Restaurant Service Robot Utilization presents the general idea of a Pneumatic Actuator Control System (PACS) in tree major parts (Load, Pneumatic Actuator, and

Valve). And also describes about the mathematical model of each part (Actuator-Load, Pressure Change Inside a Pneumatic Actuator Chamber, Valve). Friction compensation using VSC with an ON/OFF valve is proposed in this section. VSC with an ON/OFF valve is designed based on VSC for the proportional one. The experimental results provided the accuracy with 0.1 mm the same as using a proportional valve with chattering reduction.

Chapter 3: Restaurant Service Robots Development in Thailand present developed of two types of robot (order and serve). This chapter is done in collaboration with Bangkok University and MK Restaurants Group Public Company Limited. To achieve this objective, we have applied simple technologies from our experiences at the robot competition called Robocon. Risk assessment and risk reduction of the robot are shown here.

Chapter 4: Restaurant Service Robots Evaluation in Real Environment presents an evaluation of each of the robots for six months in a real environment at five branches of the MK restaurant chain are located in the Bangkok area of Thailand, from 2009 to 2012. In the evaluation, robots provided 14,280 services and attracted the interest of 235,680 customers. Lessons Learned from this four–year project have been summarized.

Chapter 5: Essential Requirements for Restaurant Service Robot Utilization from the Viewpoint of a Framework of International Safety Standards presents the essential requirements for restaurant service robot utilization based on our experience. It is divided into several groups, including management, technology, safety and maintenance. The consistency of the proposed requirements and a Framework of International Safety Standards have been carried out here.

Chapter 6: Conclusion summarizes the contribution of the thesis and a future work.

Chapter 2

Pneumatic Control System Development toward Restaurant Service Robot Utilization

[1] Compared to conventional electric and hydraulic actuators, pneumatic actuators have natural compliance due to the compressibility of air, waterproof, robust in environment change, low electrical noise. In other words, for manipulations of RSR in which compliance is required, pneumatic actuators are preferable. The advantages of a pneumatic actuator still lead us to study how to control it in a suitable way for RSR in advance before an appropriate solution for the power source issue is solved.

In this chapter, we study a pneumatic actuator control system which has good performance and reasonable cost. A pneumatic cylinder system has been difficult in position control due to the nonlinearity of the air, friction on packing seals, and parameter variations. Variable Structure Control (VSC) with a proportion valve has been used to overcome these difficulties. However, VSC with an ON/OFF valve has not been extensively investigated so far. Therefore, friction compensation using VSC with an ON/OFF valve is proposed in this chapter. VSC with an ON/OFF valve is designed based on VSC for a proportional one. Lyapunov's second method for stability analysis of a closed–loop control system guarantees that the proposed method is applicable for a restaurant service robot.

[1]this chapter appears in the journal of *The Japan Fluid Power System Society (JFPS)*, Vol.39, No.3, May 2008

2.1 Introduction

Though, in factory application, a pneumatic cylinder is widely used as an endpoint stop actuator so far, in a field of new robotics such as a disability assisting, it is expected to be controlled as adjustable stroke. However, the position control of a pneumatic cylinder has been difficult due to nonlinearity of the compressibility of air, external disturbances due to friction on packing seals, and so on. Nevertheless, the advantages have been driving researchers to seek the solution for making pneumatic actuators competitive servo systems [18].

Many advanced controllers have been applied to control of pneumatic systems and in this research, Variable Structure Control (VSC) is chosen as a controller due to the advantage of low sensitivity to plant parameter variations and disturbances, which eliminates the necessity of exact modeling. Some VSCs of pneumatic cylinders using proportional valves have been proposed with good performance, e.g. [22–24]. On the other hand, an ON/OFF valve is widely used in industrial applications because the cost is low and more robust to the environment change. Therefore, a pneumatic cylinder using ON/OFF valves is important in the viewpoint of usefulness and price advantage in the market. However, VSC with ON/OFF valves is not extensively investigated so far. For example, the approximation of control laws using Variable Structure Methods in hydraulic servo systems control [21] has been evaluated, position control of a pneumatic actuator using ON/OFF solenoid valves by using PID control technique with novel PWM had been proposed for a servo system, and the results have an overshoot when the mass was changed [25].

In this chapter, a simplified equation of chamber pressure for both cases when the piston extends and retracts is proposed. Based on the model, we design the VSC controller with full state feedback using ON/OFF valve based on proportional valve design method.

Closed-loop stability is analyzed by Lyapunov's stability method. Chattering phenomenon reduction has been shown explored experimentally. The effectiveness of the proposed method is examined experimentally.

2.2 Pneumatic Cylinder Models

2.2.1 General System

A pneumatic actuator converts energy (in the form of compressed air, typically) into motion. The motion can be rotary or linear, depending on the type of actuator. Some types of pneumatic actuators include:

* Pneumatic cylinders[1]
* Rotary actuators
* Grippers
* Rodless actuators with magnetic linkage
* Rodless actuators with mechanical linkage
* Pneumatic artificial muscles[1]
* Speciality actuators that combine rotary and linear motion–frequently used for clamping operations
* Vacuum generators

For a Pneumatic Actuator Control System (PACS), in order to control the position of the actuator, one has to finely tune the pressure levels in the pneumatic actuator chambers using the command element (the pneumatic valve). This requires detailed models for the dynamics of pressure in the chambers of the actuator, valve dynamics, and the equation of motion of load mass. So, the PACS can be construct into three main parts as shown in Fig.(2.1). A valve is the command element to provide fast and precisely controlled airflows in and out of the actuator chamber. A pneumatic actuator generates a force to move the load against an external forces.

The load mass m moved by different forces between actuator force F_{PA} and external force F_{ext} acting on itself. The detailed model of each part of a pneumatic actuator control system as shown in Fig.(2.1) will be explain in Sections (2.2.2), (2.2.3), and (2.2.4).

[1]used in this research

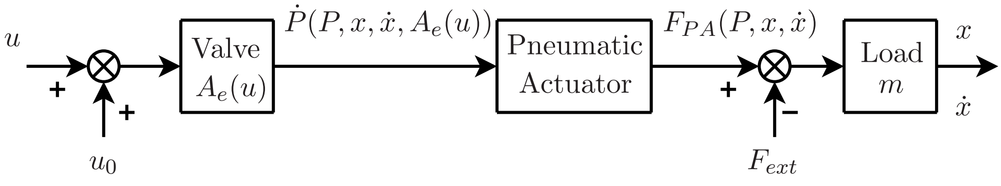


FIGURE 2.1: General Block Diagram of a Pneumatic Actuator Control System

2.2.2 Equation of Motion

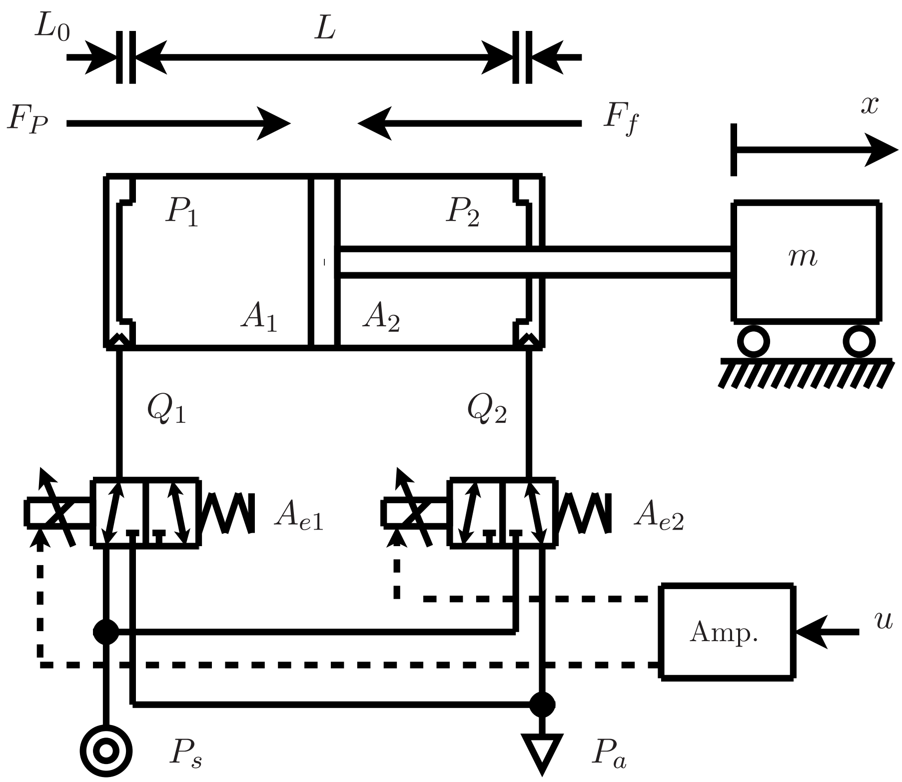


FIGURE 2.2: Pneumatic Cylinder System

Figure 2.2 shows the schematic of the system: the pneumatic cylinder mounted to two 3/2-way SMC-VEF Series valves for Proportional valve and 3/5-way SMC-SY3000 Series for ON/OFF valve with a maximum operating pressure (gauge pressure) of 0.5 MPa, two pressure sensors for P_1 and P_2, and magnetic-type position sensor for x with resolution of 0.1 mm. The equation of motion of the pneumatic cylinder system can be expressed as:

$$\ddot{x} = m^{-1}(A_1P_1 - A_2P_2 - A_3P_a - F_f) \tag{2.1}$$

m is Piston+Rod+Load mass, x is piston position, F_f is static friction (external) force, $P_{1,2}$ is the absolute pressure in pneumatic cylinder chamber, P_a is the ambient pressure, $A_{1,2}$ is the piston effective area, and A_3 is the cross-sectional area of the rod.

2.2.3 Equation of Chamber Pressure

In previous work of [23, 30, 31], the pressure change inside the chamber of the cylinder has been derived. In this section, we will review and simplify that mathematics models in detail.
The general model can be expressed the pressure changing in the chamber for a volume of gas consists of three equations [32]: an ideal gas law, the conservation of mass equation, and the energy equation. Assuming that:

(i) The gas is perfect,

(ii) The distribution of pressures and temperature inside the chamber are homogeneous,

(iii) Kinetic and potential energy terms are negligible,

(iv) Valve-Actuator connecting tube model is negligible,

Considering the control volume V, with density ρ, air mass n, pressure P, and temperature T, the ideal gas law can be written as,

$$PV = nRT \text{ or } P = \rho RT \tag{2.2}$$

where R is the ideal gas constant. Applying the continuity, the mass flow rate can be expressed as,

$$Q = \frac{d}{dt}(\rho V) \tag{2.3}$$

which can be also expressed as,

$$Q_{in} - Q_{out} = \rho\dot{V} + V\dot{\rho} \tag{2.4}$$

where, Q_{in} and Q_{out} are the mass flows entering and leaving the chamber. The energy equation can be written as follows:

$$H_{in} - H_{out} + kC_v(Q_{in}T_{in} - Q_{out}T) - \dot{W} = \dot{U} \tag{2.5}$$

where

H_{in}, H_{out}	:	Heat transfer terms,
k	:	Specific heat ratio of any gas,
C_v	:	Specific heat at constant volume,
T_{in}	:	Temperature of the incoming gas flow,
$\dot{W}$	:	Rate of change in the work, and
$\dot{U}$	:	Change of internal energy.

The total change in internal energy is,

$$\dot{U} = \frac{d}{dt}(C_v nT) = \frac{1}{k-1}\frac{d}{dt}(PV) = \frac{1}{k-1}(V\dot{P} + P\dot{V}) \tag{2.6}$$

in which we used the ideal gas relation, $C_v = R/(k-1)$. Now, substituting $\dot{W} = P\dot{V}$ and Eq. (2.6), into Eq. (2.5),

$$H_{in} - H_{out} + \frac{k}{k-1}\frac{P}{\rho T}(Q_{in}T_{in} - Q_{out}T) - \frac{k}{k-1}P\dot{V} = \frac{1}{k-1}V\dot{P} \tag{2.7}$$

Assuming that the incoming flow is already at the temperature of the gas in the chamber considered for analysis, the energy equation becomes,

$$\frac{k-1}{k}(H_{in} - H_{out}) + \frac{1}{\rho}(Q_{in} - Q_{out}) - \dot{V} = \frac{V}{kP}\dot{P} \tag{2.8}$$

Further simplification can be made by analyzing the heat transfer terms in Eq. (2.8). If the process is considered to be adiabatic ($H_{in} = H_{out} = 0$), the time derivative of the chamber pressure is,

$$\dot{P} = k\frac{P}{\rho V}(Q_{in} - Q_{out}) - k\frac{P}{V}\dot{V} \tag{2.9}$$

or, substituting from Eq. (2.2),

$$\dot{P} = k\frac{RT}{V}(Q_{in} - Q_{out}) - k\frac{P}{V}\dot{V} \tag{2.10}$$

If the process is considered to be isothermal (T = constant), then the change in internal energy is,

$$\dot{U} = C_v Q T \tag{2.11}$$

and Eq. (2.8) can be written as,

$$H_{in} - H_{out} = P\dot{V} - \frac{P}{\rho}(Q_{in} - Q_{out}) \tag{2.12}$$

Then, the rate of change in pressure will be,

$$\dot{P} = \frac{RT}{V}(Q_{in} - Q_{out}) - \frac{P}{V}\dot{V} \tag{2.13}$$

A comparison of Eqs. (2.10) and (2.13) shows that the only difference is the specific heat ratio term k. Thus, both equations can be written as,

$$\dot{P} = \frac{RT}{V}(\varepsilon_{in} Q_{in} - \varepsilon_{out} Q_{out}) - \varepsilon\frac{P}{V}\dot{V} \tag{2.14}$$

with ε, ε_{in}, and ε_{out} taking values between 1 and k, depending on the actual heat transfer during the process. In equation (2.14) one does not have to know the exact heat transfer characteristics, but merely estimate the coefficients ε, ε_{in}, and ε_{out}. The fact that the uncertainty of the estimation is bounded by $k-1$ is also very important from the control design perspective. For the charging process, a value of ε_{in} close to k is recommended, while for the discharging of the chamber ε_{out} should be choose close to 1. The thermal characteristic of compression/expansion process, due to the piston movement is better described using $\varepsilon = 1.2$ [33].

The equation of pressure changing inside the chamber is determined with an ideal gas law, the conservation of mass equation, and the energy equation [32]. Considering the control volume V, pressure P, temperature T, and assumed in isothermal system.
For notational simplicity, the two models of the mass flow rate through an valve orifice area A_{ei} (Choked-flow and Subsonic-flow) [23] is denoted by adding the unit-step function of the effective area as shown bellow:

$$\begin{aligned} \dot{P}_i &= \tfrac{k}{V_i}\left(RTQ_i - P_i\dot{V}_i\right) \\ &= \alpha_i[K_q\{\sigma((-1)^{(i+1)}A_{ei}(u))q(P_s, P_i) - \sigma((-1)^i A_{ei}(u)) \\ &\quad q(P_i, P_a)\}A_{ei}(u) + (-1)^i P_i A_i \dot{x}],\ \ i = 1, 2 \end{aligned} \tag{2.15}$$

where

$$\alpha_i = \frac{k}{V_{0i} + A_i(\frac{L}{2} + (-1)^{i+1}x)}, \tag{2.16}$$

$$K_q = RC_f\sqrt{T}, \tag{2.17}$$

$$q(P_{up}, P_{dn}) = \begin{cases} C_1 P_{up} & \text{for } \frac{P_{dn}}{P_{up}} \leq P_{cr} \\ C_2 P_{up} K_p & \text{for } \frac{P_{dn}}{P_{up}} > P_{cr} \end{cases}, \tag{2.18}$$

$$K_p = \left(\frac{P_{dn}}{P_{up}}\right)^{(1/k)} \sqrt{1 - \left(\frac{P_{dn}}{P_{up}}\right)^{(k-1)/k}}, \tag{2.19}$$

$$V_i = V_{0i} + A_i\left(\frac{L}{2} + (-1)^{i+1}x\right), \tag{2.20}$$

$$\dot{V}_i = (-1)^{i+1}A_i\dot{x}. \tag{2.21}$$

$\sigma(\cdot)$ represents the step function, $q(\cdot)$ represents the air flow entering and leaving the chamber. C_f is a non dimensional discharge coefficient, C_1 and C_2 are fluid constants [23], P_{up} is upstream pressure, P_{dn} is downstream pressure, and P_{cr} is critical pressure. Subscript $i = 1, 2$ is the cylinder chamber index, V_{0i} is the inactive volume, A_i is the piston effective area, and L is the piston stroke.

2.2.4 Equation of Valve Effective Area

The critical component of the pneumatic actuator system is a pneumatic valve. It is the command element, and should be able to provide fast and precisely controlled airflow in and out of the actuator chambers. There are many available designs for pneumatic valves, which differ by geometry of the active orifice, type of flow regulating element, number of paths and ports, type of actuating, etc. For the proportional spool valves, actuated by voice coil. A Electro-Pneumatic Proportional control valve system provide the ability to infinitely control the position of the internal spool assembly which increases or decreases the amount of flow being released from the valve by changing the active orifice of the valve. To accomplish this, combine a low power input signal with a high power output signal through the use of the power amplifier. The amplifier becomes a very important part of the total system. Without this component it is not possible to provide the infinite control.

The spool is balanced with respect to pressure and positioned at the equilibrium (closed) position. This design permits fast and precise adjustments of the valve orifice area, providing accurate flow control. If the spool is displaced in the positive direction, one chamber will be connected to the pressure tank through the supply path, and the compressed air will flow inward ($Q_{in} > 0, Q_{out} \approx 0$). The other chamber will be connected to the atmosphere through the exhaust path, and the air will flow outward ($Q_{in} \approx 0, Q_{out} > 0$). The expressions for the input and output flows will be derived in the following bellow (flow through a valve and pneumatic chamber is same).

The pressure drop across the valve orifice is usually large, and the flow has to be treated as compressible and turbulent. If the upstream to downstream pressure ratio is larger than a critical pressure value P_{cr}, the flow will attain sonic velocity (choked flow) and will depend linearly on the upstream pressure. If the pressure ratio is smaller than P_{cr} the mass flow depends nonlinearly on both pressures. The standard equation for the mass flow through an orifice of area $A_e(u)$ is (see [23]),

Choked flow: the pressure ratio $P_{dn}/P_{up} \leqslant P_{cr}$ and the mass flow rate is,

$$Q = C_f C_1 \frac{P_{up}}{\sqrt{T}} \cdot A_e(u) \tag{2.22}$$

Subsonic flow: the pressure ratio $P_{dn}/P_{up} > P_{cr}$ and the resulting mass flow rate can be express by,

$$Q = C_f C_2 \frac{P_{up}}{\sqrt{T}} (\frac{P_{dn}}{P_{up}})^{1/k} \sqrt{1 - (\frac{P_{dn}}{P_{up}})^{(k-1)/k}} \cdot A_e(u) \tag{2.23}$$

with

$$A_e(u) = \sum_{n=0}^{m} a_n u^n, \; m : \text{polynomial order} \tag{2.24}$$

The effective area of valve $A_e(u)$ is a function of control input voltage u of the valve which can be obtained experimentally and using polynomial curve-fitting method to determine the A_e and u relation from the experimental data (see Section 2.5.2 for more

detail).
where

Q : Mass flow through valve orifice,

C_f : A no dimensional, discharge coefficient [23],

P_{up} : Upstream absolute pressure,

P_{dn} : Downstream absolute pressure,

and

$$C_1 = \sqrt{\frac{k}{R}(\frac{2}{k+1})^{\frac{k+1}{k-1}}}; \quad C_2 = \sqrt{\frac{2k}{R(k-1)}}; \quad P_{cr} = (\frac{2}{k+1})^{\frac{k}{k-1}} \tag{2.25}$$

are constants for a given fluid. For air ($k = 1.4$) and the constants in Eq.(2.25) becomes; $C_1 = 0.04042$, $C_2 = 0.15617$, and $P_{cr} = 0.528$. The meaning of the upstream and downstream pressure in Eqs.(2.22) and (2.23) is different for the charging and discharging process of the cylinder chambers. For charging, the pressure in the supply tank should be considered the upstream pressure and the pressure in the cylinder chamber is the downstream one. For discharging process, the pressure in the chamber is the upstream, and the ambient pressure is the downstream pressure.

The model of effective area A_e of the Proportional valve can be obtained experimentally. The polynomial curve-fitting method is used to determine the model from experimental data. Resulting in

$$A_{ei}(u_i) = \begin{cases} a_1 + a_2 u_i + a_3 u_i^2 & \text{for} \quad u > u_0 \\ 0 & \text{for} \quad u = u_0 \\ a_4 + a_5 u_i + a_6 u_i^2 & \text{for} \quad u < u_0 \end{cases} \tag{2.26}$$

$a_{1\sim6}$ are valve constants, u_0 is equilibrium voltage.

The dynamics models of the pneumatic cylinder with ON/OFF valve is almost the same as the pneumatic cylinder with proportional valve (see Section 2.2). It is just only one of model is different, that is the ON/OFF valve model which can be expressed as:

$$\hat{A}_{ei}(u) = \begin{cases} A_{ei}^{+} & \text{for} \quad u > 0 \\ 0 & \text{for} \quad u = 0 \\ A_{ei}^{-} & \text{for} \quad u < 0 \end{cases} \tag{2.27}$$

where $\hat{A}_{ei}$ is the effective area of the ON/OFF valve. The relation between $A_e(u_i)$ (see Eq.2.26) and $\hat{A}_e(u_i)$ can be expressed as:

$$\hat{A}_{ei}(u_i) = A_{ei}(u_i) + \zeta(t) \tag{2.28}$$

where $\zeta(t)$ is a fictitious disturbance as shown in Fig.2.3 and this is represented as an additive disturbance in Fig.2.4. Note that $\zeta(t)$ is only used in stability analysis in Section 2.4, and not used in control.

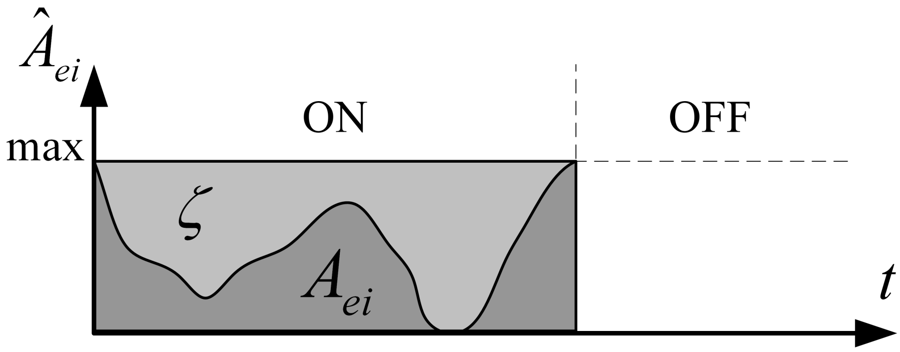


FIGURE 2.3: ON/OFF valve output $\hat{A}_{ei}(t)$ can be represented as Proportional valve output $A_{ei}(t)$ with a fictitious disturbance $\zeta(t)$.

2.3 Variable Structure Controller Design

2.3.1 VSC Design with Proportional Valve

By following the design procedure in Bonchis's [21], we have designed the control law for the case when piston extends and retracts using Eqs. (2.1), (2.15), and (2.26). From equation of motion as shown in Eq.(2.1), denoting: velocity $\dot{x} = v$, acceleration $\dot{v} = a$, then

$$\dot{a} = \frac{1}{m}(A_1\dot{P}_1 - A_2\dot{P}_2). \tag{2.29}$$

Substituting the equation of chamber pressure Eq.(2.15) into Eq.(2.29), we can rewrite Eq.(2.29) in nonlinear state equation as:

$$\dot{a} = \boldsymbol{f}(x, v, P_1, P_2) + \boldsymbol{b}(x, P_1, P_2, A_{ei}) \cdot A_e(u) \tag{2.30}$$

where

$$\boldsymbol{f}(\cdot) = -\frac{v}{m}(\alpha_1 A_1^2 P_1 + \alpha_2 A_2^2 P_2) \tag{2.31}$$

$$\begin{aligned} \boldsymbol{b}(\cdot) = \tfrac{K_q}{m}[&\alpha_1 A_1\{\sigma(A_e)q(P_s, P_1) - \sigma(-A_e)q(P_1, P_a)\} \\ &-\alpha_2 A_2\{\sigma(-A_e)q(P_s, P_2) - \sigma(A_e)q(P_2, P_a)\}] \end{aligned} \tag{2.32}$$

with

$$A_e(u) = A_{e1}(u) = -A_{e2}(u) \tag{2.33}$$

Now, define $e_x = x_d - x$ be the error in the piston position x with desired value represented by subscript d. For the system Eq.(2.30) the switching surface $s = 0$ of VSC is defined [34] [35]:

$$s = (\frac{d}{dt} + \lambda)^{n-1} \cdot e_x \tag{2.34}$$

where λ is a strictly positive constant that effects to desired rising time of the closed-loop system, $n = 3$ for our third order system. Then Eq.(2.34) becomes:

$$s = e_a + 2\lambda e_v + \lambda^2 e_x \tag{2.35}$$

and

$$\dot{s} = \dot{e}_a + 2\lambda e_a + \lambda^2 e_v \tag{2.36}$$

where $e_v = \dot{e}_x = v_d - v$ represents the tracking error of the velocity and e_a represents the acceleration error and these are obtained by a numerical differentiation method of position data. The control action can be determined from the condition of $\dot{s} = 0$, taking Eqs.(2.1) and (2.30) into Eq.(2.36), resulting in

$$A_e(u) = \boldsymbol{b}^{-1}(-\boldsymbol{f} + \dot{a}_d + 2\lambda a_d + \lambda^2 e_v - \frac{2\lambda F_P}{m}) + \boldsymbol{b}^{-1}\frac{2\lambda}{m}F_f \tag{2.37}$$

$$F_P = A_1P_1 - A_2P_2 - A_3P_a \tag{2.38}$$

Note that A_e is invertible as shown in Eq.(2.26). To eliminate the effect of the static friction F_f, it can be replaced by *signum* function of switching surface (2.34) as shown bellows:

$$F_f \to \phi \operatorname{sgn}(s) \tag{2.39}$$

$$\phi > |F_f| > 0 \tag{2.40}$$

where, ϕ is positive constant of the friction boundary. Now, we obtained the control action u as:

$$u = A_e^{-1}\left(u_{eq} + \boldsymbol{b}^{-1}\frac{2\lambda}{m}\phi \operatorname{sgn}(s)\right) \tag{2.41}$$

where

$$u_{eq} = b^{-1}(-\boldsymbol{f} + \dot{a}_d + 2\lambda a_d + \lambda^2 e_v - \frac{2\lambda F_P}{m}). \tag{2.42}$$

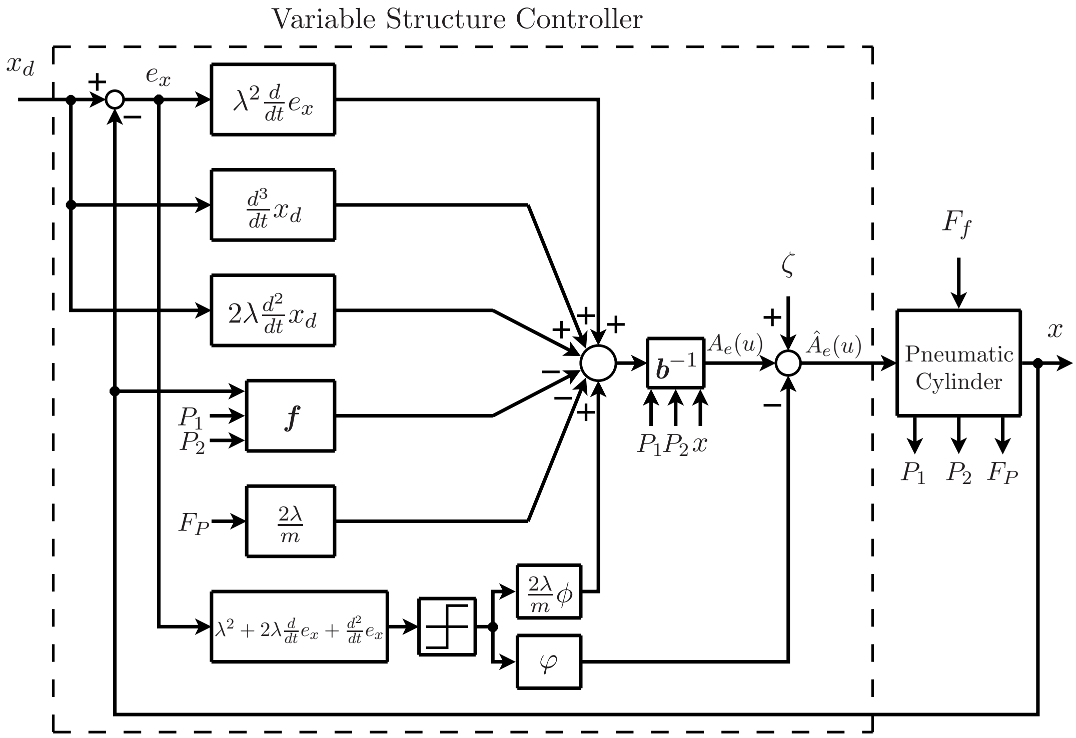


FIGURE 2.4: Variable Structure Controller Block Diagram with ON/OFF valve

2.3.2 VSC Design with ON/OFF Valve

To design the controller by using ON/OFF valve based on Proportional one, the control action in Eq.(2.30) will be replace by Eq.(2.28) and then Eq.(2.30) becomes:

$$\dot{a} = \boldsymbol{f} + \boldsymbol{b} \cdot (A_e(u) + \zeta) \tag{2.43}$$

The VSC (2.41) becomes:

$$u = A_e^{-1}\left(u_{eq} + \boldsymbol{b}^{-1}\frac{2\lambda}{m}\phi \,\mathrm{sgn}(s) - \varphi \mathrm{sgn}(s)\right) \tag{2.44}$$

where

$$\varphi > |\zeta| > 0 \tag{2.45}$$

The control action for the pneumatic cylinder with ON/OFF valve becomes:

$$\hat{u} = \begin{cases} u^+ & \text{for} \quad u > 0 \\ 0 & \text{for} \quad u = 0 \\ u^- & \text{for} \quad u < 0 \end{cases} \tag{2.46}$$

$\hat{u}$ is the control signal for the ON/OFF-type of valve, u^+ is fully control action voltage when the piston extends, and u^- when the piston retracts. Figure 2.4 shows the Variable Structure Controller Block Diagram.

