A model for assessment of human assistive robot capability

BY

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

…………………………………………… (Signed)

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Abstract

The purpose of this research is to develop a generalised model for levels of autonomy and sophistication for autonomous systems. It begins with an introduction to the research, its aims and objectives before a detailed review of related literature is presented as it pertains to the subject matter and the methodology used in the research. The research tasks are carried out using appropriate methods including literature reviews, case studies and semi-structured interviews.

Through identifying the gaps in the current work on human assistive robots, a generalised model for assessing levels of autonomy and sophistication for human assistive robots (ALFHAR) is created through logical modelling, semi-structured interview methods and case studies. A web-based tool for the ALFHAR model is also created to support the model application. The ALFHAR model evaluates levels of autonomy and sophistication with regard to the decision making, interaction, and mechanical ability aspects of human assistive robots. The verification of the model is achieved by analysing evaluation results from the web-based tool and ALFHAR model. The model is validated using a set of tests with stakeholders' participation through the conduction of a case study using the web-based tool.

The main finding from this research is that the ALFHAR model can be considered as a model to be used in the evaluation of levels of autonomy and sophistication for human assistive robots. It can also prove helpful as part of through life management support for autonomous systems. The thesis concludes with a critical review of the research and some recommendations for further research.

Key Words

Knowledge Management; Autonomous systems; Autonomy; ALFHAR; Through life management.

Acknowledgements

Glossary of abbreviations

ACL   Autonomous Control Logic

ALFUS   Autonomy Level For Unmanned System framework

ALFHAR   Levels of Autonomy and sophistication For Human Assistive Robot

AOF   Acquisition Operating Framework

ASIMO   Advanced Step in Innovative Mobility

CADMID   Concept Assessment Demonstration Manufacture In-service Disposal

CADMIT   Concept Assessment Demonstration Migration In-service Termination

DOF   Degree of Freedom

ESOS   Engineering Systems Of Systems

FMEA   Failure Mode and Effects Analysis

FTA   Fault Tree Analysis

ISO   International Standards Organisations

KM   Knowledge Management

MIPS   Million Instructions Per Second

MOD   Military Of Defence

MTTF   Mean Time To Failure

PACT   Pilot Authority and Control of Tasks

PLM   Product Life-cycle Management

SCF   Systems Capabilities Framework

SOS   Systems Of Systems

GLOSSARY OF ABBREVIATIONS

TLM   Through Life Management

UAV   Unmanned Aerial Vehicle

UML   Unified Modelling Language

UMS   Unmanned Systems

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1 Introduction

This chapter explores the background to knowledge management in autonomous systems and outlines its development in autonomous systems field whilst at the same time providing guidance regarding how to supply knowledge management support for autonomous systems design and lifecycle management. The aim and objectives of this thesis are presented as well as an overview of the remaining chapters.

1.1 Background

At the present time there are in fact a number of robots used in domestic areas such as surgery or healthcare. The development of the human assistive robot is progressing rapidly to support future human societal needs in many different areas. The levels of autonomy and sophistication for human assistive robots are becoming more and more advanced. There are more human robot interactions, robot-robot interactions, and robot-environment interactions happening during the application of autonomous systems in domestic area. The learning behaviour of autonomous systems will make systems' safety problems more difficult to predict. The safety issue is becoming an important topic with regards to the application of autonomous system in domestic areas. How to manage its entire lifecycle and supply knowledge management support for autonomous systems will be a big challenge for the current research.

With the development of autonomous systems in domestic robot areas a number of other studies have also been conducted on autonomous systems, with the aim of supplying knowledge management support for autonomous systems. For example, the current work regarding knowledge management support in autonomous systems includes the use of ontology in autonomous systems (Schlenoff 2002, Mendoza & Williams 2005), decision making support tools in autonomous systems, classification of characteristics of autonomous systems (Huang, Messina et al. 2007, Sholes 2007, Visnevski & Castillo-Effen 2009a), standards in autonomous systems (Bostelman & Hong et al. 2006, Dhillon & Fashandi 1997), and so on. A great deal of knowledge management work enhances levels of autonomy for autonomous systems, and some is helpful with regards to giving people a better understanding of autonomous systems. There remains little in the way of current research for ontologies *about* autonomous systems, which will be very helpful for designers to use.

Through analysis, although many authors work on classifications of characteristics of autonomous system, most of these are applied in defence properly, and cannot fit into domestic robot area properly (Fu, Henshaw 2010); there are more analyses in the Appendix I.

Through Life Management (TLM) is the philosophy which brings together the behaviours, systems, processes and tools to deliver and manage projects through the acquisition lifecycle (AOF 2009). At the moment, the idea of TLM is widely applied in the defence domain, and its benefits are obvious. It is helping to rapidly change organisations who, as a result can compete in global market places. It also generates more opportunities for business and reduces cost (Urwin, Pilfold et al. 2010). However the application of TLM in the autonomous robot sector is still very limited. To explore how the stakeholders can benefit from TLM for autonomous robots, a tool will be developed which will aid in supporting the lifecycle management of autonomous robots.

1.2 Research aims and objectives

1.2.1 Introduction

This section formulates a research process with a view to achieving the research aims and objectives. An overview of the present study's objectives is shown in Figure 1-1. The objectives in this figure are based on a bottom-up sequence. In this research plan, the author works towards several objectives to build towards the aims; the objectives can be considered as the building blocks of the research. There are also a number of relations between these objectives, which are combined together to reach the aims of the research. The objectives in this figure can also be considered as different stages of the research.

1.2.2 Aims and objectives of this research

The research aim is considered as: to provide Knowledge Management support to the community (engineers) responsible for design and life cycle management of autonomous systems, in order to ensure safe, reliable, cost-effective, secure, extensible, and maintainable operation.

To achieve the aim of this research, six objectives are established and will be explored more thoroughly in the following chapter. Firstly, a general explanation of the hierarchy of these objectives is shown as follows.

CHAPTER 1: INTRODUCTION

1.2.2.1 Hierarchy of objectives

In Figure 1-1 it is clearly evident that the hierarchy of objectives is based on bottom-up order. The objectives are coherent and work together to reach the research aim. The research has undergone its fair share of changes and challenges, could be continued to successfully achieve its final goal. The first three objectives are primarily designed to identify the knowledge and information needed to support the research. Based on information and knowledge gained from the first objective it is hoped that the second and third objectives will evolve. Objectives two and three are fairly reliant on how much information and knowledge is captured in objective one. For objectives two and three to be achieved thorough background research and research scope are vital; both of which will be the focus of the first objective. After analysing the stakeholders and obtaining the information required from the first three objectives, a proposed framework is put forth in objective four. Objective four pertains to the nature of the knowledgeable contribution which this research can supply to stakeholders. The work in objective four is tailored according to the research gap identified in objective one as well as the requirements from stakeholders which are identified in objectives two and three. When the model is created in objective four, a tool is developed to support the application of the model in objective five. The tool here is based on the content of the model in objective four, and is used to validate the model and make it easier to use for stakeholders. Following objectives four and five, objective six will be broached: the frameworks' benefits and measures, which is to analyse the results from objectives four and five. The work in objective six is concerned with highlighting and summarising the research results as a whole and explaining how these can offer benefits to stakeholders. All these objectives can be integrated together with a view to achieving the final research aim.

Aim:

To provide Knowledge Management support to the community (engineers) responsible for the design and life cycle management of autonomous systems, in order to ensure safe, reliable, cost-effective, secure, extensible, and maintainable operation.

Objective VI: To measure benefits

To provide benefits of frameworks and tools as measurements of support for decision making.

Objective V: To create a tool

Create an applicable tool to support decision making for stakeholders involved in the design and life cycle management.

Objective IV: To develop framework

d:Integration of components

Integrate components into the decision making support framework.

c: Guidance for designers

A set of questions will be designed in order to help stakeholders ensure that safety / ethical issues are included in their consideration.

a: Levels of autonomy

Create a generalised model for levels of autonomy for human assistive robot.

b: Development of ontology

Use ontology for autonomous systems for characterisation of autonomous systems.

Objective III: To generate the research requirement

Investigate / understand what stakeholders need, and translate their requirements into a framework.

Objective II: To identify Stakeholders

Identify stakeholders, and their roles in this research.

Objective I: To identify information and knowledge requirements for autonomous systems

Analyse information and knowledge requirements for the engineers responsible for autonomous system design and maintenance.

Figure 1-1: Overview of objectives

1.2.2.2 Objective I: To identify information and knowledge requirement for autonomous systems

Identifying the information and knowledge required for autonomous systems is achieved by means of a literature review. This is necessary in order to paint a clear picture of the current research, as well as to analyse the information and knowledge required for the engineers responsible for autonomous system design and maintenance. The main content is described in Chapter 2.

Methods:

- Primarily based on a literature search using libraries, accessing websites on ISI web of knowledge, scholar.google.co.uk, sciencediret.com, and so on.
- In order to identify the current situation in the industry as it pertains to the robotic area, a portion of the information and knowledge is collected from semi-structured interviews with stakeholders.

In this section a report of the relevant literature for this research is produced. A literature review helps to identify the information and knowledge required for autonomous systems, whilst also facilitating the identification of the research area.

1.2.2.3 Objective II: To identify stakeholders

Stakeholder analysis is essential for research. In identifying the stakeholders affected by this research and analysing their interests, the research required can be determined in addition to the most suitable data collection methods and research result validation. The main work on this objective includes group discussion, robot lifecycle analysis and literature review.

Methods:

- Group discussions will generate a set of potential stakeholders for this research before an in depth analysis is conducted based on their relationships with the research topic and research aims.
- The main stakeholder affected by this research can be determined based on the content of through life management in this research; through analysing the lifecycle of autonomous systems to identify who is stakeholder in this research and their interest.

CHAPTER 1: INTRODUCTION

Objective outcome:

A set of stakeholders are identified in this research, as well as their interests in different stages of the lifecycle. Due to the research aim, the main stakeholders in this research are designers in the human assistive robot area and health professionals who may use human assistive robots. There are also a number of other potential stakeholders such as the general public, manufactures, maintainers, and so on. There is an extensive discussion regarding stakeholders in the literature review found in Chapter 2.

1.2.2.4 Objective III: To generate the research requirement

The third objective involves the collection of data required for this research. The original requirement for this research is based on a research proposal; following this, and through the utilisation of a literature review and interviews with stakeholders, the more practical requirements are generalised.

Methods:

- A literature review will help to identify the gaps between the existing research and the proposed research;
- Interviews with stakeholders will help establish the nature of their current situations; what problems they are facing; and what questions they want to have answered.

Objective outcome:

Having identified and categorised the stakeholders, generate a set of research requirements for this research. The requirement of this research is to identify and create new methods and technologies with which to create a generalised model for levels of autonomy and sophistication for autonomous systems.

1.2.2.5 Objective IV: To develop framework

Objective four pertains to the main work in this research. This objective is further divided into four tasks:

1. Levels of autonomy: create a generalised model for levels of autonomy for the human assistive robot.

2. Development of ontology: ontology regarding the human assistive robot. This section of work is considered in the framework but will be carried out at a later date.

3. Guidance for designers: this supplies a number of guidelines for stakeholders who wish to support through life management; this research covers a certain amount of this work, however there remains work to be done in the future.

4. Integration of components: this is concerned with the integration of the previous 3 pieces of work into a decision making system, so as to supply an integrated framework which can support decision making for stakeholders.

Methods:

- Modelling techniques are identified and used in levels of autonomy; the logical model analysis method is used to analyse the definition of autonomy in order to create a conceptual model for autonomy.

- Semi-structured interviews will serve to identify stakeholders' considerations with regards to the model for levels of autonomy; their feedback will then be incorporated into the development of a model for levels of autonomy and sophistication.

- Case studies will also be utilised in order to establish whether or not the model is reasonable.

Objective outcome:

A generalised model of levels of autonomy is demonstrated and a paper: "classification of levels of autonomy for human-assistive robots" is published. The model created here aims to supply an effective technique for stakeholders to evaluate levels of autonomy and sophistication in order to manage the design and through life management of autonomous systems.

Due to the time constraints of this MPhil research, objective IV is mainly concerned with levels of autonomy and sophistication. The remaining work related to objective four may be done in the future if an opportunity presents itself.

1.2.2.6 Objective V: To create a tool

The aim of this objective is to create an applicable tool with which to support decision making for stakeholders in design and life cycle management. The tool currently under development is based on a general model of levels of autonomy and sophistication (ALFHAR model). Through this tool, users can evaluate the capability for their system, or develop requirements for the system they wish to create. This objective has been sub-divided into the following tasks:

1. Tool development: develop a tool based on a general model of levels of autonomy and sophistication.
2. Study certain scenarios in order to demonstrate how the tool is used and to validate whether the tool can adequately represent the model.

Methods:

- Using Java programme language to develop a tool based on the model content;
- Using scenarios study to analyse how the tool works as a representation of the model, and also to show how users can participate in this tool.

Objective outcome:

A tool is developed based on Java language; scenarios are created to help stakeholders understand the usage of the tool and to validate whether the model can be used to evaluate levels of autonomy. The tool can be used to support the model in its quest to become more applicable.

1.2.2.7 Objective VI: To measure benefits

The fourth objective is designed to provide benefits of the framework and a tool with which to measure support for decision making. The work in this objective includes: case study based on the tool and analysis of how this model can be helpful for stakeholders; it also includes analysis of the model for the potential application area.

Methods:

- Case studies are used to identify potential application areas of the model;

- The results of these case studies are then analysed in order to demonstrate the benefits of the model.

Objective outcome:

Several case study tests are carried out on the tool to demonstrate how the model can be applicable; there is also a discussion on the benefits of the model for stakeholders, and analyses of exactly how the model relates to through life management.

1.3 Thesis layout

This thesis contains seven chapters, the first of which has just provided an introduction to the research background, research aims and objectives. Chapter 2 is the literature review, which explores and critically reviews the knowledge management, autonomous systems, and issues related to autonomous systems, such as safety, lifecycle of autonomous systems, robot design, and classification of autonomous systems. Stakeholder analysis of this research is also presented in Chapter 2.

Chapter 3 focuses on the research methodology and identifies the appropriate research methods for this research.

Chapters 4 and 5 detail the process of creating the ALFHAR model, starting with the logical model of autonomy. Following this, and based on feedback from stakeholders, a revised model is demonstrated in Chapter 5. Chapter 5 also introduces a computer model based on ALFHAR.

Chapter 6 presents the verification and validation of the ALFHAR model. It starts with verification of a computer model of ALFHAR, and details several tests conducted with participants based on the computer model of ALFHAR to validate the ALFHAR model. Chapter 7 discusses the findings of the research and their implications whilst also identifying the research limitations and opportunities for further research.

2. Literature review

This chapter provides a brief background summary of knowledge management, the methods used to support knowledge management, and how knowledge management can help in the development of autonomous systems. Following this there is an introduction to autonomous robots, through life management, and the importance of these in relation to autonomous systems; the chapter then discusses the issues related to through life management of autonomous systems. It also analyses stakeholders involved in this research and their interests, which includes a classification of autonomous systems; this will be developed further in the thesis and can be considered as part of the support for through life management of autonomous systems.

2.1 Information and knowledge management

Nowadays there is a wealth of research on information and knowledge management; much of which is applied in various areas. Microsoft, IBM, HP et al., use knowledge management to manage their information and knowledge to achieve great success (Lai & Chu 2000). Knowledge, which can be considered as forming the heart of today's global economy, is becoming increasingly important for an organisation's development. How to manage knowledge has now become a crucial factor in companies' success. With regards to the autonomous robots area, it is entering into a period of rapid development. During this period information and knowledge management support will be extremely helpful to its product development, cost reductions, supporting product lifecycle management and enhancing its organisation's compatibility. In the following section there is a basic introduction to knowledge management and its framework.

2.1.1 Knowledge management (KM) definition

The research topic of knowledge management has developed rapidly over the last decade. Many definitions of knowledge management are given by people in different areas. Jashapara (2004) has defined KM as follows:

"The effective learning processes associated with exploration, exploitation and sharing of human knowledge (tacit and explicit) that use appropriate technology and cultural

environment to enhance an organisation's intellectual capital and performance" (Jashapara 2004).

This definition demonstrates that the key factor in knowledge management is learning processes. It also requires an exploration of new information and knowledge with which to support learning. Another important factor in knowledge management is sharing knowledge, which enhances an organisation's capability. However, occasionally we also need to know how to protect an organisation's key knowledge in order to ensure that their profits are not affected by competitors. With this in mind it is essential to know where an organisation's important knowledge is located or stored as well as which parts of the knowledge can be shared with others and which cannot.

The mission of knowledge management is stated as:

"To connect those who know with those who need to know. To convert personal knowledge to organizational knowledge" (O'Leary 2002).

Through knowledge management it is possible that personal knowledge flows fluently and effectively within organisations, and that personal knowledge is shared with others within the organisation. This will obviously increase the efficiency of organisational knowledge and hence leverage its value. In terms of the area of robotics, it is about how to identify engineer / designer knowledge and experience as well as how to manage and share it within an organisation with a view to enhancing its creativity.

2.1.2 Relations among data, information, knowledge and wisdom

Data is defined in the dictionary as 'known facts or things used as a basis of inference or reckoning'. It has no meaning without a context. Information in the dictionary definition is 'something told' or 'the act of informing or telling'; information can be considered as 'systematically organised data'; information gives meaning to the data and makes a difference to the outlook or insight of the receiver of the data. In this sense, it is the receiver of the data who determines whether a message is data or information (Jashapara 2004). Knowledge derives from people's minds when they are actively involved in different activities. Davenport & Prusak (1998) have defined knowledge in an organisation as follows:

"Knowledge is a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers. In organizations, it often becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms" (Davenport & Prusak 1998).

This definition clearly shows that knowledge is a mixture of various elements. It exists in people's experience, their minds, and organisations. Wisdom is the ability to act critically or practically in a given situation. It is often captured in famous quotes, proverbs and sayings (Jashapara 2004).