2.4 Stability Analysis of VSC with ON/OFF Valve

To analyze the stability of close-loop control, by using the Lyapunov's second theorem on stability [36, 37] candidate,

$$\mathcal{V} = 0.5s^2 \tag{2.47}$$

a stability condition is given by

$$\dot{\mathcal{V}} = s\dot{s} \leq 0. \tag{2.48}$$

Taking Eqs.(2.1),(2.30), and (2.44) into Eq.(2.36) and assumed that the desired value is step-type function. The treatment of the another functions of desired value are similar.

Now, the first time derivative of Eq.(2.47) can be obtained as

$$\dot{\mathcal{V}} = s\left(-\frac{2\lambda}{m}\left(\phi\text{sgn}(s) - F_f\right) + b\left(\varphi\text{sgn}(s) - \zeta\right)\right). \tag{2.49}$$

Taking Eqs.(2.32),(2.35),(2.40), and (2.45) into consideration, the condition of (2.48) is satisfied if

$$\left|\frac{2\lambda}{m}\left(\phi\text{sgn}(s) - F_f\right)\right| \geq \left|b\left(\varphi\text{sgn}(s) - \zeta\right)\right| \geq 0. \tag{2.50}$$

Note that, inequality (2.50) with $\zeta = \varphi = 0$, which implies that the proportional valve case makes the inequality (2.50) always be satisfied, is identical to the stability condition of VSC with a proportional valve to eliminates the effect of the static friction [36].

2.5 Experimental Results

2.5.1 Experimental Apparatus of the Pneumatic Cylinder System

This section describes about the experimental apparatus for this research as shown in Figs. 2.5 and 2.6. The pneumatic circuit connection based on safety engineering sense, air pressure supply P_s have to connect to P-Port of the proportional valve. The

Table 2.1: The equipment of an experimental apparatus

Equipments	Maker	Model
Air compressor	ANEST IWATA	OL-165PB
Reservoir	MAX	AK-T30
Air Dryer	SMC	IDF1D-1
Air Regulator	SFR-08-D	TAIYO
Stroke reading cylinder	SMC	CE1
Solenoid Valve	SMC	Flow style: VEF3121-1-02
Pressure sensor	OMRON	E8CC-10C
DSP	dSPACE	DS1102

compressed air generated by the air compressor and dried out using an air dryer before supply to the pneumatic cylinder (stroke reading cylinder) mounted to two 3/2-way proportional solenoid valves with a maximum operating pressure (gauge pressure) of 0.5 MPa, a power amplifier are exclusively used for driving proportional solenoid valves, the amount of rod movement in the stroke reading cylinder is detected using an Magnetic

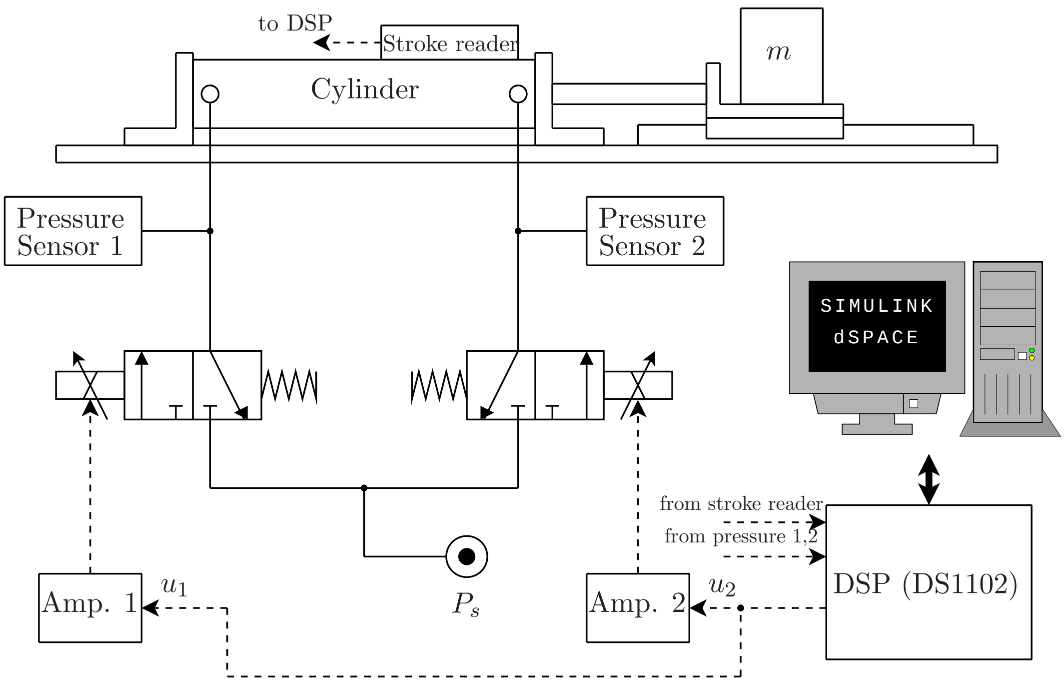


FIGURE 2.5: Experimental Apparatus of the Pneumatic Cylinder System

Resistance Element (MRE) with resolution 0.1 mm, two analog gauge pressure sensors is used for feedback the pressure changing inside a cylinder. At the stage of simulation is performed in SIMULINK. After simulated controller is able to control a real plant, the next step is to build the real-time code for the controller and to download it onto the dSPACE hardware (DSP-Card). The equipment of an experimental apparatus shows in Table 2.1.

2.5.2 Experimental Validation of Valve Model

To obtain the effective area related to control input voltage equation. The area of the valve A_e is given by the spool position relative to the radial holes in the valve sleeve. To obtain the effective area equation, we will use the air mass flow through valve orifice equation as shown in Eqs. (2.22, 2.23). Figure 2.7 shows the experimental set-up. Air absolute pressure supply $P_s = 0.6$ [MPa].

With increasing the voltage of the power supply (see Table 2.2) and records the pressure

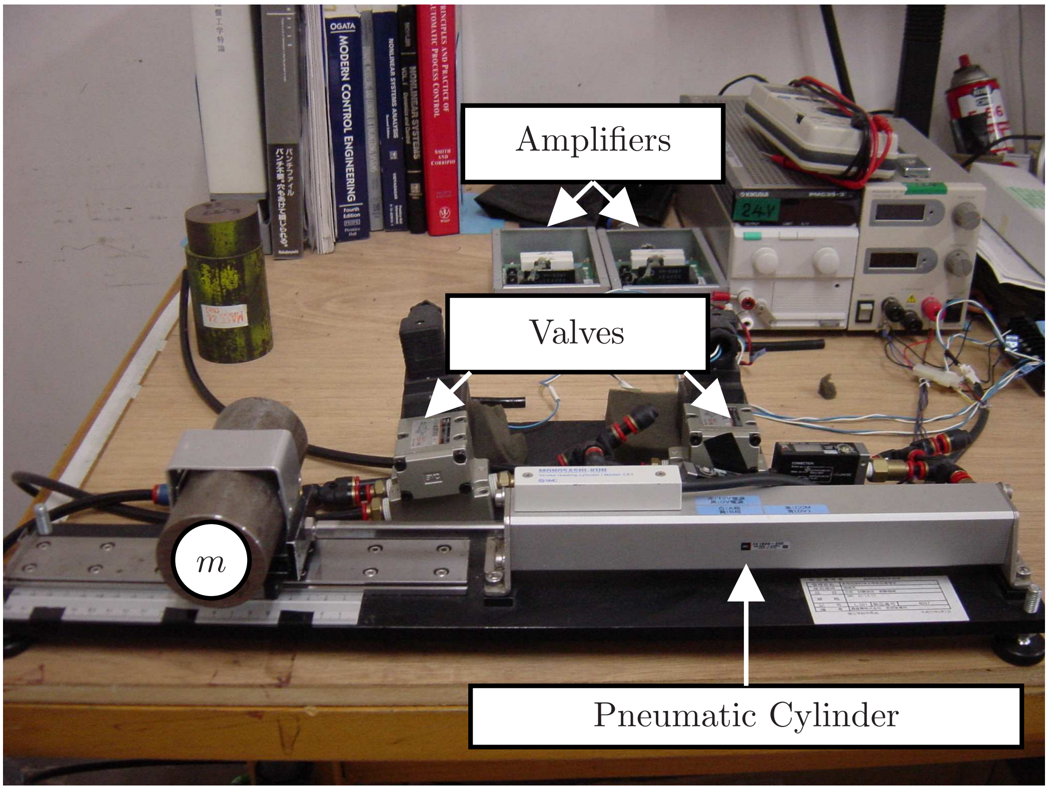


FIGURE 2.6: Photo of the Experimental Apparatus of the Pneumatic Cylinder System

both side of inlet and outlet port of the valve. And records the value of the mass flow rate by flow meter. After that, switch the Air supply to R-port and records. Then we obtain the data as shown in Table 2.2. From Fig. 2.7, we have to convert the unit of mass flow meter from liter per minute to kilogram per second (SI-unit) that determine by following,
From

$$\begin{aligned} \text{mass} &= \text{density} \times \text{volume}. \\ \text{Air 1 Liter} &= 0.001\ [\text{m}^3] \\ \text{Density of air} &= 1.225\ [\text{kg/m}^3] \end{aligned}$$

Therefore

$$\text{Air 1 Liter} = 0.001\ [\text{m}^3] \times 1.225\ [\text{kg/m}^3] = 0.001225\ [\text{kg}]$$

Now, we obtain

Table 2.2: Air mass flow rate and effective area experiment of valve

Valve1	u [V]	I [A]	P_s [MPa]	P_1 [MPa]	P_1/P_s [-]	**Flow rate** [kg/s]	A_e [mm^2]
R to A	1.9	0.4	0.57	0.12	0.21	2.96e-4	0.97
	1.95	0.41	0.55	0.12	0.22	2.65e-4	0.90
	2	0.42	0.56	0.12	0.21	2.37e-4	0.79
	2.05	0.43	0.56	0.11	0.20	2.10e-4	0.70
	2.1	0.44	0.56	0.1	0.18	1.80e-4	0.60
	2.15	0.45	0.57	0.1	0.18	1.55e-4	0.51
	2.2	0.46	0.57	0.1	0.18	1.33e-4	0.44
	2.25	0.47	0.575	0.1	0.17	1.10e-4	0.36
	2.3	0.48	0.58	0.1	0.17	8.78e-5	0.28
	2.35	0.49	0.58	0.1	0.17	6.94e-5	0.22
	2.4	0.5	0.58	0.1	0.17	5.51e-5	0.18
	2.45	0.51	0.58	0.1	0.17	4.08e-5	0.13
	2.5	0.52	0.59	0.1	0.17	2.86e-5	0.09
	2.55	0.53	0.59	0.1	0.17	2.04e-5	0.07
	2.6	0.54	0.59	0.10	0.17	1.43e-5	0.05
	2.65	0.55	0.59	0.10	0.17	8.17e-6	0.03
	2.7	0.56	0.60	0.10	0.16	0	0
	2.75	0.57	0.60	0.10	0.16	0	0
P to A	2.5	0.52	0.6	0.10	0.16	0	0
	2.55	0.53	0.6	0.10	0.16	6.13e-6	0.02
	2.6	0.54	0.59	0.1	0.17	1.43e-5	0.05
	2.65	0.55	0.59	0.1	0.17	1.84e-5	0.06
	2.7	0.56	0.59	0.1	0.17	2.45e-5	0.08
	2.75	0.57	0.59	0.1	0.17	3.06e-5	0.10
	2.8	0.58	0.58	0.1	0.17	4.90e-5	0.16
	2.85	0.59	0.58	0.1	0.17	6.33e-5	0.20
	2.9	0.6	0.58	0.1	0.17	7.96e-5	0.26
	2.95	0.61	0.57	0.1	0.18	1.02e-4	0.33
	3	0.62	0.57	0.1	0.18	1.23e-4	0.40
	3.05	0.63	0.57	0.1	0.18	1.45e-4	0.48
	3.1	0.64	0.57	0.1	0.18	1.69e-4	0.56
	3.15	0.65	0.56	0.11	0.20	1.98e-4	0.66
	3.2	0.66	0.56	0.11	0.20	2.29e-4	0.76
	3.25	0.67	0.56	0.12	0.21	2.55e-4	0.85
	3.3	0.68	0.56	0.12	0.21	2.80e-4	0.93

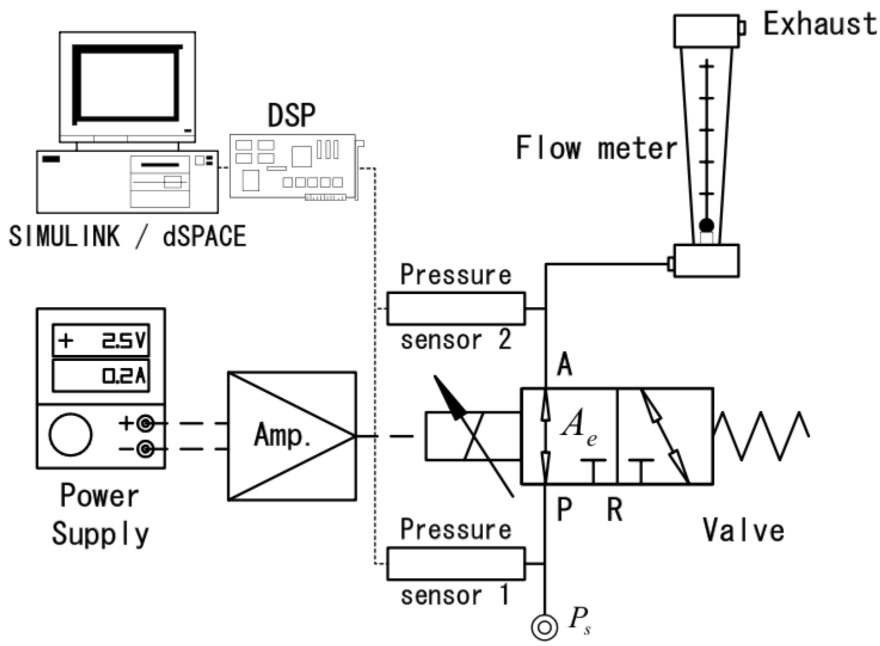


FIGURE 2.7: Valve Effective Area experimental Apparatus

$$1 \text{ [L/min]} = 20.41666667\text{e-}6 \text{ [kg/s]}$$

To determine the effective area of the valve, we will use the Eqs. (2.22,2.23) which $P_d = P_1$ and $P_u = P_s$. Table 2.2 shows the ratio between P_1 and P_s, its less than critical pressure ($P_{cr} = 0.528$) therefore we will use the mass flow rate equation to determine the orifice area as,

$$A_e = \frac{Q\sqrt{T}}{C_f C_1 P_s} \tag{2.51}$$

where $T = 293$ [K] and $C_f = 0.226711$ [-].

Figure 2.8 is a data plotting from Table 2.2 to graph. This figure shows the relation between control input voltage and air mass flow rate, right axis shows the relation of input voltage and effective area of the valve also. And top axis represent the control electric current of the valve.

From Fig. 2.8, by using a Polynomial fit curve method, the equation of the effective

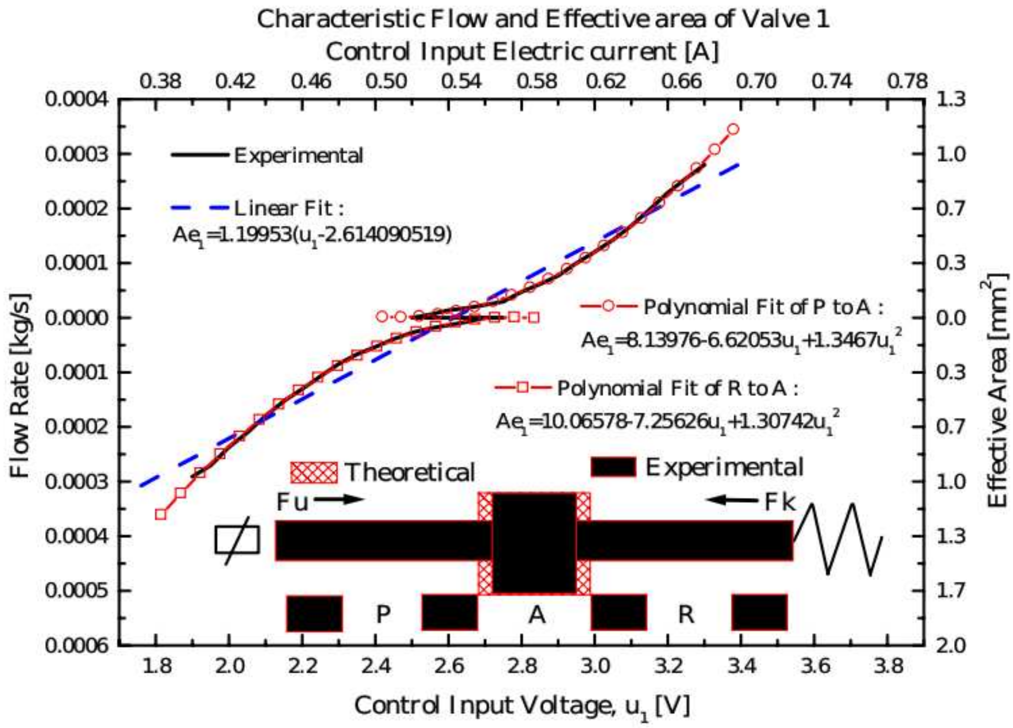


FIGURE 2.8: Characteristic flow and Effective area of valve

area A_e [m^2] between P-port and A-port can be described by,

$$A_e = (8.13976 - 6.662053u + 1.3467u^2) \times 10^{-6} \tag{2.52}$$

and we obtain the control input u_1 [V] in the case when piston extends as following bellows,

$$u = 2.45806 + 861.717\sqrt{|A_e| - 2.94083 \times 10^{-9}} \tag{2.53}$$

The equation of the effective area A_e [m^2] between R-port and A-port can be describe by,

$$A_e = (10.06578 - 7.25626u + 1.3074u^2) \times 10^{-6} \tag{2.54}$$

control input u [V] in the case when piston retracts,

$$u = 2.77505 - 874.569\sqrt{|A_e| + 2.67037 \times 10^{-9}} \tag{2.55}$$

The effective area Eqs. (2.52 or 2.54) as mention above can be estimate by linear equation as,

$$A_e = 1.19953 \times 10^{-6}(u - 2.614090519) \quad (2.56)$$

Now, the control input u_1 [V] expressed by,

$$u = \frac{A_e}{1.19953 \times 10^{-6}} + 2.614090519 \quad (2.57)$$

2.5.3 VSC with Proportional Valve

The valves in Table.2.3 are used in the experiment.

Table 2.3: Proportional VS. ON/OFF Valve

Valve	A_e [mm^2]	RT* [ms]	Price[USD]
Proportional	1.0	30	180
ON/OFF	1.0	10	80

* RT:Response Time in catalog

2.5.3.1 Control Parameter Determination

Two major parameters λ and ϕ of the controller in Eq.(2.41) are determined under the stability condition of Eq.(2.50) with $\varphi = \zeta = 0$. The value of $\phi = 30$ can be determined by expression of Eq.(2.40), with experimental consideration of F_f. The value of $\lambda = 50$ can be obtained by trial and error technique in tuning phase that depends on desire rising time of the closed-loop system. The reference position of closed-loop system control is a Square-wave with 0.05 m amplitude and 0.25 Hz frequency and Table 2.4 shows the experimental parameters. The designed controller (2.44) provided position response curve with chattering phenomenon as shown in Fig. 2.9. The chattering phenomenon [34] is in bound 20 (see Fig. 2.9 bottom), and this value of switching surface will be discuss in next section.

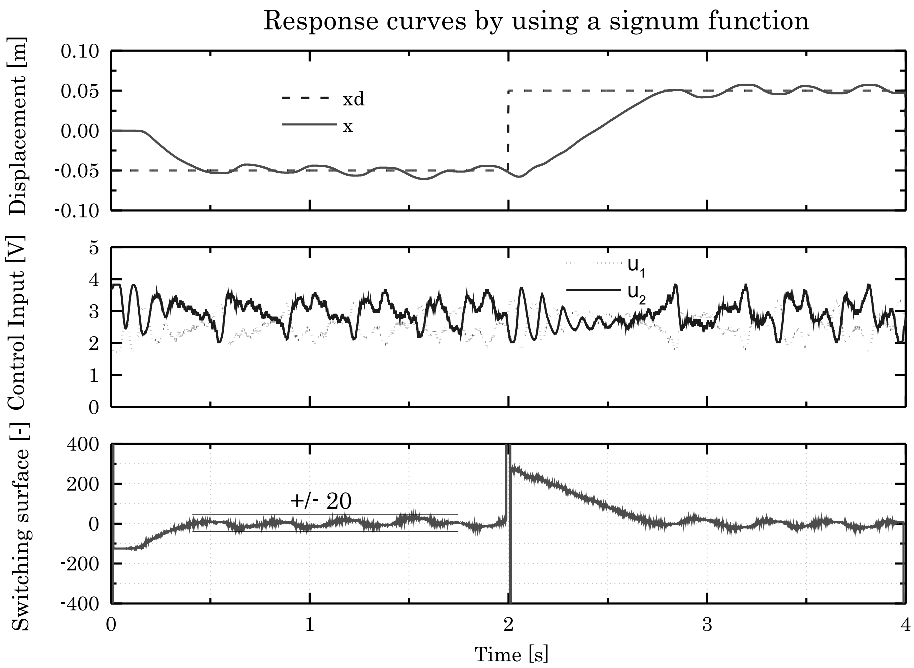


FIGURE 2.9: Position Response using Proportional-valves without chattering reduction

2.5.3.2 Chattering Reduction

In order to reduce the chattering phenomenon, the *signum* function in control action Eq.(2.44) can be replace by one of four functions as follows:

- **Smoothing Function** : This function is an addition some positive value into the denumerator part of a signum function as shows in smoothing function,

$$\operatorname{sgn}(s) \rightarrow \frac{s}{|s| + \delta} \tag{2.58}$$

  This function can be reduce the chattering but the value of this equation will be decreases when δ increases. Figure 2.10, shown the output of a smoothing function. In this figure, dash line represents the output when the value of δ is a small value and the solid line represents the output when the value of δ is a large value. The magnitude of, this function is lower than 1 that effect to the nonlinear control u_{nl} is lower than its possible.

Table 2.4: Experimental Parameters

Parameters	Value	Unit
A_1	314	mm^2
A_2	235	mm^2
A_3	78.5	mm^2
m	3.0	kg
L	0.2	m
V_{01}	314	mm^3
V_{02}	235	mm^3
R	287	N·m/kg·K
C_f	0.23	-
C_a	0.04	$\sqrt{1/K}$
C_b	0.16	$\sqrt{1/K}$
T	293	K
k	1.4	-
P_a	0.1	MPa
P_s	0.6	MPa
P_{cr}	0.5	-

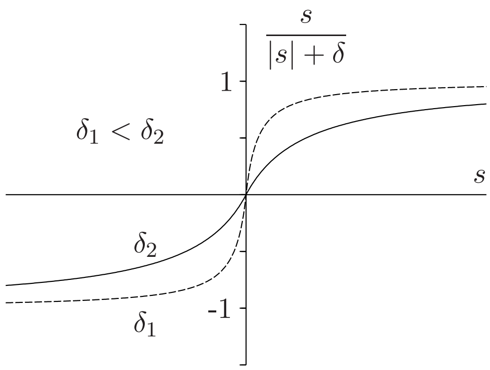


Figure 2.10: Smoothing function

- **Dead-Zone Function** : Figure 2.11, shows the output of this function. The value of δ is a dead zone of input s.

$$\operatorname{sgn}(s) \rightarrow \begin{cases} +1, & \text{for} \quad s > \delta \\ 0, & \text{for} \quad -\delta \le s \le \delta \\ -1, & \text{for} \quad s < -\delta \end{cases} \tag{2.59}$$

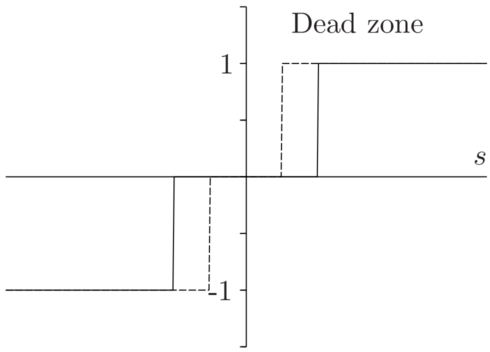


FIGURE 2.11: Dead zone function

- **Hyperbolic Tangent Function** : The output signal of this function like an s-latter, so-called s-function. The hyperbolic tangent can be express as;

$$\mathrm{sgn}(s) \rightarrow \tanh\left(\frac{s}{\delta}\right) \tag{2.60}$$

Figure 2.12 shows the output of this function.

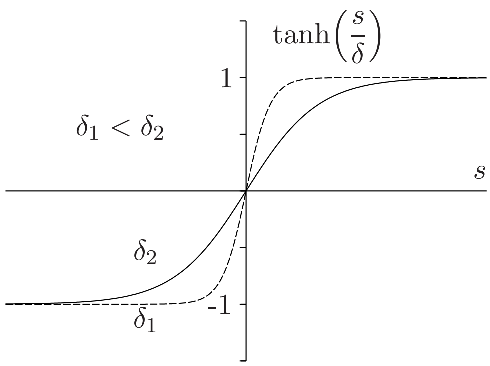


FIGURE 2.12: Hyperbolic tangent function

- **Saturation Function** : Figure 2.13 shows the output of this function.

$$\mathrm{sgn(s)} \rightarrow \mathrm{sat}\left(\frac{\mathrm{s}}{\delta}\right) = \begin{cases} +1, & \text{for} \quad \mathrm{s} > \delta \\ \frac{\mathrm{s}}{\delta}, & \text{for} \quad -\delta \leq s \leq \delta \\ -1, & \text{for} \quad s < -\delta \end{cases} \tag{2.61}$$

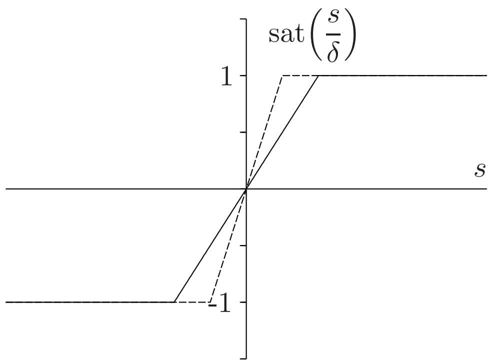


FIGURE 2.13: Saturation function

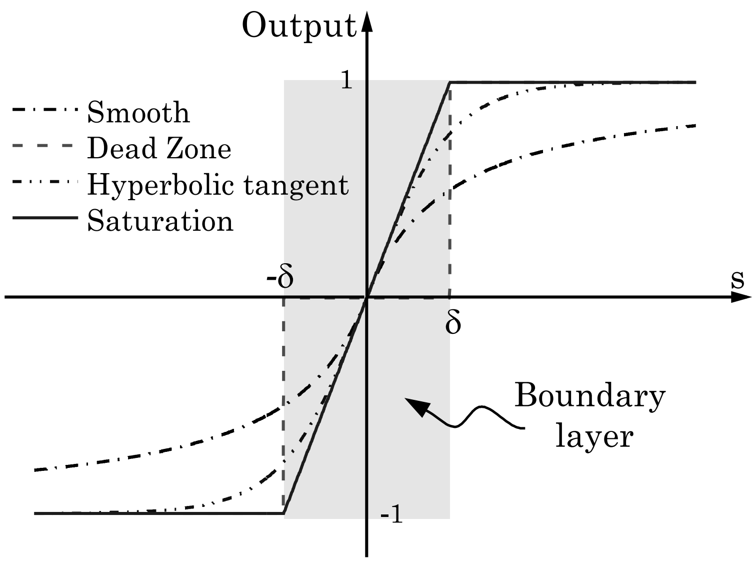


FIGURE 2.14: Chattering Reduction Methods with same δ

Figure 2.14 shows the output of above chattering reduction methods with same value of δ. Now, let we investigate the performance of each chattering reduction method using δ is 20, and Fig. 2.15 shows the results. Observing that, all chattering reduction methods can reduce the chattering phenomenon. The differences in position accuracy can be discussed as follows: the position response curves using *Smooth* and *Hyperbolic tangent* function when the switching surface is out of boundary layer neighboring the switching surface [34] are less than one (see Fig.2.14), that have been an effect to the control action is lower than properly. For the *dead-zone* and *saturation* function has no such an effect as described above but the *dead-zone* function is zero when s is in the bound of switching surface that also degrade the control action and provide the largest steady-state error. The comparison of VSC with chattering reduction methods are shown in Table 2.5. Consequently, the VSC with *saturation* function is an appropriate improving method to reduce the chattering phenomenon since its provided of lower rise time, smaller error, and smoother motion than other three methods. Now, let we compares the position

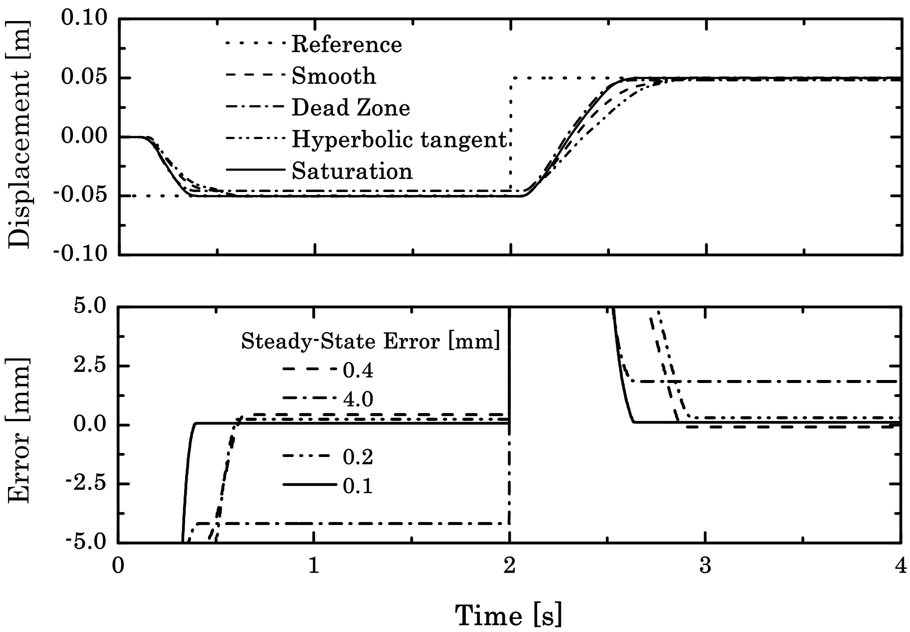


FIGURE 2.15: Position Response using Proportional-valves with chattering reduction

TABLE 2.5: Comparison of Chattering Reduction Methods

Methods	Settling time[s]	error[mm]
Smooth Function	0.36	0.4
Dead-Zone Function	0.31	4.0
Hyperbolic Tangent	0.39	0.2
Saturation Function	0.30	0.1

responses of each chattering reduction into same graph as shown in Fig. 2.15. The comparison of each chattering reduction shows in Table 2.6, the position response of the saturation function provided best of high-response, small-error, and smooth motion. Therefore, chattering reduction using saturation function is preferable in this case.

TABLE 2.6: The Comparison of each chattering reduction

Chattering Reduction Methods	**Low rise time**	**small error**	**Smooth motion**
Smooth Function	◯	◯	◯
Dead-Zone Function	◎	□	◎
Hyperbolic Tangent	□	◯	□
Saturation Function	◎	◎	◎

Remark: ◎=Great ◯=Good □=Fair

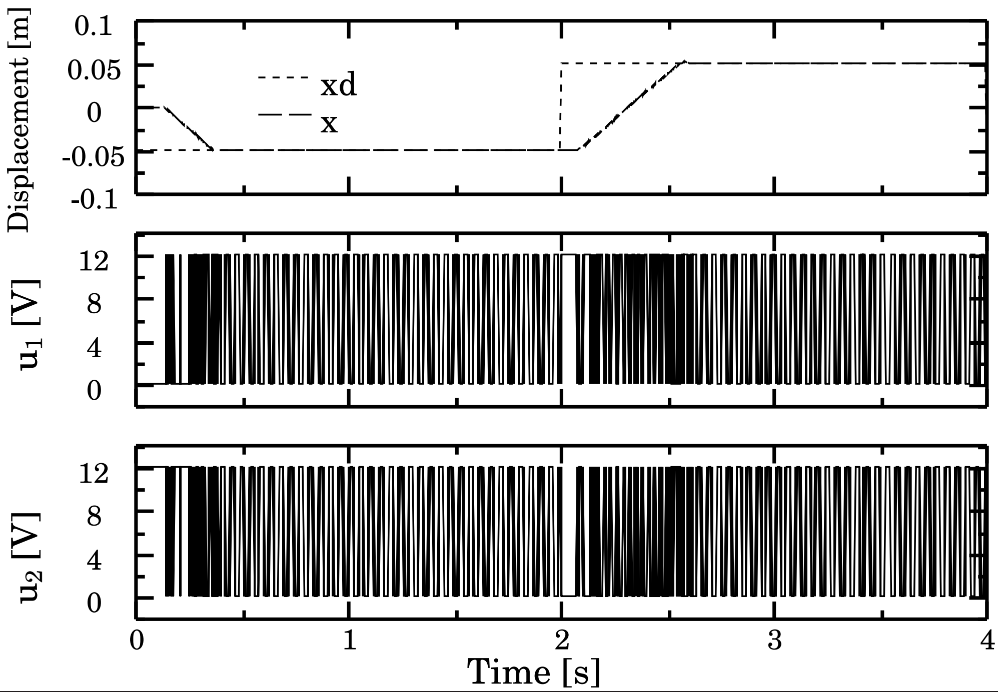


FIGURE 2.16: Position Response using ON/OFF valves with chattering reduction of *saturation* function

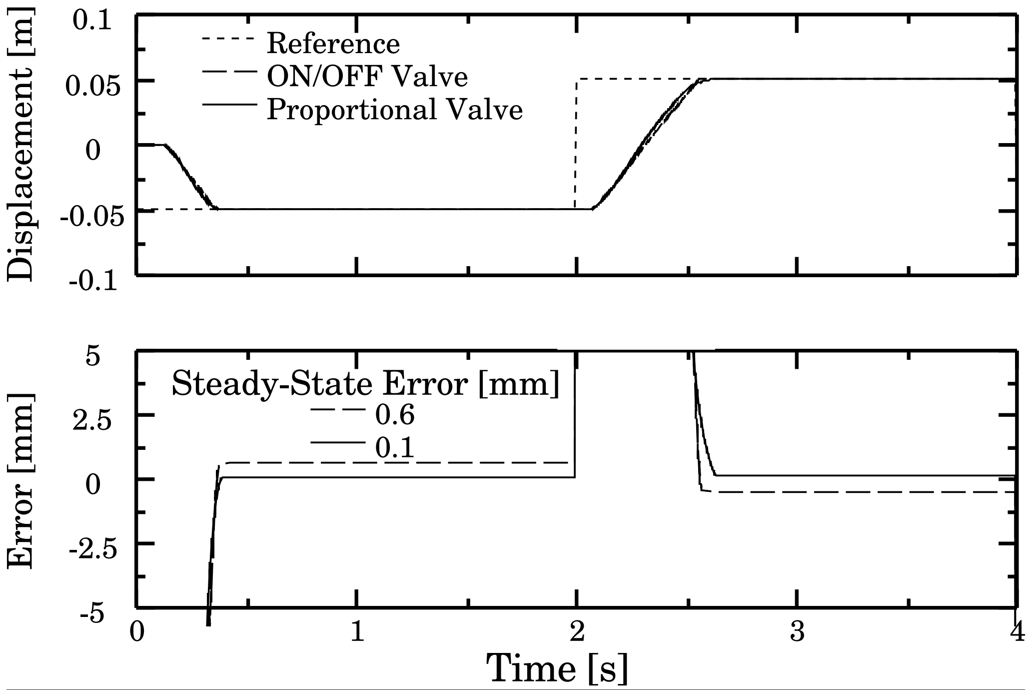


FIGURE 2.17: VSC with Proportional and ON/OFF valve with chattering reduction of *saturation* function

2.5.4 VSC with ON/OFF Valve

2.5.4.1 Control Parameter Determination

Three major parameters of the controller in Eq.(2.44) are also determined under the stability condition of Eq.(2.50) with the same plant parameters as VSC with proportional valve with chattering reduction method of *saturation* function. For λ and ϕ are same as VSC with proportional valve as shown in Section 2.5.3.1 (The value of $\lambda = 50$ can be obtained by trial and error technique in tuning phase that depends on desire rising time of the closed-loop system.), and $\varphi = 1.01$ can be determined by expression (2.45) with consideration of maximum value of the effective area of the valve with 1.0 mm^2.

2.5.4.2 Comparison to Proportional Valve

The experimentals with ON/OFF valves are carried out by using the same reference position of Square-wave as VSC with proportional valve in Fig.2.15. The result are shown in Fig. 2.16.

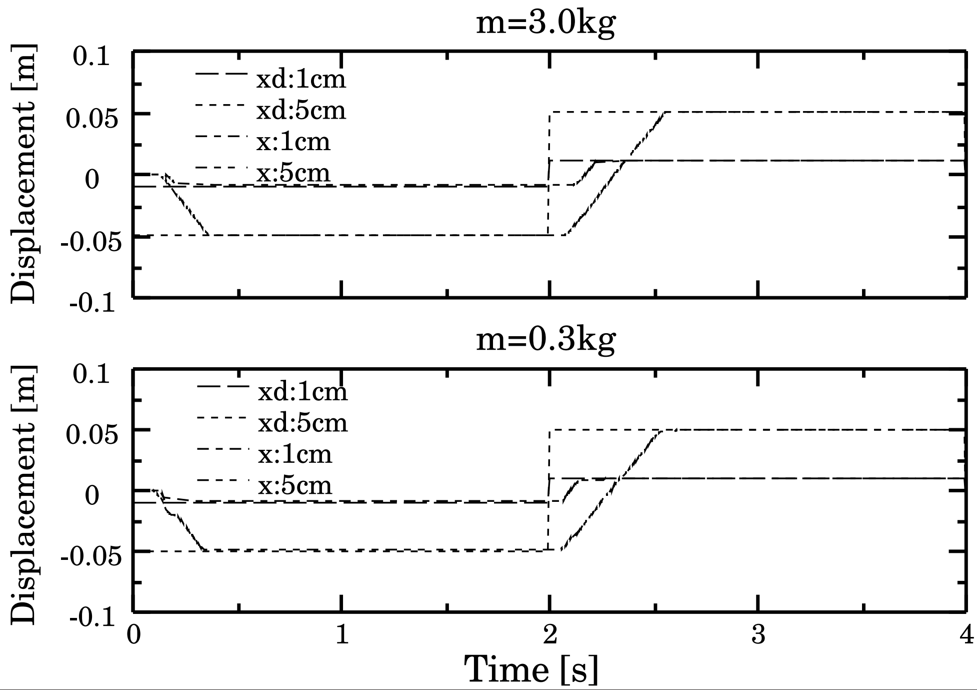


FIGURE 2.18: VSC with ON/OFF valve Robustness Investigation in Variation of references input and payload

VSC with ON/OFF valve provided good performance of position controls same as the using of proportional valves. The comparison of both results between proportional and ON/OFF valves in detail are shown in Fig. 2.17. Observing that, the VSC with both type of valves provided almost the same settling time and the steady-state error is 0.1 mm for VSC with proportional valve, 0.6 mm for VSC with ON/OFF valve.

2.5.4.3 Robustness Investigation

The robustness investigation are carried out as follow. Figure 2.18 above ($m = 3.0$ kg) shows the experimental results with square-wave position reference signal of 0.05 m, 0.01 m amplitude and 0.25 Hz frequency. Dash-dot line represents the position response of 0.01 m reference input and Dash-dot-dot line represent the position response of 0.05 m reference input. For both of position response curves, the VSC with ON/OFF valve still provided good performance in position control, and the steady-state error is in bound of the allowable tolerance (2% of reference) as shown in Table.2.7.

And also the robustness of designed VSC in payload and input variation are investigated.

Table 2.7: Comparison of Variation of Reference Input

Reference Position[mm]	Steady-state error[mm]
10	0.1
50	0.6

The nominal-mass of the system (piston, rod, linear slide, and payload) is $m = 3$ kg. The remove of the payload decreased the mass by 10 times to $m = 0.3$ kg. Figure 2.18 bellow ($m = 0.3$ kg) shows position response with the same reference signal as in Fig.2.18 above ($m = 0.3$ kg). Observing the responses, the designed VSC provided similar rise time to nominal one and the overshoot phenomenon [25] is not appeared. Even though the steady-state error of VSC wiht ON/OFF valve is bigger than proportional valve, the VSC with ON/OFF valve having a useful on price advantage (Table.2.3).

2.6 Concluding Remarks

From the viewpoint of the inherently safe design strategies. We have minimized the number of pneumatic control devices, e.g. servo amplifier for proportional valve, we have substituted the ON/OFF valve for the proportional one, we have moderated and simplified the overall of the pneumatic actuator control system by using the Variable Structure Control (VSC) with an ON /OFF valve to eliminate the effect of the static friction have been proposed based on VSC with proportional valve. A fictitious disturbance in control action has also been proposed to examine the robustness theoretically as in Eq.(2.50). Experimentally an identified model with ordinary equations has been carried out. By using the models, the VSC with ON/OFF valve has been designed based on proportional valve method. Closed-loop stability analysis of VSC with ON/OFF valve using Lyapunov's function has been carried out. The chattering phenomenon reduction by using the *saturation* function has been introduced by comparison to other methods experimentally. The comparison of VSC using proportional and ON/OFF valve with the same of control parameters has been carried out and both have comparable performances. The robustness of the designed VSC with an ON/OFF valve for the variation of reference input and payload have been investigated and experimental results provided similar responses to nominal ones, which implies good robustness of the proposed method. Therefore, by using the proposed VSC with an ON/OFF valve, the ON/OFF valves can be a replacement of the proportional valves in pneumatic cylinder systems. A further issue is a detailed interpretation of the robustness condition in Eq.(2.50).

Note that in order to apply a pneumatic actuator into a restaurant service robot, a compressed air tank (main power source of a pneumatic actuator) is needed and we have at no appropriate solution to put the tank into the robot in a safe way at present. Therefore, we have not applied a pneumatic actuator with the proposed method into our restaurant service robot. Nevertheless, the proposed method can be useful for RSR utilization in the future.

Chapter 3

Restaurant Service Robots Development in Thailand

[1]This chapter describes our development of service robots evaluated in real restaurants. Our objective is to develop two types of robot for 1) taking orders from customers and 2) delivering an order to the table. This project is in collaboration between Bangkok University and MK Restaurants Group Public Company Limited. To achieve this objective, we have applied simple technologies from our experiences at the robot competition called Robocon. And also risk assessment and risk reduction of the robot are shown here.

3.1 Introduction

The purpose of this chapter is to describe our service robot development and to evaluate whether the design requirements $R1 - R14$ in Section 3.3.2 have been satisfied or not in the real environment. These have been carried out through the collaboration between Bangkok University and MK Restaurants Group Public Company Limited (MK Company). The author was involved as the project manager and robot system designer from 2009 to 2012. The developed robots are expected to go to a customer's table by using simple Robocon technology to provide the services of taking orders and serving food.

[1]this chapter appears in the journal of *Robotics and Mechatronics (JRM)*, Vol.27, No.1, 2015. Except the Section 3.4

The first and second robots were developed to take orders from a special menu. The third, fourth, and fifth robots were designed to deliver a specific menu to the customer's table. These five robots work at five separate branches of the restaurant.

A Systematic Approach of Engineering Design [27] and the ISO safety standard for service robots in ISO/FDIS 13482 [28], have been used as design guides in developing these robots. To evaluate the robots, five branches of MK Company in the Bangkok area of Thailand have been used for six months and a Lessons Learned Report in [29] has been used to summarize evaluation results.

3.2 MK Restaurant Robot Project

3.2.1 Project Overview

MK company has more than 450 restaurants in Thailand and the president of the company proposed the idea to use a robot for a particular service task in all of their restaurants in 2009. This would be the first service robot project in Thailand, utilized in a real–world situation. Bangkok University (BU) is an engineering partner in the project. From both business and education viewpoints, the objectives of this project are:

1. To develop a robot for restaurant service tasks and customer entertainment.

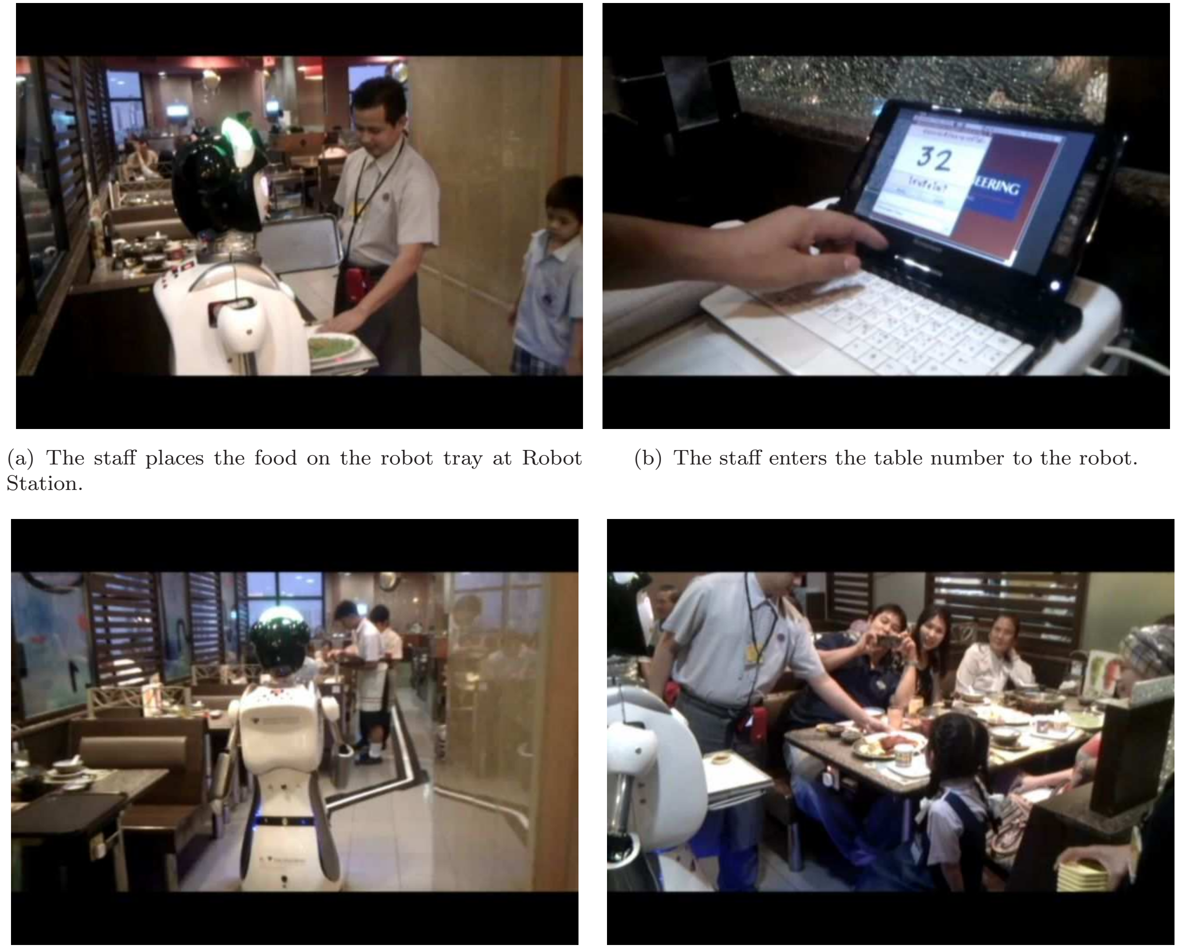
2. To attract students in engineering fields.

To achieve both objectives, the robot development team should involve not only engineers but also a designer for ensuring that the product has an attractive exterior design. This project is thus organized through three parties: 1) MK company, 2) the BU School of Engineering, and 3) the BU School of Fine and Applied Arts. There is no precedent related to this project in Thailand, so systematic project management is important in compensating for any lack of experimental knowledge in this area. The BU Robotics Laboratory (BURL) became the project manager and the V-model [38] and Matrix Organization [39] was used for providing systematic project management tools.

3.2.2 Real Restaurant Environment

MK Company restaurants (from here on referred to as MK) are located in shopping centers and large public spaces, rather than in their own separate buildings. MKs 11:00 until 21:30, MKs use the table top cooking style shown in Fig.3.1(d): Customers are seated and use a casual meal set. Food is prepared by the restaurant and customers cook it using an induction pot. The MK layout is similar to a road block and the tables are separated from each other by a seated customer's head height partition (Fig.3.1(c),3.1(d)). The customer capacity is 300–500 for each restaurant. These features of MK are summarized as follows:

- The customers and staff of MK are from the general population.
- Sanitation restaurant.
- Hot boiled water (soup) in a pot is placed on the customer's table.
- The floor is designed for easy staff operation, i.e., a flat ceramic tile floor without steps and cable rails.
- Most of the interior furniture, i.e., tables and chairs, are fixed to the floor.
- Service carts are moved by staff for service tasks along a walkway.



(a) The staff places the food on the robot tray at Robot Station.

(b) The staff enters the table number to the robot.

(c) The robot moves to the destination table using line tracing.

(d) The staff dish out and places the food on to the table. Customers cook the food by themself in the Tabletop cooking style.

FIGURE 3.1: Restaurant environment and typical robot operation scenario.

3.2.3 Typical Conceptual Scenario

The typical conceptual scenario is designed by considering potential MK requirements. The scenario is used as a guide in determining the detailed conceptual design of an individual robot component and the feasibility of the idea of a robot being used by the development team. The scenario for the Server robot is as follows (Fig.3.1): Initially, the robot is located at an assigned station (close to the kitchen, A in Fig.3.2). A robot operator (MK staff member, trained by BURL) turns on the robot. The operator places food in the food container (on the robot's chest, Fig.3.1(a)). The operator then enters the table number in the robot, which then selects a path to move along automatically (Fig.3.1(b) and 3.1(c)). Upon reaching the table, the robot greets the customer and opens the lid of the food container (B in Fig.3.2). The robot operator or a waiter near the robot moves the food from the food container (Fig.3.1(d)) and puts it on the table. The robot then returns to its station and waits for further service requests. The robot operator decides whether to deploy the Order robot to take an order, especially for new customers. The robot then follows the steps detailed above.

3.3 Robot Function Development

3.3.1 Development Team

Main BURL robot development members have graduated from the BU School of Engineering of BU undergraduate course. Their participation in the project is a good opportunity for robotic career design in Thailand. To develop a variety of robot designs and styles, the BU School of Fine and Applied Arts became a development member specializing in handcrafts. Coordination between the engineering and art groups is challenging due to their different cultures.

3.3.2 Design Requirements

MK wants to have two types of robot:

1. An Order robot to take food orders directly from customers at specified tables.

2. A Server robot to take food to the designated tables.

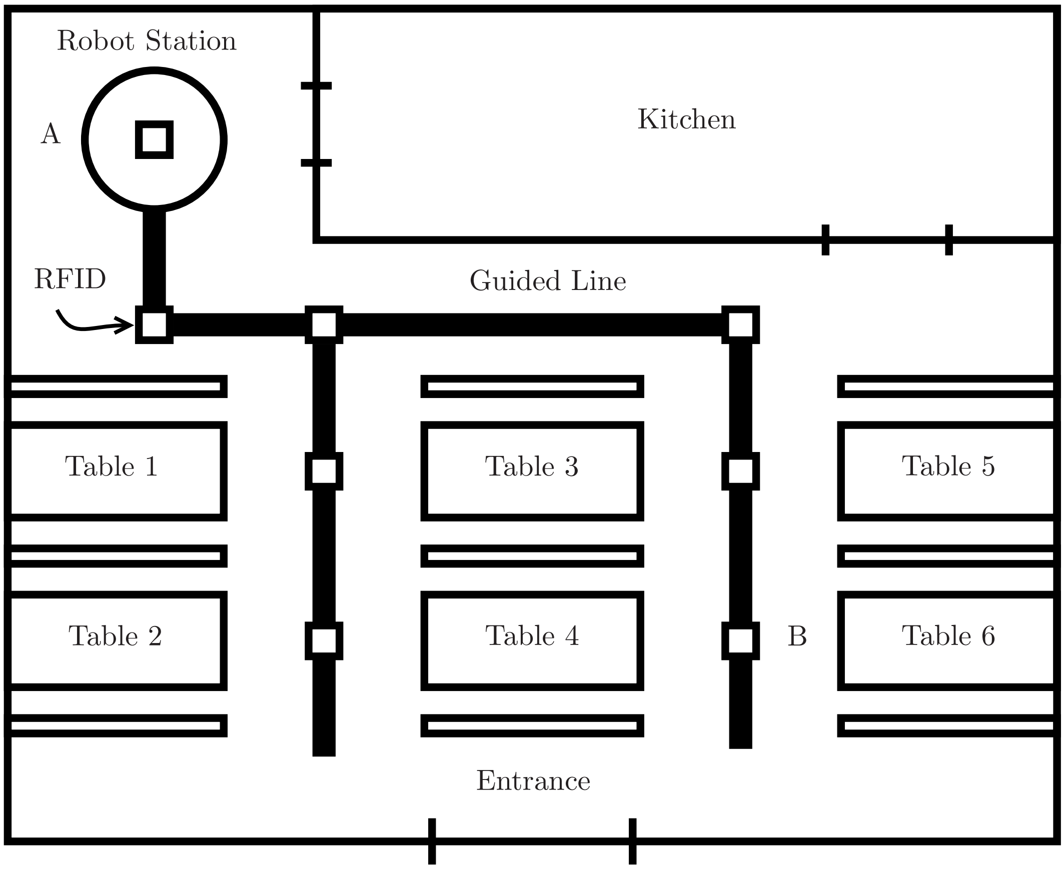


FIGURE 3.2: Image of the restaurant floor plan and robot guidance system.