Sometimes it is not easy to explicitly separate data, information, knowledge and wisdom as there is a transition among them. As shown in Figure 2-1 (Bellinger 2004) and Figure 2-2, there is a hierarchy among those four themes. For information it is data in context, and understanding the relationships between data. Once data is given in a certain context, data changes into information. Out of context data is meaningless. Knowledge is considered
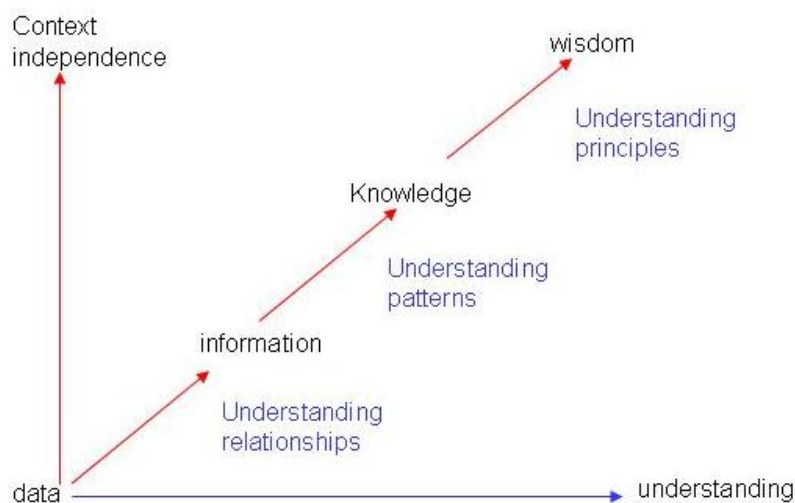
Figure 2-1: Relationships between data, information, knowledge and wisdom
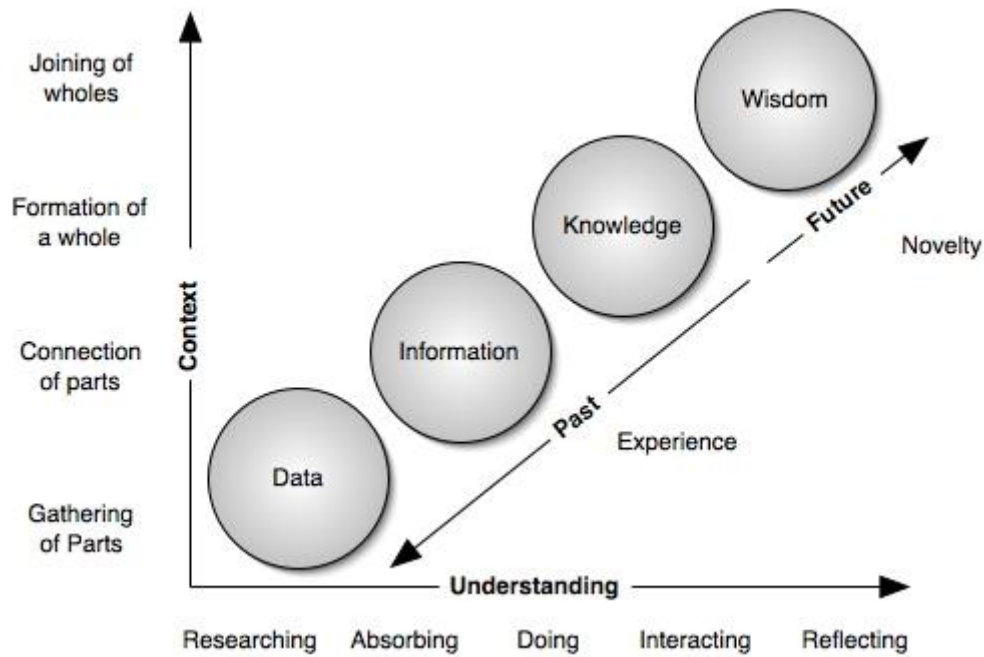
Figure 2-2: The continuum of understanding (Clark 2010)

as "actionable information" in the practical sense (Jashapara 2004). It about how information can be used in practical work. As people understand how the information works, and apply this information into practice, then information becomes knowledge in people's minds. For example, people can make predictions about what would happen next based on relevant information provided. Wisdom could be considered as evaluated understanding, which is "why" information works. Wisdom is more than knowledge and can help to create new knowledge. On the other hand, the accumulation of knowledge will be the foundation for generating wisdom. Data, information, knowledge, and wisdom exist on different layers of a pyramid from bottom to top (Frické 2009).

The relationships analysis here is designed to help provide a detailed understanding of what knowledge management is, whilst also making it easier to manage different types of objects in autonomous systems. The work on management of knowledge in the area of autonomous robotics may emerge from very important data from previous designs; it may come from customers' opinion / feedback on the product; it may come from the designer's experience with the design; it may also come from design guideline / standards from the robotic industry. All information related to robotic development should be considered in the scope of knowledge management for autonomous systems.

2.1.3 Explicit and tacit knowledge

Generally, knowledge management deals with two types of knowledge: tacit and explicit (or formal and informal). These two types of knowledge exist simultaneously in an organisation. Explicit knowledge represents formal knowledge which can be organised as information. Explicit knowledge can usually be found in an organization in the form of reports, articles, documents, manuals, patents, pictures, images, video, sound, software and so on. It is an organisation's intelligent asset and exists independently of its employees. Having said this, its growth and evolution depends on its employees' tacit knowledge. Tacit knowledge is personal knowledge which exists in one's experience and can only be transferred through social interaction (Jashapara 2004), meaning that it is hard to share tacit knowledge within an organisation. Tacit knowledge is much more difficult to manage. With experience and continued learning, the tacit knowledge matures and evolves into new knowledge, which remains tacit within the individual or group. Explicit knowledge and tacit knowledge can be changed with each other (Yang & Farn 2009). Explicit knowledge changes into tacit knowledge dependent on one's learning capability with regards the existing explicit knowledge. Tacit knowledge will change into explicit knowledge if one's experience is documented into some fashions. These two kinds of knowledge also exist in the robotic area. For example, component usage and safety guidelines in the design can be considered as explicit knowledge for robotic designers; their work experience and educational background can be considered as tacit knowledge which cannot be stored through a given method, and which only exists in their brains.

2.1.4 Knowledge management framework

Currently many researchers use a variety of approaches to knowledge management for various organisations. Indeed, Rubenstein-Montano & Liebowitz give two recommendations which are that the knowledge management framework should be both prescriptive and descriptive and that knowledge management activities must be consistent with system thinking (Rubenstein-Montano & Liebowitz et al. 2001). Based on the knowledge management literature reviewed by them, they suggest that knowledge management tasks must be prescribed and should include activities such as finding, verifying, storing, organising, sharing, and using knowledge; secondly, there should be a distinction between explicit and tacit knowledge and they should be handled separately; the framework should include both single-loop learning and double-loop learning methods (Rubenstein-Montano &

Liebowitz et al. 2001). Here single-loop learning refers to the process which maintains the central features of the organisation's 'theory-in-use' by detecting and correcting errors within a given system of rules. It is a kind of behavioural learning. Double-loop learning is a cognitive learning which involves the questioning of current organisational norms and assumptions with a view to establishing a new set of norms. Through a combination of single-loop learning and double-loop learning organisations can act and work more effectively (Jashapara 2004).

Data, information and knowledge are very important assets for organisations. Through effective utilisation of these 'commodities' an organisation can enhance competitiveness. Different organisations may use different strategies for their information and knowledge management based on different cultures and contexts of the organisation.

In the area of autonomous systems, to achieve a certain level of safety, and life cycle management, a knowledge management framework is employed. This is an environment which manages domain expert's knowledge, and integrates a number of other software applications and /or IT technologies, as well as safety principles and guidelines. The valuable aspects in the area of autonomous systems can include documentation, component catalogues, ontology for / about autonomous systems, past designs, new technologies, complex methodologies as well as a whole range of explicit and tacit knowledge developed through discussions and meetings (Hicks & Culley et al. 2002). Effective management of these items will help to enable the generation of feasible design alternatives and assist with a better decision-making process.

2.2. Development of autonomous system: An example of a human assistive robot

Generally speaking, autonomous robots are robots which can perform desired tasks in unstructured environments without continuous human guidance. The original robots were used as complex tools without autonomy. After they achieved mobility, robots were then developed in different ways to help human beings. Indeed, they are employed as mobile robots, industrial robots, service robots, and robot explorers among others. With the technological evolution of society, people want to get more help from robots; many researchers are concerned about humanoid robots and human-level robots, which are humanlike in structure and behaviour. They want robots which can help with things like

housework for the elderly. With the development of computer technology, the capability of computers is increasing faster than ever; from 1 MIPS (million instructions per second) in the 1980s to 76,383 MIPS in 2008 (e.g. Intel Core i7). However, this is still far from the processing speed of a human brain, which is maybe equivalent to approximately 100 million MIPS. Taking into account the speed of present day computer techniques, Moravec (2003) has predicted that by around 2020, the first true "universal" robots may appear, bringing with them advanced programs which enable a robot to tidy or clean a house, wash a warehouse, or even play games with children; by 2040 robots will match human intelligence and surpass it by 2050 (Moravec 2003). Table 2-1 is a list of robot events which is organised by Henderson (2006). It briefly summarises the development of robots in different areas from 1870 up until now, although some of them can only be considered as mechanical systems rather than real robotic systems.

Table 2-1: Historical Development of Robots

1870	Early walking machines are developed, but they can only walk stiffly and in a straight line.
1980	Japanese researchers build a four-legged (Quadra pedal) machine which can climb stairs.
1990s	Navlabs demonstrate the ability of robot-controlled vehicles to drive on real roads.
Mid-1990s	Brooks develops the interactive learning robot Cog, which is an attempt to create a robot with human-like abilities.
1997	First landing of a rover (Sojourner) on Mars.
2002	iRobot's first Roomba robotic vacuum cleaner is put on the market.
2003	iRobot's PackBots are used in Afghanistan and Iraq.
2006	Asimo robots such as the Honda Humanoid Robot, begin to serve as receptionists and guides.

2.3. Ontology

2.3.1. Development of ontology

Ontology is a powerful means for expressing and sharing knowledge in a meaningful way, and is becoming accepted as a viable modelling approach. It has been developed over a long period of time and has been tested in many areas. It is a tool or method with which to

improve our level of information organisation, management and understanding. The purpose of ontology is to define an entity, attribute and relationship among knowledge concepts within a specific domain using explicit descriptions and specifications that present an interoperable format that both humans and machines can understand, thereby realising knowledge sharing and reuse (Chen & Chen et al. 2009). Past ontology studies have been conducted in the area of autonomy and have used ontologies to help increase the level of autonomy. For example, one particular study has focused on developing ontology for obstacles to aid autonomous driving (Schlenoff 2002).

2.3.2. Review of ontology development systems and tools

Over the last few years, a set of dedicated tools have emerged to support the development of ontology in many areas. Ontology is one way in which to organise information and knowledge and an ontology tool is a software application which supports the ontology development processes. According to Corcho's research, a new generation of ontology-engineering environments have been developed in recent years, namely Protégé2000, WebODE, and OntoEdit (Corcho & Fernández-López et al. 2003). Following thorough analysis it is evident that a widely used ontology development tool is Protégé2000. It is a tool developed by the Stanford Medical Informatics (SMI) at Stanford University. Protégé is a free, open source ontology editor and knowledge-based framework. It is based on Java, is extensible, and provides a plug-and-play environment thus making it a flexible base for rapid prototyping and application development. Protégé is supported by a strong community of developers and academic, government and corporate users, who are using Protégé for knowledge solutions in areas as diverse as biomedicine, intelligence gathering, and corporate modelling.

2.3.3. Methods for the creation of an ontology for autonomous systems

The development of an ontology for autonomous systems should abide by certain principles during the design process. When reviewing the entire ontology life cycle (shown in Figure 2-3), it should include knowledge acquisition, edition, browsing, integration, merging, ontological mappings, reengineering, evaluation, translation to different languages and formats, as well as the interchange of content with other tools and so on (Corcho & Fernández-López et al. 2003). During this period, it will require information and knowledge mapping methods to analyse relationships, ownerships and constraints based on several key

conceptualisations in the ontology. It would also be necessary to import or merge other people's work as it relates to an ontology for autonomous systems in order to reduce the duplicate work.
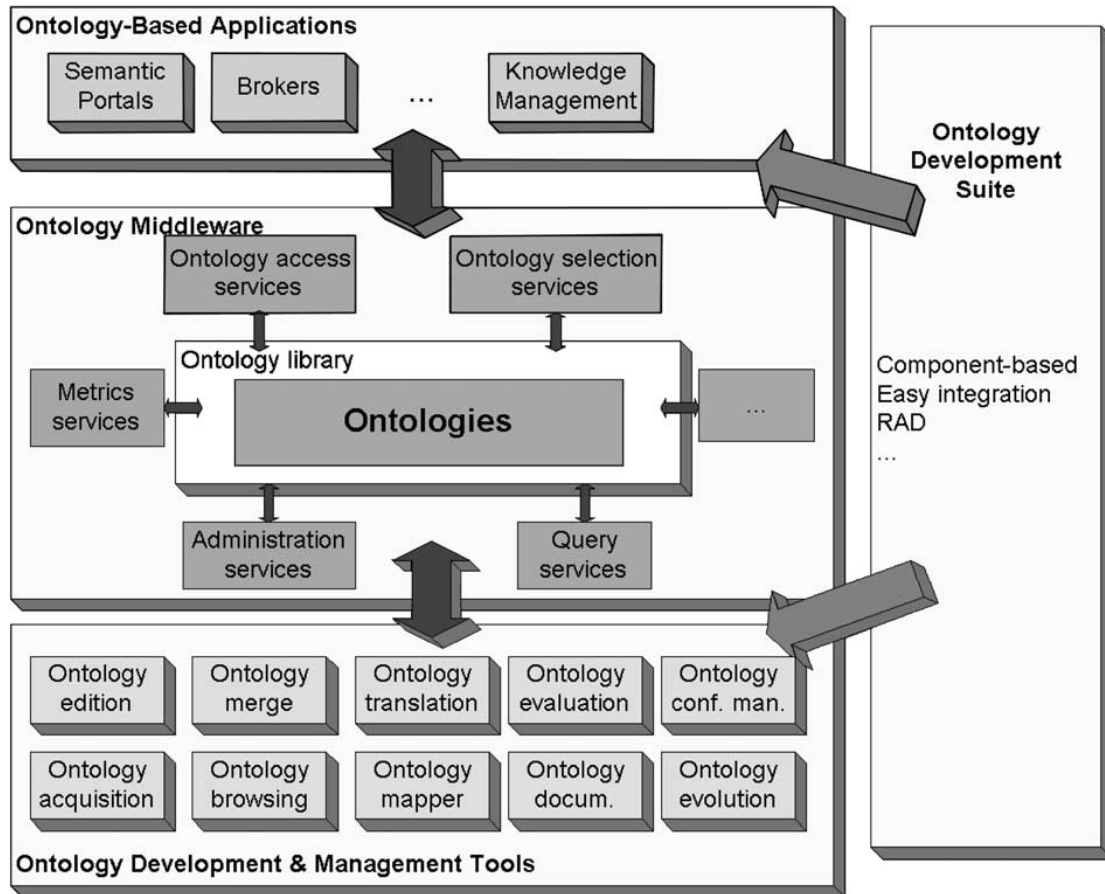
Figure 2-3: A proposed workbench for ontology development and use (Corcho & Fernández-López et al. 2003)

2.3.4 Aim of ontology for autonomous systems

As shown in Figure 2-3, one aim of ontology is used for knowledge management to share knowledge. It is a key process in a number of the knowledge management frameworks. In this research, the supposed purpose was to work on supporting knowledge management for autonomous system design in order to ensure safety, reliability and maintainability of operation. It includes creation of ontology for autonomous systems to support this research aim. The creation of key definitions regarding relationships of autonomous systems can provide stakeholders with a better understanding of the through life management of autonomous systems. Ontologies which relate to safety can be separated into two aspects: (i) for sharing information required for safety analysis, and (ii) for sharing safety analysis results (Zhao & Bhushan et al. 2003). It would be useful to share information which is needed for

safety analysis and safety analysis results with other autonomous systems. A number of studies already exist in this area (Anaki & Bentin 2009). Having said this, there remains a lack of research into ontology with regards reliability, extensibility, and so on. Indeed more extensive research into these areas would be extremely helpful for the development of autonomous systems.

2.4. Robot safety

There is already a considerable amount of research on robot safety. Generally speaking, it can be categorised into six types, which are general safety; human-factors; safety standards; safety methods; accidents; safety systems (Dhillon & Fashandi et al. 2003). Research into robot safety has made various suggestions for the achievement of robot safety, with detailed discussion of how "human factors" act in robot accidents and encourage "human factors" to prevent accidents. Others studies have used different methods to assess hazards that might occur. In addition, safety standards have already been formulated by several organisations (Gaskill & Went 1996).

2.4.1. Robot safety introduction

Robots are employed both in industrial areas and domestic environments, interactions between humans and robots will become increasingly common. The safety of humans when interacting with robots has become a key issue in our society (Kulić & Croft 2006). Famous laws of robotics do exist and were provided by Asimov in 1940 who summarised them as follows: First Law: a robot may not injure a human being, or, through inaction, allow a human being to come to harm; Second Law: a robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law; Third Law: a robot must protect its own existence as long as such protection does not conflict with the First or Second Law (Clarke 1993).The laws were provided as an illustration of the type of rules that would be required for robots to be accepted by the general public, but, in reality , the first law may cause confusion for an autonomous robot (Moor 1995). For example, some autonomous robots are designed to rescue a soldier who is hurt in a battle. Sometimes this kind of robot can only save a soldier's life by cutting off their arms or legs. In this way, a robot will harm human being first in order to protect their lives. There are also many other ethical questions regarding robots, many of which are discussed by Moor and which are areas of on-going debate among scholars (Moor 1995). As there are many uncertainties regarding

autonomous robots' life cycle, many accidents also take place in the area of robotics, especially in industrial robots which perform their tasks at a high speed and with unpredictable motion patterns which mean that people cannot understand or easily predict their behaviour. Serious injury or death due to industrial robots is partly due to unfamiliarity with the movement of robot system characteristics (Karwowski & Rahimi et al. 1991). Many researchers have investigated various ways to reduce accidents due to robotics. They have created many regulations with regards to requirements during operation and maintenance periods in order to avoid accidents. The application of robots in the domestic environment is a young discipline, and despite the existence of much research on the safety of human robot interaction (Kulić & Croft 2006, Kulic & Croft 2004), there remains little in the way of regulations on how to design a safe human assistive robot. According to the International Organization for Standardization (ISO), they have designed an ISO 10218-1:2006. This is a robot designed specifically for industrial environments and research has suggested that it may be utilised for surgery or healthcare whilst also being effective in the service industry (OSHA 2008). As autonomous systems such as these would contain learning systems, the safety within autonomous systems would be more difficult to predict, thus making safety standards within this area more difficult to design.

2.4.2. Robot accidents in real life

Robot related accidents have been defined since the 1980s, with the definition below proving the most concise:

"Contact between the person and a robot either directly or indirectly, leading to a record of the accident" (Dhillon & Fashandi et al. 2003).