Robots thus are used and interact with customers and the MK staff, including managers. The basic demands of both robots are as follows:

D1. Easy use and entertainment for customers

D2. Easy use and maintenance by MK staff

D3. No waiting for battery charging

D4. Water resistant/proof design

D5. Automatically moving to tables

D6. Safety, e.g., notification, warning signals and emergency stop switch

D7. Satisfy the MK's sanitation standard

To meet these demands, both types of robot require the following:

R1. Thai language graphic user interface (*D1,D2*)

R2. Waterproof skin (*D2,D4*)

R3. Simple sentences (voice) for communication of greetings (*D1,D2*)

R4. Pushed by hand (*D2*)

R5. Pause button (*D2*)

R6. Robust operating system requiring minimal intervention (*D2*)

R7. Swappable battery (*D3*)

R8. Enclosed circuit boards (*D4*)

R9. Robot localization (*D5*)

R10. Obstacle detection (*D5,D6*)

R11. Sound and light for warning and entertainment (*D1,D6*)

R12. Minimum sufficient motor power (*D6*)

R13. Emergency stop switch (*D6*)

R14. Sanitary food container (*D7*)

R15. Two movable arms (*D1*)

R16. Movable head (*D1*)

R17. Battery charging station (*D3*)

Note ($D\sharp$) indicates the demands, which correspond to the requirements.

In consideration of the above information, the following technical specifications have been made:

T1. Tablet computer for robot operator (*R1,R6*): Android OS with a 7 inch monitor size.

T2. Thermoforming plastic (*R2*): ABS plastic 2 - 3 mm thin.

T3. Stereo speaker (*R3,R11*): 3W-RMS, 150Hz-20KHz.

T4. Back-drive-ability of the drive wheels with casters (*R4*): 127 mm diameter of two drive wheels and front/rear caster.

T5. Average body size of restaurant's female staff (*R1*): A cylinder shape of 500 mm diameter and 1,500 mm height.

T6. Average weight similar to restaurant's female staff (*R1*): <50 kg.

T7. Emergency switch (*R5,R13*): IEC class 3 SW.

T8. Linux operating system. (*R6*): Ubuntu distribution.

T9. Battery drawer (*R7*): slide by hand.

T10. Water proof circuit boxes (*R8*): Industrial standard water proof box.

T11. Position confirmation device (*R9*): Low frequency RFID reader and RFID cards.

T12. Guided line (*R9*): black and write vinyl stickers.

T13. Guided line tracing sensor (*R9*): Bulk of fiber optic sensor with serial port.

T14. Long range measure sensor (*R10*): Ultrasonic range sensors with I2C.

T15. Near range measure sensor (*R10*): IR range sensor with analog output.

T16. Human or not sensor (*R10*): PIR sensor with digital output.

T17. Changeable color lamp (*R11*): 12 V RGB LED lamp.

T18. Less than one-fifth of human walking speed (1.4 m/s) [40] (*R12*): < 0.28 m/s.

T19. DC motor with planetary gear box (*R12*): 12 V, 20 rmp.

T20. DC motor driver with current control (*R12*): 24 V, 2 A.

T21. Rounded edge of the food container and tray (*R14*): Thin stainless steel sheets.

T22. Two arms with 3-DOF (*R15*): Pitch/Roll Shoulder with Fixed Yaw and Pitch Elbow joints.

T23. 2-DOF of head joint (*R16*): Pitch/Yaw joint.

T24. Sealed Lead Acid battery (*R17*): 12 V, 20 Ah.

Note ($R\sharp$) indicates the requirements, which correspond to the technical specifications.

The relation of the demands, requirements, and technical specifications shown in Figure 3.3.

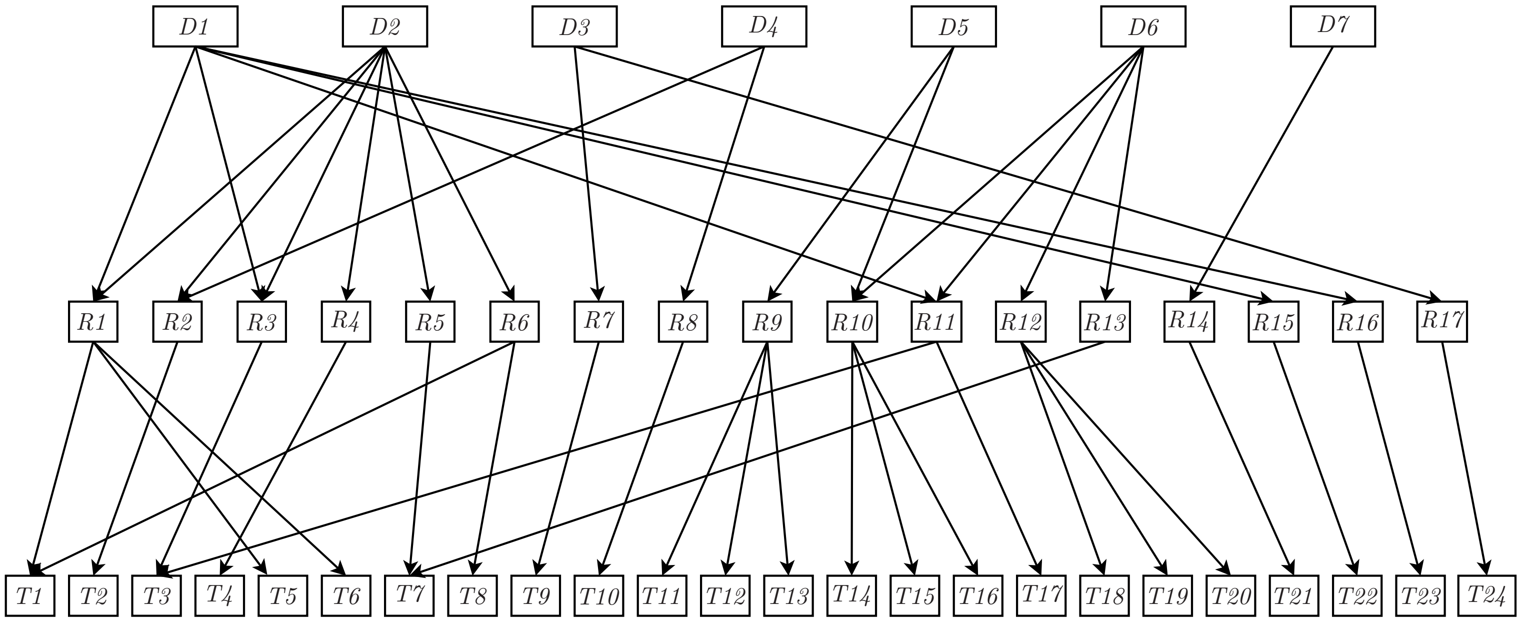
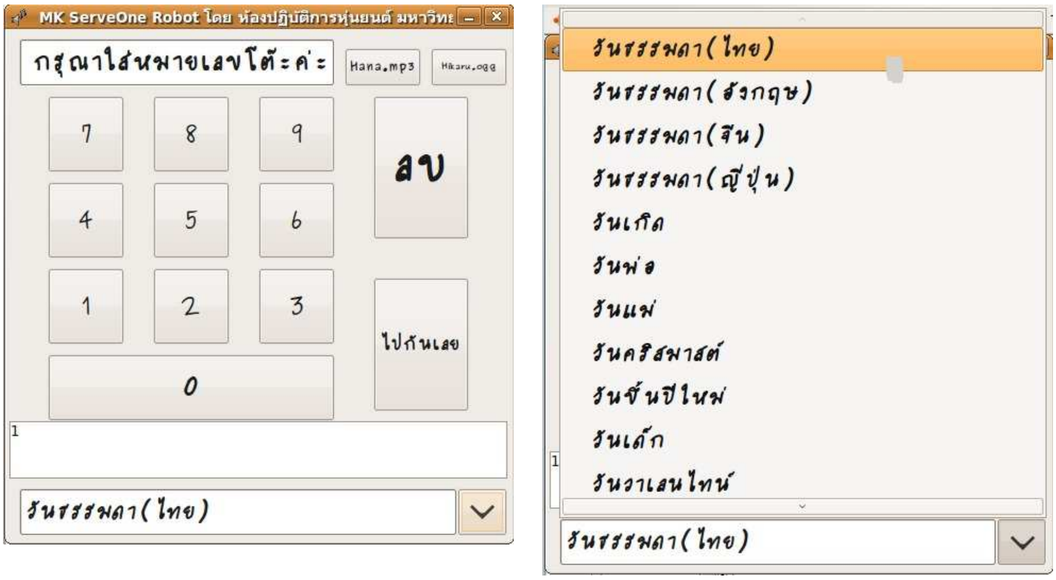


FIGURE 3.3: Relation diagram of the demands, requirements, and technical specifications



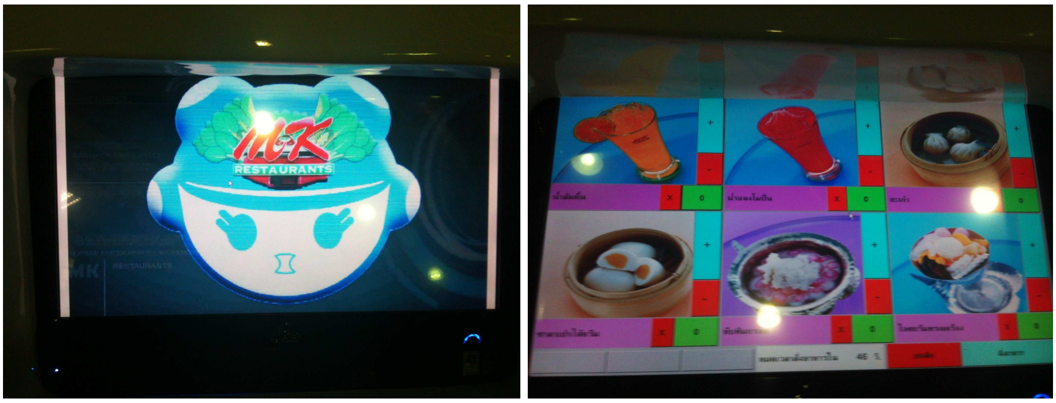
(a) (b)

FIGURE 3.4: Staff Interface with GAMBAS2 : Thai language Graphic User Interface (GUI) for, (a) entering the destination, (b) choosing a special feature for robot entertainment.

3.3.3 Conceptual Design and System Description

3.3.3.1 Control System

The requirements, the robot should perform multiple tasks simultaneously, e.g., robot localization, obstacle detection, robot arm movement for entertainment and warning system. A single controller is not sufficient to control all units in real time, e.g., the robot is getting a lot of data from obstacle sensors while it moves. Therefore, to satisfy the requirements based on the Distributed Control System concept [41, 42], a Master–Slave control system is used here. The slave controllers will be used to control hardware directly, while the Master will be used to control the Slave. The Master and Slave are connected together with a data communication bus to reduce the complexity of the circuit design.



(a) (b)

FIGURE 3.5: Customer Interface, (a) cute character as the robot face, (b) food items that the customer can order from the robot.

3.3.3.2 User Interface

By considering the requirements *R1* to *R14*, a computer operating system (OS) will be needed for the robot here. Since the robot is used in a real restaurant environment for some months, the OS should be robust and reliable, i.e., strong computer virus protection at the least. In addition, the cost of the OS including maintenance and upgrade should be minimized according to real business requirements. Therefore, the Linux OS has been chosen for the project. Figure 3.4 shows the user interface and it has been developed with GAMBAS2 Programming on the Linux OS. GAMBAS2 is accompanied with the integrated development environment, which makes the development procedure simple and reliable. The developed user interface application is used to enter the table number and choose a pre-programmed lighting and sound performance that correspond to some special days (e.g., birthday, national father's day). Moreover, the robot is designed to interact with customer, greeting customers in four pre-programed languages: Thai, Chinese, Japanese, and English. Figure 3.5(a) shows the Robot face of the Order-robot. It has been created by flash and C language, and the motion of the mouth synchronizes with the music and the robot voice. Figure 3.5(b) shows the ordering system, where customers can order by themselves.

3.3.3.3 Safety and Water Protection

Since the robot is used by the general public in the restaurant, safety is the most important part of the design. By following the safety design principle, using the international safety standard (ISO 12100), the safety of the public is assured. According to the risk assessment, typical hazards of the robot are the gap between moving parts (pinching point), falling over especially when children are present and the motion speed (kinetic energy) of any moving parts (wheels, arm and head joint). Most of these risks from the robot can be made tolerable by minimizing the power of the robot (low inertia, low torque and speed, and low voltage). ISO 13854 (Safety of machinery – Minimum gaps to avoid crushing a part of the human body) is also used to determine gap size of all–moving parts of the robot to avoid pinching and crushing.

During the robot's operation, drinking water, soup, and sauce are dangerous to the electronic circuits inside the robot. To prevent such liquid from coming in contact with the robot, the outer covering is made of ABS plastic. It is used as a primary-protector and a water proof box for electronic circuits is used as a secondary-protector.

3.3.4 Embodiment Design and Developed Robots

Based on the conceptual design, the embodiment design is brought forth. Since automatic travel among the tables is the most important feature of the robot, a simple and well-tried technology using line tracing from the Robocon is applied for guiding the robot, which is described as below:

- Moving mechanism: Two wheel drive with backdrivability and steerable caster wheels are used as shown in Fig.3.6(a)(b).
- Line tracing sensors: A bulk of digital fiber optic sensors (16 nodes) with red LED emitting elements in a compact dimension of 10mm x 30mm x 65mm and serial communication (RS-485) units are used.
- Sensing and Notification: During movement of the robot, if an obstruction is detected, the slave microcontroller of the sensing unit recognizes the obstacle, and the Passive Infrared (PIR) sensors distinguish whether it is human or not human. The sensor data is transferred to the master microcontroller and then the

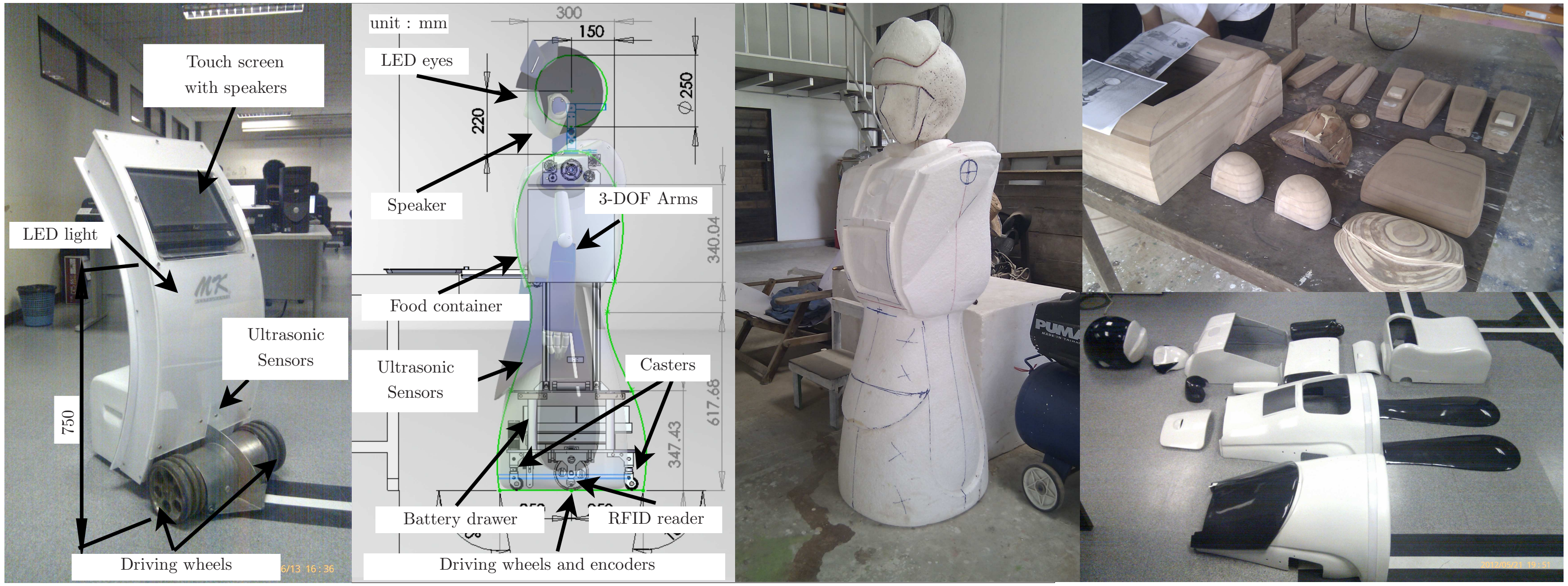
master sends a temporary stop command to the mobility unit via the data bus (Fig.3.7). And also if a human is detected, the master sends a command signal in the notification voice and light signals to the user interface unit ot illustrate what occurred. Such warning system are important to improve safety and operability.

- Robot localization: To identify the robot location, an encoder mounted on a separate small wheel installed side-by-side to the robot driving wheel is used as an odometer. In addition to this, some RFID Cards (credit card size) are attached on to the floor surface (under the guided line sticker) as the robot position confirmation.

- Sanitary food container: A thin plate of stainless steel with a curved tray is used for the food container for easy cleaning.

- Outline dimension: The robots are cylindrical in shape of 40–50 centimeter diameter and less than 155 centimeter in height. These sizes are determined for easy operation in the restaurant environment.

- External skin: The external skin development team has a good ability to handcraft but limited experiences of engineering tools such as 3D-CAD. Therefore a wooden mold approach is used as a feasible embodiment design of the skin. By using this ABS plastic skin was developed. See Fig.3.6(c).



(a) (b) (c–1) (c–2)

Figure 3.6: Embodiment design: (a) Order robot, (b) Server robot. Note robot dimension is in Table 3.1. Handmade skin production: (c–1) Full scale modeling by foam board, (c–2) The foam board is cut into small pieces and Molds are made by using a polywood layering and make ABS plastic Thermoforming.

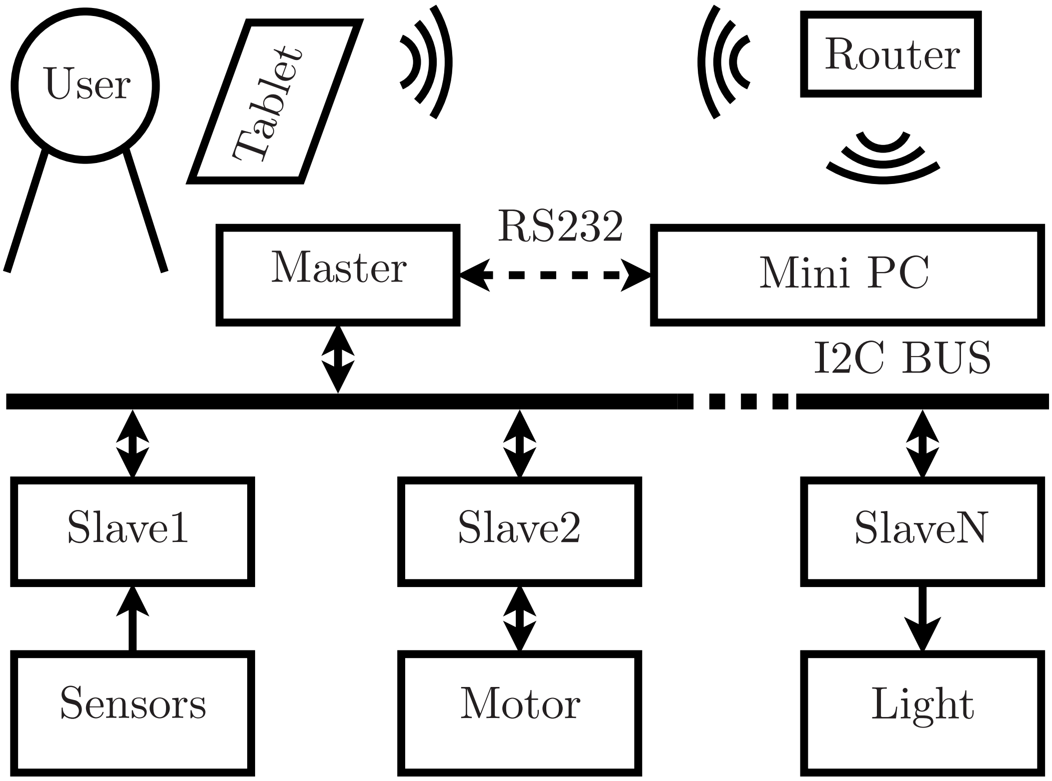


Figure 3.7: Control system block diagram.

Figure 3.7 shows the control system block diagram: a master DSP microcontroller is connected to the slave ones via a Data Bus (100kHz I2C-Bus). The robot joints and drive wheels at each are controlled by using a PID controller in the slave microcontrollers, while another one of the slave controls the color of lights. The master microcontroller obtains a command from the host computer (Mini PC) via Serial Communication (RS-232). A user commands the robot with a touch screen tablet device through the host computer via a Wi–Fi router.

FIGURE 3.8: Developed MK service robots since 2009 until 2012: From left side, ServeTwo (2012), OrderOne (2009), Slim (2012), OrderTwo (2009), and ServeOne (2010).

Table 3.1: Developed robots specification

Robot	Dimension [cm] (W×D×H)	Weight [kg]	Speed [cm/s]	Battery *1 [V,Ah]	UI *2	Obstacle Sensing *3	OPT *4	Skin material *5	OS
OrderOne	50×80×120	60	50	12, 5.5	TSC *6	IR	30	ACL	Windows
OrderTwo	50×50×120	35	30	24, 5.5	TSC	IR	60	FBG	Windows
ServeOne	50×50×145	45	35	12, 11	Tablet *7	US	60	ABS	Linux
ServeTwo	50×50×155	55	25	24, 20	Tablet	US	90	ABS	Linux
Slim	45×45×80	15	25	24, 5.5	Keypad 7s-LED	IR US	60	ACL	No OS

*1 : Swappable Battery (Sealed Lead Acid), *2 : User Interface, *3 : IR InfraRed / US Ultrasonic, *4 : Operation Time in minute (Continuous), *5 : ACL Acrylic / FBG Light Fiber Glass / ABS Acrylonitrile Butadiene Styrene, *6 : Touch Screen Computer, *7 : Remote Tablet Desktop.

Figure 3.8 shows the two types of the five developed robots; Order and Serve, in this project from 2009 until 2012. The Order-robots are named OrderOne and OrderTwo, respectively. The mechanical and electronic circuit designs are almost the same in both. The only difference is the material: OrderOne is made of a stainless steel for robust mechanical performance and maintenance. From the experience of OrderOne, OrderTwo is made of aluminum that leads to easier manufacturing at lower cost and easy transportation to the locations by the staff.

The Server robots are named ServeOne, ServeTwo, and Slim, respectively. ServeOne and ServeTwo are almost the same, and the only difference is the food container area. ServeTwo has special mechanisms to push the food tray down on to the table, ServeOne just opens the lid and slide the tray out for easy removal of the food by hand. ServeOne and ServeTwo use Linux OS for the host controller. The User Interface (UI) of host controller can be a Tablet PC or any Smartphone with Wi–Fi connection capability. On the other hand, the Slim has no OS, it uses a microcontroller, 4x4 matrix keyboard for input, and 7 Segment LED as a UI. The specifications of the robots are summarized in Table 3.1.

3.4 System Safety Development of a MK Robot

In the ISO 12100:2010, the strategy for risk assessment and risk reduction must take the following actions (Figure 3.9),

1. Determine the limits of the robot (intended use and foreseeable misuse),
2. Identify the hazard,
3. Estimate the risk for each identified hazard,
4. Evaluate the risk and take decisions about which risks should be reduced,
5. Eliminate the hazard or reduce the risk.

Note : Numbers one to three are called Risk Analysis, Numbers one to four are called Risk Assessment and number five is called Risk Reduction.

Among the developed robots, we chosen the ServeTwo as a role model of the risk assessment and risk reduction due to it being the most complex system.

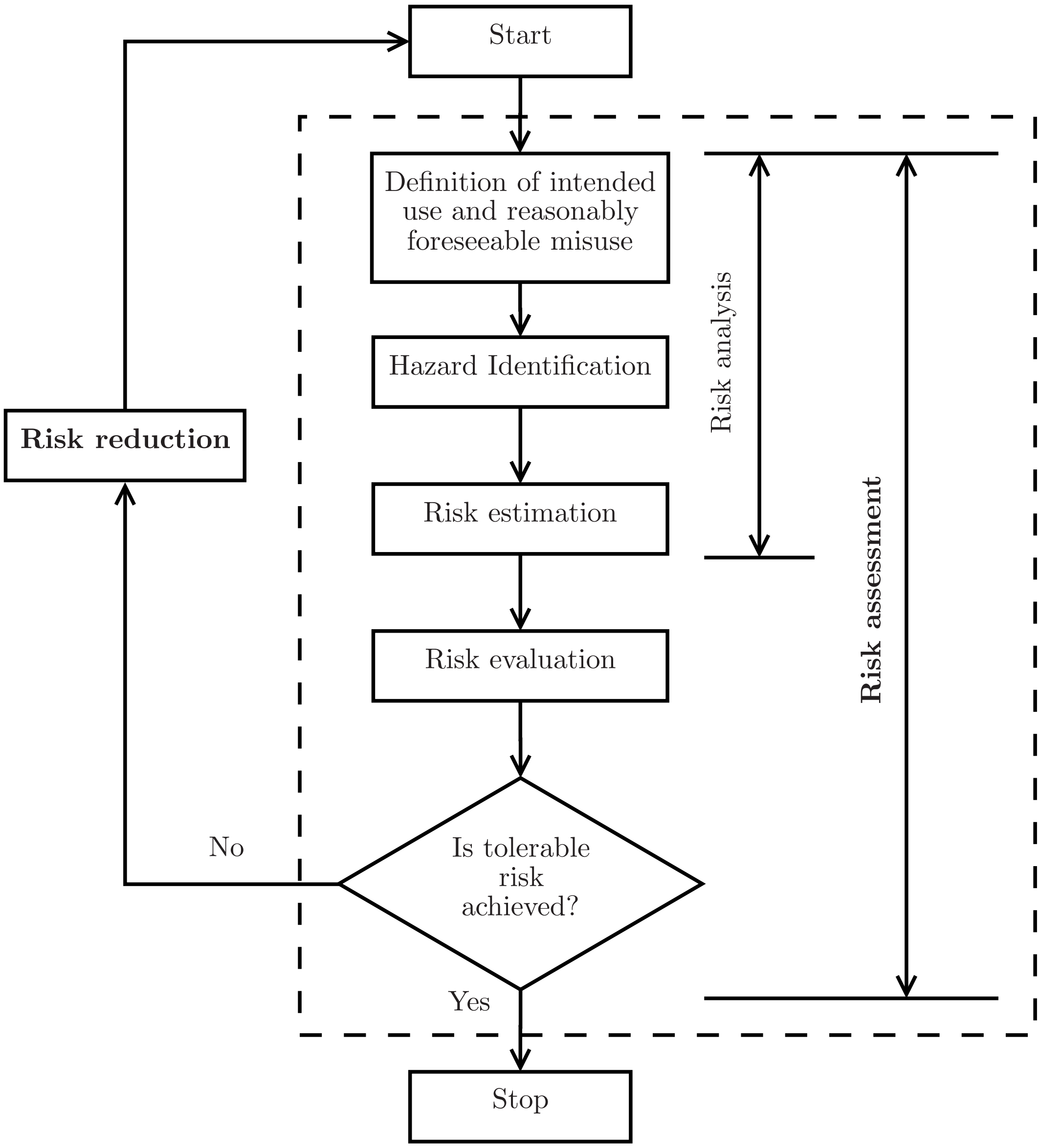


FIGURE 3.9: Risk assessment and risk reduction process

3.4.1 Risk Assessment

The information for risk assessment in accordance with the ISO 12100:2010 clause 5.2 [43] should include the followings: related the robot description, related regulations, standards and other applicable documents, related experience of use, and relevant ergonomic principles.

3.4.1.1 Initial Specifications of the Robot

The initial specifications of ServeTwo are below:

Basic Specifications : According to the robot category ISO 13482:2014 [8], the ServeTwo can be categorized as a Mobile servant robot, Type 1.2 with manipulator. The ServeTwo is used for a restaurant service task with the customer entertainment. The basic specifications of the robot are as follows:

B1. Used as entertainment for customer,

B2. Carry the food to the table,

B3. Used by one operator,

B4. Hand-Loading/Unloading,

B5. Automatically move to the table, and

B7. Battery supplied.

Staff's work to be performed with the robot : The intended use of the ServeTwo is to bring a food (correspond to a carry capability of the robot) to a customer's table and provide entertainment to the customer while moving and at the table. The work to be performed by this robot is as follows:

W1. Hand-Loading/Unloading of food
The operator places the dish of food into the robot at the robot station. When the robot reaches the destination table, the operator retrieves and places the dish onto the customer's table.

W2. Enter the destination
Enter the table number that the robot has to go to.

W3. Follow the robot
The operator goes to the table along with the robot.

W4. Battery swapping/charging
When the battery is depleted, the operator has to change the battery and charges it again.