In the area of industrial robotics, according to research carried out in the 1970s and 1980s, the greatest risk of accident occurs during development and maintenance with only 10% of the accidents happening during normal operation. It is said that more than one third of accidents were caused by operator error and around two-thirds were due to robotic problems (Dhillon & Fashandi et al. 2003). As the application of autonomous robots changes, an increasing number of robots are being employed in domestic areas. This may necessitate direct communication between human beings and robots meaning that autonomous robots should be more compatible with human beings various behaviour. With this said, a set of safety measures should be considered before robots are used in this manner. To avoid /reduce robot

accidents, there should be a number of standards and guidelines for stakeholders to help them in the lifecycle management of autonomous systems.

2.4.3. How safe is safe enough?

How safe is safe enough? Indeed, the distance between humans and robots is rapidly decreasing, whilst robots are becoming larger and more powerful. The question arises: How to make people believe that domestic robots are safe for use in our daily life? It is usually more psychologically difficult to prove that something is safe than unsafe (Bahr 1997). Indeed, recent studies have even investigated how a robot's appearance can affect people's minds. According to the online investigation, a robot's appearance seems to play an important role in how they are perceived and determines which applications are proposed by the general public (Manja Lohse, Frank Hegel & Britta Wrede 2008). As a result of this, people may feel more comfortable and have more confidence in a robot whose appearance closely resembles that of a humanoid. A robot's acceptance by the general public is also strongly dependent on their safety, reliability and good appearance.

As discussed above, in this research, the safety issue of human assistive robots will be considered in order to achieve the research aim.

2.5. Through life management

Generally, the level of autonomy for robots nowadays remains low. In most situations robots' behaviour is under human control. Even letting a humanoid robot perform a simple action remains a difficult thing. The industrial (large scale) development of autonomous robots is still at the prototyping stage. However, through life management (TLM) is fairly important in the engineering area and will help to manage the whole life cycle of autonomous robots. Before introducing through life management, it may prove useful to provide a basic introduction to product life cycle management. Indeed, this can be very helpful with regards to comparisons with TLM.

2.5.1 Product lifecycle management

There are already many studies in existence regarding product life-cycle management. One of the explicit definitions of product lifecycle management is expressed by Grieves (2006) in the following:

"Product Lifecycle Management (PLM) is an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product's life, from its design through manufacture, deployment and maintenance—culminating in the product's removal from service and final disposal. By trading product information for wasted time, energy, and material across the entire organization and into the supply chain, PLM drives the next generation of lean thinking" (Grieves 2006).

The PLM describes a product from managing descriptions and properties of said product through to its development and useful life, mainly from an engineering perspective. The core of PLM is in the creation and central management of all product data as well as the technology used to access this information and knowledge.

2.5.2 What is through life management?

Through Life Management (TLM) is the philosophy which brings together the behaviours, systems, processes and tools to deliver and manage projects through the acquisition lifecycle (AOF 2009). It involves the management of the delivery of all aspects of a capability throughout its life-cycle. It is said that the principles of TLM must be applied to the management of projects throughout the MOD (AOF 2009). However, through life management is not only relevant to the defence business; it is a generic philosophy that involves taking a complete and coherent approach to managing the cost-effective delivery of outputs.

TLM enables the decisions made early in the process to take account of Whole Life Costs. Figure 2-4 summarises cost distribution over the whole lifecycle based on CADMID/CADMIT models.
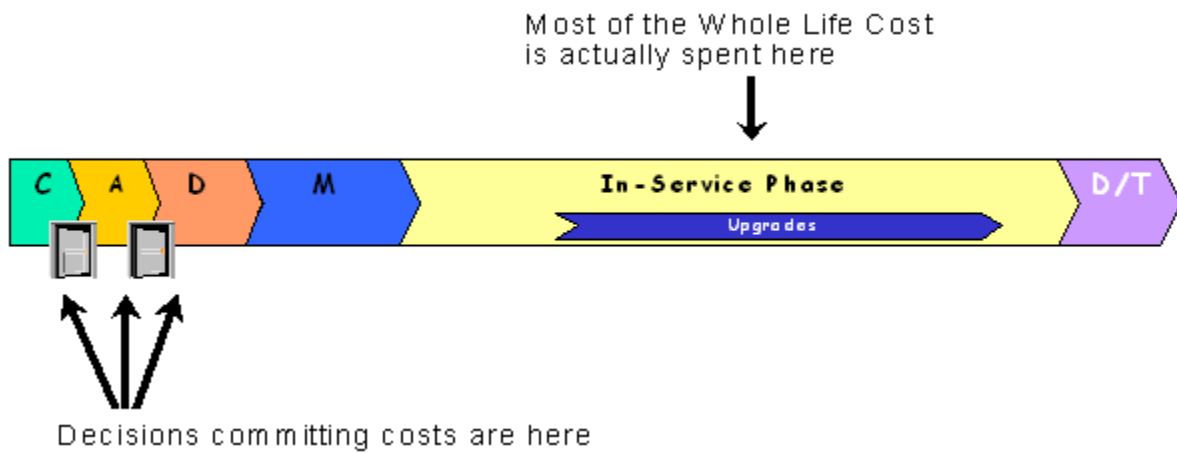
Figure 2-4: Cost distribution throughout the entire life cycle (AOF 2009)

CADMID means Concept, Assessment, Demonstration, Manufacture, In-service, Disposal. It has been used by the UK Ministry of Defence (MOD) since 1999; CADMIT means Concept, Assessment, Demonstration, Migration, In-service, Termination (AOF 2009). These are two different models for lifecycle analysis, and are used to demonstrate the whole life costs.

Through life management is an organisational development strategy, the aim of which is concerned with continuously enhancing a product's competitiveness and hence company's competitiveness, for a long period of time. Through life systems or capability management is intensively used in the defence sector. However, many other organisations have already begun to use such kinds of management strategy, not only in the defence sector. Through life management not only considers a single product's performance, but also defines strategies on how to improve the product in order to satisfy customer requirements. To effectively execute through life management, a proper knowledge management support is helpful. As through life management requires previous experience, data and information through effective knowledge management, this will help to achieve better through life management for the product and thus the organisation.

2.5.3 Difference between product life-cycle management and through life management

According to the definition and main elements of PLM and TLM, a comparison between the two approaches is shown in Table 2-2.

Table 2-2: Comparisons between PLM and TLM main content (AOF 2009, Grieves 2006)

Product Life-cycle Management	Through Life Management
• Product data, information, knowledge. • Entire life of the product. • An approach that is more than software or processes. • Crosses boundaries: functional, geographical, and organisational. • Combines the elements of people in action, processes, and technology. • Drives the next generation of lean thinking.	• Whole life outlook. • Whole life system outlook. • Whole Life Costs. • Involvement of Stakeholders. • Through Life Management Plan. • More informed decision making. • Integrated Project Team (IPT) and stakeholder processes.

Based on Table 2-2, we can conclude that there is a considerable difference between PLM and TLM. Product Life-cycle management is more about the management of specific product; through life management is more about the management of capability of system, and not focus on some specific product.

2.5.4. Why we need through life management for autonomous robots

The design for autonomous robots should incorporate the need for long-term usage; occasionally a robot's life can even span more than 20 years. The learning behaviour of autonomous robots will make the system's safety more complicated; which is in stark contrast to normal vehicles. How to effectively manage the entire life cycle of an autonomous robot is a big challenge for stakeholders. Generally, through life management is based on system thinking, and will involve consideration of the whole life-cycle. To some extent, this will enhance an autonomous robot's capability in its lifecycle. During its long life cycle, it may face large scale emergencies, but the through life management will help to reduce the risk of emergency. Based on the key theme of through life management described in Table 2-2, this will help designers and stakeholders to consider the whole life outlook, the whole life system outlook, whole cost outlook, and also plan to manage its lifecycle. Indeed, through life management for autonomous robots will aid the design of autonomous robots in a more safe, reliable, cost-effective and maintainable style.

2.5.5. Autonomous robots lifecycle

Following thorough analysis, it is evident that the lifecycle of autonomous robots is comprised of 7 main components: stakeholders' requirement; product design; product manufacture; marketing; product use; maintenance; disposal (Chen & Chen et al. 2009). For CADMID model, the lifecycle is composed of concept, assessment, design, manufacture, in-service and disposal stages. Each stage and activity involves different kinds of information and knowledge. However, some autonomous systems may complete their entire life cycle having never experienced these components. For example, in some special applications which require autonomous systems to work in outer space or in the deep sea, their life cycle may not include maintenance or disposal. Identifying the whole lifecycle of autonomous robots can help to identify the knowledge and information which is required for autonomous robots' design and maintenance, hence helping to manage the knowledge and information which is essential for the whole lifecycle of autonomous robots. For through life management, each stage is equally important if the cost-effective delivery of outputs is to be achieved.

2.6. Design analysis

A successful design should consider every element which relates to the product, such as safety, reliability, maintainability, and cost-effectiveness. How to make a decision on balancing these factors will affect the success of a product. Considering the enormous market of human assistive robots over the next 20 years, an in-depth analysis regarding robot design is delivered in this research.

2.6.1. Safety design

Safety design is the basic requirement for an autonomous robot and ensures that autonomous robots pose no risk to people as a result of their behaviour or appearance. The central concept in system safety is the definition of a hazard (Bahr 1997). Once a hazard is defined, it will be able to help autonomous robots to identify and correct or avoid these hazards. To achieve this aim, it should use system thinking to identify possible hazards and a set of safeguards can be used to reduce the hazard. Engineers should also obey several safety standards when designing a human assistive robot.

At present there are not too many autonomous systems in practice. Indeed, the development of autonomous systems is at the research stage. Some researchers are trying to identify safety

issues relating to human robot interaction, which are helpful for the further development of human-care robots (Ikuta & Ishii et al. 2003, Kulić & Croft 2006). Work on the safety issues of autonomous systems remains a big obstacle standing in the way of the world-wide application of autonomous systems.

2.6.2. Reliable design

Although there is a huge amount of research in robotics, there is still limited effort on robot system reliability. In technical terms, reliability is defined as the probability that a product performs its intended function without failure under specified conditions for a specified period of time (Yang 2007). An important reliability assessment method for a product is the mean time to failure (MTTF), which was introduced in the 1980s to assess a robot's reliability (Dhillon & Fashandi et al. 2003). In addition, fault tree analysis (FTA) is a graphical method commonly used in both reliability engineering and system safety engineering (Bahr 1997). Using FTA will help engineers to list various faults which must not occur if a robot is to be deemed fit for service. Through fault tree analysis for autonomous robots, engineers will be able to focus more on a number of key components and functions in order to design a more reliable system. There are also a number of other reliability techniques which can be employed such as robust reliability design, failure mode and effects analysis (FMEA). Reliability verification testing is also widely used in reliability engineering (Yang 2007). In reality, failures are inevitable. Using this reliability technique will help engineers to design a more reliable autonomous robot, and hence enhance the safety of these machines when in the presence of human beings.

2.6.3. Maintainable design

Usually, one system is designed to perform a number of missions and consists of several units or components, and subsystems. System reliability can be evaluated by means of unit reliability and system configuration, and can be improved through the application of various appropriate maintenance policies. There is no difference in autonomous robots. To enhance the safety and reliability of autonomous robots, some proper maintenance policies should be considered in the product design period. Three main maintenance policies are used and are as follows (Nakagawa 2005):

1. Repair of failed units
2. Provision of redundant units

3. Maintenance of units before failure

These three policies are used in different situations based on different units. The first is the most basic maintenance policy which is also called corrective maintenance. It is suitable for cases where units can be repaired and their failure does not obviously affect a whole system. The second policy is adopted in the situations when system reliability can be improved by providing redundant and space units. Sometimes the failure of products may cause danger to others or be costly. In these cases we should adopt the third maintenance policy. However, on occasions it is not wise to maintain units with unnecessary frequency (Nakagawa 2005).

Considering different units' contribution to autonomous robots, several different strategies can be applied to different components of the autonomous robot in order to ensure safety, reliability and cost-effectiveness.

2.6.4. Cost-effective design

Cost-effective design is one of the most important factors in autonomous robots. There is a fundamental contradiction between the interests of the product user and those of the manufacturer. How to cope with relationships among them will be a key factor directly related to their success. Usually, one product's cost can be catalogued as manufacturing costs, total costs and lifecycle costs (see Figure 2-5) (Hundal 2007). One of the aims of through life management for autonomous robots is to make design cost-effective. However, the question is: How can cost-effectiveness truly be achieved for the whole lifecycle? There may be several different ways in which to achieve a successful design, however, only some of them can be considered as cost-effective. One common way of analysing cost-effectiveness is through the use of decision analysis. Some models can be created through different levels of autonomy, and requirements from stakeholders. Based on the result of several potential outcomes, this will help designers to make a better decision regarding which method would be the most cost-effective. As it is thought that autonomous robots could work for human beings for more than 20 years, some key factors should be included in engineers' considerations, that is, autonomous robots must be safe, reliable and easy to maintain. How to tackle these elements in the design phase of autonomous systems is still a tricky problem.
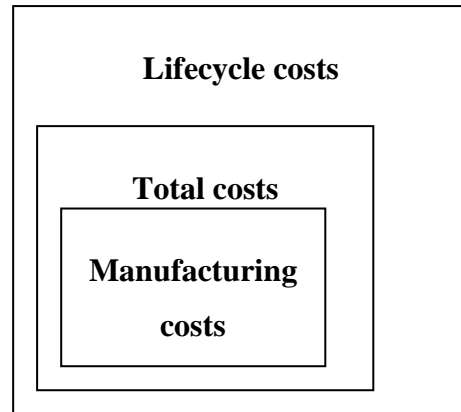
Figure 2-5: Classification of costs

One aim of through life management for autonomous systems is to maintain cost-effectiveness for the whole life cycle. A possible way to do this is by analysing and predicting the whole life cycle cost of an autonomous system. From existing analysis it appears as though the cost composition of autonomous systems is not considerably different from other robots. Usually the total life-cycle cost of a product can be considered as the following:

Life cycle Cost = Acquisition Costs + Sustaining Costs (Barringer & Barringer et al. 2003)

For the acquisition part, as autonomous systems are generated through research design and manufacture, they require facilities, engineers and techniques to join together. For the sustaining stage, the autonomous systems may need daily maintenance service, and will be replaced or upgraded after a certain amount of time. The fact that issues may arise during this service time is also something which must be taken into consideration. The analysis for the details of each component for the through life cost of an autonomous system is shown in Figure 2-6 and Figure 2-7.
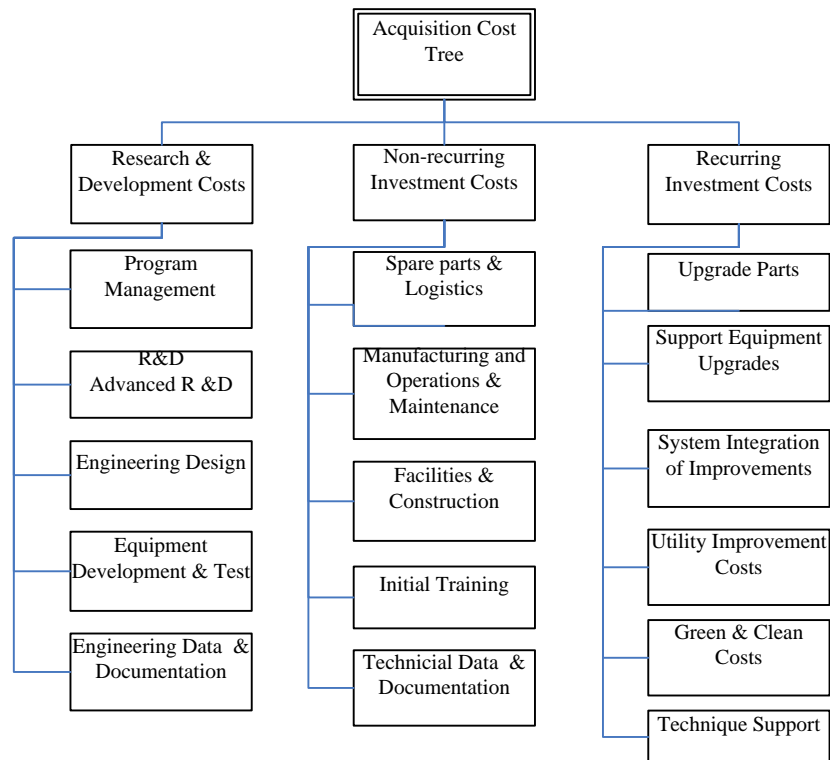
Figure 2-6: Acquisition Cost (Barringer & Barringer et al. 2003)
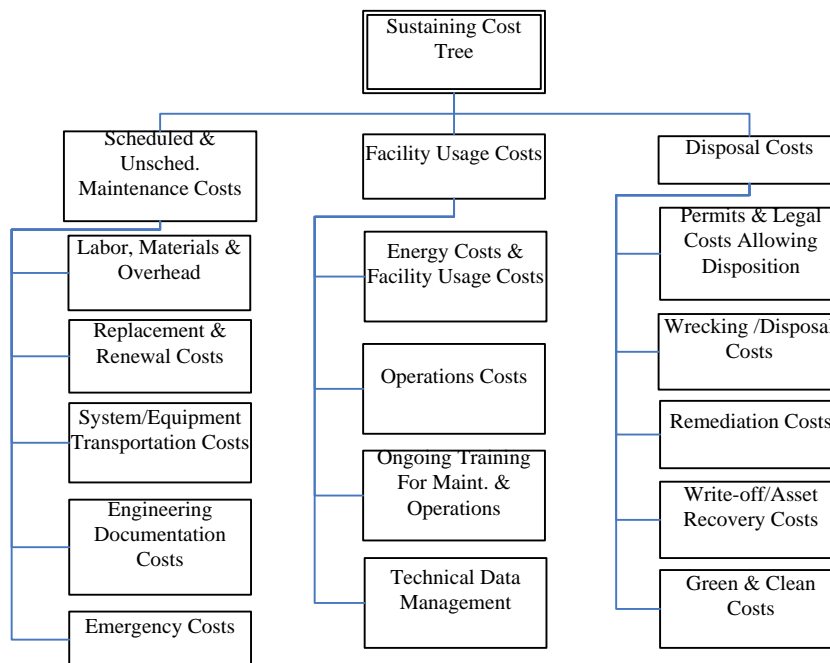
Figure 2-7: Sustaining Cost (Barringer & Barringer et al. 2003)

From the figures above, we can see that the whole life cost of an autonomous system is quite complex. When adjusting the cost composition, it will affect different aspects of its life cycle.

To what extent can one product to be cost-effective? Indeed, different people have different opinion on this matter; usually it depends on its application and the management strategy for its life cycle.

2.6.5 Extensibility Design

Extensibility design can be considered as an important characteristic for one product. This kind of design can be achieved through software, systems architecture, and hardware. There are also some differences between software and systems architecture according to their requirement for extensibility. In software engineering, extensibility is a system design principle where the implementation takes into consideration future growth. It is a systemic measure of the ability to extend a system and the level of effort required to implement the extension. Extensions can be through the addition of new functionality or through modification of existing functionality. The central theme is to provide for change while minimising the impact on existing system functions.

In systems architecture, extensibility means that the system is designed to include hooks and mechanisms for expanding/enhancing the system with new capabilities without having to make major changes to the system infrastructure.

For autonomous systems, the extensibility design can be considered as within the composition of hardware, software and systems architecture. As it is thought that autonomous robots will work for human beings for more than 20 years, during the long period of its lifecycle, the systems may need to be extended on occasions in order to obtain some new functions or communicate with new environments. Extensibility design will be important for enhancing the capability of systems. In addition, an effective extensibility design will, to some extent, enhance the cost-effectiveness and reliability of autonomous systems.

2.7 Systems safety

Systems safety is a general subject about failure analysis in the context of systems safety. A proper failure analysis for a product will obviously enhance the product's reliability, maintainability, safety and cost-effectiveness. There has been a great deal of research about systems safety (Dhillon & Fashandi 1997, Dhillon & Fashandi et al. 2003). The theory on systems safety includes: fault tree analysis, event tree analysis, Weibull analysis, Failure Mode and Effect Analysis, Monte Carlo simulation, and so on. All of these have been widely

used in our real world for years. If we can collect proper data from previous practices, then we can select proper methods and analyse the data in order to make a better prediction regarding future failures. Through effective knowledge management, the reliability of systems safety management for autonomous systems can be significantly improved.

2.8 Stakeholder analysis

The stakeholder plays a key role in this research. Stakeholder analysis is a process of systematically gathering and analysing qualitative information to determine whose interests should be taken into account in this research. There are many methods for identifying stakeholders and their stake, such as focus group, semi-structured interview, and social network analysis (Reed & Graves et al. 2009). In this research the identification is based on a literature review as well as group discussions to identify the main stakeholders and their interest. The object of this research is based on the human assistive robot, and more specifically an attempt to supply through life management for the human assistive robot. Considering this research aim, we attempt to analyse stakeholders though analysing the lifecycle of autonomous systems, following which we will identify the potential stakeholders for this research.

Who is a stakeholder?

After analysing the whole lifecycle of autonomous systems, it is obvious that different groups of people will be interested in different aspects of the autonomous system. As seen in Figure 2-4, the stage of lifecycle includes: concept, assessment, demonstration, manufacture, in-service and disposal/termination. Indeed, different stages of the lifecycle of autonomous systems will interest different stakeholders.

In this research, through brain-storming sessions with several research staff within ESOS group, the stakeholders are generated, including the main stakeholders, and their relationships. The stakeholders for autonomous systems may include designers who design autonomous system, customers who will use such kinds of autonomous systems, the general public who may be affected by such kinds of autonomous systems, and maintainers who will maintain the autonomous systems. A stakeholder relationship picture is described as follows: Figure 2-8. The relationship picture is based on the results of group brainstorming on stakeholders, their interest, and other attributes. They are also categorised into certain groups.
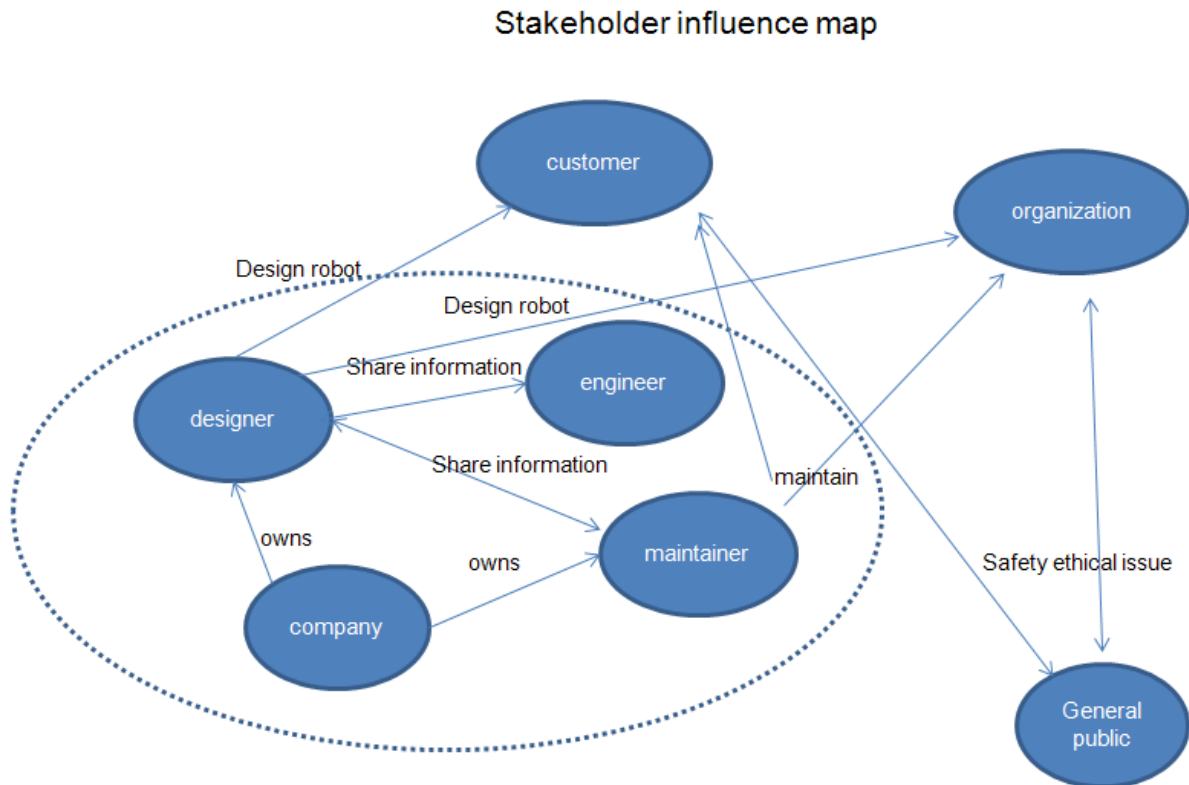
Figure 2-8: Stakeholder relationships analysis

Due to the aim of this research, the stakeholders we considered are mainly designers in the area of robotics and customers who wish to use robots to assist with their daily life. The customers in this specific area are also related to healthcare professionals. People who are healthcare professionals can understand what customers need to assist with their daily life. Both designers and health care professionals are helpful for the research requirement development and research outcome validation.

2.9 Classification of autonomous system

According to the research activities in autonomous robots on classification, the accomplished framework for evaluation of unmanned systems are various. There are several main published frameworks which are commonly used by others, namely:

- Autonomy Level For Unmanned System framework (ALFUS) (Huang & Pavek et al. 2005): this is used to describe characteristics of unmanned systems and evaluate levels of autonomy of unmanned systems.
- Systems Capabilities Framework (SCF) (Visnevski & Castillo-Effen 2009a): this is used to illustrate relationships between cognitive, adaptive and simple reactive systems. It is also used to analyse the capability of unmanned autonomous systems.

- Autonomous Control Logic (ACL)(Sholes 2007, Sholes 2007): this involves the use of metrics to characterise autonomy by establishing a peer-reviewed set of universal metrics for autonomous control.

These frameworks have been widely applied in the field of unmanned vehicles but fail to address the classification of levels of autonomy for human-assistive robots. There are also A number of other output regarding metrics of characteristics of autonomy have been put forth by Clough (2002). These are primarily an attempt to measure autonomy for UAV whilst some other common metrics for human-robot interaction proposed by Steinfeld & Fong et al. (2006) focus on identifying common metrics for task-oriented human-robot interaction.

Through comparison, the ALFUS framework is considered the most applicable, as the main context and definitions can be used to evaluate levels of autonomy for unmanned systems. However, at present, it seems that there is still no application of the ALFUS framework in the domestic service area (Huang & Messina et al. 2007, Fu & Henshaw 2010). In accordance with the requirements of stakeholders in this research, it is necessary to generate a model for levels of autonomy for the human assistive robot. This model could be used to model levels of autonomy for human assistive robots, in order to support design and lifecycle management.

2.10 Classification of human assistive robot

Through literature review above, there is still lack of models for assessing levels of autonomy for human assistive robot. The model for classification of human assistive robot is considered to be able to assess human assistive robot's capability, which will be helpful for robot lifecycle management and ensure safety, reliability, cost-effectiveness for stakeholders. On the other hand, the work on classification of human assistive robot will be some knowledge contribution for research in human assistive robot area. Currently, the development of human assistive robot is in a rapid period, the research of modelling human assistive robot capability will support the development of human assistive robot in some extend.

2.11 Summary

As identified by this literature review, knowledge management is very important for an organisation's development. Recent times have seen it develop quickly in many areas, also including the autonomous systems area. The review has identified knowledge management development, its components, categories, knowledge management tools, and also how

knowledge management is applied in the area of autonomous systems. Following analysis, it is evident that ontology regarding human assistive robots is extremely helpful for the development of autonomous systems.

Having identified knowledge management and its methods as applied in autonomous systems, the literature review then moves on to explore through life management issues of autonomous systems, which takes into consideration safety, design, maintenance, and lifecycle cost. Indeed, the review discusses various issues including how to design a safer, more reliable, maintainable, and cost-effective autonomous system.

To support the designer in making better decisions, the literature review then moves on to the classification of autonomy. Through identifying the main model in the modelling autonomy, and comparing their characters and application area, the literature review establishes any deficiencies in these models as they relate to their application to human assistive robots.

3 Research methodology

This chapter discusses the general philosophical principles used in the research area and explains the reason for the selection of the current research methodology. The first step is to discuss the current research methodology used in systems engineering, which can be a guideline to select a proper methodology for this research. Then according to this research, a number of possible methodological research methods are discussed whilst an in depth analysis is conducted based on the research approach used in this research; the chapter also gives a general introduction into how these methods are used in the research.

3.1. Forms of Research

Generally speaking, research methods can be classified into two paradigms: positivism and phenomenalism. The research methodology for both natural and social sciences can be traced back to the term: 'scientific method' (Allison 1996). The scientific method which is used in the science research and social sciences can be called positivistic research because positivistic research normally uses measurable evidence, and is sometimes referred to as quantitative research. Phenomenological research has emerged due to the fact that some researchers, especially those working in social sciences, hold the view that each and every phenomenon is unique and its uniqueness is its most important quality. Phenomenological research is usually referred to as naturalistic, qualitative or hermeneutics (Allison 1996). There are several distinctions between these two forms which are organised by Collis & Hussey (see Table 3-1).

Table 3-1: Comparisons between positivism and phenomenalism(Collis & Hussey 2003)

Positivistic Paradigm	Phenomenological paradigm
Tends to produce quantitative data.	Tends to produce qualitative data.
Uses large samples.	Uses small samples.
Concerned with hypothesis testing.	Concerned with generating theories.
Data is highly specific and precise.	Data is rich and subjective.
The location is artificial.	The location is natural.
Reliability is high.	Reliability is low.
Validity is low.	Validity is high.
Generalises from sample to population.	Generalises from one setting to another.

After comparison it is evident that these two research approaches are rather different. However, in reality, these two research approaches are complementary rather than incompatible (Allison 1996). People usually combine qualitative and quantitative designs in order to achieve their research objectives in the area of systems engineering. The current research will use positivistic paradigm and phenomenological paradigm based on the different periods of this research and research questions within this research.

3.2 Research Strategies Criteria

(Denscombe 2007) describes seven research strategies which are surveys, case studies, internet research, experiments, action research, ethnography, phenomenology and grounded theory. In reality, the researcher is usually faced with a variety of options and alternatives and must make decisions about which strategy to select. In fact, there is no 'one right' direction to take due to a number of specific problems. Some strategies will perform better than others for tackling specific issues. For specific kinds of problems, people usually use more than one strategy and the research strategies are simply chosen on a 'fit for purpose' basis.

3.2.1 Evaluation of methodological choices

One way in which to make methodological choices involves the evaluation of criteria in order to assess the validity of any research findings. Gill & Johnson (1997) give four criteria which may be used for this evaluation. These are expressed below:

1. *Internal validity*: it is the validity of (causal) inferences in scientific studies, and is usually based on experiments as experimental validity (Mitchell & Jolley 1988). Internal validity is only relevant in studies which attempt to establish a causal relationship and it is not relevant in most observational or descriptive studies (Trochim 2006).
2. *Population validity*: this criterion concerns the extent to which it is possible to generalise from the sample of people involved in the research to a wider population. This means it evaluates whether the sample population represents the entire population, and whether the sample method is acceptable (Shuttleworth 2009).
3. *Ecological validity*: this criterion is typically concerned with whether or not one can generalise from observed behaviour in the laboratory to natural behaviour in

the world (Schmuckler 2001). The methods, materials and setting of the study in the research must approximate the real-life situation that is under investigation (Reis & Judd 2000).

4. *Reliability*: this criterion essentially refers to the consistency of results obtained in research. It focuses on whether other researchers are able to perform exactly the same experiment, under the same conditions whilst generating the same results.

According to these four criteria, there are some evaluation details regarding these research strategies which are mentioned above, (see Table 3-2).

Table 3-2: Evaluation for research strategies

	Internal validity	Population validity	Ecological validity	Reliability
Surveys	Low	Median	Median-high	Low
Case studies	Low	Low	High	Low
Experiments	High	Low	Median-high	High
Action research	Low	Low	High	Low
Ethnography	Low	High	High	Low
Phenomenology	Low	High	High	Low
Grounded theory	Low/media	Low	High	Low

3.3 Research approaches

As introduced above, there are seven research approaches which are demonstrated by Denscombe (2007). The details are described below.

3.3.1 Surveys

Survey research is a procedure used to collect data and information based on a set of cases within a defined population from which estimates or conclusions of a wider population can be made (Thomas 1996). The survey approach is a research strategy rather than a research method, and many methods can be used in a social survey, like questionnaires, internet surveys, interviews, documents and observations (Denscombe 2007).

3.3.2 Case studies

Case study is a strategy for conducting research which involves the investigation, observation and analysis of an individual situation to probe a phenomenon deeply through multiple sources of evidence (Yin 1994). Case studies are focused on one or a few instances of a particular phenomenon with many specific details based on natural settings; they allow researchers to use multiple sources and methods for the investigation (Denscombe 2007). Denscombe also suggests that case studies can work best in a situation whereby researchers want to investigate an issue in depth and provide an explanation which can deal with the complexity of real life situations.

3.3.3 Experiments

The goal of experimental research is to test the relationship between identified variables in a research study. It is used in a situation where the independent variable is carefully manipulated by the investigator in certain given conditions (Blaxter & Hughes et al. 1996). It is widely used as a research approach in a number of social sciences, particularly psychology, but also economics, healthcare and education.

3.3.4 Action research

Action research (AR) is a complex, dynamic activity involving the best efforts of both members of communities or organisations and professional researchers (Blaxter & Hughes et al. 1996). It is social research which is carried out by professional researchers and stakeholders to improve their situation. AR promotes broad participation in the research process and democratises the relationship between the professional researcher and the local interested parties (Greenwood & Levin 1998).

3.3.5 Ethnography

Ethnography offers an unparalleled set of methods for exploring and gaining insight into people's values, beliefs, and behaviours (Perecman & Curran 2006). Ethnography will provide a description and interpretation of the culture and social structure of a social group (Robson 2002). The main purpose and central benefit offered by this approach is the production of a rich description free from participant's concepts and ideas.

3.3.6 Phenomenology

Phenomenology research concentrates on human experiences which are pure, basic and raw and which have not been analysed or theorised (Denscombe 2007). It focuses on understanding the essence of experiences about a phenomenon (Creswell 2007). As an approach to social research, it is sometimes considered as an alternative to positivism, which is also discussed in Table 3-1. It often places emphasis on subjectivity, description, interpretation and agency, and generally deals with people's perceptions or meanings, attitudes and beliefs, as well as feelings and emotions (Denscombe 2007).

3.3.7 Grounded theory

A grounded theory study is used to generate a theory that relates to the particular situation forming the focus of the study; the theory is "grounded" in the data collected during the research, and is particularly dependent on the people involved (Robson 2002). Theories should be generated by means of a systematic analysis of the data (Denscombe 2007). Interviews are the most common data collection method, but methods such as observation, or analysis of documents can also be involved (Robson 2002).

3.4 Choice of research approach

The nature of each objective in Chapter 1 (Figure 1-1) implies that one overarching approach would not be appropriate for the research. The first objective focuses on understanding the state of the art both within the general field of KM and also within the autonomous robot industry, which required a survey approach. Objectives two and three focus on stakeholder analysis and requirement capture, which also requires a survey approach. Objectives four, five and six are designed to generate a framework, with specific focus on modelling levels of autonomy and sophistication for the human assistive robot through the development of a web-based tool to support the model; it also included validation of the model. With regards to these objectives, stakeholder participation is essential in order to validate the model. A number of case studies are also needed to validate whether or not the model could work. Thus, experiment, ethnography, phenomenology, action research and grounded theory are not suitable. The research is conducted using a combination of surveys and case study. It is also helpful to establish a proper research approach using Table 3-2. Similar to the objectives discussed in Chapter 3, the research findings in this study should reveal low internal validity, population validity between low and median, high ecological validity, and low reliability.

When looking at the evaluation results in Table 3-2, we can see that only survey, case study, action research and grounded theory are suitable for the current research. Based on the objectives tasks analysis, some practical approaches are then chosen for this research, which is a combination of survey and case study.

3.5 Research method

As discussed in the previous section, not all approaches presented in Table 3-2, namely experiments, phenomenology, ethnography, and grounded theory are relevant to this research and will not be explored. It is also important to clarify that the 'surveys' method in this research is mainly based on semi-structured interviews.

The research methods used in this research are introduced in Chapter 2. Below are some descriptions of these methods.

- Interview with stakeholders: this is used to collect data directly from stakeholders to support the current research. This can help to identify how stakeholders manage knowledge within organisations; how they manage autonomous systems, and to what extent they apply through life management to their product.

- Case studies: these focus on how the model for levels of autonomy can be useful for stakeholders to make better decisions for the through life management of autonomous systems. The case studies should be a fairly self-contained entity and must have fairly distinct boundaries (Denscombe 2003). Case studies will aid in assessing and revising the framework/ tool created in this research.

- Group discussion: this is used quite often in the current research. Through group discussion, a number of methods such as information/ knowledge mapping can be used to collect information and knowledge from stakeholders in order to identify stakeholders and key definitions within autonomous robot systems. We can also collect knowledge in this way to establish how people manage knowledge, how people think about through life management, and how they manage autonomous systems.