Description of the robot concept : Figure 3.10 shows the robot concept. Initially, the robot will be located at an assigned robot station (near the kitchen). Then a robot operator (Trained restaurant staff) turns on the robot. The operator will place the food into the food container of the robot. After that, the operator enters the table number to the robot, then the robot will select a moving path and move automatically. When the robot reaches to the table, the robot will say a greeting and it opens the lid of the food container. The robot operator or a waiter near the robot will bring the food down to the table from the container. The robot will close the lid and go back to the station and wait for the next command.

The ServeTwo consists of eight main parts:

- Mobility unit,
- Food container,
- Arms,
- Head,
- Illumination,
- Sound,
- Battery drawer, and
- Battery charging station.

And all over of the ServeTwo's body is covered by painted plastic skin.

3.4.1.2 Experience of Use

The MK project is the first project in Thailand to develop a service robot for the restaurant industry. Few similar applications exist in the world. So, no statistical information is available.

3.4.1.3 Regulations, Normative Reference and Technical Sheets

The following standards were initial candidates to be considered: ISO 12100:2010 and ISO 13482:2014.

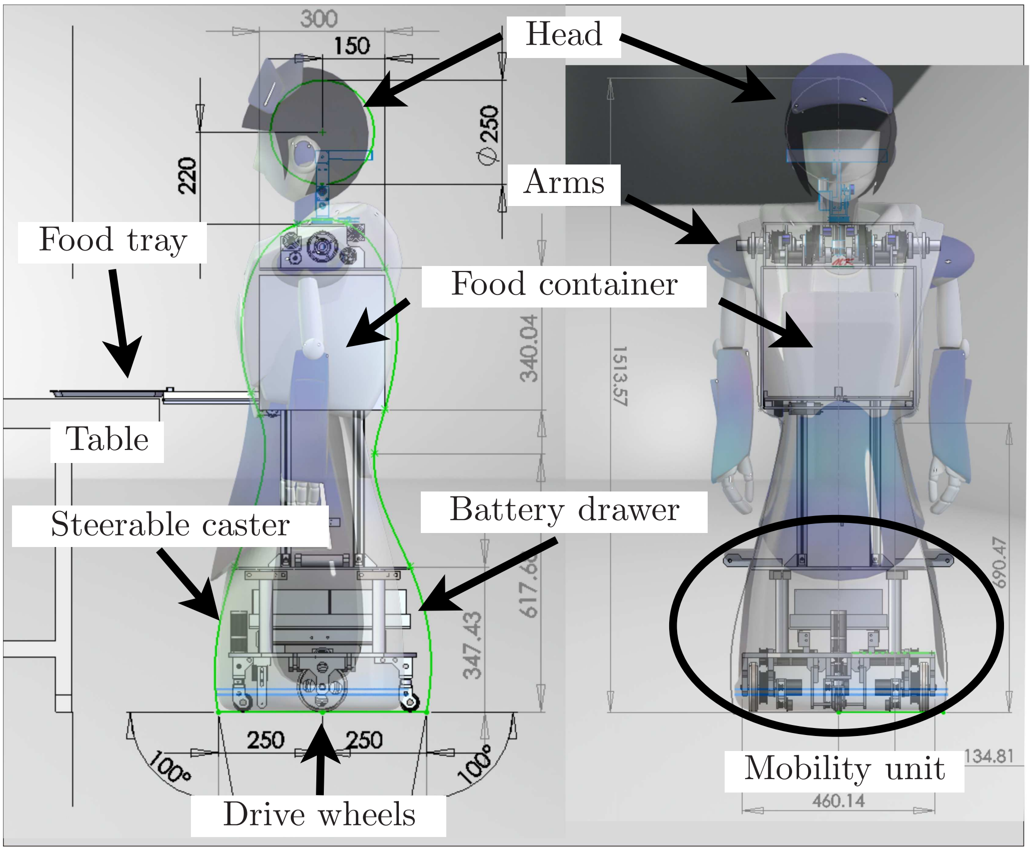


FIGURE 3.10: Main parts of the ServeTwo

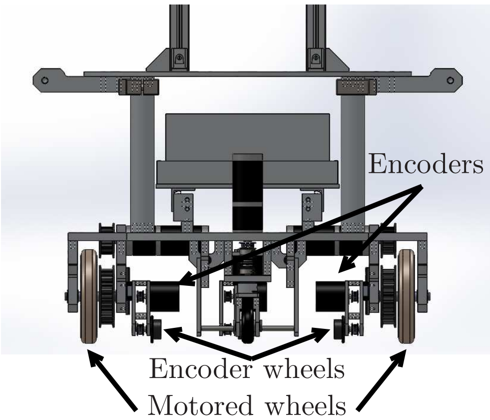
3.4.1.4 Preliminary Design of the Robot

In order to achieve the basic specifications, the ServeTwo needs the following common requirements and technical specifications which are provided in Section 3.3.2 (*R1 – R17* and *T1 – T24*).

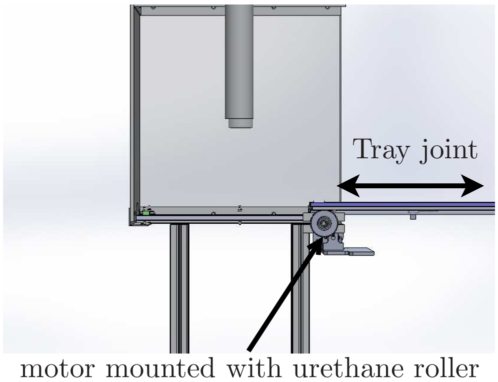
The ServeTwo consists of machined aluminum for the main frame. The most critical parts of the ServeTwo are the:

- Mobility unit,
- Arms transmission, and
- Food container system.

Figure 3.11–(a) shows the detailed mechanism of the mobility unit. In order to prevent a feedback error of the mobility unit controller, between a slippery floor surface and the



(a) Mobility unit



(b) Food conditioner (right view)

FIGURE 3.11: Preliminary design drawings

drive wheels surface, the rotary encoders mounted with knurled urethane wheels have been used as a separate-type of the feedback device.

The food container has two joints, one for open/close the lid and another one for sliding the food tray in/out from the ServeTwo's chest. To prevent from any accident from the geared joint, a friction drive with flat surface is used here. Figure 3.11–(b) shows the detailed mechanism of the prismatic joint, the motor mounted with knurled urethane roller are used as the mechanical power source. To produce sufficient friction force to move the tray, the surface of the roller closely touches on the surface of the tray.

3.4.2 Determination of the Limits of the Robot

3.4.2.1 Description of the Operation Phase of the Robot

To obtain the limitation of robot usage (operation), we have to know about every case of the robot operation. We apply the Unified Modeling Language (UML) for modeling the whole phases of the robot life–cycle. Type of UML diagrams used here is a sub-type of the Behavioral Diagrams called Use Case diagram.

In our case, we have identified the use case from each cycle of the robot operating life–cycle described in Fig. 3.12.

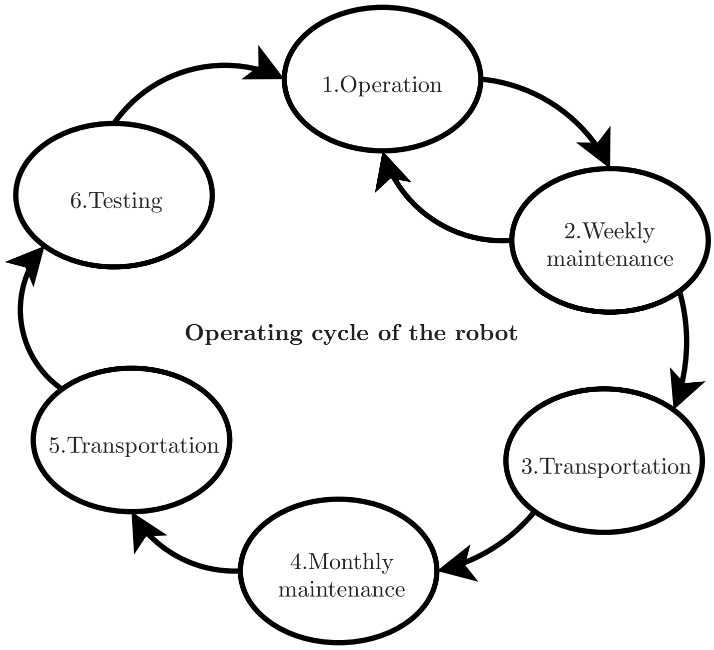
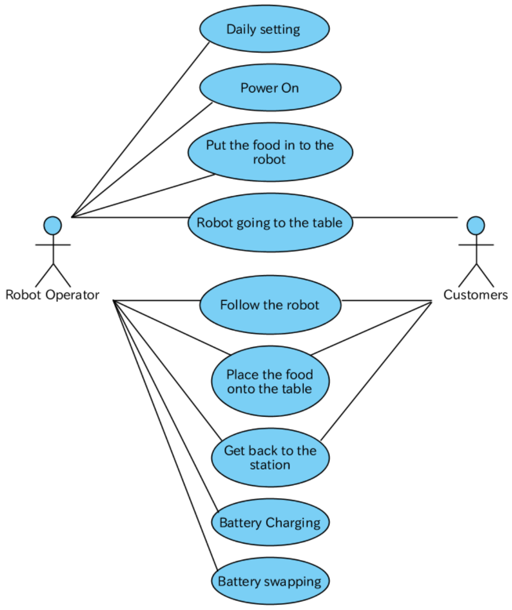


FIGURE 3.12: Typical ServeTwo operating cycle

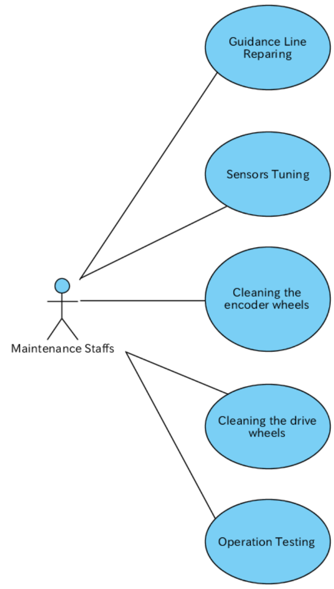
1. Robot operates in real environment, see Figure 3.13(a).
2. Weekly maintenance, see Figure 3.13(b).
3. Transportation the robot to the developing place, see Figure 3.13(c).
4. Monthly maintenance, see Figure 3.13(d).
5. Transportation back to the restaurant, see Figure 3.13(c).
6. Function testing, see figure 3.14.

3.4.2.2 Use Limits

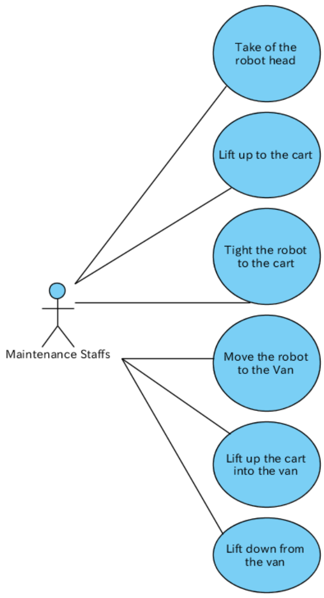
Intended use The ServeTwo robot is intended to bringing food to the customer's table and to entertain the customer while moving to the table and at the table. The food is put in the ServeTwo's food container.



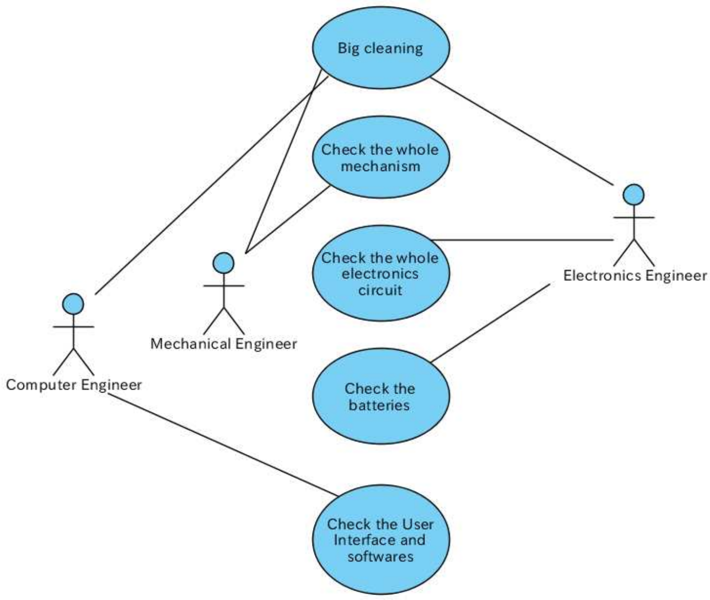
(a) Use Case diagram of the service cycle.



(b) Use Case diagram of the weekly maintenance cycle.



(c) Use Case diagram of the transportation cycle.



(d) Use Case diagram of the monthly maintenance cycle.

FIGURE 3.13: Use case diagram of ServeTwo operating cycle

The staff's work to be performed with this robot is as follows:

W1. Daily setting,

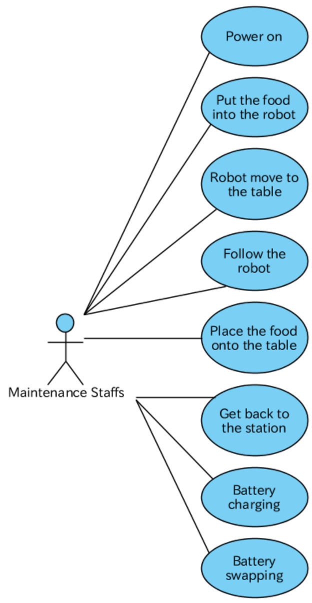


FIGURE 3.14: Use Case diagram of the testing cycle

W2. Hand-Loading/Unloading a food,

W3. Walk after the robot,

W5. Battery swapping/charging.

The ServeTwo is intended to be operated by following restaurant staff as:

- Position : restaurant's employee (long term),
- Age : 16 – 25,
- Height : 155 – 170 cm,
- Sex : Male,
- other : Familiar with smart-device, e.g., smart-phone. Trained for emergency situations.

The followings are typical uses of the robot:

- The ServeTwo robot is intended to be operated with the robot operator (mentioned above) in an upright standing position.

- The operator holds the robot control device and walks after the robot while the robot is moving.
- The operator is allowed to be used only in Automatic mode.
- The ServeTwo robot is intended to pause or stop the ServeTwo's operation at anytime by operator's decisions.
- The ServeTwo robot is intended to be maintained (daily check) by a skilled/qualified operator following the instructions given in the operating instruction manual.
- The ServeTwo robot is intended to have its battery swapped/charged by a skilled/qualified operator following the instructions given in the operating instruction manual.
- The ServeTwo robot is intended to be moved by operator, by hand when the unit is powered off and following the instructions given in the operating instruction manual.
- The ServeTwo robot is intended to be kept at ServeTwo's station and covered (cover provided) when the ServeTwo robot is powered off.

Reasonably foreseeable misuse The reasonably foreseeable misuse taken into account is as follows:

- Operating the ServeTwo with a wet food and/or drink (e.g., soup),
- Use of the ServeTwo by untrained operator,
- Operator move the robot's joint by hand when the ServeTwo is powered or not powered,
- Not keeping the ServeTwo in the proper way,
- Juvenile(s) misusing or vandalizing the ServeTwo robot arm.

Space limits Space limits are as follows:

- The ServeTwo robot is intended for use in an indoor restaurant environment with air conditioner.

- For use, a flat ceramic tile floor or robot walkway of at least 1,000 mm width, free of static obstacles is required.
- The ServeTwo is intended to be used in the area of guided line where robot localization system are installed.
- The ServeTwo is not intended to be used at locations having a wet floor.
- The ServeTwo is not intended to be used in high humidity areas.
- The ServeTwo has a blank distance 15 cm dead zone of radius from outer skin surfaces of the mobility unit.
- Other parts of ServeTwo (except the mobility unit) do not have any other any obstacle sensors are installed.

Time limits Time limits are as follows:

- The ServeTwo is intended for an operational 4 – 5 hours a day.
- Guided line : repair monthly and replace every six months,
- Battery : verify that the battery can provided a power at least 60 minutes and 3 – 4 hours full charge.
- Cleaning of visible and reachable surfaces and food conditioner is to be carried out every shift.
- Invisible and unreachable surfaces cleaning is to be carried out every month.

3.4.3 Hazard Identification

In this section, hazard identification is carried out by using the checklist of ISO 13482:2014 (Annex A of the ISO 13482:2014) and ISO 12100:2010 (Annex B of the ISO 12100:2010), where the following robot operation life–cycle, operating modes, and hazard zone are considered;

Robot Operation Life–cycle

- Operation
- Maintenance
- Transportation
- Functional testing

Operating Modes

- Automatic mode : Loading food, choose the destination table.
- Manual mode : unit testing.
- Setup mode : zero setting of the joints, guided line tracing sensor tuning.

Hazard Zones and Accident Scenarios

- Food container : Lid and Tray joints of the food conditioner.
- Arms : Gaps of the arm joints.
- Mobility unit : gap between the floor and robot's skin.
- Walkway : moving arms touch on unattended customer's body due to they in a dead zone of obstacles sensors.
- Battery charging station : the battery falls down on the operator toes.

Table A.1 to A.6 in Appendix A summarized the operation hazard identifications of the ServeTwo robot. In total, we have 25 of hazards and Table 3.2 shows an example of the hazard identification of the cycle of robot operation.

Table 3.2: Operation hazard identification (for illustration only)

Risk assessment (Operation hazard identification)							
Machine (Robot)			ServeTwo		**Analyst**	EKSIRI A.	
Source			Specification, preliminary design		**Current version**	1.0	
Extent			Operation		**Date**	April, 2014	
Method			Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)		**Page**	2	
Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**			**Ref. no.**
				Hazard	**Hazardous situation**	**Hazardous event**	
6	Operation					Crushing between the mobility unit and the fixed partition	**6**
7		Battery swapping	Battery drawer	Electric shock	Lifting, loading, unloading by staff	Contact with both side of live battery terminals	**7**
8				Fire, discharge of hazardous fumes or substances	Lifting, loading, unloading by staff	Battery short-circuit	**8**
9				Crushing, trapping, pinching, cutting, severing, stabbing, or abrasion	Lifting, loading, unloading by staff	Battery falling	**9**
10						Contact with holes or gaps between moving parts of the battery drawer	**10**
11						Contact with sharp edges	**11**
12		Battery charging	Charging station	Fire, discharge of hazardous fumes or substances	Charging of deeply discharged batteries	Charger failure	**12**
13					Lifting, plug-in	Battery short-circuit	**13**
14				Electric shock	Lifting, loading, unloading	Contact with live battery terminals	**14**

3.4.4 Risk Estimation, Risk Evaluation and Risk Reduction

3.4.4.1 Risk Estimation and Risk Evaluation

For risk estimation, the hybrid of risk graph and risk matrix estimation method has been used, by considering ISO/TR 14121-2:2012 [clause 6.5] [44] with the following parameters;

Severity of the harm : S

- S1 : Minor (no injury, slight injury)
- S2 : Moderate (significant injury)
- S3 : Serious (severe debilitating injury, able to return to work at some point)

Frequency and/or duration of exposure to hazard : F

- F1 : Seldom
- F2 : Frequent

Probability of Occurrence of a hazardous event : O

- O1 : Low
- O2 : High

Probability of Avoidance or reduction of harm : A

- A1 : Possible
- A2 : Impossible

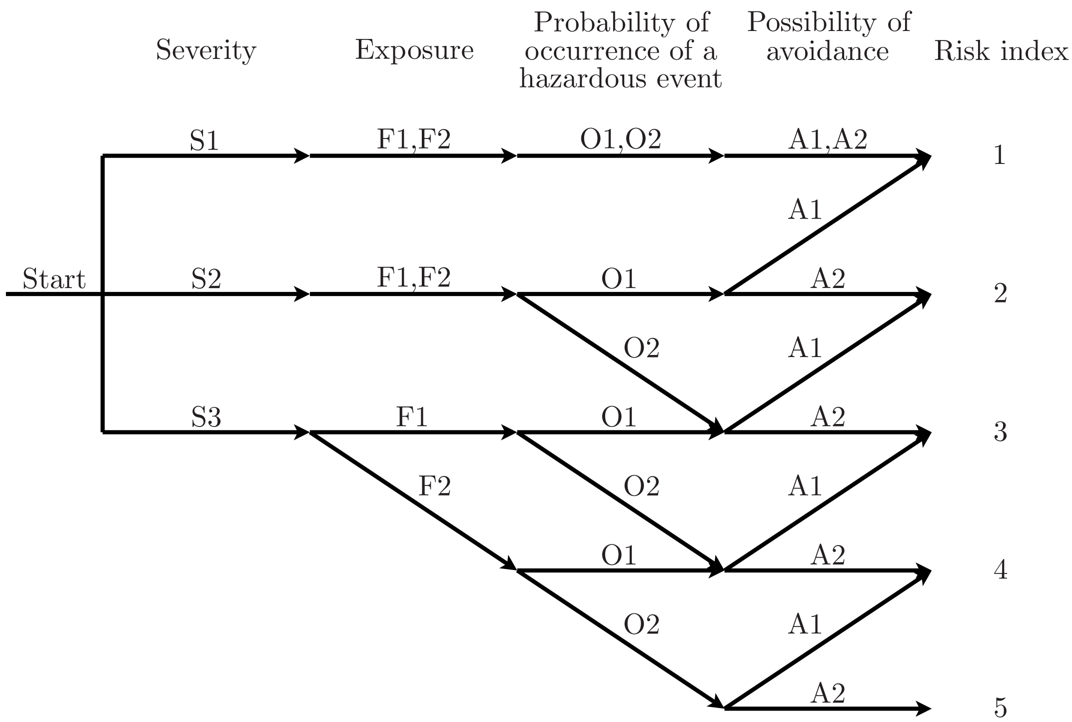


FIGURE 3.15: Risk graph

TABLE 3.3: Risk matrix equivalent to the risk graph in Figure 3.15

		Risk index calculation			
		O1		O2	
		A1	A2	A1	A2
S1	F1	1	1	1	1
	F2	1	1	1	1
S2	F1	1	2	2	3
	F2	2	2	2	3
S3	F1	2	3	3	4
	F2	3	4	4	5

A form is filled in with the result of this first risk estimation: each hazardous situation is allocated a Risk Index (RI), and RI 1 (min.) to 5 (max.).

Then we can construct the risk matrix that equivalent to the risk graph as shown in Table 3.3. Here we use the following risk evaluation; The result of risk estimation (initial risk) have been summarized in Table B.1.

TABLE 3.4: Risk evaluation

Risk index	Risk evaluation	Action
1, 2	Trivial	No action
3	Tolerable (Acceptable)	Monitor
4, 5	Moderate (Unacceptable)	Action

3.4.4.2 Risk Reduction

As the result of the risk estimation (initial risk) (see Table B.1), the summary of which hazard have to be reduced are shown in Table 3.5. As shown in Table 3.5, the nine of hazards (Unacceptable risk) needs a risk reduction (Hazards Ref. No. 3, 4, 9, 10, 11, 13, 15, 22, and 23). By following the three step method of risk reduction, considering ISO 12100:2010 [clause 4] [43] with Inherently safe design measures, Safeguarding and complementary protective measures, and Information for use. The solution to reduce the Moderate (Unacceptable) risks that we have been carried out are shown in Table B.1 (Risk Reduction Protective/Risk Reduction Measures). As the result, the Unacceptable risks (Ref. No. 3, 4, 9, 10, 11, 13, 15, 22, and 23) have been reduced to Tolerable (Acceptable) Risk as shown in Table B.1 (risk estimation after Risk Reduction) and the summary of the Risk estimation (after risk reduction) is shown in Table 3.6. The example of the risk assessment and risk reduction (Protective measures implemented by the designer and Protective measures implemented by the user) are shown in Table 3.7.

TABLE 3.5: Summary of the risk estimation (initial risk)

Risk index (initial risk)	Risk evaluation	Ref. No. (Table A.1 to A.6 and B.1)	Total
1, 2	Trivial	1, 2, 5, 6, 19, 20	6
3	Tolerable (Acceptable)	7, 8, 12, 14, 15, 16, 17, 18, 21, 22, 23, 24, 25	13
4, 5	Moderate (Unacceptable)	3, 4, 9, 10, 11, 13, 15, 22, 23	9

TABLE 3.6: Summary of the risk estimation (after risk reduction)

Risk index (initial risk)	Risk evaluation	Ref. No. (Table A.1 to A.6 and B.1)	Total
1, 2	Trivial	1, 2, 5, 6, 19, 20, 3, 4, 9, 10, 11, 13, 15, 22, 23	15
3	Tolerable (Acceptable)	7, 8, 12, 14, 15, 16, 17, 18, 21, 22, 23, 24, 25	13
4, 5	Moderate (Unacceptable)	N/A	0

Table 3.7: Risk assessment and risk reduction (for illustration only)

Risk assessment and risk reduction													
Machine						ServeTwo	**Analyst**					EKSIRI A.	
Source						Specifications, preliminary design	**Current version**					1.0	
Extent						Use phase: Operation Table A.1 – A.6	**Date**					July 2011	
Method						Hybrid	**Page**					2	
Ref. No.	**Risk estimation (initial risk)**					**Risk reduction Protective/risk reduction measures**	**Risk estimation (after risk reduction) [sub-RI]**					**Further risk reduction required**	**Ref. No.**
	S	**F**	**O**	**A**	**RI**		**S**	**F**	**O**	**A**	**RI**		
6	2	2	2	1	2	Inherently safe design with minimum sufficient power of motor, pause and emergency switches	1	2	2	1	1	No	**6**
7	3	1	2	1	3	providing an insulator to the terminals	3	1	1	1	2	No	**7**
8	3	1	2	1	3	Use an female enclosed connector	3	1	1	1	2	No	**8**
9	3	2	2	2	5	Inherently safe design with as low as possible of the battery drawer height	2	2	1	1	[1]	No	**9**
	3	2	2	2	5	use the battery with a handle	2	2	1	1	[1] 1	No	
	3	2	2	2	5	battery cart	3	1	2	1	[3]	No	
	3	2	2	2	5	staff training	3	2	1	1	[3]	No	
10	3	2	2	1	4	Inherently safe design and manufacturing with gap < 1 [cm]	1	2	1	1	1	No	**10**

3.5 Concluding Remarks

We have developed two types of five restaurant service robots from 2009 to 2012, i.e., two Order robots and three Server robots. The developed robots have the following features: a swappable battery, waterproofing, a Thai language user interface, a robust operating system, easy preventive maintenance and customer-friendliness and attractive skin, which are important for robot operation in real environments. The skin design of the robots is based on handcraft production. The robots we developed have the advantages of minimal cost and maximized delivery time, making them a possible role model for further service robots with reasonable performance in Thailand. The result of a risk assessment and risk reduction with inherently safe design measures, protective measures, and information for use of the ServeTwo shows that developed robots are safe for operating in the real environment.

Note : Assume that well-trained staff can reduce the severity for minor harms, because it strongly depends on the behavior of the staff. In addition, the severity of severe harm can not change by staff training.

Chapter 4

Restaurant Service Robots Evaluation in Real Environment

[1] We have evaluated each of our robots for six months in a real environment where five branches of the MK restaurant chain are located in the Bangkok area of Thailand, from 2009 to 2012. In the evaluation, robots provided 14,280 services and attracted the interest of 235,680 customers. "Lessons Learned" from this four–year project have been summarized, and should prove useful to similar service robot development projects.

4.1 Operation Outline

(1) *Operation scheme and comparison to staff*:
Figure 4.1 shows the service comparison between conventional servicing of the restaurant staff and the Order-robot. The Order-robot moves to the table when the operator enters the table number. Then, the Order-robot takes an order from the customer via its UI, and return to the robot station, automatically. In the case of the Server robot, the comparison is shown in Fig.4.2. The Server robot moves after the operator places the food into its food container and enters the table number. The Server robot and the operator goes to the table, then operator picks and places the food onto the table. After that the robot will go back to the robot station, automatically.

[1]this chapter appears in the journal of *Robotics and Mechatronics (JRM)*, Vol.27, No.1, 2015

(2) *Operation place*:
The developed robots are operated in real environment of the restaurants in service hours. Each robot is operated separately in difference branches of the restaurant as shown in Table 4.2.