- Scenarios development: A scenario is a description of a person's interaction with a system. The scenario is particularly useful when the research wishes to describe system interaction from a user's perspective. The method used in this research is

designed to aid stakeholders in developing a better understanding of how they can use tools to evaluate levels of autonomy.

Table 3-3 provides an overview of different research methods which are applied to this research.

Table 3-3 Research approaches: strengths and weakness

Approach	Summary	Strengths	Weaknesses
Surveys	Surveys can be used to obtain stakeholders' opinion, and interest within a certain situation. Different analytical techniques can be used to predict the different relationships which may exist.	Easily capture stakeholders' insight; and the result is reliable based on their experience.	Surveys can be superficial, and biased.
Cases studies	Detailed attempt to validate whether the model is reasonable or not.	Easy to identify whether the model works properly. Data collected using this method is reliable.	It is often robot specific and difficult to represent a large area.
Group discussion	Information captured from brain storm; creative approach to research.	Provides insights regarding when to identify potential stakeholders. Helps to organise content in an appropriate sequence.	May be difficult to achieve an agreement.
Scenario study	Descriptions of how user interacts with the tool.	Provides scenes which users can understand without any technical background.	The practice of scenario is very time-consuming.

3.6 Modelling techniques

For systems engineering, there are many kinds of modelling tools, methods and techniques with which to support system analysis, system design and validation. One of the main methods is Unified Modelling Language (UML). UML was originally developed for software engineering, but is now gravitating toward systems engineering (Dickerson & Mavris 2009). It combines techniques from data modelling, business modelling, object modelling, and components modelling. Based on this research, UML techniques can be used to create some component modelling. Another common method used in systems engineering is the logical model. The logical model is defined as a relational structure and a collection of sentences, which can be interpreted as true in the relational structure (Dickerson & Mavris 2009). Logical modelling provides a systematic method of creating models from definitions and sentences.

In this research, the UML is used to support the description in the logical model. For logical modelling, it will be used to analyse the definition of autonomy. This approach can help to capture some of the key information from sentences and the relationships between components within these sentences.

3.7 Developing the interview

The methods selected for collecting data and information from stakeholders are based on semi-structured interviews. It is also useful to conduct a semi-structured interview in order to get confidence from peers to support model development in this research. To conduct semi-structured interviews the stakeholders in this research must first be identified, as well as how important their answers will be for this research. This is done through analysing what information must be collected, and then designing a set of questions which may be asked during interviews with different stakeholders. Some of the common questions can be asked during interview, and then according to the different backgrounds of participants and their responses, the discussion can be adapted in order to obtain more information which is related to the research. In this research, the people involved in the semi-structured interviews are mainly designers in the robot industry, researchers in autonomous systems, and a number of robotic research organisations. Some interviews are used to collect information about how people manage knowledge in a robot company; some are to identify the design process of a

robotic system; some are to collect information for the model development. The interview method plays an important part in the research development.

3.8 Developing the model

The main output of this research is a generalised model for levels of autonomy and sophistication for the human assistive robot. The development of this model involves several formal processes. After requirement analysis and stakeholder analysis, an initial model is created through logical model analysis method regarding the definition of autonomy. When the initial model was created, some cases studies were used to prove whether or not the model was reasonable. In addition, several semi-structured interviews are conducted with peers and people in the area of autonomous systems in order to collect data and information to support the model's development. The model development is a process with rotation of model creation, model development, feedback from stakeholders, and model revision.

3.9 Validation and verification approach

For research purposes, the created model must be validated. Validity entails assessing whether the data and methods are 'right' for the research questions and output (Denscombe 2003). In this research, it means that the research needs to assess whether or not the created model can be used to properly evaluate levels of autonomy for the autonomous robot; and also that the evaluation scale within the model is reasonable. Through analysis, it is difficult to validate the research output. Studies have been conducted to build the confidence of the research output. These consist of case studies for the model validation, peers reviews, scenarios studies and semi-structured interviews. Firstly, the way to verify this model is based on case studies. The case selections cover autonomous robots and non-autonomous systems, which are considered to verify the model from different aspects in order to clarify the model's application area. As previously discussed, case study also has its limitations; it is often robot specific and difficult to represent to a large area. Another step is to create a tool based on the model and then to verify whether or not the tool can be considered as representative of the model in the real application. The validation is carried out through inviting several stakeholders to evaluate levels of autonomy for given robotic systems based on the tool. The evaluation result can be considered to support the validation of the model. When the tool is created, there is also a scenario study detailing how the tool can be used in a given robotic system, or in some special periods of a robotic system.

Generally, the verification work in this research is based on the comparison of results from the model and the software tool. The validation work is achieved through a set of numbers regarding peers' participation. The results from this validation can help gain some confidence from peers on this model and the validation of said model.

3.10 Summary

This chapter presents methods used in this research and the reasons behind the choice of different research methods. Based on the discussion of different research methods, the semi-structured interview method is adopted to collect data and information for this research. An initial version of the model for levels of autonomy is created using the logical model technique, and then through interview and cases study to support the model's development and modification. When a tool based on this model is created, several case studies and scenario studies are developed to support the validation and verification of the current research.

Table 3-4 outlines the research strategies that were adopted in this research.

Table 3-4 Research strategy

Stage	Research strategy	Reason
Creating the autonomy model	Logical model	Generate a conceptual model for levels of autonomy.
Validate the model	Semi-structure interview Case study	Collect information and knowledge from stakeholders and their suggestions for model development.
Evaluation	Case study	Through case study, participants can use the tool for application of the model and generate a set of data for research; it can also help for further analysis regarding the model's validity.

4 Initial development work on the model of Autonomy Levels For Human Assistive Robot (ALFHAR)

This chapter firstly gives a general introduction to the whole research plan before then analysing the gaps between the existing research and the requirement from stakeholders using logical model analysis for the conception of autonomy. The components in the logical model are demonstrated in order to explain how the model is reasonable. It also includes the sophistication aspect of a human assistive robot. Following these analyses, an initial model— ALFHAR is proposed in this research. There are also two cases studies which are used to validate whether the initial model can be considered as a model to describe the capability of the human assistive robot. Further analyses then follow regarding how the ALFHAR model is related to TLM and how stakeholders may benefit from this model. The initial model is based on a conceptual description of autonomy/sophistication. This requires evaluation standards to support the initial model so that the model can be used to evaluate the level of autonomy possessed by a particular human assistive robot. Further details are described in Chapter 5.

4.1   Introduction

The main purpose of this research is to develop a generalised model for levels of autonomy and sophistication for autonomous systems. In the original plan detailed in Chapter 1, the framework development for this research in objective 4 includes several sub-objectives. Figure 4.1 presents a map which shows how these sub-objectives relate to each other. First of all, there is a basic introduction to the functions of each task:

- Ontology for the human assistive robot aims to supply a common conception within human assistive robots, including concepts, design, lifecycle, standards, and so on.
- Questioning based method is designed to assist designer/stakeholders in the design and through life management using a set of questions generated from different stages of the lifecycle, which may include safety, communication, ethics, decision making issues in the requirement analysis, design, maintenance, service stages, and so on.
- Generalised model for levels of autonomy. The work here aims to create a model for the evaluation of autonomous system capability, especially in the area of human assistive robots.

The relationships between the three components in Figure 4-1 are described as follows:

- Ontology for human assistive robot can supply a common conception for the human assistive robot and will support the component of "generalized model for levels of autonomy". It can also be useful for the component of "questioning based method".

- Generalised model for levels of autonomy. This provides support for the through life management of autonomous systems, and can be an integral part of the decision making support system. A number of definitions can emerge from "ontology for human assistive robot" which are aimed at sharing knowledge between stakeholders; some of the content in this section of the work may be helpful for generating questions for the "questioning based method".
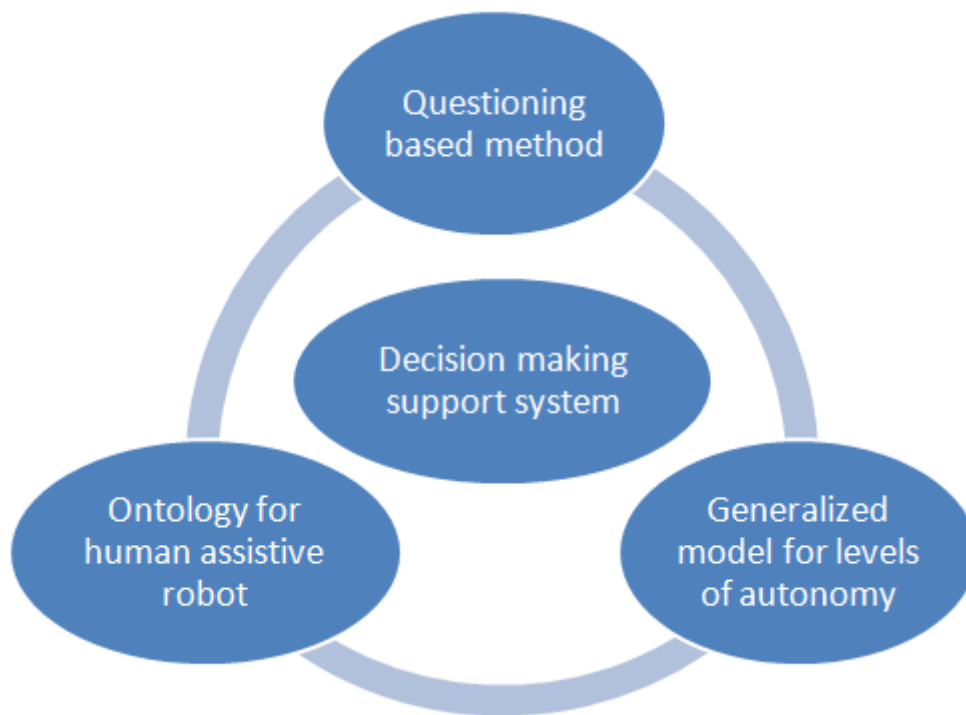
Figure 4-1: System framework for the research

Due to time limitations, the current research is mainly focused on creating a generalised model for levels of autonomy.

4.2 Gaps in the modelling levels of autonomy for human assistive robot

Having critically reviewed the literature regarding the classification of levels of autonomy in Chapter 2, it is apparent that many researchers are beginning to explore the autonomy model for robotic systems / autonomous systems, and that a great deal of progress has been made in

this regard. With this said, much of the research has focused on defence applications, for which significant human-robot interaction in theatre is comparatively low. Indeed, defence robots are generally used in hostile environments in place of humans to reduce the risk to human life; the so-called dirty, dull, or dangerous environments. However, robots are now being seriously considered for applications in which the interaction with human beings would include significant physical contact. For instance, a high priority driver for such applications is as a means to support the welfare of an increasingly aged population. In fact, there is an urgent requirement for the development of autonomous, domestic service robots. The existing frameworks for autonomous, unmanned systems do not adequately cover such domestic applications. Although the ALFUS framework (Huang & Messina et al. 2007) is one of the most comprehensive, it does not allow for a proper distinction between different levels of autonomy for the case of human-assistive robots. It is acknowledged that ALFUS was created with unmanned vehicles in mind, but as one of the most comprehensive frameworks, the lack of extensibility to the human-assistive case raises some gaps as far as its area of application is concerned (Fu & Henshaw 2010).

4.2.1 Difference between defence robot and human assistive robot

There are significant differences between the application of autonomous robots in the defence area and those in the domestic area. Consider the level of autonomy for Unmanned Air, Ground, surface, or Underwater Vehicles (UXV) used for defence purposes. Huang & Pavek et al. (2005) propose evaluation through the consideration of environmental difficulty, human interface, and mission complexity. A higher level of autonomy implies that the UXV will accomplish more complex missions, be resilient in a wider range of environments, and require fewer human-robot interactions to achieve the mission. But for a human-assistive robot, a higher level of autonomy may be associated with greater complexity due to an increased number of human-robot interactions, working in cluttered environments in close proximity to human beings, but remaining safe at all times. The complexity of communication is also significantly higher than for a UXV.

The rules governing the human-robot interaction are very different between these applications. Expressed in an extreme sense, a domestic robot must interact with humans in an entirely safe (do no harm) manner, whereas for a defence robot (UXV) the purpose may be to deliver violent effect. Table 4-1 provides a comparison between these two domains.

Although not all UXVs are associated with defence, in general this has been the main application area that has driven their development so far.

Table 4-1: Comparison between defence robot and domestic assistive robot

	Defense robot	Domestic assistive robot
Definition	'The application of the science of robotics to military uses, such as remotely piloted vehicles, automated ammunition and supply handling, and the like' (The Encyclopedia.com 2010).	'A service robot is a robot which operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations' (SRI Consulting Business Intelligence 2008).
Typical applications	UXVs: Surveillance, mine detection, kinetic effects, search and destroy.	Unitary application: cleaning, porterage, monitoring, Telemedicine Pharmacy Automation (Healthcare).
Aims of application	Inhospitable and dangerous environments / persistent tasks.	Replace human-beings in repetitive 'DDD' tasks.
Safety considerations	Avoid human proximity, correct identification of targets, occupation of separate spaces (e.g. airspace), remote piloting.	Fail-safe, predictable behaviors, prescribed actions.
Communication	Wireless communication (infrequent communications).	Advanced sensors-vision, touch, voice, etc. (continuous communications).
Standards	Engineering standards, legal restrictions on area of operations.	Engineering standards.
Operational responsibility	Domain experts operate and control the robot.	Generally non-expert users.
Human robot interaction	Higher level of autonomy, lower degree of human intervention.	Human robot interaction occurs during the whole application.

4.2.2 Human assistive robot

In this research, the focus is on how to evaluate levels of autonomy for human assistive robots. At present there remains no clear definition of the human assistive robot. Some research activities provided definitions and comparisons for robots which are related to the human assistive robot, such as socially assistive robot, assistive robot, and socially interactive robot (Feil-Seifer & Mataric 2005). According to work by Feil-Seifer, in this research, we will give a definition for human assistive robot, which is based on current human assistive robot projects.

A human assistive robot is a robot which can supply service to human beings for the aims of assistance, guidance, learning, and entertainment. To some extent, it will include assistive robotics, socially interactive robotics, and socially assistive robotics; or the integration of this robotics' ability to supply a better service to human beings. Table 4-2 provides a list of definitions and comparisons for different kinds of assistive robot.

Table 4-2: Assistive robots comparisons (Feil-Seifer & Mataric 2005)

Assistive robot	an assistive robot is one that gives aid or support to a human user.
Socially interactive robot	is used to describe robots whose main task involves some form of interaction.
Socially assistive robot	is to create close and effective interaction with a human user for the purpose of giving assistance and achieving measurable progress in convalescence, rehabilitation, learning, etc.

In this research, human assistive robot is the integration of assistive robot, socially interactive robot, and socially assistive robot. Figure 4-2 shows how these different kinds of robot integrate together to compose the area of human assistive robotics.
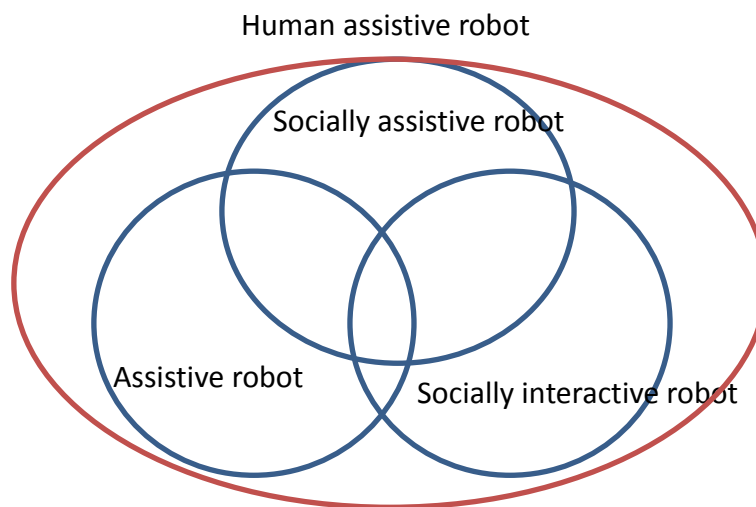
Figure 4-2: Relationships for assistive robots

4.3 Stakeholder's requirement

As critically analysed in Chapter 2, the main stakeholders in this research include designers in the area of robotics and customers who wish to use robots to assist with their daily life. The requirement of modelling levels of autonomy and sophistication for human assistive robots can be considered as:

- To provide a common vernacular which could be used to articulate capabilities.
- A means by which to articulate the amount of autonomy/sophistication required/expected from an Unmanned System (Huang & Pavek et al. 2005).

The level of autonomy and sophistication for human assistive robots is to provide a way in which to articulate the amount of capability required/expected from a human assistive robot. It can also be used as a guideline for design to support the through life management of autonomous systems.

4.4 Initial model development

As analysed above, there is a need to develop a model for levels of autonomy/sophistication for human assistive robots. One effective way is to understand what autonomy/sophistication is and how to demonstrate autonomy/sophistication using common words in order to model levels of autonomy/sophistication in the area of human assistive robotics.

4.4.1 Autonomy

Autonomy is a word used to describe the ability of unmanned systems. One of the important definitions in this regard is as follows:

"*A UMS's own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned* " (Huang & Messina et al. 2007).

This pertains to a robot's own ability, independent of human interaction. For human assistive robots, autonomy is a robot's own ability of integrated sensing, situation awareness, mobility, decision-making, interaction, and mechanical ability to achieve its goals as assigned. The autonomy of a robot can be assessed by analysing how sensing, situation awareness, mobility, decision-making, interaction and mechanical ability integrate together.

Here a logical model is used to analyse the concept of autonomy for human assistive robots (see Figure 4-3). This research is focused on analysing how these attributes work within human assistive robots, and how a human assistive robot can be evaluated based on the different levels of attributes.
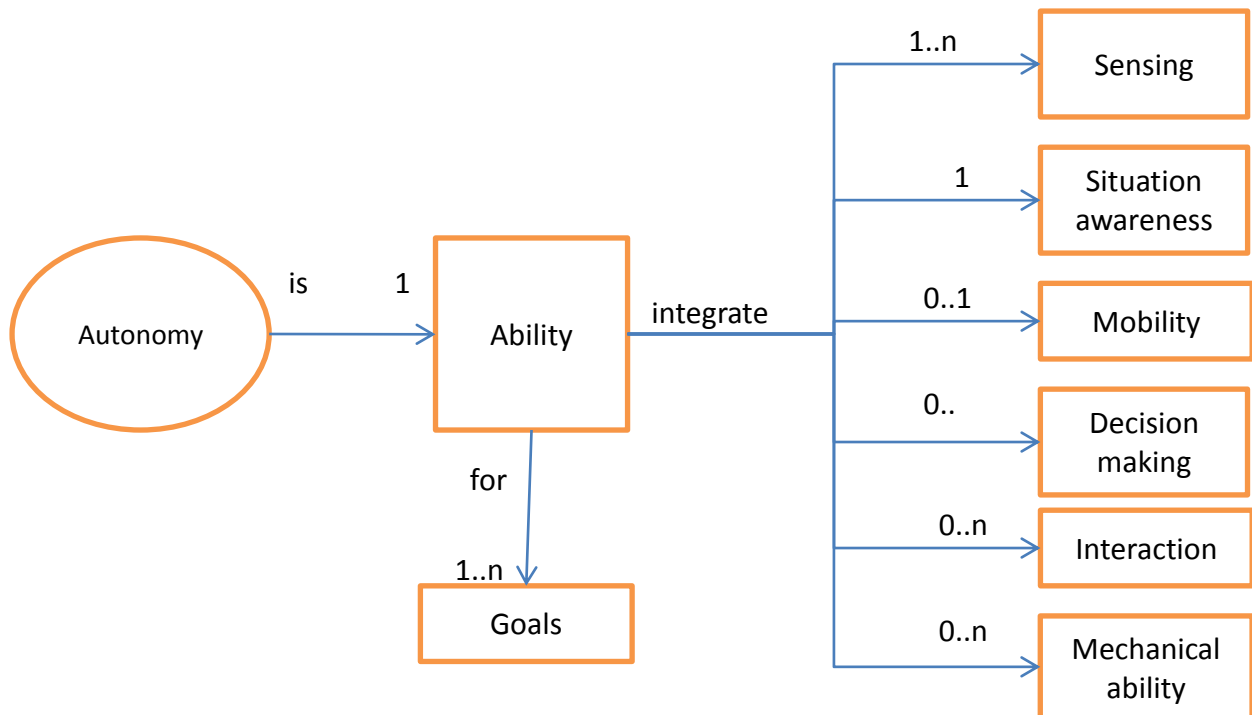
Figure 4-3: Autonomy conceptual logical model

4.4.2 Mobility

Mobility is not essential for different kinds of human assistive robots, but can be important for some kinds of robots. Mobility is normally related to speed, localisation, route planning, movement type, navigation and emergency control. All of these categories work together to achieve certain levels of mobility. To classify the different levels of mobility, more detail is required regarding how these factors contribute to mobility. This can be collected from interviews with stakeholders, and is discussed in the following chapter.

4.4.3 Decision making

Decision making: the ability of robot's decision making will be a significant factor in determining the level of autonomy. The level of decision making can span from non-decision making ability to autonomous decision making. Decision making is a process of output from a set of information and logical analyses. The level of decision making depends on what kind of information can be collected for the decision making process, and what input is present when certain special decisions have to be made. There is already a wealth of research on robot decision making, revealing that the decision making ability increases significantly in different application areas. The higher decision making ability a robot has, the more autonomous it is considered to be.

4.4.4 Interaction

Interaction is the most important factor for human assistive robots. The interaction ability will help a robot to communicate with human beings much more easily, and give assistance to human beings in a convenient and acceptable way.

Interaction is a kind of action that is used to transfer information and deliver objects between robots and human beings. During the human robot interaction, there may be physical interaction, communication, and body language integrated together to express some kind of interaction. This interactive ability can be considered as part of autonomous behaviour for the human assistive robot.

4.4.5 Situation awareness

"Situation Awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley 1988).

For robot systems, situational awareness is dependent on many different aspects, such as sensing capabilities, an internal model of the environment, recognition of objects and/or environmental features, projection of likely changes and so on. The complexity of the task is dependent on the environment and upon the mission's complexity. Situational awareness affects decision making ability; in this way, it is also an important factor for the autonomy level of robotic systems.

4.4.6 Sensing ability

Sensing ability is an ability which relates to the detection of information. For human assistive robots, sensing ability is dependent on the numbers of sensors it has, the intensity of information collected, the detection scope it has, and the numbers of different type of sensors it has. In other words, the complexity of sensors will decide the different levels of sensor ability. Normally the sensor ability is shown through different kinds of environments. For example, one sensor can only work in day time, and another can work in both day time and evening; from this point of view, the second one has higher ability than the first one due to the environmental factor. The sensor's ability affects decision making ability, and thus can affect the autonomy level of robotic systems to a certain extent.

4.4.7 Mechanical ability

Human assistive robots' mechanical ability can be considered as the ability to act or execute tasks. The complexity of tasks normally means high levels of mechanical ability. Mechanical ability is used to explain what a robot can do, and how it can help human beings. It is also the basic requirement for a human assistive robot to supply service for human beings. The mechanical ability is not necessarily part of autonomy, but autonomy can be expressed in some kind of mechanical ability. For example, a robot arm is used to execute a task automatically; in this situation, it has a certain level of mechanical ability, but no autonomy. For another robot, which is used to care for people at a home, tasks may include delivering cups or food to human beings; in this way, the robot again has a certain level of autonomy, and the autonomy is represented by the mechanical behaviour.

4.4.8 Summary of autonomy

From the definition of autonomy and the subsequent analysis of its components, we can find that descriptions of the autonomy aspect of human assistive robots is based on decision making; it is also quite related to situational awareness. The mobility, interaction, and mechanical ability are the carriers through which autonomy is delivered. On the other hand, sensor ability is also essential for robots' decision making, situational awareness, and also their autonomous ability.

4.4.9 Sophistication

When considering a human assistive robot's capability, it is not only about how autonomous it is. Focus must also be placed on what kinds of ability it has, and also how complex it is with regards to executing missions.

According to analyses regarding the details for autonomy, it is interesting to find that autonomy cannot fully describe human assistive robots in an effective way. On occasions another word - sophistication - is needed in order to evaluate how the robot is. As mobility, interaction, and mechanical ability are the carriers for autonomy, there are some other attributes that we may want to analyse for these abilities. For example, some robots may have high levels of mobility, but low levels of autonomy; or a robot may have some ability to interact with human beings, and may possess certain levels of decision making ability, but different levels of ability when it comes to expression or understanding. To describe such

kinds of robot, this research suggests that it is better to demonstrate it using autonomy and sophistication, which will cover the entire robot's capability. In this way, every robot will be described in terms of autonomy and sophistication.

Sophistication for human assistive robots involves discrimination between different capabilities. For example, if there are two type of human assistive robot, which are at the same level of autonomy, but with different scopes of application, length of lifecycle, complexity of tasks, and so on, then these two robots are at different levels of sophistication. In the following, an analysis is presented regarding how sophistication can be used to describe human assistive robot capability.

Generally, human assistive robot capability is delivered through planning, decision making, mobility, interaction, and mechanical ability aspects. The complexity of mobility, interaction and mechanical ability can be parts of sophistication for human assistive robots. In this way, sophistication should be considered when discussing the human assistive robot's capability. The sophistication analysis of a robot system will also include a detailed description of each function within a robot system.

4.4.9.1 Difference between autonomy and sophistication

From the analysis above, it is clear that autonomy for human assistive robots is based more on the system decision making aspect, whilst sophistication is more concerned with the complexity of robots' ability in the application. Both autonomy and sophistication ability are delivered through a set of robot behaviours. Certain robot behaviours may have only sophistication aspects but no autonomy, whilst some may be the opposite. These two dimensions are combined for an apt description of a robot system's capability.

4.5 Proposed model

Through analysing autonomy and sophistication, there is a proposed model for human assistive robot's capability, which is considered for use when evaluating levels of autonomy and sophistication for human assistive robots (ALFHAR), (see Figure 4-4).
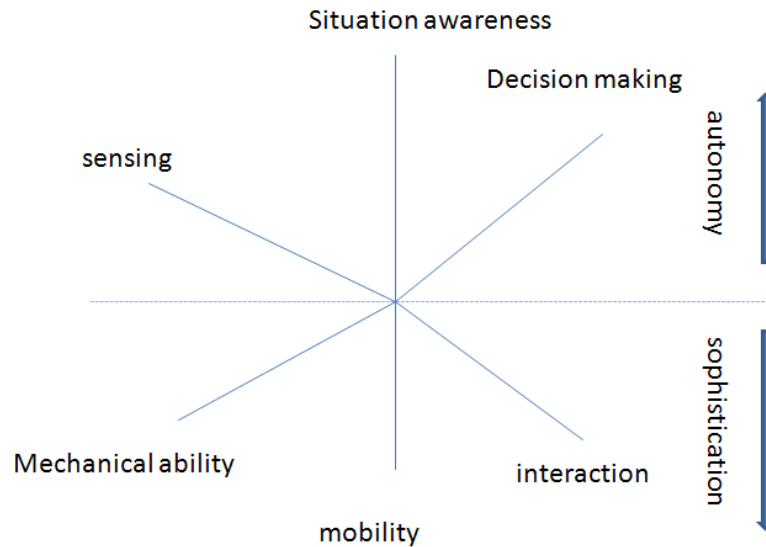
Figure 4-4: Proposed model for human assistive robot's capability

In Figure 4-4, the human assistive robot's capability can be described through autonomy and sophistication, which includes mechanical ability, mobility, interaction, sensing, situation awareness and decision making. The sophistication aspect of a human assistive robot is more related with its mechanical ability, mobility and interaction; and the autonomy aspect of a human assistive robot is more dependent on its decision making, situational awareness, and sensing ability. In this chapter, the focus is on whether these dimensions are suitable for the evaluation of a robot's capability. There will be a more detailed description of how to measure human assistive robot capability in Chapter 5.

4.6 Cases study for proposed model

Based on the logical modelling analysis and conceptual analysis of the components in the logical model in Figure 4-3, the proposed model is described in Figure 4-4. Here we attempt to use normal human assistive robots to evaluate how this model can be considered as one of the acceptable frameworks for evaluating levels of autonomy for human assistive robots. The cases selected are mainly based on the area of human assistive robotics; the study attempts to use the ALFHAR model to describe selected cases and to establish whether it is suitable for the work at hand.

Case 1: Here we take "Wakamaru" for example. "Wakamaru" is the world's first communication robot (Shiotani, Tomonaka, Kemmotsu, Asano, Oonishi & Hiura 2006). It is primarily intended to provide service and assistance to elderly and/or disabled people.

Wakamaru can connect to the internet, has a limited speech capability (in both male and female voices), makes eye contact, and has speech recognition abilities. Its functions include reminding the user to take medicine on time, and calling for help if it detects that something is wrong. It has high reliability of self-localisation and avoidance of obstacles using sensors, but errors may occur and their frequency increases when there are changes in lighting and location of people.

First of all, according to the function description of "Wakamaru", there is a mapping from the function description into models' attributes. The aim of this step is to make the model easier to be used in the following stages.

Table 4-3: Case study 1

	Wakamaru	
Functions in Wakamaru		Descriptions in Wakamaru.
Interaction	Yes	Speech, eye contact, speech recognition.
Decision making	Yes	Reminding the user to take medicine on time, calling for help if it detects that something is wrong.
Situation awareness	Yes	Detect environment.
Mobility	Yes	Self-localisation, avoidance of obstacles using sensors.
Sensing ability	Yes	Vision sensor, voice sensor, distance sensor, etc.

In Table 4-3, we can see that case study 1 can be described through the initial model. To explore how this model may work, another case study is relevant.

Case 2: Shepherd / Guide. In this case, a robot is used as a Guide / Shepherd, which can help people as a guide to move from one place to another, whilst also assisting as a personalised caregiver. This robot can also serve as a person's eyes and ears, is easy to command and interact with, is unobtrusive, encourages socialisation and increases human quality of life.

Based on the descriptions of Shepherd / Guide above, we can map the function description above into the model's attributes.

Table 4-4: Case study 2

	Shepherd / Guide	
Functions in Shepherd		Descriptions in Shepherd.
Interaction	Yes	Speech, touch.
Decision making	Yes	Route planning.
Situational awareness	Yes	Human-centre environment.
Mobility	Yes	Move from one place to another.

Sensing ability	Yes	Vision, touch, distance sensor, etc.

Similar to the mapping above, we may find that these two mappings show the relationships between the model and robot function descriptions. The functions of these two robots can also be described using the model's main attributes. To some extent, the initial ALFHAR model can be considered as a proper model for evaluation of autonomy/sophistication for human assistive robots. Further work for establishing this model includes validating whether the model can be accepted by stakeholders in the area of autonomous systems, and providing evaluation rules for the model so that it can help calculate the autonomy/sophistication level in a standard way.

4.7 Through life management support

As the aim of ALFHAR is to integrate this model into through life management of autonomous systems, there is some analysis regarding how the ALFHAR model can be related to TLM. The key theme of through life management is an "executive" philosophy which involves taking a coherent and holistic approach to managing the whole life costs and outlook across a project or programme's life cycle. It brings together people, knowledge, processes and systems, and aims to simplify complex management systems and support arrangements, whilst encouraging better decision making, planning and involvement of stakeholders (tlmNEXUS 2011). For the proposed model, it can be used to analyse what kind of autonomy a robotic system needs, and can also support designers in better decision making regarding the requirement capture and analysis. The model may also be used for evaluating a system's capability so that it can be helpful to robotic system deployment. It may also be useful for stakeholders to use robotic systems. The model proposed here can support the life cycle management of autonomous system to save time and money to some extent.

Take CADMID model for example. The lifecycle of autonomous systems is analysed by this model. According to the aim of ALFHAR, the model can be used in the concept analysis, assessment, demonstration, manufacture or in-service stage, as shown in Figure 4-5. This means that ALFHAR is in fact related to the CADMID model. It can be used during different stages of lifecycle for human assistive robots, and is considered as part of support for TLM of autonomous systems.
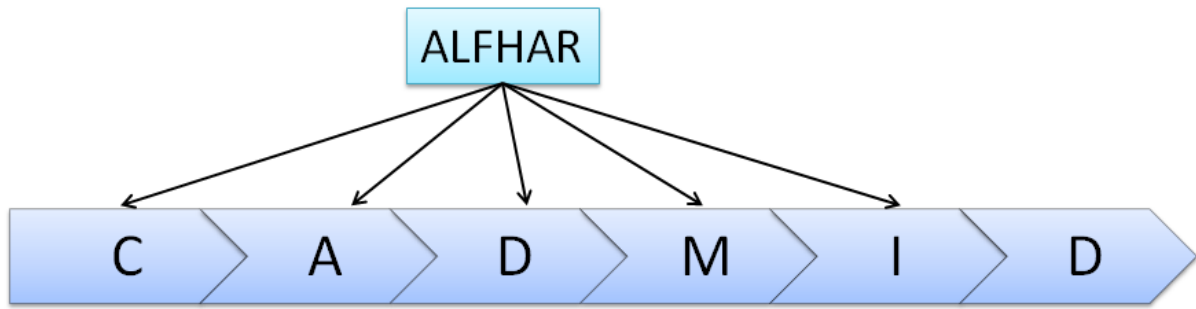
Figure 4-5: Relationships between ALFHAR and CADMID

4.8 Stakeholder benefits analysis

From through life management analysis, we can see that the ALFHAR model can be used in different stages of the lifecycle. Stakeholders may use this model for conceptual analysis for a robot system in the requirement analysis stage based on the system's capability requirement; designers can also use ALFHAR model to assess the robot system capability based on the concept and evaluate whether it is reasonable for design. In the demonstration stage, the ALFHAR is also important for stakeholders to validate whether the product is designed as required. It can also be a guideline during the manufacture and in-service stage. Certain maps show how stakeholders can use the ALFHAR model during different stages of the lifecycle. Figure 4-6 and Figure 4-7 show how stakeholders participate in the human assistive robot lifecycle and how they can evaluate robots' capability through the ALFHAR model; they can use the ALFHAR model in different stages of the lifecycle, depending on the necessity of it.
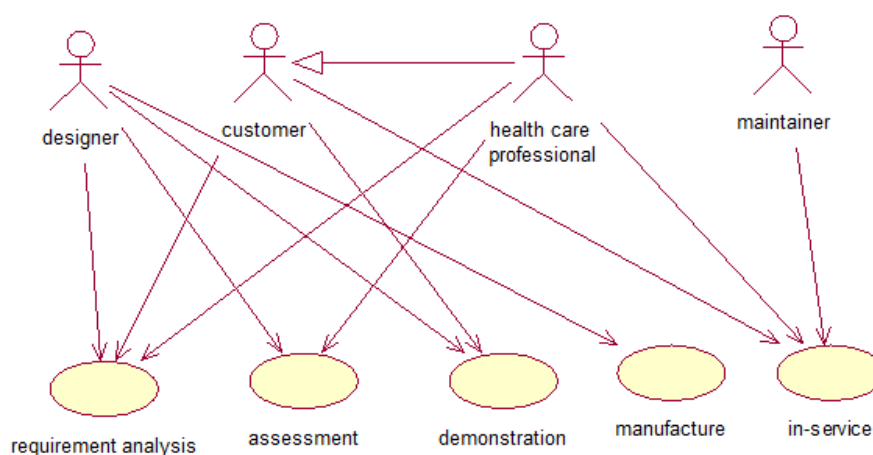
Figure 4-6: Use case diagram for stakeholders in the human assistive robot lifecycle
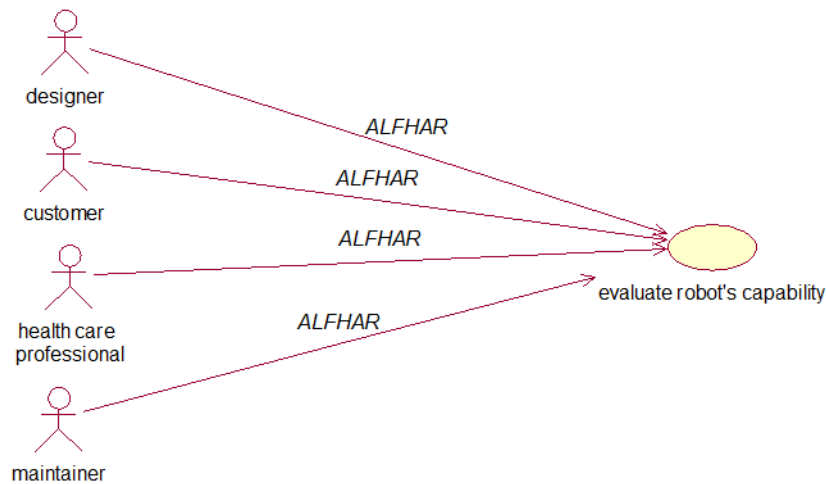
Figure 4-7: Use case diagram for stakeholders using ALFHAR model

Generally, the ALFHAR model can support parts of through life management for human assistive robots based on the analysis above and can also benefit stakeholders with regards to their application of ALFHAR in different situations.