(3) *Operation Schedule*:
In the morning time around 8:00am to 10:00am, the robot operator has to do the job to comply with the prepared check-sheet, such as batteries checking (Full or Empty), clean up the food containers of the robot, robot condition check by using a pre-programed function of the robot user interface. When the restaurant opens at 11:00am, the robot operator starts the robot running. The Order-robot starts moving to get the order form the customers automatically. The Server robot wait for a command from the operator. When the operator puts the food into the Server robot's food container, and enters the table number of the costumer, the robot moves to the table for the food delivering. Then it gets back to the robot station and wait for the next order. The robot operating time for the first round is finished at 01:00pm. For the next round is from 05:00pm to 07:00pm. The other period is rest time for the robots. The robot operation schedule is summarized in Table 4.1.

Table 4.1: Daily operation schedule

Time	Activities
08:00am–10:00am	Set the robot by following a prepared check-sheet.
11:00am–01:00pm	Service Time.
01:00pm–01:30pm	Battery charging.
05:00pm–07:00pm	Service Time.
07:00pm–07:30am	Battery charging.

(4) *Training*:
To use the robot in real environment, the robot operation training is important. We have a 30 minutes training for the restaurant staff. The training topics are about daily preparation, robot commanding, battery swapping/charging, cleaning, safety and troubleshooting. For the operational sustainability reason, multiple MK staff are equally trained and work as a robot operator in the restaurant.

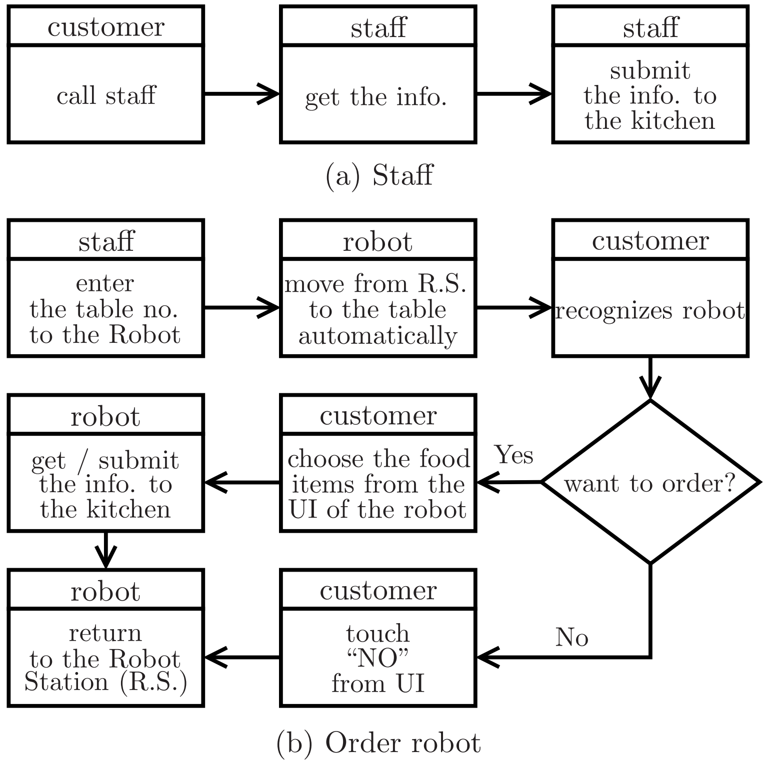


FIGURE 4.1: Ordering service comparison of the staff and Order robot. (a) by staff, (b) by Order robot.

(5) *Maintenance*:

The restaurant uses the robots five days a week. Therefore, the Preventive Maintenance (PM) is important for reliable use. The PM can be separated into two jobs, the first one is about the robot itself and the second one is about the robot environment (guidance system and battery charging station). For the robot PM, electronic circuits, software, and mechanical parts are examined. For the electronic circuit hardware, cleaning is a main PM and an air blower and a brush are used. For the control system with software, PM is divided into two diagnosis parts, the master-slave microcontrollers and the user interface of host controller. The both diagnoses are manually carried out based on the operation manual. For the mechanical parts, the PM team checks every single nuts and bolts, lubricates the bearings, and removes dirt from the drive/steering wheels and odometer wheels, especially on the tire surfaces and wheel shafts.

(6) *Safety*:

In the view point of the operational safety for both customers and staff, the foods to be

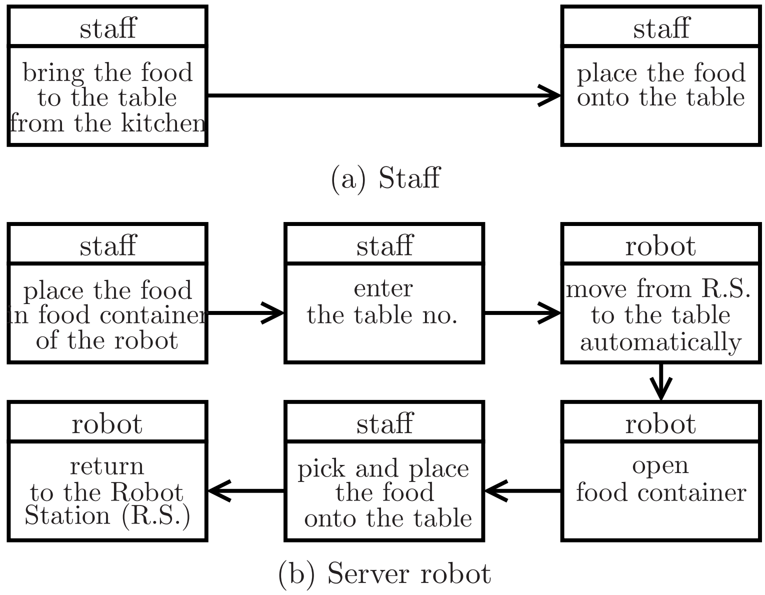


FIGURE 4.2: Delivering service comparison of the staff and Server robot. (a) by staff, (b) by Server robot.

delivered are non-heated foods. In addition, a staff follows the robot anytime in operation to maintain the robot safety. The robot has a pause switch to stop the movement temporarily, and when the switch is released, the robot continues the movement as before automatically. The staff is allowed to use this temporary pause switch when the staff finds something uncertain of the robot. Even if a staff is unsure to the robot, the pause switch make the staff ease in the real operation. Moreover, if a customer is standing to block the way of the robot, the ultrasonic sensor unit sends the command to stop the robot temporarily. If this happens, the robot speaks in a gentle voice to the customer for informing that the robot is coming and needs the way. The staff also helps this.

Table 4.2: Customers and Services in robot operation for 6 months (4 hours/day, 20 days/month)

Robot Name	OrderOne	OrderTwo	ServeOne	ServeTwo	Slim	Total
Period	May. to Oct. 2009	Aug. 2009 to Jan. 2010	Apr. to Sep. 2010	Apr. to Sep. 2011	Apr. to Sep. 2012	30M
Branch Name	Bangna	Cheangwat-tana	Rama 3	Lardprao	Bangkok University	–
Interested customer per day*	296	401	469	512	286	1,964
Services per day**	12	15	30	36	26	119
Interested customer in 6M	35,520	48,120	56,280	61,440	34,320	235,680
Services in 6M	1,440	1,800	3,600	4,320	3,120	14,280

M : Month. * : The customer who are interested in the robot, e.g., take photo, ask staff, and use the robot. ** : Rounded up of the average value. The number of the interested customer is estimated by the robot operator staff.

4.2 Results

We had operated the five robots (OrderOne, OrderTwo, ServeOne, ServeTwo, and Slim) in crowded hour (lunch and dinner), 4 hours a day, 5 days a week at the 5 branches of the restaurant in Bangkok area. Table 4.2 shows the operation in 6 months of five robots. During robot usage, 1) the customer interested in the robot and 2) service numbers of the robot is counted. To count the customer who are interested in the robot (e.g., use robot, take a photo), the robot operator staff counts such behavior, then PM team collects the counted data once a week. To count the service numbers of the robot, the service log files of each robots are used. For example, the ServeTwo robot operation was about 512 interested customers/day (61,440 customers/6 months). ServeTwo also provided 36 services per day on average. Therefore, in 6 months of 120 working days, the robot has 4,320 services. In a total of our five robot's operational, 235,680 customers were interested in our robots and the robots provided 14,280 services to the customers.

4.2.1 Stakeholders responses

The stakeholders of the robots here are (a) customer, (b) general restaurant staff, and (c) robot operator restaurant staff. During whole operational period of the robots in Table 4.2, we have observed the stakeholder's behaviors, and their responses can be summarized as follows:

(1) *The customer group*:
They are divided into three sub-groups as

1. Elderly (over 50 years old): not familiar with technologies, e.g., just using mobile phone as a phone.
2. Adult (18 to 50 years old): familiar with technologies, e.g., using Smart-phone and Internet.
3. Young (less than 18 years old): familiar with technologies in a positive way.

The three sub-groups of the customers have different behaviors as shown in Table 4.3: Elderly customers never took a photo and/or video. Adult customers always took a

Table 4.3: Typical customers response

Customers	Take Photo/Video	Need service from robot	Touch the robot	unexpected action to the robot	Question to staff
Elderly	X	S	S	X	S
Adult	A	O	O	X	O
Young	S	A	A	A	S

A:Always, O:Often, S:Sometimes, X:Never.

photo and/or video by using their Smart-phone. Young customers took a photo and/or video in some time, because they would not have their own camera or Smart-phone. Young customers always wanted a service from the robot, and they asked and welcomed the food or the dessert of which the robot brings. These Young customer's demands made additional orders. The Young customers less than (roughly) 12 years old always had unexpected behaviors such as pulling/pushing/patting any parts of the robot. Such behaviors were supervised and controlled by the staff. In contrast, the Adult and Elderly customers were never had unexpected behaviors. The Adult customers were often asking the question to the staff about, e.g.,

- "Who is the robot developer?",
- "Is that robot made in Thailand?",
- "How much is it?",
- "How to make the robot?" (from a young customers, sometimes),

and most of them were asked in a positive way. However, it should be noted that some customers asked in not positive way, especially the Elderly ones, such as

- "Why did you use a robot?. Is it just an obstacle that makes us difficult for walking".

(2) *General restaurant staff*:
In fact, the robot did not directly help the staff, or it made the staff operation more complex in their customer services. On the other hand, the robot attracted the customers and made more customers coming. To investigate these contradict features of

Table 4.4: Results of the restaurant staff interview in the 5 restaurants

Question	20 General Staff* [Yes/No]	20 Robot Operator Staff** [Yes/No]
Does the robot help you?	10/10	12/8
Do you need the robot?	4/16	12/8
Does the robot make you happy?	14/6	16/4
What do you want the robot to work for?	Cleaning the floor, serve a drink, delivered a food, reception, guide the customer to the table, dancing with staffs***	

* : General service task. ** : General service task and robot operation, *** : Dancing is the most wanted feature of the robot.

the robot to the general staff, we have interviewed of 20 staff about;

- "Does the robot help you?",
- "Do you need the robot?",
- "What do you want the robot to work for you?",
- "Does the robot make you happy?"

According to the interview, it can be concluded that the general staff accept the robots. See Table 4.4.

(3) *The robot operator staff*:
We had interviewed 20 robot operators. The interview was carried out when we had visited the restaurant for PM about daily robot preparation and the robot usage. According to the interview, we found that the robots were welcomed and its usage was easy with the Thai language user interface of text and speech. A more bigger button of the user interface is needed.
Note that, since this research is the initial phase of the project, the questionnaires are made as simple as possible.

4.2.2 Technical results

In the view point of our robot development, we have the following technical results.

- The guided line is a vinyl sticker with black and white colors. During 6 months of the operation, the floor cleaning procedure of the restaurant effected to the sticker line. That is, a little damage on the edge of the guided line had been caused by the floor wiping and foot stepping. After 6 months, though the robot still can trace the line, we have replaced a new sticker at the end of the 6 months for appearance reasons and it increased the maintenance cost.
- According to the daily cleaning procedure of the restaurant, the food container of the robot had kept the sanitary condition until the end of 6 months operation.
- The two wheel drive with backdrivability and the steerable caster wheel had satisfied the push-movable requirement. That is, when a staff wanted to move the robot (when power switch is off), it was easy to move it by pushing with hands.
- The pause button was useful in many situations, e.g., when a child runs into in front of the robot from behind the partition, when a customer wants to take a photo, when another staff needs more working space.
- Music sound, light, and voice greetings, notifications, and warnings were used for warnings and entertainment. Customers and staff were positive about them, especially foreign customers when they heard their own language from the robots, which use in Thai, Chinese, English, and Japanese.
- Liquid such as water, soup, and sauce dropped on robots caused no reported damage. Such liquids were wiped and the robot continued operating.
- Battery swapping enabled robots to operate continuously during crowded hours.

Table 4.5: Developed robots evaluation summary in real environment of the restaurant

Technical requirements	Solution	Evaluation method*	Result**
R1. Thai language user interface (UI)	Use capable OS and UI development tools.	Customers and robot operators experience interview and observation (D, I)	○
R2. Waterproof skin	ACL/FBG/ABS Material with Industrial grade of color painting.	Drip water all over outside the robot in BURL (B)	○
R3. Simple sentences (voice) for greeting	Playback the prerecorded voice of native speakers (Thai, English, Japanese, and Chinese.) selected by robot operator.	Observing the feedback from the Customers (D)	○
R4. Pushed by hand	Two wheel drive with backdrivability and steerable caster wheel.	Robot operator experience interview and observation (D, I)	○
R5. Pause Button	Use a switch to shut off the motors power while the control circuits are still functioning.	Experimental test and robot operator experience interview (B, D, I)	○
R6. Robust OS	Linux OS	Take the battery off before shut down the robot. Then it can restart without trouble (B)	△*1
R7. Swappable Battery	5kg Battery with hand-drawer.	Experimental test and real situation observation (B, D)	○

Continued on next page

Table 4.5 – continued from previous page

Technical requirements	Solution	Evaluation method*	Result**
R8. Enclosed circuit boards	Put all of the circuit boards into the waterproof boxes.	Test in a real environment with dripping water (B)	○
R9. Robot Localization	Vinyl sticker as a guided line and RFID for position confirmation.	Experimental test and real environment observation (B, D)	○
R10. Obstacle detection	Ultrasonic and passive/active infrared sensors.	Experimental test in real situation (D)	△*2
R11. Sound and light for caution and entertainment	Play a music and blink the light during robot movement.	Observing a response from the customers and the staffs (D)	○
R12. Minimum and sufficient power of motor	Safety factor is equal to one in the motor power calculation process.	Crash test in BURL (B, C)	○
R13. Emergency stop switch	Use standard circuit design for emergency stop.	Operation in real situation and robot operators experience interviewing (D, I)	○
R14. Sanitary food container	Use stainless steel material and curved corner tray.	Follow the standard of contamination testing of MK (D,G)	○
R15. Two movable arms	Two arms with 3-DOF (Pitch/Roll Shoulder with Fixed Yaw and Pitch).	Experimental test and real situation observation (B, D)	○
R16. Movable head	2-DOF of head joint (Pitch/Yaw joint).	Experimental test and real situation observation (B, D)	○

Continued on next page

Table 4.5 – continued from previous page

Technical requirements	Solution	Evaluation method*	Result**
R17. Battery charging station	Sealed Lead Acid battery (12 V, 20 Ah).	Experimental test and real situation observation (B, D)	◯

* : A Inspection, B Practical tests, C Measurement, D Observation during operation, E Examination of circuit diagrams, F Examination of software, G Review of task-based risk assessment, H Examination of layout drawing and relevant documents, and I Interview (A–H are referred from [28]). ** : ◯ Satisfied, △ Partially Satisfied, × Not Satisfied. *1 : OrderOne and OrderTwo use the Windows OS which shows negative result in evaluation. *2 : Due to dead zone of the sensors and quick movement of the Young customers.

Table 4.5 evaluates robots in real environments, i.e., where technical requirements in Section 3.3.2 and corresponding solutions and evaluations are listed. Because the robot is the fist service robot in a real environment in Thailand, simple easy-to-understand evaluation was preferred by project members, especially MK company managers. Practical technical evaluation tests and observation during operation were used to ensure this. Interviews were also used for response evaluation. Note that evaluation methods are categorized by referencing [28].

4.3 Lessons Learned

In summarizing experimental results, this section describes the "Lessons Learned" that explains what went wrong or right and was accomplished or not during the project and notes suggestions. By following a PMBOK template [29], we categorized Lessons Learned as robot production, robot operation, general management, and quality management. Table 4.6 lists lessons and their category, issue, problem or success, impacts, and recommendations. The following are typical:

- Skin production handcraft without using advanced machines became an alternative choice for robot skin that is especially suitable for Thailand {I3}.
- Human communication is a key to success. From the robot operation, a problem come from communication mistakes in project objectives between restaurant managers and staff {I4}.
- The behavior of young customers damaging robot was unexpected, so we must consider a repair budget {I6}.
- Higher priority authority from management was useful for robot development because it eases access to all information needed by the project {I7}.
- Well-documented technical drawings referencing international standard smoothed robot production {I8}.

Table 4.6: Lessons Learned from this project

Category	Issue Name	{P}roblem/{S}uccess	Impact	Recommendation
Robot Production	{I1} Initial Product Idea	{S1}The simple mobile robot is effectively combined with the existing MK ordering system (Fig.3.5(b))	Develop within a short time and small budget.	It must be decided which is strong points in overall project resources.
	{I2} Production Material	{P1}The new motor price is high, so used motors are used	The maintenance cost is increased and the performance of the motor is low.	Reduce the project requirements to an appropriate level. Apply an advanced control approach to compensate the low performance motor.
	{I3} Skin Production	{S2}Low cost skin production without using advanced machines. (Fig.3.6)	It became an alternative for robot skin production.	Integrate an engineering production concept and technology to the handcraft skin production process to increase the accuracy.

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Table 4.6 – continued from previous page

Category	Issue Name	{P}roblem/{S}uccess	Impact	Recommendation
Robot Operation	{I4} Staff's attitude	{P2}There is miss understand between the staffs and manager. Some staffs are against the robot.	The staffs are afraid to lose their job. High level managers had made a meeting with local branch managers and staffs to explain that the robot never did service jobs instead of people.	Should communicate to all the staffs to understand the project objectives and FAQ document beforehand.
	{I5} Customers feedback	{S3}Excited and proud of Thai robot can work in reality. (Fig.3.1)	Inspire children to be a robot developer. Good feedback from journalism and TV (Both domestic and abroad).	Must examine the desire of customer before robot development.

Continued on next page

Table 4.6 – continued from previous page

Category	Issue Name	{P}roblem/{S}uccess	Impact	Recommendation
	{I6} Damage caused by Young customers.	{P3}Motor of arm joints are often broken. Children always want to touch and make hand checking. Sometimes they pull the arms.	The robot operators got a tension about this. They afraid to respond repairing cost of damaged. Need repair time.	Must design the robot arms robust against the mischief. Communicate to the robot operators to feel free about that. Should be considered budget for repairing.
General Management	{I7} Authority	{S4}The development team has the authority of high prioriy from top management.	Concentrate on the development and easy access to all information, which accelerate the development.	Should communicate with contract parties about the authorization before start project.
Quality Management	{I8} Documentation	{S5}Technical information about the mechanical, electronics , and software system have been well-documented.	The development team can work with the sub-contractors smoothly.	Always design the system by referring to international standards. This helps to avoid delays and cost overruns.

4.4 Concluding Remarks

In 4 years of evaluation in 5 real restaurants in the Bangkok area, these robots have shown their acceptability for real environment implementation and operation. This has been verified by simple questionnaires on restaurant staff. As for the first step, these robots provided 14,280 services and attracted the interest of 235,680 customers. Most customers, both young and adult, responded positively to the robots, e.g., customers enjoyed robot services and young customers were so proud of Thai robots that some wanted to become robot developers. Restaurant staff members also responded positively to the robots.

Lessons Learned from this project are summarized in Section 4.3 into 3 categories: 1) robot production, 2) robot operation, and 3) project management avoiding mistakes and repeating success in the future.

Chapter 5

Essential Requirements for Restaurant Service Robot Utilization from the Viewpoint of a Framework of International Safety Standards

Although a Restaurant Service Robot (RSR) might not be something new from the viewpoint of the process of developing a robot that can run on demand, especially for short period like a laboratory test, its long–term evaluation in a real environment has not been studied well for utilization. We have evaluated each of our robots for six months in a real environment at five branches of the MK restaurant chain located in the Bangkok area of Thailand, from 2009 to 2012. In the evaluation, robots provided 14,280 services and attracted the interest of 235,680 customers. Lessons Learned from this four year project have been summarized in Chapter 4.

In this chapter, we re-examine the overall study of RSR development and real environment evaluation in MK restaurants. The essential requirements for RSR utilization have been derived in order to accelerate similar service robot development projects for utilization. Safety is the most important consideration for utilization. Therefore, the proposed Essential Requirements (ER) are verified from the viewpoint of a Framework of International Safety Standards, where the essence of the International Standards related to System Safety are considered. Note that System Safety is most general concept of safety. The following standards related to System Safety are used for the verification : ISO 13482 of the personal care robot safety in accordance with ISO 12100:2010, ISO 31000 of risk management, IEC 62278 of railway RAMS (Reliability, Availability, Maintainability and Safety). The ER are also verified from the summary idea of the Lessons Learned. According to the verification, we conclude that the proposed essential requirements for RSR utilization are adequate from the viewpoint of System Safety.

5.1 Essential Requirements for the RSR Utilization

Based on our experiences as mentioned in the prior chapters, we have been involved in most of the whole life–cycle of the robot utilization: design, risk assessment, risk reduction, development, production, evaluation, operation, and maintenance. In order to re-examine what will be the essential requirements for the RSR utilization, the following points have been taken into account for consideration.

- Basic demands (*D1–D7* in Section 3.3.2)
- Technical requirements (*R1–R17* in Section 3.3.2)
- Technical specifications (*T1–T24* in Section 3.3.2)
- Evaluation results (Section 4.2)
- Lessons Learned (Section 4.3)

According to the general knowledge about a robotics, we have categorized the above points into four categories of the essential requirements; management, technology, safety, and maintenance. The individual ER are as follows:

1. E1-1 : Policy
2. E1-2 : Balance in decision
3. E1-3 : Social and Cultural Context
4. E2-1 : Appropriate “behavior” and function

5. E2-2 : Stay on the hilltop of the Uncanny Valley
6. E2-3 : Human-Robot Interface
7. E2-4 : On-demand power source
8. E3-1 : Safety of machinery
9. E3-2 : Sanitary
10. E4-1 : Preventive Maintenance
11. E4-2 : Corrective Maintenance

The details are described in Sections 5.1.1 to 5.1.4 with the explanations based on our experiences.

5.1.1 E1 : Management

- **E1-1 : Policy**
  The policy affects what we will and will not let robots do. In a restaurant, we have many kinds of service tasks (e.g., ordering, fetching and bringing food, payment etc.). The policy of the manager or restaurant owner has to be considered when one makes a decision as a prior step of consideration. In the MK robot project, one policy is people (staff) and robots can work better together (not use a robot instead of people). Another policy is, give a happiness to our customers by using a robot but don't disturb our customers. One our example of this issue is why we do not use a floor cleaning robot in a restaurant because such a robot makes a customer feel a loss of privacy when a robot with a navigation system with a camera is moving around their chair.

- **E1-2 : Balance in decision**
  The typical main parts of the RSR are mobility, perception, manipulator, and human-robot interaction. For example, the mobility unit of a service robot in a restaurant requires a navigation system to travel to the destinations. At present there are many different technologies that can be used as a navigation system for the robot, e.g., Laser range finder, Stereo camera, etc. Those devices makes the robot costs too high. From the viewpoint of investment, the technology with

reasonable performance and cost is a one of an important consideration. That is why in the MK robot project we chose to use a line tracing technique as a navigation system, where black and white vinyl stickers with a RFID card as a robot guidance system.

- **E1-3 : Social and Cultural Context**
  Around the world, people's expectations of robots and response to robots design are different; For most of Asians, robots might be cute as a cartoon human character or pet. On the other hand, in the European areas, robots might be scary and they might be thought as threatening. As [45] writes "Japanese people looks at robots as helpmates, Americans view robots as dangerous, while the others imagine them as assistance for aging people." Our culture influences the behavior and function of the robot, and may influence the application target to be developed. In order to utilize the robot into a restaurant, just a robot and people do better together is not enough. To do this, we need to consider the psychological aspect. From our experience, "Entertainment" will be the key to success, e.g., the robot sings a famous song while traveling to the table.

5.1.2 E2 : Technology

- **E2-1 : Appropriate "behavior" and function**
  In the process of designing a robot, the robot must have appropriate functions that meet the requirements. In addition to this, the robot's behavior is another thing that we have to considered, how the robot reacts or responds to different kinds of customers, such as young, adult, and the elderly. We may need a prior survey (social analysis) before the designer decide on committing to the project and finding a solution to the requirements, e.g., the robot behaves like female staff of the restaurant.

- **E2-2 : Stay on the hilltop of the Uncanny Valley**
  The Uncanny Valley explains how's people reacts to robots that looks like almost human, or the relationship between the *human likeness* of robots and the *people's emotional response* (familiarity) for it. The familiarity of robots does not linearly increase with human likeness. Instead, the familiarity increases with human likeness at the beginning, but shortly before reaching realism it turns into eeriness creating a valley or "The Uncanny Valley" [46] (Figure 5.1). The hilltop could

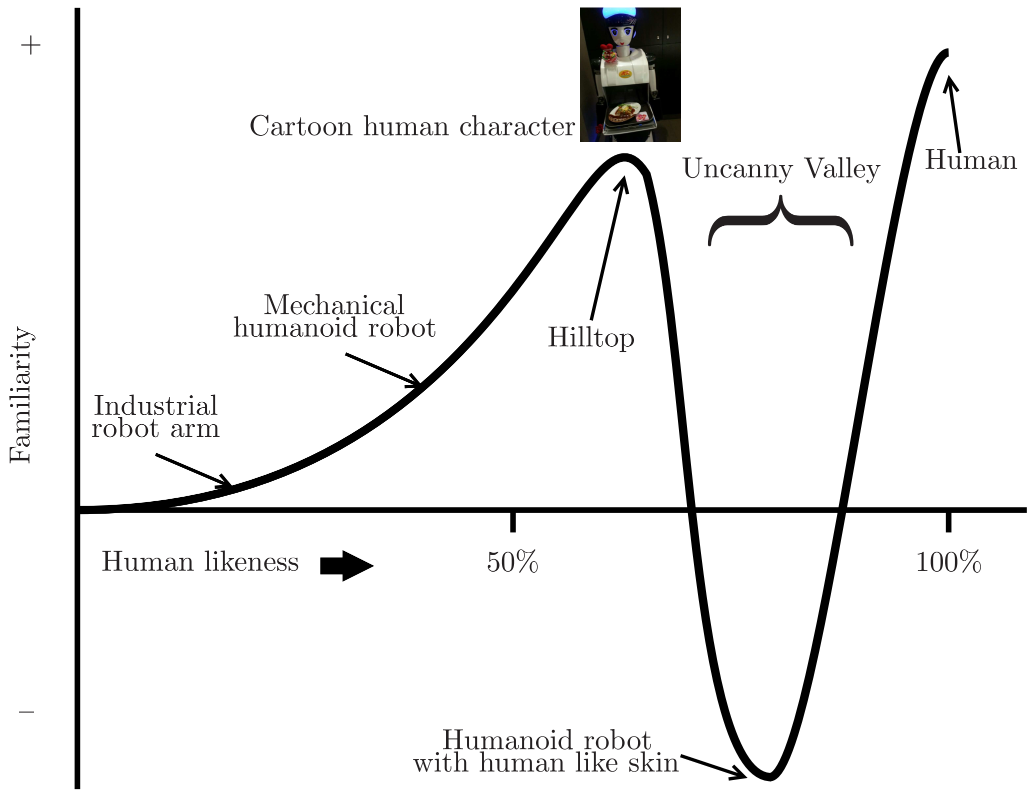

FIGURE 5.1: The Uncanny Valley : *"When human features look and move almost, but not exactly, like natural human beings, it causes a response of revulsion among human observers. The uncanny valley is the region of negative emotional response towards robots that seem almost human. Movement amplifies the emotional response"* – Masahiro Mori.

be the place for a movable cartoon human character. Therefore the hilltop is an appropriate place for robot designing in both of behavior and function, e.g., the skin cover of the robot may look like female staff dressing, but in the sense of a cartoon human character.

- **E2-3 : Human-Robot Interface**
  The robot communicates with the robot's operator and customer. The robot control device is the one for the input of commands to a robot by an operator; big button, native language, robust, mobile are the basic requirements of RSR. In addition, light, voice–greeting sound, and music used for customer entertainment in the interface. More over, the natural user interface is also a key technology (e.g., hand gesture, voice recognition, etc.). For example in our RSR, Thai language GUI

and Thai, Japanese, Chinese, and English of greeting voice have been welcome fro the operators and the customers.