4.9 Summary

The initial development work on the ALFHAR model is based on logical model analysis regarding the definition of autonomy and conceptual analysis based on its components within the logical model. After the model is proposed, two cases studies follow. These are used to validate whether this model can be used to describe autonomous systems properly. Analysis is also provided with regards how the ALFHAR model can integrate into the through life management support of autonomous systems and how stakeholders may use this model during different stages of the lifecycle for human assistive robots. The model developed here is based on theory analysis and focuses on the main dimensions for human assistive robots; the following step is designed to collect data and information from stakeholders in order to support the model development from a more detailed aspect.

5   ALFHAR Model development

Chapter 4 presented the initial ALFHAR model, and this chapter will detail the model's development as well as how stakeholders contribute to the model's development. This research also develops a tool based on the model to support the application of the model. There is also a scenario study about how the tool can be used by stakeholders to support the evaluation of autonomous systems.

5.1 Collect information from stakeholders

The initial ALFHAR model was created based on logical model analysis. It works fine in case studies. To identify whether it meets stakeholders interest, however, information must still be collected from stakeholders regarding this model. A number of questions must be clarified by stakeholders in order to validate the model.

5.1.1 Development of interview with stakeholders

In the ALFHAR, the model describes levels of autonomy through sensing, situation awareness, mobility, decision-making, interaction, and mechanical ability. There are questions regarding whether the evaluation from these dimensions is reasonable or not. Some of the questions may be asked by stakeholders in the robotic area. The main questions are designed as follows:

- What is your consideration on autonomy of a robotic system?
- How do you measure autonomy of a robotic system?
- What is your opinion about mobility, interaction, situational awareness, sensor ability, decision making, and mechanical ability?
- What is the lifecycle of a robotic system in your product? Who is responsible for each different stage of its lifecycle? Which aspect of lifecycle will be interesting for you?

The method used for collecting data and information is based on semi-structured interviews with stakeholders in the area of autonomous systems. The data obtained from semi-structured interviews will be more detailed and rich, meaning that it can offer some immediate means of validating the data (Denscombe 2003).

CHAPTER 5: ALFHAR MODEL DEVELOPMENT

To conduct semi-structured interviews those who are interested in this research should be identified, as well as those who are available for interview. Based on the stakeholder analysis in the literature review in Chapter 2, the main interviewees are designers in the robotic area, researchers on autonomous systems, and also some systems engineers in autonomous systems. After analysing who may be helpful for this research, a wide invitation is distributed in order to attract potential stakeholders to join the interview stage. Generally, the results from interviews with stakeholders are vitally important for this research. It collects information and knowledge from stakeholders directly to support the model's development. Some of the interviews are listed in Appendix II.

5.1.2 Discussions on feedback from stakeholder

Several interviews have been conducted in order to support the research development. The interviews are recorded in their entirety so as to help further data analysis. Through conducting semi-structure interviews, it is interesting to find that some of the comments from interviewees differ from the original ALFHAR model.

According to Professor A from one British University, the components' mobility in the proposed model ALFHAR should be part of mechanical ability. This seems reasonable for robotic systems' mechanical ability, and can include the movement component. There is also a suggest from him that the system configuration should be part of the model, as the system configuration can be considered as part of the contribution to the whole system's mechanical ability.

With regards to sensor ability and situational awareness, both are related to decision making. A robot designer R in a robot design company commented that the sensors' redundancy, and the number of ways in which sensors are used would affect the decision making ability. However, he thought that situational awareness might not be the right word to describe robots' decision making, as robots' decision making processes are slightly different from human beings. Normally the decision making of human beings will consider a number of factors simultaneously, but for robot systems, the decision making process is mainly based on data. Through further analysis and literature reviews, this research is still of the belief that situational awareness will be important for robotic systems' decision making (Steinfeld & Fong et al. 2006); many robotic systems are currently enhancing their decision making ability through the input of situational awareness model into its system in advance (Gehrke 2009).

Having said this, the inputted situational awareness is also in data format. In interviews, it is mentioned that the mechanical ability can be determined by degrees of freedom (DOF) of a robotic system.

Through analysis, the research finds that some views from interviewees are extremely useful for the model's revision and some of their advice could be helpful for the model's detail development and model validation. The following section will demonstrate how to evaluate different aspects of autonomous system characteristics.

5.2 Detailed model development

Based on the feedback from interviewees, a revised version for ALFHAR is considered as follows, see Figure 5-1. In this model, we try to describe human assistive robots' capability from autonomy and sophistication aspects. The autonomy aspect is based on decision making ability, and the sophistication is focused on its mechanical ability and interaction. There are details on how the research is trying to measure those attributes of human assistive robots.
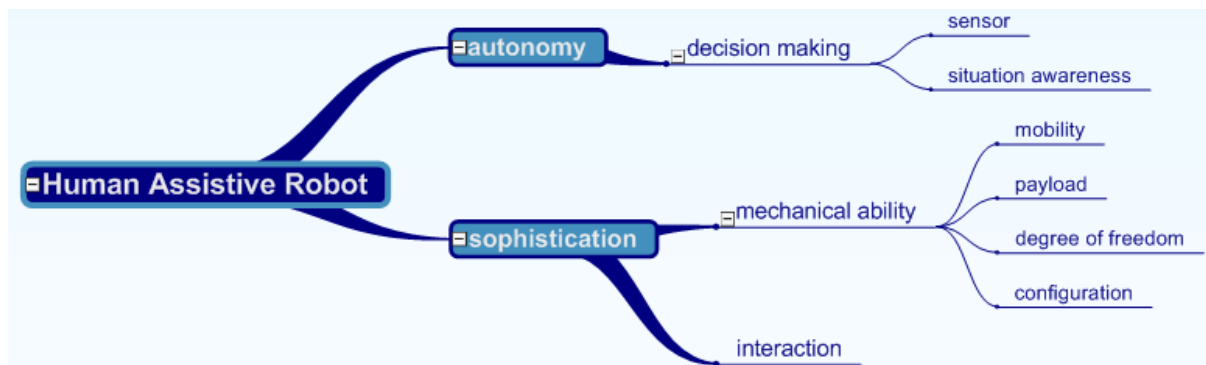
Figure 5-1: A revised version of ALFHAR

5.2.1 Autonomy and its details

Through analysis in Chapter 4 and results from interviews with stakeholders, the autonomy of human assistive robots within stakeholders' minds is about how decision making is approached by robots. In the following, there is analysis on decision making, sensor ability, and situational awareness, from which to understand the autonomy of a human assistive robot as well as how autonomy can be evaluated from detailed information of human assistive robots.

5.2.1.1 Decision making analysis

Similar to the analysis above, decision making is directly related to autonomy. The decision making ability will support human assistive robots to own some level of autonomy. Normally, the decision making of a robot can be considered as follows: sense—perceive—plan—decide—action (Visnevski & Castillo-Effen 2009a). The first step for decision making pertains to data and information collection, which is based on sensors. From this point, the sensors' ability can enhance systems' decision making. The sensors ability will decide what kind of information will be collected, as well as the accuracy of the data available. On the other hand, situational awareness is also very important for robotic systems' decision making. Many studies currently exist with regards how to enhance a system's situational awareness. For example, some techniques are based on inputting some training records into robotic systems' database, in order to enhance its perception when detecting data and information from the outside environment (Freedman & Adams 2009). The decision making ability for human assistive robots aims to enhance robots' ability to ensure that certain activities are delivered correctly and autonomously. From the analysis above, decision making ability depends on the sensor ability and situational awareness of a robot system.

5.2.1.2 Sensor ability analysis

Sensors are necessary for each robot. Based on the role of sensors in robotic systems, sensors can be used for different aims of application. When talking about sensors in a robotic system, there are several topics which must be considered. These include sensor type, number of sensors, the configuration of sensors, and the sensor application environment.

Sensors in robotic systems are not directly related to systems' autonomy; they are used to supply necessary information for decision making and automatic action in robotic systems. A robotic system can have many sensors in different applications and different configurations, but without autonomy; on the other hand, a robotic system with some levels of autonomy cannot exist without sensors.

For decision making ability, the way a sensor is used is vitally important. It will relate to how reasonable the decision is. For example, if a robot has a camera sensor, it can work well in a light place, but can hardly work in a place without light. To ensure the data collection for decision making, other kinds of sensors may be required such as infrared radiation to support the deficiencies of the camera. This is normally a cheaper choice to ensure that a robot can

work in different environments. This will depend on the requirement and the cost from customer.

5.2.1.3 Situational awareness analysis

Situational awareness of a human assistive robot, as summarised in the decision making section, relates to a robot's perception of the outside environment and inside status, and may provide robots with a greater understanding. Normally situational awareness exists because of common sense data stored within the robotic system. It is considered as the robotic system's experience of the real world. It relates to a robot's understanding of its environment, and self-status. Through inputting situational awareness into a robotic system, this will obviously enhance a system's decision making. The main application of situational awareness in human assistive robots is in navigation and recognition. Normally, there are three levels of situational awareness: perception, comprehension, and prediction.

5.2.2 Level of autonomy

The levels of autonomy can be evaluated from decision making ability. Currently, there are already several studies regarding categories for levels of decision making in unmanned systems. One of the most popular models is Pilot Authority and Control of Tasks (PACT) (Hill & Cayzer et al. 2007), which is applied in defence areas, and used as a guideline for pilots to control an unmanned system.

For human assistive robots, the level of autonomy is based on decision making ability, the understanding of its environment, and itself situation. These robots are capable of total independence from operator intervention.

According to PACT's description of decision making ability, the decision making level for human assistive robots is considered as follows, (see Table 5-1).

Table 5-1: Decision making levels (Hill & Cayzer et al. 2007)

Level 5B	Robot does everything autonomously, understands its environment thoroughly.
Level 5A	Robot chooses action, performs it and informs human.
Level 4B	Robot chooses action and performs it unless human disapproves.
Level 4A	Robot chooses action and performs it if

	Human approves.
Level 3	Robot suggests options and proposes one of them.
Level 2	Robot suggests options to human.
Level 1	Human asks robot to suggest options and human selects.
Level 0	Whole task done by human except for actual operation.

For level 4, robots can be used to directly support humans, and for level 5, it will autonomously execute tasks.

Generally, the table here shows what robots can do for human beings. One important thing is that the autonomy level of robots here is given from a whole system aspect: for example, a human assistive robot may have several functions, but each function is at a different level. If this is the case then the evaluation result for the whole system will be the same as the one with the highest level.

From these descriptions, we find that the autonomy aspect of robots cannot differentiate the sophistication of its mechanical ability, or interaction. To fully demonstrate human assistive robots' capability, in the following, more analyses are presented regarding the nature of sophistication for human assistive robots, as well as how we can measure it.

5.2.3 What is the sophistication for human assistive robot?

The sophistication of a human assistive robot is related to system design and system capability. It is possible to enhance a human assistive robot's capability through system configuration, a system's mechanical ability, and the interaction ability between robot and human being. The sophistication aspect of the human assistive robots we consider here is from a mechanical ability and interaction perspective. To analyse how sophisticated a robot is, detailed analyses similar to the following are essential.

5.2.3.1 Mechanical ability analysis

The mechanical ability of a human assistive robot is the main criterion through which to assist a human's life in a better way. According to the interview from a robotic engineer, the basic understanding for robot mechanical ability is: the more a system can change to the world, the more mechanical ability it has (see more information in Appendix II). For a human assistive robot, its mechanical ability can cover mobility, mechanical component

configuration, the ability to deliver a task, and degrees of freedom (DOF). In the following, analyses are presented regarding mechanical ability, and from which aspects we can measure mechanical ability for human assistive robots.

5.2.3.1.1 Degrees of freedom

One of the common ways to evaluate mechanical ability is based on DOF, which are independent displacements and/or rotations that specify the orientation of the body or system. The more DOF a robot system has, the more flexible the robot will be.

5.2.3.1.2 Mobility

Generally, the mobility of a human assistive robot is dependent on the requirement of the application. Some applications may not need a robot to have mobility, such as kitchen robots, which may simply be installed in the kitchen to do special cooking. On the other hand, there are also many other robots which need mobility to execute missions; for example, autonomous vacuum cleaners, ASIMO, and so on. Mobility plays a very important role for such robots.

The sophistication of mobility includes the complexity of locomotion components and the complexity of the environment in which a robot is involved. For example, a human assistive robot which works in a domestic environment may have to deal with the complexity of environment, whether this is uneven ground or whether the environment around the robot is dynamic, such as human beings / living animals around it or changing light conditions; occasionally the application environment may include stairs, and so on. The sophistication of environment requires human assistive robots to have a certain level of sophistication of mobility in the real application.

The following section will mainly focus on what the main locomotion types are for human assistive robots as well as how to classify the sophistication of mobility for human assistive robots.

The main mobility for human assistive robots includes locomotion, sensing, control, and the environment complexity. When talking about the locomotion of human assistive robots, many kinds of designs are already in existence such as crawl, wheel, bipedal, and so on. The selection of moving type is also dependent on the application, and the requirement from the

customer. Each moving type has its own advantage in special applications. Table 5-2 is a basic comparison between some forms of locomotion. It shows some of the robot locomotion and their strengths in specific areas.

Table 5-2: Locomotion type description

Wheel	Energy efficiency on flat surfaces; good at balance; easy for design and control.
Bipedal	Humanoid design, attractive and sophisticated.
Crawl	Can move in rough terrain, narrow spaces, or walls; sophisticated in design.

To evaluate how sophisticated the mobility of an assistive robot is, environmental complexity is a crucial factor. The structure and complexity of the environment has a significant influence on task performance. How robots can move in a complex environment, and how they can control and sense will be significant for higher mobility. Considering the main application of human assistive robots, the level of environmental complexity is suggested in Table 5-3.

Table 5-3: Environment complexity levels

Level 5	Can move in dynamic environment, which involves human beings, living animals on rough terrain around, or stairs, steep hills, with changing weather conditions such as wind, light conditions, wet / slippery ground, and so on.
Level 4	Can move in dynamic environments, which involves human beings, living animals on rough terrain around, or stairs, and steep hills.
Level 3	Can move in a static environment on rough terrain around, or stairs, and steep hills.
Level 2	Can move in dynamic environments, which involve human beings, living animals on a plain ground.
Level 1	Can move in static environments on plain ground.

The difference between different levels of environmental complexity is from static to dynamic, from plain ground to rougher, steep floor conditions.

When talking about mobility, people normally think about speed. As for a vehicle system, speed is an important factor. However, if we discuss sophistication of mobility, then speed is not a crucial factor for consideration. As for higher speed, it is based on a more powerful engine; the sophistication for robots with different speed capabilities will be almost identical.

Generally, mobility for human assistive robots is dependent on the application; in some applications, the mobility for a human assistive robot is vitally important to its mission completion. The work done above aims to analyse how mobile a human assistive robot it is and from which aspects we can analyse mobility.

5.2.3.1.3 Payload

The payload ability of a robot is directly related to what a robot can do, and it is based on mechanical ability. Different domestic tasks require different abilities; some focus on balance; some are based on weight; some others may simply require a robot to supply a communication service, which does not necessitate a payload. The sophistication of mechanical ability here is how tasks can be executed successfully, and to what extent a robot can meet people's requirements. The payload ability must be considered when a robot is executing a number of other tasks; for example, robots may reduce speed when carrying objects.

5.2.3.1.4 System Configuration

The configuration of a robot system includes components configuration, resource reallocation and adaptive design. It is one solution for systems agility and enhances systems' capability. For example, if a robot system has adaptive design in robot hand, then it may execute different tasks at the same time, or execute tasks more safely in an emergency situation. For resources reallocation, it is about the capability of a robot system in systems of systems (SOS) environment; it will enhance robot capability through SOS resource reallocation and through collaboration with other robots or people. The components configuration in robot systems is also very important. For example, through configuration, a robot hand can be used to execute different types of tasks based on the requirements; this will, to some extent, reduce price, and enhance systems' capability. Based on the components re-configuration and adaptive design this may help robots to integrate into a systems of systems environment, which will enhance the whole system's capability.

5.2.3.2 Methods for evaluation of mechanical ability

As with the discussion regarding mechanical ability above, the evaluation of mechanical ability can be considered in this way:

Effective mechanical ability means that a robot can complete tasks efficiently with cost-effectiveness, and operational safety. The sophistication of mechanical ability will depend on how many degrees of freedom a system has, what mobility the system has, how efficiently a task is carried out by the robot, and the agility of the system component design.

The evaluation of mechanical ability is a result of evaluating each detail of mechanical ability in the discussion above. As mechanical ability is not necessary for all human assistive robots, the results can range from no mechanical ability to high mechanical performance. We can only describe mechanical ability from several aspects. A total amount of mechanical ability for a given robotic system is meaningless.

5.2.3.3 Interaction analysis

Interaction covers the understanding of interaction context, and the interaction expression. As each interaction is rich in expression and communication, it is difficult to ascertain which interaction is more complex than the others. Several kinds of interaction are currently used in robotics; the complexity is different based on the requirement and application. The main interaction types are as follows: touch, speech, vision, and voice. The selection of interaction types is normally based on the requirement of application. To explore how interaction is more sophisticated, two aspects are normally considered: one pertains to how many kinds of interaction a robot can make with humans; another is about understanding the context, and specifically how much a robot can understand the context of interaction from human beings. Identifying these two aspects is useful for discussions regarding how sophisticated a robot is when it comes to human robot interaction. One of the possible evaluation standards is shown in Table 5-4 below:

Table 5-4: Interaction levels

Level 5	Robot fully understands all information supplied from humans, and is able to show some kind of interaction (easy to communicate with in its work area).
Level 4	Robot can understand/ recognise the multi-meaning of some

	interactions; and is able to show some kind of interaction.
Level 3	Robot can understand some of interaction with humans, and is able to communicate with humans with some kind of interaction (speech, gesture recognition, and understand its meaning).
Level 2	Robot can learn some limited interaction with humans, (follow people's gestures, speech, etc.).
Level 1	Robot is able to show limited kinds of interaction by one type of interaction such as touch, voice, gesture, and does not understand the context of interaction (remind people to do something).

From this table, we can see that the more understanding a robot has of the context, the more sophisticated the interaction is. There are many robots which already possess certain levels of interaction, some of them have basic interaction, and some have a higher level of interaction.

5.2.4 Sophistication evaluation

Through analysis, the sophistication of a human assistive robot can be analysed from mechanical ability and interaction, which will cover degrees of freedom, mobility, system configuration, and interaction. The details of this are shown in Table 5-5.