- **E2-4 : On-demand power source**
  A restaurant needs continuous operation of a robot during crowded hours (service hours). Battery swapping enabled the robot to carry out that requirement.

5.1.3 E3 : Safety

- **E3-1 : Safety of machinery**
  RSR applications require close human-robot interaction and collaborations, including physical human-robot contact. ISO 13854 (safety of machinery – minimum gaps to avoid crushing of parts of the human body) [47] is used to determine gap size of moving parts of the robot. In addition, the a waterproof box for electronic circuits is used, e.g., sufficient of motor power, gap, motion speed.

- **E3-2 : Sanitary**
  Most restaurants have sanitation standards, e.g. HACCP[1]. In the process of designing a robot, robot designers need to focus and design a robot that can follow those standards, e.g., a food container designed with rounded edges for easy clean up.

5.1.4 E4 : Maintenance

The robot itself and the robot environment (e.g., charging station, guidance system) need the jobs of the maintenance.

- **E4-1 : Preventive Maintenance**
  This is performed weekly on a piece of equipment to lessen the likelihood of robot failure. Preventative maintenance is performed while the equipment is still working, e.g., clean up the surface of the drive wheel and odometer wheel surface.

- **E4-2 : Corrective Maintenance**
  This is performed when the robot has broken down unexpectedly, e.g., elbow joint

[1] Hazard Analysis Critical Control Point (HACCP) is an approach to food safety that is systematic and preventive.

of the robot arm is out of function due to the unexpected behavior of a young customer.

The essential requirements for RSR utilization (**E1** $-$ **E4**) as mentioned above, if suitable or not will be discuss in the next sections.

5.2 The Essential Requirements and a Framework of International Safety Standards Viewpoints

Safety is the most important for utilization. Therefore, the proposed Essential Requirements (ER) are verified from the viewpoint of a Framework of International Safety Standards, where the essence of the International Standards related to System Safety is considered. Note that System Safety is the most general concept of safety. The following standards related System Safety are used for the verification : ISO 13482 of the personal care robot safety in accordance with ISO 12100:2010, ISO 31000 of risk management, IEC 62278 of railway RAMS (Reliability, Availability, Maintainability and Safety). The ER are also verified from the summary idea of the Lessons Learned. According to the verification, we conclude that the proposed essential requirements for RSR utilization are adequate from the viewpoint of System Safety.

A principle theme of System Safety is to ensure that we know what the hazards are before the system is allowed to operate and System Safety is needed for better understanding of accident prevention.

The Military Standard MIL-STD-822E of System Safety [48] describes the approach for identifying hazards and assessing and mitigating associated risks encountered in the development, test, production, use, and disposal of defense systems. The definitions of the System Safety in MIL-STD-882E are as follows:

- “System”. The organization of hardware, software, material, facilities, personnel, data, and services needed to perform a designated function within a stated environment with specified results.
- “Safety”. A freedom from conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.

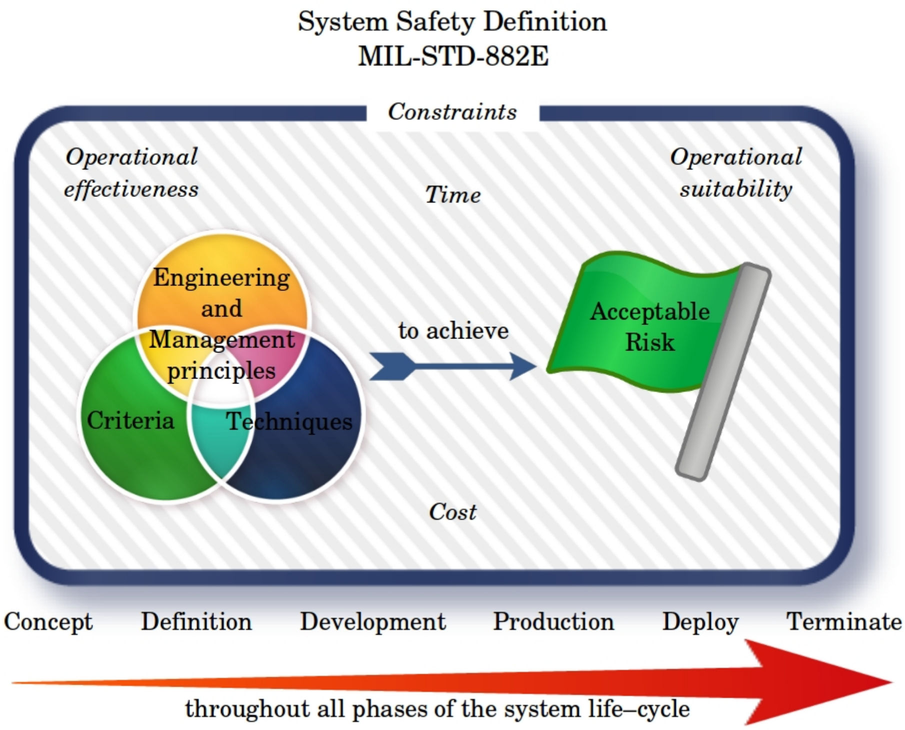

FIGURE 5.2: System safety definition in accordance with MIL-STD-882E

- "System safety". The application of engineering and management principles, criteria, and techniques to achieve acceptable risk within the constraints of operational effectiveness and suitability, time, and cost throughout all phases of the system life–cycle (Figure 5.2).

The system safety focuses on the application of systems engineering and systems management to the process of hazard, safety and risk analysis.

In order to apply System Safety to an actual problem, A System Safety Process is needed to be considered [48].

The system safety process consists of eight elements. Figure 5.3 describes the typical logic sequence of the process. However, iteration between steps may be required.

1. **Document the system safety approach.** Documenting the developer's and program manager's approved system safety engineering approach will:

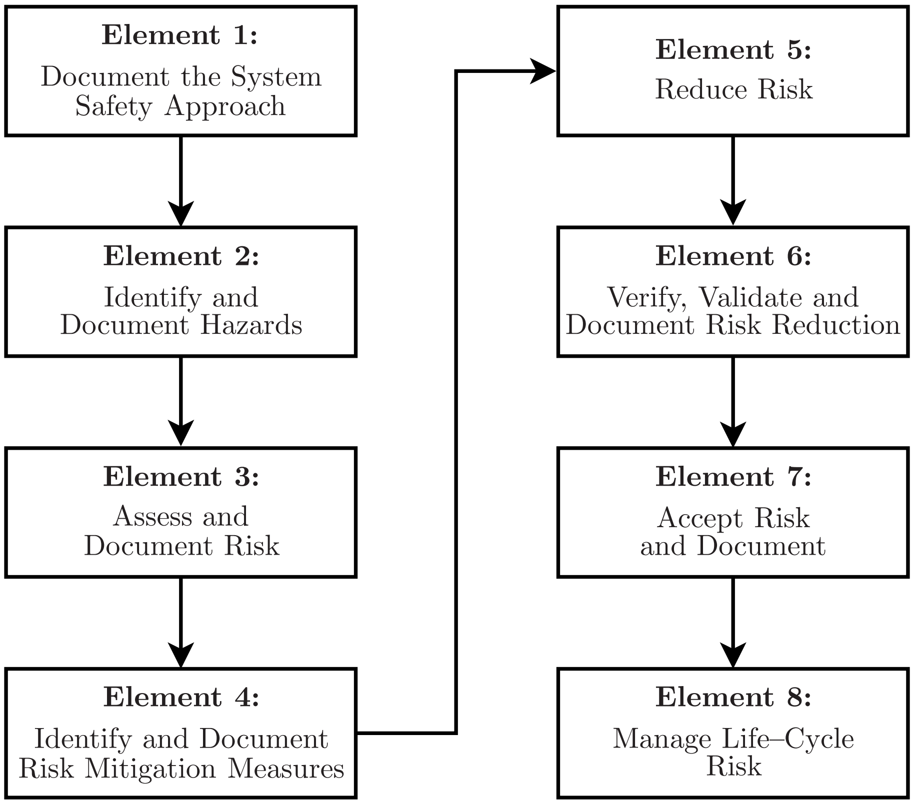

FIGURE 5.3: Eight elements of the system safety process.

– Describe the program's implementation using the requirements. Include information on system safety integration into the overall program structure and software development life–cycle.
– Define how hazards and mishap risks are communicated to and accepted by the appropriate risk acceptance authority and how hazards and mishap risk will be tracked.

2. **Identify and document hazards.** Hazards are to be identified through a systematic hazard analysis process that encompasses detailed analysis of system hardware and software, the environment and the intended use or application. Identification of hazards is a responsibility of all program members.

3. **Assess and document risk.** Assess the severity and probability or software control category of the mishap risk associated with each identified hazard to determine the potential negative impact of the hazard.

4. **Identify and document risk mitigation measures.** Identify potential mishap risk mitigation alternatives and the expected effectiveness of each alternative or method. To mitigate identified hazards, the following procedures must be performed in the order given:
   – Eliminate hazards or reduce hazard risk through design selection.
   – Incorporate safety devices.
   – Provide warning devices.
   – Develop procedures and training.
5. **Reduce risk.** Reduce the mishap risk through a mitigation approach that both the developer and program manager mutually agree upon.
6. **Verify, validate, and document risk reduction.** Verify the mishap risk reduction and mitigation through appropriate analysis, testing or inspection. Document the determined mishap risk and report all new hazards identified during testing to the program manager and developer.
7. **Accept risk and document.** Notify the program manager of identified hazards and mishap risk. The program manager will then ensure that remaining hazards and mishap risk are reviewed and accepted by the appropriate risk acceptance authority. The appropriate risk acceptance authority will formally acknowledge and document acceptance of hazards and mishap risk.
8. **Manage life–cycle risk.** Track hazards, their closure actions and the mishap risk by maintaining a tracking system that includes hazards, hazard severity and probability, hazard causes, controls for each cause and verification for each hazard control, their closure actions and mishap risk throughout the system life–cycle.

5.2.1 From the Viewpoint of ISO 13482 (Safety requirements for personal care robots)

5.2.1.1 Outline of ISO 13482

ISO 13482:2014 is a type-C standard (particular machine safety) in accordance with ISO 12100:2010 of safety of machinery, therefore the ISO 13482:2014 introduces a general principles for design and deals with risk assessment and risk reduction for personal care robots, which interact human directly like RSR.

ISO 13482:2014 specifies requirements and guidelines for the:

a) Inherently safe design,
b) Protective measures, and
c) Information for use

of personal care robots.

These robots typically perform tasks to improve the quality of life of intended users, irrespective of age or capability.

ISO 13482:2014 presents significant hazards and describes how to deal with them for each personal care robot type. ISO 13482:2014 covers robotic devices used in personal care applications, which are treated as personal care robots. ISO 13482:2014 is limited to earthbound robots and does not apply to:

- robots traveling faster than 20 km/h;
- robot toys;
- water-borne robots and flying robots;
- industrial robots, which are covered in ISO 10218;
- robots as medical devices;
- military or public force application robots.

ISO 13482:2014 deals with four main parts

1. Safety requirements and/or protective measures
2. Safety-related control system requirements
3. Verification and Validation
4. Information for use

The scope of ISO 13482:2014 is limited primarily to human care related hazards but, where appropriate, it includes domestic animals or property (defined as safety-related objects), when the personal care robot is properly installed and maintained and used for its intended purpose or under conditions which can reasonably be foreseen.

ISO 13482:2014 deals with all significant hazards, hazardous situations or hazardous events as described in Annex A of ISO 13482:2014. Attention is drawn to the fact that for hazards related to impact (e.g. due to a collision) no exhaustive and internationally recognized data (e.g. pain or injury limits) exist at the time of publication of ISO 13482:2014.

5.2.1.2 Discussion and Verification

Table 5.1 shows the relation between our proposed Essential Requirements (ER) and the ISO 13482:2014. From the viewpoint of ISO 13482:2014 that is deals with a Risk Assessment (RA) and Risk Reduction (RR) for personal care robots.

E1 : Management is not corresponded to the ISO 13482:2014 because of the ISO is not dealing with a management.

E2 : Technology except "E2-2:Stay on the hilltop of the Uncanny Valley". Various technologies are used in a robot. It is very important to consider safety issues as a first step. Therefore, the E2 are almost corresponded to the ISO 13482.

E3 : Safety except "E3-2:Sanitary"is directly corresponded to ISO 13482 because of both are dealing with safety issues.

E4 : Maintenance are corresponds to ISO 13482 because of the maintenance is the job of the maintenance team, not the job of the customer or the robot operator. During the maintenance of the robot must take the safety of the maintenance team must be taken into account as well.

Therefore, the ISO 13482:2014 does not cover the ER for RSR Utilization.

TABLE 5.1: Relationship between the proposed Essential Requirements and ISO 13482:2014 (Safety requirements for personal care robots)

The Essential Requirements for RSR Utilization		Corresponded to ISO 13482
E1 : Management (Section 5.1.1)	E1-1 : Policy	×
	E1-2 : Balance in decision	×
	E1-3 : Social and Cultural Context	×
E2 : Technology (Section 5.1.2)	E2-1 : Appropriate behavior and function	◯
	E2-2 : Stay on the hilltop of the Uncanny Valley	×
	E2-3 : Human-Robot Interface	◯
	E2-4 : On-demand power source	◯
E3 : Safety (Section 5.1.3)	E3-1 : Safety of machinery	◯
	E3-2 : Sanitary	×
E4 : Maintenance (Section 5.1.4)	E4-1 : Preventative Maintenance	◯
	E4-2 : Corrective Maintenance	◯

◯ : Yes, × : No.

5.2.2 From the Viewpoint of ISO 31000 (Risk management)

5.2.2.1 Outline of ISO 31000

Risks affecting organizations can have consequences in terms of economic performance and professional reputation, as well as environmental, safety and societal outcomes. Therefore, managing risk effectively helps organizations to perform well in an environment full of uncertainty.

The success of risk management will depend on the effectiveness of the management framework providing the foundations and arrangements that will embed it throughout the organization at all levels. The framework assists in managing risks effectively through the application of the risk management process at varying levels and within specific contexts of the organization. The framework ensures that information about risk derived from the risk management process is adequately reported and used as a basis for decision–making and acceptability at all relevant organizational levels.

ISO 31000:2009 [49] provides principles and generic guidelines on risk management.

ISO 31000:2009, *Risk management – Principles and guidelines*, provides principles, framework and a process for managing risk. It can be used by any organization regardless of its size, activity or sector. Using ISO 31000 can help organizations increase the likelihood of achieving objectives, improve the identification of opportunities and threats and effectively allocate and use resources for risk treatment. However, ISO 31000 cannot be used for certification purposes, but does provide guidance for internal or external audit programs. Organizations using it can compare their risk management practices with an internationally recognized benchmark, providing sound principles for effective management and corporate governance.

ISO 31000:2009 can be used by any public, private or community enterprise, association, group or individual. Therefore, ISO 31000:2009 is not specific to any industry or sector.

ISO 31000:2009 can be applied throughout the life of an organization, and to a wide range of activities, including strategies and decisions, operations, processes, functions, projects, products, services and assets.

ISO 31000:2009 can be applied to any type of risk, whatever its nature, whether having positive or negative consequences.

Although ISO 31000:2009 provides generic guidelines, it is not intended to promote uniformity of risk management across organizations. The design and implementation of risk management plans and frameworks will need to take into account the varying needs of a specific organization, its particular objectives, context, structure, operations, processes, functions, projects, products, services, or assets and specific practices employed.

It is intended that ISO 31000:2009 be utilized to harmonize risk management processes in existing and future standards. It provides a common approach in support of standards dealing with specific risks and/or sectors, and does not replace those standards.

ISO 31000:2009 gives a list on how to deal with risk:

1. Avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk
2. Accepting or increasing the risk in order to pursue an opportunity
3. Removing the risk source
4. Changing the likelihood
5. Changing the consequences
6. Sharing the risk with another party or parties (including contracts and risk nancing)
7. Retaining the risk by informed decision

For risk management to be effective, an organization at all levels should comply with the principles below (Figure 5.4).

a) Creates and protects value. Risk management contributes to the demonstrable achievement of objectives and improvement of performance in, for example, human health and safety, security, legal and regulatory compliance, public acceptance, environmental protection, product quality, project management, efficiency in operations, governance and reputation.

b) Integral part of all organizational processes. Risk management is not a standalone activity that is separate from the main activities and processes of the organization. Risk management is part of the responsibilities of management and an

FIGURE 5.4: Risk Management Principles in accordance with ISO 31000:2009

integral part of all organizational processes, including strategic planning and all project and change management processes.

c) Part of decision making. Risk management helps decision makers make informed choices, prioritize actions and distinguish among alternative courses of action.

d) Explicitly addresses uncertainty. Risk management explicitly takes account of uncertainty, the nature of that uncertainty, and how it can be addressed.

e) Systematic, structured and timely. A systematic, timely and structured approach to risk management contributes to efficiency and to consistent, comparable and reliable results.

f) Based on the best available information. The inputs to the process of managing risk are based on information sources such as historical data, experience, stakeholder feedback, observation, forecasts and expert judgment. However, decision makers should inform themselves of, and should take into account, any limitations of the data or modeling used or the possibility of divergence among experts.

g) **Tailored.** Risk management is aligned with the organization's external and internal context and risk profile.

h) **Takes human and cultural factors into account.** Risk management recognizes the capabilities, perceptions and intentions of external and internal people that can facilitate or hinder achievement of the organization's objectives.

i) **Transparent and inclusive.** Appropriate and timely involvement of stakeholders and, in particular, decision makers at all levels of the organization, ensures that risk management remains relevant and up-to-date. Involvement also allows stakeholders to be properly represented and to have their views taken into account in determining risk criteria.

j) **Dynamic, iterative and responsive to change.** Risk management continually senses and responds to change. As external and internal events occur, context and knowledge change, monitoring and review of risks take place, new risks emerge, some change, and others disappear.

k) **Facilitates continual improvement of the organization.** Organizations should develop and implement strategies to improve their risk management maturity alongside all other aspects of their organization.

Table 5.2: Relationship between the proposed Essential Requirements and ISO 31000 (Risk management)

The Essential Requirements for RSR Utilization		Corresponded to ISO 31000 principles										
		a	b	c	d	e	f	g	h	i	j	k
E1 : Management (Section 5.1.1)	E1-1 : Policy	○	○	○	×	×	○	○	○	○	○	○
	E1-2 : Balance in decision	○	○	○	○	○	○	○	○	○	○	○
	E1-3 : Social and Cultural Context	○	○	○	×	×	○	○	○	○	○	○
E2 : Technology (Section 5.1.2)	E2-1 : Appropriate behavior and function	○	○	○	○	○	○	○	○	○	○	○
	E2-2 : Stay on the hilltop of the Uncanny Valley	○	○	○	×	○	○	○	○	○	○	○
	E2-3 : Human-Robot Interface	○	○	○	○	○	○	○	○	○	○	○
	E2-4 : On-demand power source	○	○	○	○	○	○	○	○	○	○	○
E3 : Safety (Section 5.1.3)	E3-1 : Safety of machinery	○	○	○	○	○	○	○	○	○	○	○
	E3-2 : Sanitary	○	○	○	○	○	○	○	○	○	○	○
E4 : Maintenance (Section 5.1.4)	E4-1 : Preventative Maintenance	○	○	○	○	○	○	○	○	○	○	○
	E4-2 : Corrective Maintenance	○	○	○	○	○	○	○	○	○	○	○

○:Yes, ×:No, a:Creates and protects value, b:Integral part of all organizational processes, c:Part of decision making, d:Explicitly address uncertainty, e:Systematic, structured and timely, f:Based on the available information, g:Tailored, h:Takes human and cultural factors into account, i:Transparent and inclusive, j:Dynamic, iterative and responsive to change, k:Facilitates continual improvement of the organization

5.2.2.2 Discussion and Verification

Table 5.2 shows the relation between our proposed Essential Requirements (ER) and the principles of risk management of ISO 31000. From the viewpoint of ISO 31000 which is dealing with a Risk Management with a wide range of activities, including strategies and decisions, operations, processes, functions, projects, products, services, and assets. And bellows are relationship between the risk management principles and proposed essential requirements for RSR utilization.

- **a:Create and protects value** Every part of the essential requirements are directly affect to the value of the restaurant service robot which is the reason why the a–principle is corresponded to E1 to E4.
- **b:Integral part of all organizational process** The b–principle corresponds to E1 to E4 because of every part of restaurant service robot have to blended together.
- **c:Part of decision** The c–principle corresponds to E1 to E4 because of the they are need a decision, e.g., which technology should be using for a robot.
- **d:Explicitly address uncertainty** The d–principle does not corresponds to *E1-1:Policy* because of the E1-1 is just an overview of the robot utilization.
  The d–principle does not corresponds to *E1-3:Social and Cultural Context* because of the E1-3 is uncertainty.
  The d–principle does not corresponds to *E2-2:Stay on the hilltop of the Uncanny Valley* because of the E2-2 depends on the E1-3. The remaining ER corresponds to the d–principle due to their are associated with the risk assessment process.
- **e:Systematic, structured and timely** The e–principle does not corresponds to *E1-1:Policy* because of the E1-1 such a kind of project overview.
  The e–principle does not corresponds to *E1-3:Social and Cultural Context* because of the E1-3 is not in development phase. The remaining ER corresponds to the e–principle due to their needs a systematic, structured and timely.
- **f:Based on the available information** Every step of RSR utilization needs the information.

- **g:Tailored** The g–principle is a kind of customization. In order to utilize the robot in real environment, the g–principle is require. That is a reason why the g–principle corresponds to all of the ER.
- **h:Takes human and cultural factors into account** Restaurant service robot intended to provide service task to a human. Therefore, the h–principle corresponds to the E1 to E4.
- **i:Transparent and inclusive** At all levels of the organization, the stakeholders have to access any information and to have their views taken into account in determining risk criteria. Therefore, the i–principle corresponds to all of the ER.
- **j:Dynamic, iterative and responsive to change** The j–principle is continually senses and responds to change based on external and internal factors. Therefore, the j–principle corresponds to all of the ER.
- **k:Facilitates continual improvement of the organization** If all level of the organization have taken the risk management principles into account. Then the organization will improve. Therefore, the k–principle corresponds to all of the ER.

5.2.3 From the Viewpoint of IEC 62278 (Railway RAMS)

5.2.3.1 Outline of IEC 62278

The RAMS standard (IEC 62278 [50]) came into effect in October 2002. RAMS stands for the four assessment indicators of

- **Reliability** is a probability that an item can perform a required function under given conditions for a given time interval
- **Availability** is ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided.
- **Maintainability** is a probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.

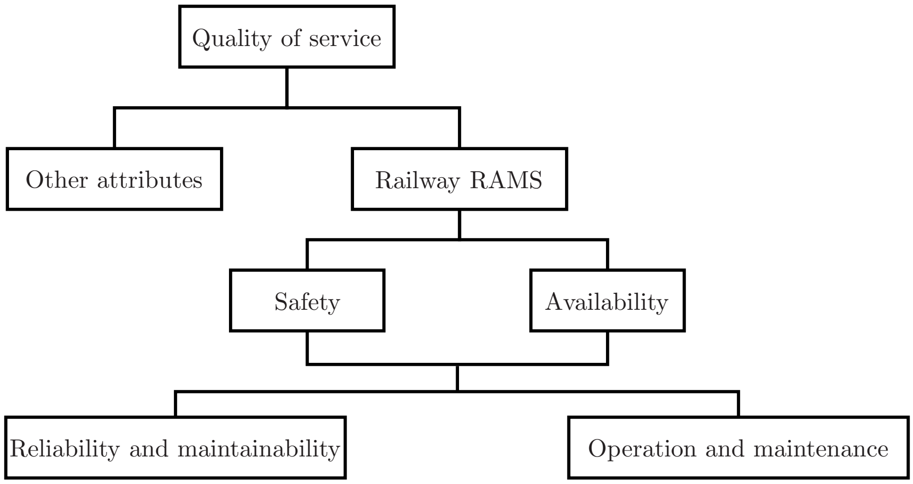

FIGURE 5.5: The Concept of Railway RAMS

- **Safety** is a freedom from unacceptable risk of harm.

Railway RAMS requires systems to which it is applied to maintain good balance, considering relevant indicators and economical efficiency.

RAMS shown in Figure 5.5 are stipulated in the standard. Here, quality of service is seen as being most important, and that quality of service is made up of RAMS for railways and other attributes. Furthermore, RAMS for railways is made up of safety and availability, which are based on reliability and maintainability plus operation and maintenance. In this way, the components of RAMS are expressed in a straightforward manner. The life–cycle from system concept to disposal in the RAMS standard is stipulated as being classified in 14 phases as shown in Figure 5.6.

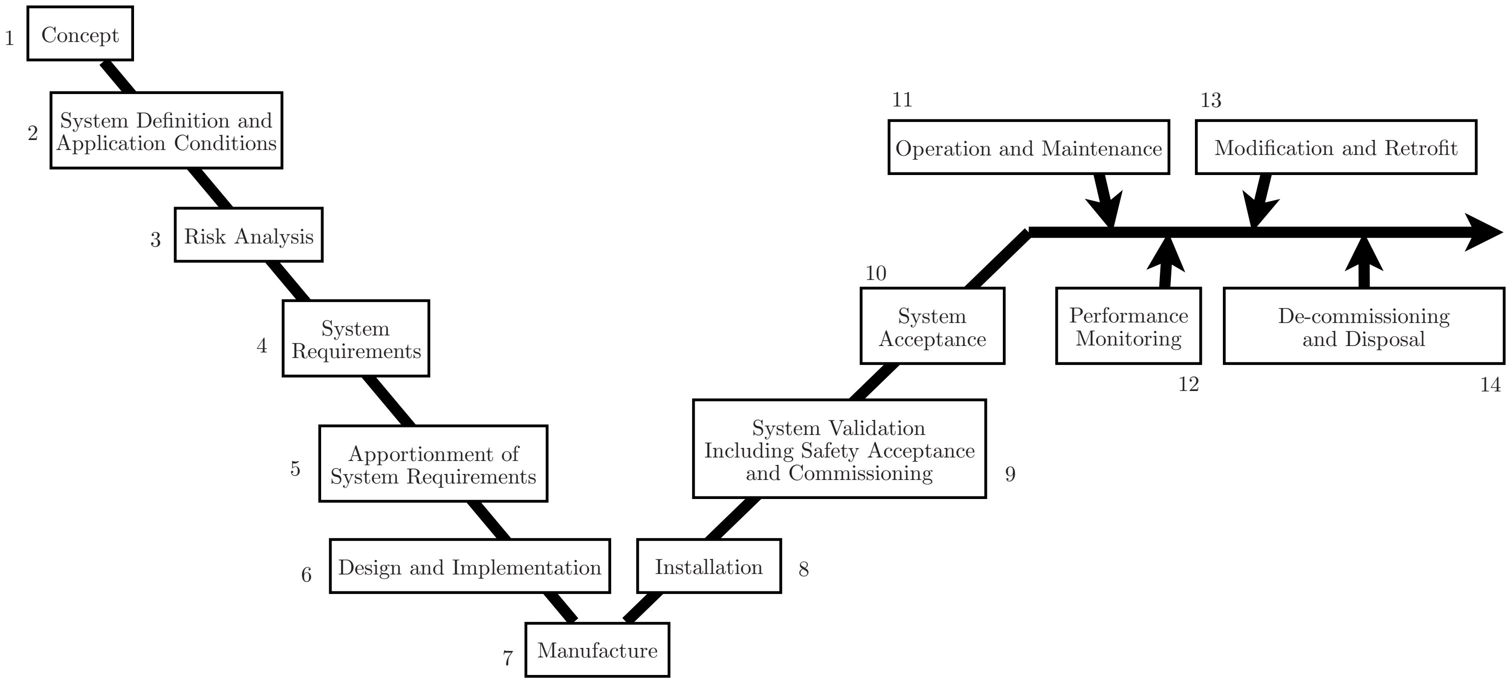

Figure 5.6: The RAMS Life–cycle

5.2.3.2 Factors Influencing Railway RAMS

The RAMS of a railway system is influenced in three ways:

F1) System conditions By sources of failure introduced internally within the system at any phase of the system life–cycle.

F2) Operating conditions By sources of failure imposed on the system during operation.

F3) Maintenance conditions By sources of failure imposed on the system during maintenance activities.

These sources of failure can interact with each other. This relationship is detailed Figure 5.7.

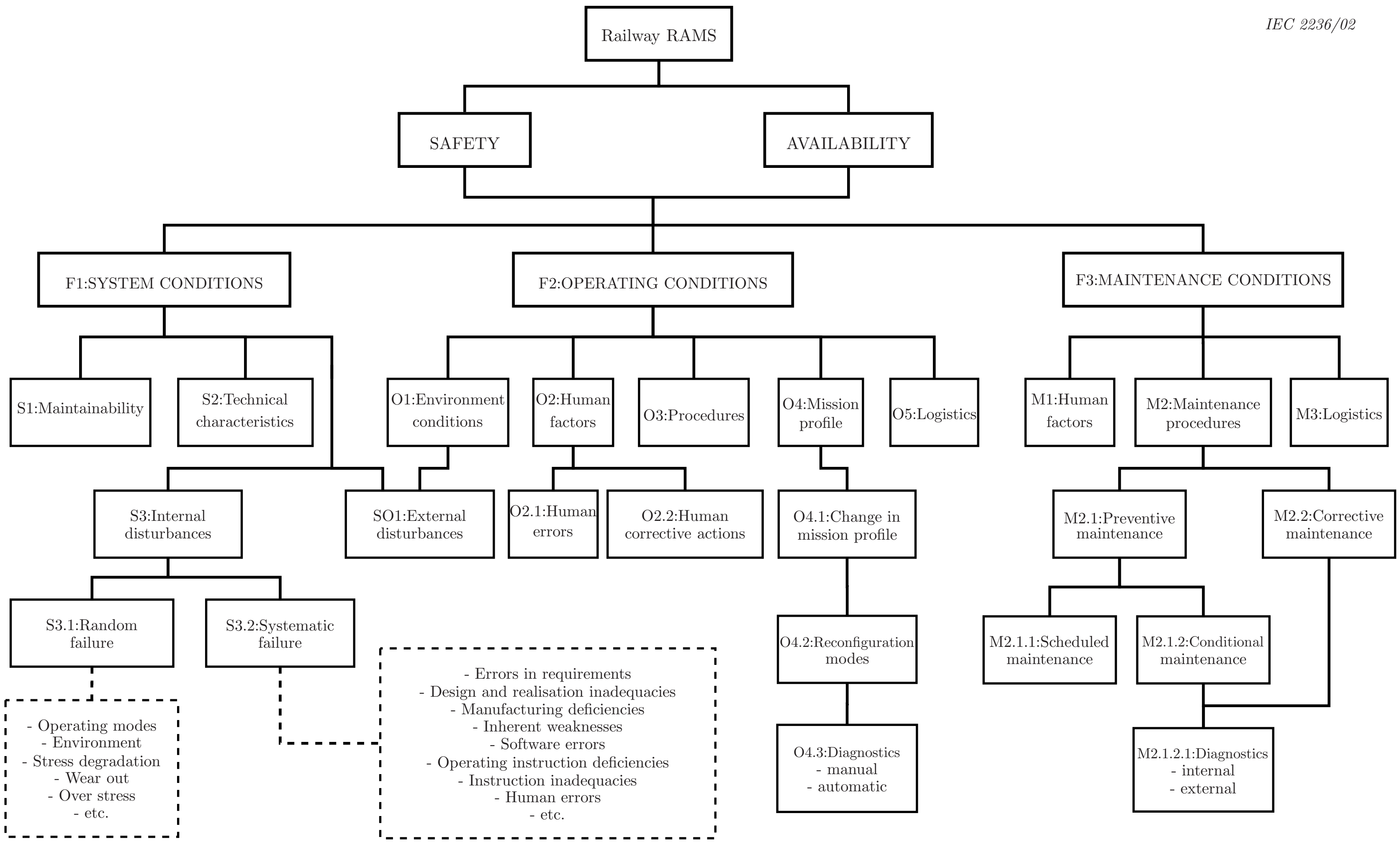

Figure 5.7: Factors Influencing Railway RAMS in accordance with IEC 62278

Table 5.3: Relationship between the proposed Essential Requirements and IEC 62278 (RAMS)

The Essential Requirements for RSR Utilization		Corresponded to Factors Influencing RAMS (Fig.5.7)											
		F1:System			F2:Operating						F3:Maintenance		
		S1	S2	S3	SO1	O1	O2	O3	O4	O5	M1	M2	M3
E1 : Management (Section 5.1.1)	E1-1 : Policy	○	○	○	○	○	○	○	○	○	○	○	○
	E1-2 : Balance in decision	○	○	○	○	○	○	○	○	○	○	○	○
	E1-3 : Social and Cultural Context	○	○	○	○	○	○	○	○	○	○	○	○
E2 : Technology (Section 5.1.2)	E2-1 : Appropriate behavior and function	○	○	○	×	○	○	○	○	○	○	○	○
	E2-2 : Stay on the hilltop of the Uncanny Valley	×	×	×	×	×	○	×	○	○	○	○	○
	E2-3 : Human-Robot Interface	○	○	○	×	×	○	○	○	○	○	○	○
	E2-4 : On-demand power source	×	×	×	○	×	○	○	○	○	○	○	○
E3 : Safety (Section 5.1.3)	E3-1 : Safety of machinery	○	○	○	○	○	○	○	○	○	○	○	○
	E3-2 : Sanitary	○	○	○	○	○	○	○	○	○	○	○	○
E4 : Maintenance (Section 5.1.4)	E4-1 : Preventative Maintenance	○	×	×	×	○	○	○	○	○	○	○	○
	E4-2 : Corrective Maintenance	○	×	×	×	○	○	○	○	○	○	○	○

○:Yes, ×:No, F1:System condition, F2:Operating condition, F3:Maintenance condition, S1:Maintainability, S2:Technical characteristics, S3:Internal disturbances, SO1:External disturbances, O1:Environment conditions, O2:Human factors, O3:Procedures, O4:Mission profile, O5:Logistics, M1:Human factors, M2:Maintenance procedures, M3:Logistics

5.2.3.3 Discussion and Verification

In order to maintain the quality of service. The factors F1, F2, and F3 in Table 5.3 and Figure 5.7 are the key to success. Chapter 3 and Chapter 4 shows that how the MK robot project has involved in those factors.

From the viewpoint of the RAMS, all off factors influencing RAMS (F1:System, F2:Operating, and F3:Maintenance conditions) correspond to E1:Management of the proposed ER because of each factors needs a management.

F1:System conditions and E2:Technology

- The column of the F1 (System Conditions) which are consist of maintainability (S1), technical characteristics (S2), internal disturbances (S3), and external disturbances (SO1).
- The S1 corresponds to "E2-1:Appropriate behavior and function" because of in order to utilize the restaurant service robot in a real environment, we have to design a maintainable robot in the robot designing phase.
- The S2 corresponds to the E2-1 because of each the technical characteristics of the robot parts can influence the system condition.
- The S3 corresponds to the E2-1 because of the internal disturbances can influence the system condition.
- The SO1 corresponds to the E2-1 because of the external disturbances (e.g. floor condition, customer reaction, etc.) are uncontrollable factors. Therefore, we have to design a robot to prevent from such factors.
- The S1, S2, S3, and SO1 are not corresponded to "E2-2:Stay on the hilltop of the Uncanny Valley" because of the E2-2 is about the appearance of the robot, the appearance of the robot does not influence the system conditions.

F1:System conditions and E3:Safety

- The S1, S2, S3, and SO1 are corresponded to the "E3:safety" because the safety of the robot comes from the good condition of the robot's systems.

F1:System conditions and E4:Maintenance

- The S1:Maintainability is directly related to the E4:Maintenance that is a reason why S1 corresponds to E4.

F2:Operating Conditions and E2:Technology

- The column of the F2 (Operating Conditions) which are consist of Environment conditions (O1), Human factors (O2), Procedures (O3), Mission profile (O4), and Logistics (O5).
- The "O1:Environment conditions" corresponds to "E2-1:Appropriate behavior and function" because of the environment condition is a considering point of robot designing. On the other hand, the O1 does not correspond to E2-2, E2-3, and E2-4 because those ER do not depend on the environment conditions.
- The "O2:Human factors" corresponded to all of our proposed E1 to E4 because of the O2 deals with a human and every parts of the RSR has take the human factors into account.
- The "O3:Procedures" corresponds to E2-1, E2-3, and E2-4 because of the procedures of operation is a basic requirements of the robot designing and E2-1, E2-3, and E2-4 are directly related to robot designing. On the other hand, the O3 does not corresponded to E2-2 because the appearance of the robot is no related to the procedure of a robot operation.
- The "O4:Mission profile" corresponds to E2-1 and to E2-4 because of the O4 is a goal of a RSR project, in order to reach to the goal the E2-1 to E2-4 are also need.
- The "O5:Logistics" corresponded to E2-1 to 2-4 to make sure the robot will be safe during transportation.

F2:Operating Conditions and E3:Safety

- During robot operation, safety comes first. Therefore, the factors O1 to O5 are corresponded to E3:Safety.

F2:Operating Conditions and E4:Maintenance

- In order to keep good operating conditions, maintenance is very important. Therefore, the factors O1 to O5 are corresponded to E4:Maintenance.

F3:Maintenance Conditions and E2 to E4

- Maintenance is most important thing to keep the service quality of the restaurant service robot in good condition. Therefore, the F3 corresponds to all of the essential requirements.

5.3 The Essential Requirements and the Lessons Learned

The Lessons Learned explains what went wrong or right and what was accomplished or not during the project and notes suggestions. By following a Project Management Body of Knowledge (PMBOK) template [29, 51], the category of the Lessons Learned is as follows:

a) Production,
b) Operation,
c) General management, and
d) Quality management.

Table 4.6 lists lessons and their category,

I) Issue (I1 – I8),
II) Problem or Success (P,S),
III) Impacts, and
IV) Recommendations.

5.3.1 Discussion and Verification

Table 5.4 shows the relationship between the Essential Requirements (ER) for RSR utilization (Section 5.1) and the Lessons Learned (Table 4.6).

For example, the E1-1:Policy of our ER corresponds to the issue I7:Authority of the Lessons Learned because the authority comes from the policy of all parties. And the S4 (allowed to access to all information as needed by the project) verified that relation.

The I8:Documentation corresponds to all our ER (except E3-2:Sanitary), well-documented by referring to international standards made the project goes smoothly.

The E3-2:Sanitary is not applicable here because the sanitary issue is not in the Lessons Learned table (Table 4.6).

Table 5.4: The proposed Essential Requirements and the Lessons Learned

The Essential Requirements for RSR Utilization		Corresponded to Lessons Learned (Table 4.6)
E1 : Management (Section 5.1.1)	E1-1 : Policy	S4, S5
	E1-2 : Balance in decision	S1, P1, S5
	E1-3 : Social and Cultural Context	P2, S3, S5
E2 : Technology (Section 5.1.2)	E2-1 : Appropriate behavior and function	S1, P1, S2, S5
	E2-2 : Stay on the hilltop of the Uncanny Valley	S3, S5
	E2-3 : Human-Robot Interface	S3, S5
	E2-4 : On-demand power source	S3, S5
E3 : Safety (Section 5.1.3)	E3-1 : Safety of machinery	S3, P3, S5
	E3-2 : Sanitary	N/A
E4 : Maintenance (Section 5.1.4)	E4-1 : Preventative Maintenance	P3, S5
	E4-2 : Corrective Maintenance	P3, S5

N/A:Not Applicable, S1:Initial Product Idea, S2:Skin Production, S3:Customers feedback, S4:Authority, S5:Documentation, Feedback, P1:Production Material, P2:Staff's attitude, P3:Damage caused by young customer.

5.4 Concluding Remarks

The proposed Essential Requirements (ER) for a Restaurant Service Robot (RSR) Utilization based on our own experiences have been summarized here. From the viewpoint of a Framework of International Safety Standards, which is related to System Safety ([8], [49], and [50]) and the Lessons Learned have been used to verify whether the ER is appropriate or not. As the results, the proposed ER corresponds to those ISOs and the Lessons Learned. Therefore, we conclude that the proposed Essential Requirements for the RSR Utilization have been verified.

From the viewpoint of ER, a pneumatic actuator controlled by VSC with ON/OFF valves proposed in Chapter 2 is suitable for RSR utilization because it potentially satisfies the followings.

E1-2 : Balance in decision because of low cost and adequate performance.

E2-1 : Appropriate "behavior" and function because of the gentle motion, natural compliance, and shock resistance.

E3-1 : Safety of machinery because of inherent stiffness due to the air and low Electromagnetic Compatibility (EMC).

E4 : Maintenance because of a pneumatic actuator is easy to maintain and has long life time of use.

Note that for actual utilization of RSR with pneumatic actuators, the power source is an important issue. When the power source issue has been solved, a Pneumatic Cylinder with an ON/OFF valve can enhance the RSR Utilization in the future.

Chapter 6

Conclusion

In this thesis we have studied about the Restaurant Service Robot (RSR) Utilization by considering a Framework of International Safety Standards. Firstly, to develop an actuator with reasonable performance and cost for RSR, the friction compensation using Variable Structure Control with an ON/OFF valve has been proposed to control a pneumatic cylinder. Next, development and real environment evaluation of RSR for four years have been described with 14,280 services and 235,680 customers interested. Based on such experiences, the Essential Requirements for RSR Utilization have been derived, and they have been verified from the viewpoint of a Framework of International Safety Standards, where the essence of the International Standards related to System Safety have been condensed.

Chapter 2

- The Variable Structure Control (VSC) Design to eliminate the effect of the static friction on a Pneumatic Cylinder System with an ON/OFF valve have been carried out.
- A fictitious disturbance in control action has also been proposed to examine robustness theoretically as in Eq.(2.50).
- Closed-loop stability analysis of VSC with an ON/OFF and Proportional valve using Lyapunov's function has been carried out.
- The chattering phenomenon reduction by using the *saturation* function has been introduced by comparing to other methods experimentally.

As a result, if the complexities of the control devices has been reduced, then it would be applicable for a service robot from the viewpoint of cost effectiveness for investment and safety.

Note, a compressed air tank as a power source for a pneumatic cylinder is needed and the appropriate solution to put the tank into the robot in a safe way is not available, yet. Therefore, we have not applied the proposed method into our robot.

Chapter 3

- We have developed two types of five restaurant service robots from 2009 to 2012, i.e., two Order robots and three Server robots.
- Based on our Robocon experience, we developed robots that have the following features: a swappable battery, waterproofing, a Thai language user interface, a robust operating system, easy preventive maintenance, and customer-friendliness and attractive skin, which are important for robot operation in real environments.
- The skin design and production of the robots is based on handcraft production.
- The robots we developed have the advantages of minimal cost and maximized delivery time, making them a possible role model for further service robots with reasonable performance in Thailand.
- The result of a risk assessment and risk reduction with inherently safe design measures, protective measures, and information for use of the ServeTwo shows that the foreseeable risks have been reduced.

Chapter 4

- In 4 years of evaluation in 5 real restaurants in the Bangkok area, these robots have shown their acceptability for real environment implementation and operation.
- This has been verified by simple questionnaires by restaurant staff. As a first step, these robots provided 14,280 services and attracted the interest of 235,680 customers.
- Most customers, both young and adult, responded positively to the robots, e.g., customers enjoyed robot services and young customers were so proud of Thai

robots that some wanted to become robot developers. Restaurant staff members also responded positively to the robots.

- Lessons Learned from this project are summarized in Section 4.3 into 3 categories: 1) robot production, 2) robot operation, and 3) project management avoiding mistakes and repeating success in the future.

Chapter 5

- We have proposed the eleven Essential Requirements for Restaurant Service Robot Utilization based on our experience which categories of management, technology, safety, and maintenance.
- The international standards which are related to risk assessment/reduction/management ([8], [49]), quality of service ([50]), and the Lessons Learned (Table 4.6) have been used as an examination tools.
- As a result, the Essential Requirements for Restaurant Service Robot Utilization meet the expectations of the System Safety Framework.

Future issues are as follows: improving customer satisfaction and implementation of a natural robot-human interface, e.g., Thai language voice recognition and customer recognition. Safety is most important and we will considering the ISO 13482:2014 [8] in robots designing. To evaluate details, e.g., the System Usability Scale (SUS) method [52] will be applied. Lessons Learned here are initial, so the deeper consideration of these lessons will be part of our further work.

Appendix A

Operation Hazard Identification of the ServeTwo Robot

Table A.1: Operation hazard identification (1/2)

Risk assessment (Operation hazard identification)			
Machine (Robot)	ServeTwo	**Analyst**	EKSIRI A.
Source	Specification, preliminary design	**Current version**	1.0
Extent	Operation	**Date**	April, 2014
Method	Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)	**Page**	1

Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**			**Ref. no.**
				Hazard	**Hazardous situation**	**Hazardous event**	
1	Operation	Start-up OR Restart after unscheduled stop	Robot station and Restaurant walk way	Unintended/Unexpected start-up	Staff operates near robot	Robot arm moves and touches staff's eye	**1**
2				Hazardous actions taken during start-up or restart	Operator stands in not proper place	Robot arm moves and touches staff's eye	**2**
3		Serving	Food container	Crushing, trapping, pinching, cutting, severing, stabbing, or abrasion	Hands into the food container for Loading/Unloading the dish	Contact with sharp edges	**3**
4						Contact with holes or gaps between moving parts of the food container joints	**4**
5			Restaurant walk way	Crushing, impact, shearing	Staff walks to the table along with the robot	Contact with moving arms	**5**

Table A.2: Operation hazard identification (2/2)

Risk assessment (Operation hazard identification)			
Machine (Robot)	ServeTwo	**Analyst**	EKSIRI A.
Source	Specification, preliminary design	**Current version**	1.0
Extent	Operation	**Date**	April, 2014
Method	Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)	**Page**	2

Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario: Hazard**	**Accident scenario: Hazardous situation**	**Accident scenario: Hazardous event**	**Ref. no.**
6	Operation					Crushing between the mobility unit and the fixed partition	**6**
7		Battery swapping	Battery drawer	Electric shock	Lifting, loading, unloading by staff	Contact with both side of live battery terminals	**7**
8				Fire, discharge of hazardous fumes or substances	Lifting, loading, unloading by staff	Battery short-circuit	**8**
9				Crushing, trapping, pinching, cutting, severing, stabbing, or abrasion	Lifting, loading, unloading by staff	Battery falling	**9**
10						Contact with holes or gaps between moving parts of the battery drawer	**10**
11						Contact with sharp edges	**11**
12		Battery charging	Charging station	Fire, discharge of hazardous fumes or substances	Charging of deeply discharged batteries	Charger failure	**12**
13					Lifting, plug-in	Battery short-circuit	**13**
14				Electric shock	Lifting, loading, unloading	Contact with live battery terminals	**14**

Table A.3: Maintenance hazard identification for staff (1/2)

Risk assessment (Maintenance hazard identification)							
Machine (Robot)			ServeTwo		**Analyst**	EKSIRI A.	
Source			Specification, preliminary design		**Current version**	1.0	
Extent			Maintenance		**Date**	April, 2014	
Method			Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)		**Page**	1	
Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**			**Ref. no.**
				Hazard	**Hazardous situation**	**Hazardous event**	
15	Oper-ation	Cleanup	Robot's skin sur-faces and Food condi-tioner at Robot sta-tion	Skin rash	Cleanup with cleaning solution by hands	Cleaning with out a proper grove, Contact with cleaning solution	**15**
16				Eye inflammation	Cleanup with cleaning solution	Splashes/Ejection of a cleaning solution while wiping without wearing an safety glass	**16**
17			Wheels sur-face	crushing, impact	Lifting of robot	Instability of the lifter	**17**

Table A.4: Maintenance hazard identification for staff (2/2)

Risk assessment (Maintenance hazard identification)							
Machine (Robot)			ServeTwo		**Analyst**	EKSIRI A.	
Source			Specification, preliminary design		**Current version**	1.0	
Extent			Maintenance		**Date**	April, 2014	
Method			Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)		**Page**	2	
Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**			**Ref. no.**
				Hazard	**Hazardous situation**	**Hazardous event**	
18	Operation	Repairing the guidance system	Vinyl sticker and RFID card	cutting or severing	Replacement of the sticker	Cut the vinyl sticker by a cutter and cut finger	**18**
19		Tuning the guided line tracing sensors	bottom edge of robot's skin	Cutting, severing, stabbing, or abrasion due to Sharp edges	Adjusting the sensors by hand	Loss of direct visibility of the working area and hand touches the edge	**19**
20		Batteries checking	Charging station	burn, shock, fire, chemical effects due to short-circuit	Inspection the batteries voltage and current	Wrong mode setting of measuring equipment	**20**
21				burn, shock, fire, chemical effects due to contact with live battery terminals	Inspection the batteries voltage and current	Direct contact with battery terminals	**21**

Table A.5: Transportation hazard identification for staff

Risk assessment (Transportation hazard identification)								
Machine (Robot)			ServeTwo		**Analyst**	EKSIRI A.		
Source			Specification, preliminary design		**Current version**	1.0		
Extent			Transportation		**Date**	April, 2014		
Method			Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)		**Page**	1		
Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**				**Ref. no.**
				Hazard	**Hazardous situation**	**Hazardous event**		
22	Operation	Load or Unload the robot from / to a cart	Robot body	Crushing, impact, shearing, severing	Lift-up/down the robot to a cart by hands	Unbalance of the robot and fall down together		**22**
23		Load or Unload the robot from / to a truck	Robot body	Crushing, impact, shearing, severing	Lift-up/down the robot with cart to a truck by hands	Unbalance of the robot and fall down together		**23**

Table A.6: Full testing hazard identification for staff

Risk assessment (Full testing hazard identification)							
Machine (Robot)			ServeTwo		**Analyst**	EKSIRI A.	
Source			Specification, preliminary design		**Current version**	1.0	
Extent			Full testing		**Date**	April, 2014	
Method			Checklist: ISO 13482:2014 (Annex A) and ISO 12100:2010 (Annex B)		**Page**	1	
Ref. no.	**Life cycle**	**Task**	**Hazard zone**	**Accident scenario**			**Ref. no.**
				Hazard	**Hazardous situation**	**Hazardous event**	
24	Operation	“Same as the Operation Hazard Identification”	“Same as the Operation Hazard Identification”	“Same as the Operation Hazard Identification”	“Same as the Operation Hazard Identification”	“Same as the Operation”	**24**

Appendix B

Risk Assessment and Risk Reduction of the ServeTwo Robot

Table B.1: Risk assessment and risk reduction

Risk assessment and risk reduction													
Machine						ServeTwo	**Analyst**					EKSIRI A.	
Source						Specifications, preliminary design	**Current version**					1.0	
Extent						Use phase: Operation Table A.1 – A.6	**Date**					July 2011	
Method						Hybrid	**Page**					1	
Ref. No.	**Risk estimation (initial risk)**					**Risk reduction Protective/risk reduction measures**	**Risk estimation (after risk reduction) [sub-RI]**					**Further risk reduction required**	**Ref. No.**
	S	**F**	**O**	**A**	**RI**		**S**	**F**	**O**	**A**	**RI**		
1	2	1	1	1	1	Rounded shape hand, Trained staff, Operation regulations, Instruction manual	1	1	1	1	1	No	**1**
2	2	1	2	1	2	Rounded shape hand, Trained staff, Operation regulations, Instruction manual, Information for use	1	1	1	1	1	No	**2**
3	3	2	2	1	4	Inherently safe design and manufacturing with curving edges	1	1	1	1	[1] 1	No	**3**
	3	2	2	1	4	Staff training	2	2	2	1	[2]	No	
4	3	2	2	1	4	Inherently safe design and manufacturing with gap < 1 [cm]	1	1	1	1	1	No	**4**
5	1	2	2	1	1	Inherently safe design with minimum sufficient power of motor and EOF speed < 25 [cm/s], pause and emergency switches	1	2	2	1	1	No	**5**

Continued on next page

Table B.1 – continued from previous page

Risk assessment and risk reduction													
Machine						ServeTwo	**Analyst**					EKSIRI A.	
Source						Specifications, preliminary design	**Current version**					1.0	
Extent						Use phase: Operation Table A.1 – A.6	**Date**					July 2011	
Method						Hybrid	**Page**					2	
Ref. No.	**Risk estimation (initial risk)**					**Risk reduction Protective/risk reduction measures**	**Risk estimation (after risk reduction) [sub-RI]**					**Further risk reduction required**	**Ref. No.**
	S	**F**	**O**	**A**	**RI**		**S**	**F**	**O**	**A**	**RI**		
6	2	2	2	1	2	Inherently safe design with minimum sufficient power of motor, pause and emergency switches	1	2	2	1	1	No	**6**
7	3	1	2	1	3	providing an insulator to the terminals	3	1	1	1	2	No	**7**
8	3	1	2	1	3	Use an female enclosed connector	3	1	1	1	2	No	**8**
9	3	2	2	2	5	Inherently safe design with as low as possible of the battery drawer height	2	2	1	1	[1]	No	**9**
	3	2	2	2	5	use the battery with a handle	2	2	1	1	[1] 1	No	
	3	2	2	2	5	battery cart	3	1	2	1	[3]	No	
	3	2	2	2	5	staff training	3	2	1	1	[3]	No	
10	3	2	2	1	4	Inherently safe design and manufacturing with gap < 1 [cm]	1	2	1	1	1	No	**10**
11	3	2	2	1	4	Inherently safe design and manufacturing with curving edges	1	2	1	1	[1] 1	No	**11**
	3	2	2	1	4	Instruction manual	3	2	1	1	[3]	No	

Continued on next page

Table B.1 – continued from previous page

Risk assessment and risk reduction			
Machine	ServeTwo	**Analyst**	EKSIRI A.
Source	Specifications, preliminary design	**Current version**	1.0
Extent	Use phase: Operation Table A.1 – A.6	**Date**	July 2011
Method	Hybrid	**Page**	3

Ref. No.	**Risk estimation (initial risk)**					**Risk reduction Protective/risk reduction measures**	**Risk estimation (after risk reduction) [sub-RI]**					**Further risk reduction required**	**Ref. No.**
	S	**F**	**O**	**A**	**RI**		**S**	**F**	**O**	**A**	**RI**		
12	3	1	1	2	3	Trained staff, Operation regulations, Instruction manual, Information for use	2	1	1	1	1	Operation time warning signal to the operator	**12**
13	3	2	2	1	4	Use an enclosed connector	2	1	1	1	[1]	No	**13**
	3	2	2	1	4	Staff training	3	2	1	1	[3] 1	No	
	3	2	2	1	4	Instruction manual	3	2	1	1	[3]	No	
14	3	1	2	1	3	providing an insulator to the terminals	1	1	2	1	1	No	**14**
15	3	1	2	2	4	Use the MK's cleaning standard process and materials	1	1	1	1	1	No	**15**
16	3	1	2	1	3	Use the MK's cleaning standard process and materials	1	1	1	1	1	No	**16**
17	3	1	2	1	3	Inherently safe design with the ServeTwo handle, use a spacer while cleaning	1	1	1	1	1	No	**17**
18	3	1	2	1	3	Trained staff	2	1	1	1	1	No	**18**

Continued on next page

Table B.1 – continued from previous page

Risk assessment and risk reduction													
Machine						ServeTwo	**Analyst**					EKSIRI A.	
Source						Specifications, preliminary design	**Current version**					1.0	
Extent						Use phase: Operation Table A.1 – A.6	**Date**					July 2011	
Method						Hybrid	**Page**					4	
Ref. No.	**Risk estimation (initial risk)**					**Risk reduction Protective/risk reduction measures**	**Risk estimation (after risk reduction) [sub-RI]**					**Further risk reduction required**	**Ref. No.**
	S	**F**	**O**	**A**	**RI**		**S**	**F**	**O**	**A**	**RI**		
19	3	1	2	1	3	Trained staff, Inherently safe design and manufacturing with curving edges	2	1	1	1	1	No	**19**
20	3	1	2	1	3	Trained staff, information for use	3	1	1	1	2	No	**20**
21	3	1	2	1	3	Trained staff, information for use, providing an insulator to the battery's terminals	3	1	1	1	2	No	**21**
22	3	1	2	2	4	Ergonomic Inherently safe design with the ServeTwo handle, Trained staff	1	1	1	1	1	No	**22**
23	3	1	2	2	4	Inherently safe design with the ServeTwo handle, Trained staff, fix the robot to the cart by rope	3	1	1	1	2	No	**23**
24	Same as Ref. No. 1 to 14												**24**

Note : Assume that well-trained staff can reduce the severity for minor harms, because it strongly depends on the behavior of the staff. In addition, the severity of severe harm can not change by staff training.

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