Table 5-5: Sophistication levels analysis

Sophistica-tion level	Degrees of freedom	Mobility	Configuration	Interaction
level 5	3-d dimensional space; degree of freedom is more than 6; configurable, adaptive mechanisms;	Can move in dynamic environment, which involves human beings, living animals on rough terrain around, or stairs, steep hills, with changing weather conditions like	Has high agility in system configuration to execute different tasks or in SOS situation	Robot fully understands all information supplied from humans, and is able to show some kind of interaction (easy to communicate with in its work area).

		wind, light conditions, wet / slippery ground, and so on.		
level 4	3-d dimensional space; degree of freedom is more than 6; (configurable).	Can move in dynamic environment, which involves human beings, living animals on rough terrain around, or stairs, steep hills.	Has some agility in system configuration to execute different tasks.	Robot can understand/ recognise the multi-meaning of some interactions; and is able to show some kind of interaction.
level 3	3-d dimensional space, Heave: Moving up and down Surge: Moving forward and backward Sway: Moving left and right Rotations Yaw: Turning left and right flight Roll: Tilting side to side Pitch: Tilting forward and backward; degree of freedom is 6; (configurable).	Can move in a static environment on rough terrain around, or stairs, steep hill.	Has adaptive design for executing tasks in different conditions.	Robot can understand some of interaction with humans, and is able to communicate with humans with some kind of interaction (speech, gesture recognition, and understand its meaning).
level 2	Two Dimensional (2-D) space, moving forward/backward, up and down, or left and right; degree of freedom is 3.	Can move in dynamic environment, which involves human beings, living animals on a plain ground.	Has some agility in system configuration to execute a task (e.g. speed setting, length...).	Robot can learn some limited interaction with humans, (follow people's gestures, speech).

level 1	1-Dimension, moving forward/backward, up and down, or left and right; degree of freedom is 1.	Can move in static environment on plain ground.	No configuration, just based on original design.	Robot is able to show limited kinds of interaction by one type of interaction such as touch, voice, gesture, and does not understand the context of interaction (remind people to do something).

The table above shows how the sophistication of human assistive robots is considered in this research.

5.2.5 Description of final model

The model described above shows how we demonstrate autonomous systems from autonomy and sophistication aspects. These two aspects exist within every human assistive robot. There are also some relationships pertaining to how autonomy and sophistication are related to a human assistive robot:

- Autonomy and sophistication are two different aspects of human assistive robots, and both contribute to human assistive robot capability.
- Autonomy is shown through a set of human assistive robot behaviours, and sophistication is shown by system design, configuration, and management.
- For human assistive robots, it is not necessary that autonomy and sophistication level be at the same level. It may have a high level of autonomy, but low sophistication.

Generally, the framework created in this research is for assessment of levels of autonomy and sophistication from which a specific model of autonomy / sophistication for an individual robot can be constructed. The research to date has created a final model for levels of autonomy and sophistication for human assistive robot, which attempted to evaluate levels of autonomy from decision making aspects and evaluate levels of sophistication from interaction and mechanical ability, including degree of freedom and mobility, as well as system configuration, also the research has generated the evaluation criteria for each dimension within the model. A full description of model framework for assessment of human

assistive robot capability is shown in Figure 5-2. As sensors support most of divisions in Figure 5-2, it is not considered as an individual division for modelling robot capability. There are more details for the evaluation criteria in Table 5-5.
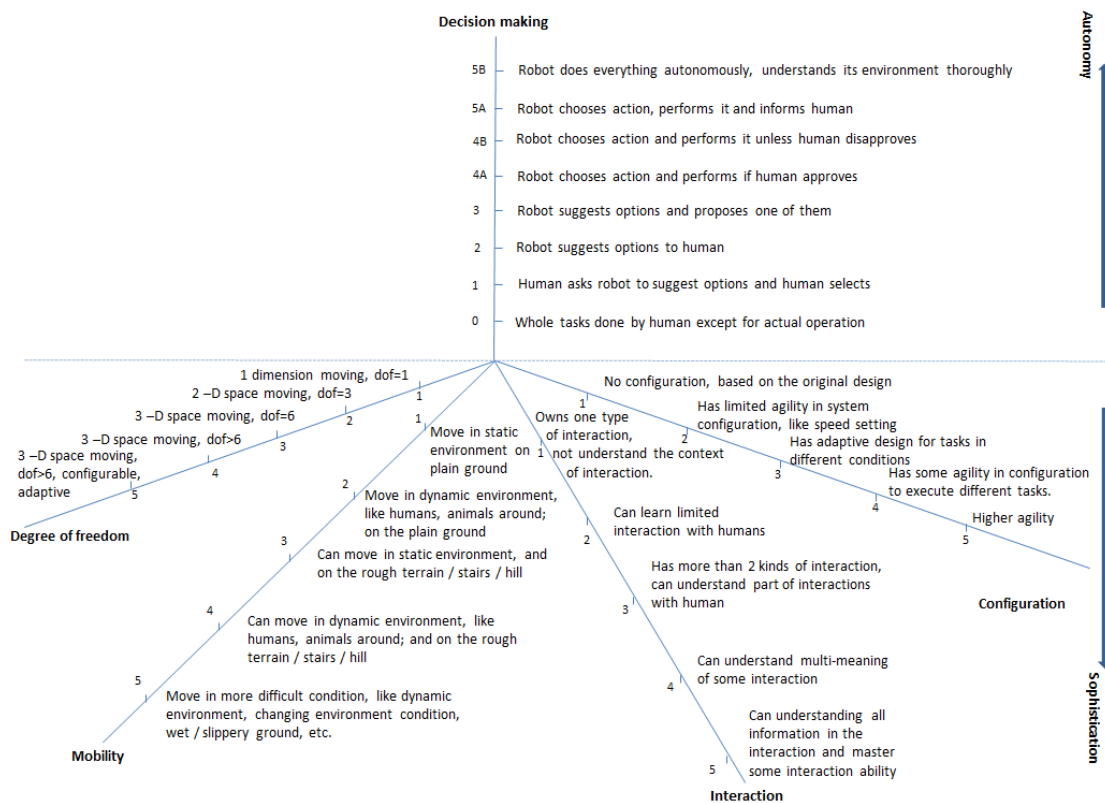
Figure 5-2: A full description on the model framework for human assistive robot's capability

The output model is a profile generated using the framework in Figure 5-2. Scores in dimensions are not combined because the relationship between them is context dependent; instead, a profile is generated using a fixed geometric representation. For example, if a robot system is evaluated using the ALFHAR model framework and based on the scores in Table 5-5, then the ALFHAR model of this particular robot is represented by the yellow shaded area in Figure 5-3.

Table 5-6: Example of an evaluation result

Interaction	Level 2
Decision making	Level 2
System configuration	Level 1
Mobility	Level 1
Degrees of freedom	Level 5
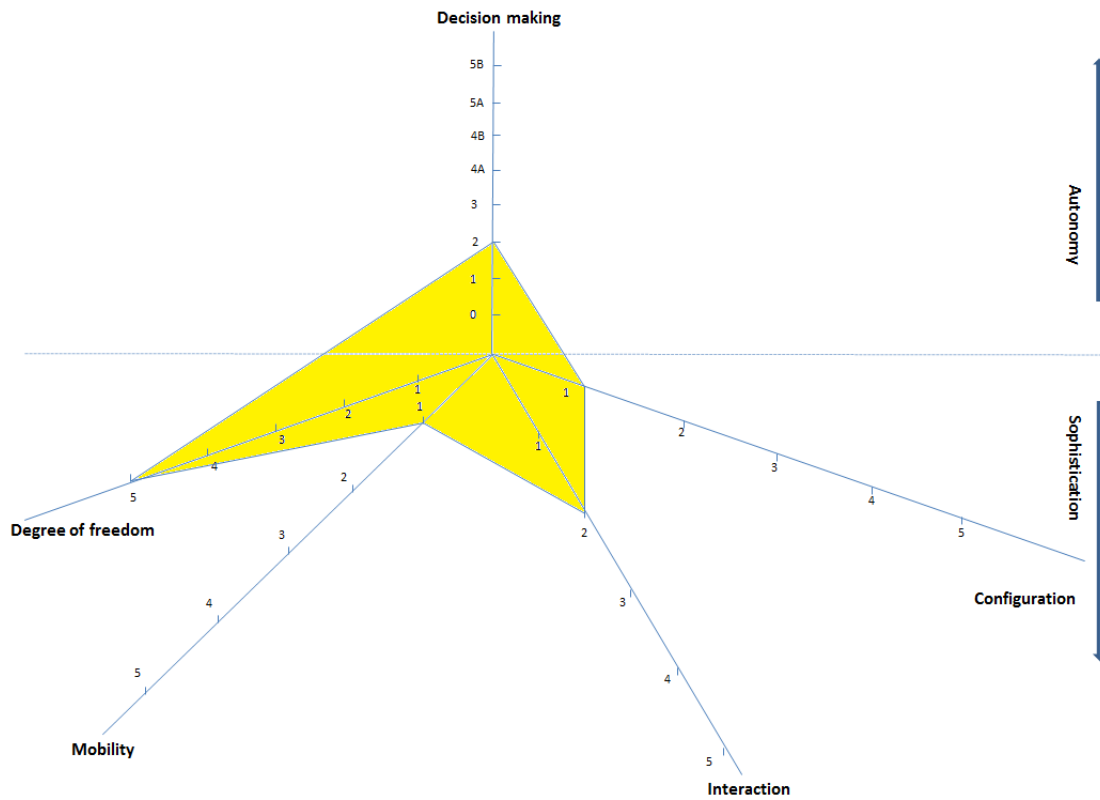
Figure 5-3: ALFHAR model of an example robot (Table 5-6)

 The following section will discuss how the model can be applied in the application; there is also a tool developed based on this model in the present research.

5.3 Model application target analysis

Generally, the way of evaluation for the model of autonomy and sophistication is discussed with several stakeholders in industry and research area. Some of the ideas are collected and applied to this model.

One of the validations for this model is through several case studies, to verify whether the model can be used to demonstrate human assistive robot capability in the right way. There are many kinds of human assistive robots currently in existence in the world. In order to create the case study, we choose a number of typical robot examples, so as to assess whether or not the model will work. Other machines which are not human assistive robots will also be analysed in order to assess whether or not the model is still working.

CHAPTER 5: ALFHAR MODEL DEVELOPMENT

Case 1: Asimo is a humanoid robot created by Honda. The name is an acronym for "Advanced Step in Innovative Mobility". It has a vision system with which it can move objects, follow the movements of people, interpret postures and gestures, recognise surrounding environments, distinguish sounds, and perform facial recognition (Honda Motor Co. 2007). The degree of freedom allocation in Asimo is: 3 in the head, 7 in each arm, 2 in each hand, 1 in torso, 6 in each leg (Honda Motor Co. 2010).

Table 5-7: Case study--Asimo

	Asimo	
Functions in Asimo		Descriptions in Asimo
Interaction	Yes	Follows the movements of people, interprets postures and gestures.
Decision making	Yes	Interprets postures and gestures, recognises surrounding environment, and distinguishes sounds, facial recognition.
Situation awareness	Yes	Recognises surrounding environment.
Mobility	Yes	Follows the movements of people.
Degrees of freedom	Yes	34 in total.

The evaluation for Asimo based on this model is considered as:

Table 5-8: Evaluation result of Asimo

Interaction	Level 2
Decision making	Level 2
Situation awareness	Level 2
Mobility	Level 1
Degrees of freedom	Level 5

Similar to the mapping above, we may find that these two mappings show the relationships between the model and robot function descriptions. The functions of these two robots can also be described using the model's main attributes. The following report will introduce the details of the model and how the model can be used to evaluate levels of autonomy for human assistive robots.

Based on the discussion above, we may need more details of these two cases in order to get a more accurate result for each case.

Case 2: automatic washing machine: auto-washing machine is also considered as an automatic tool to support people's daily life.

Features available in most modern consumer washing machines:

- Predefined programs for different laundry types.
- Variable temperatures including cold wash.
- Rotation speed settings.
- Delayed execution: a timer to delay the start of the laundry cycle.

Additionally some of the modern machines feature:

- Child lock.
- Time remaining indication.
- Steam.

These functions are very common in current washing machines, and then make a mapping from the function description into the model's attributes, (see Table 5-9).

Table 5-9: Case study—auto washing machine

	Auto Washing machine	
Functions in washing machine		Descriptions in washing machine
Interaction	Yes	Rotation speed settings. Time remaining indication. Predefined programs for different laundry types. Rotation speed settings.
Decision making	No	
Situation awareness	Yes	Time remaining indication.
Mobility	No	

As we can see, although some auto-washing machine's functions can be described in this model, which shows some levels of sophistication in interaction, there are still some others which do not fit into the model; another important issue is that auto-washing machines have no autonomy in this model, they are simply automatic washing machines.

As the cases analysed above show, it is clear that the model can be used to adequately describe human assistive robot autonomy and sophistication.

5.4 Tool development

According to the demonstration of levels of autonomy for human assistive robots above, the demo tool is created and can be used to evaluate the levels of autonomy for a human assistive robot. Figure 5-4 shows the demo tool development process, which is mainly based on the

final ALFHAR model; and then a set of requirement are derived for this tool, which help for creation of the specification of the tool.
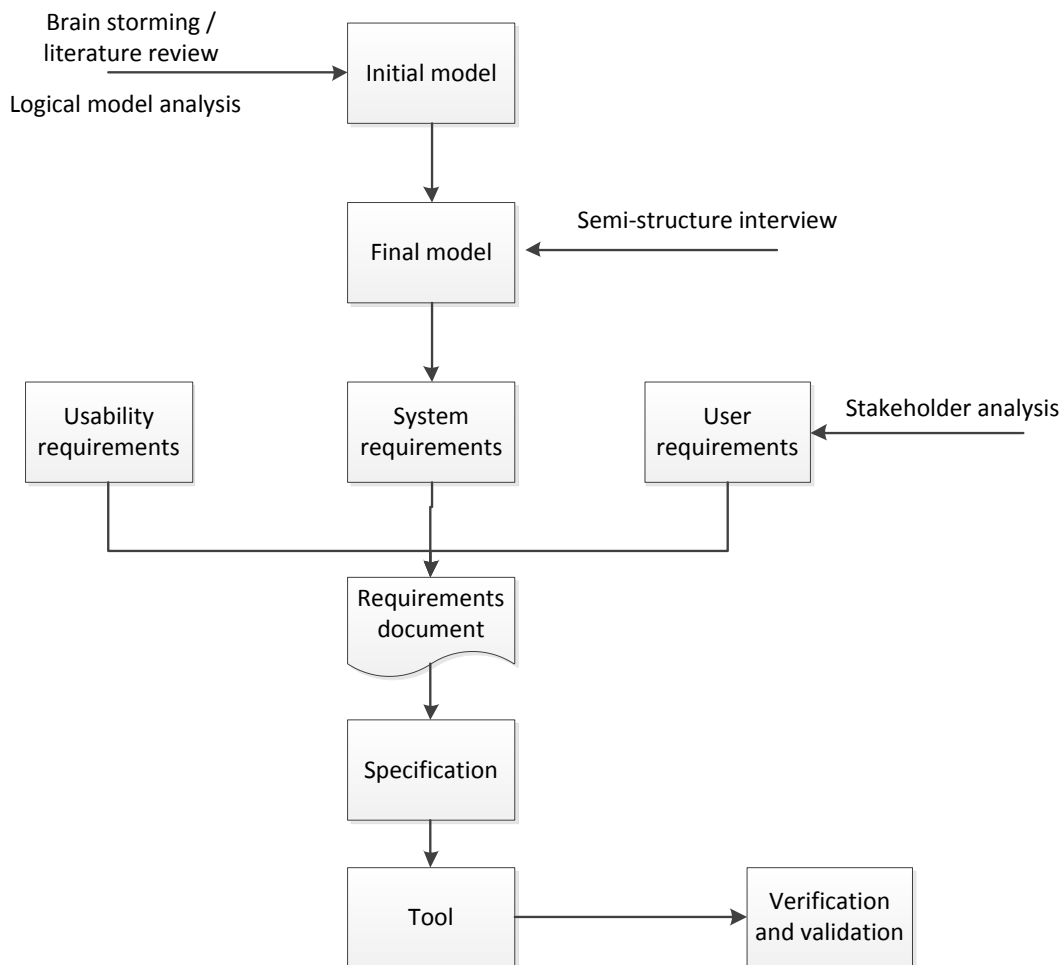
Figure 5-4: Tool design process

The tool is developed as a web project and can be easily published through an internet server. The main functions of the tool are: input robot functions detail; evaluate robot function details; and show the evaluation result in a diagram. There are more details about the tool requirement specifications in Appendix III. According to the system function requirements, the functional flow diagram is shown as Figure 5-5.
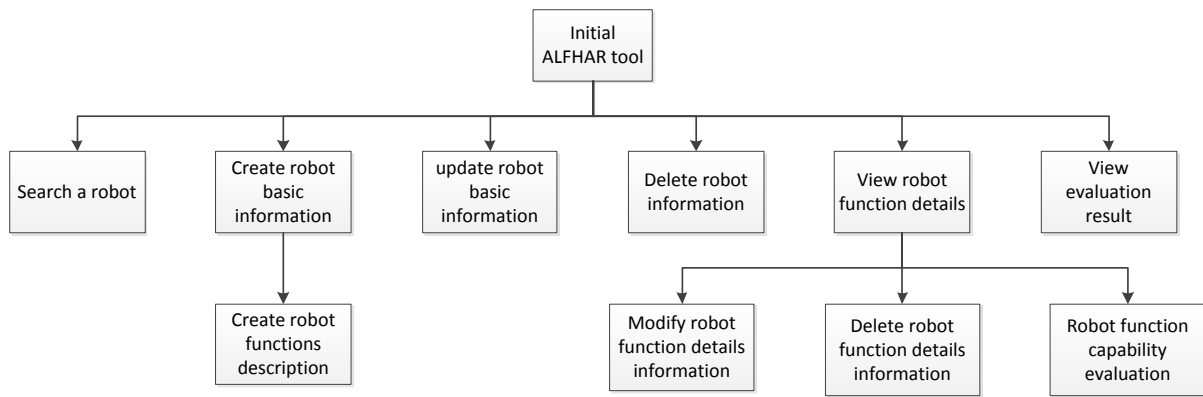
Figure 5-5: Tool function flow diagram

Figure 5-6 shows the Use Case for the tool, which covers the main functions of this tool. Some examples of user interfaces are shown in Figure 5-7, Figure 5-8, Figure 5-9, Figure 5-10, and Figure 5-11. The source code is in Appendix IV.

According to the tool design process, the computer software tool of ALFHAR is originated from ALFHAR model; its main functions are considered to help the ALFHAR model to be used more conveniently by the user. The tool function flow diagram in Figure 5-5 also shows that the evaluation process in the tool is the same as ALFHAR model framework. There is no difference between the model framework and the tool in the evaluation levels of autonomy and sophistication for human assistive robot according to the evaluation process and evaluation criteria.
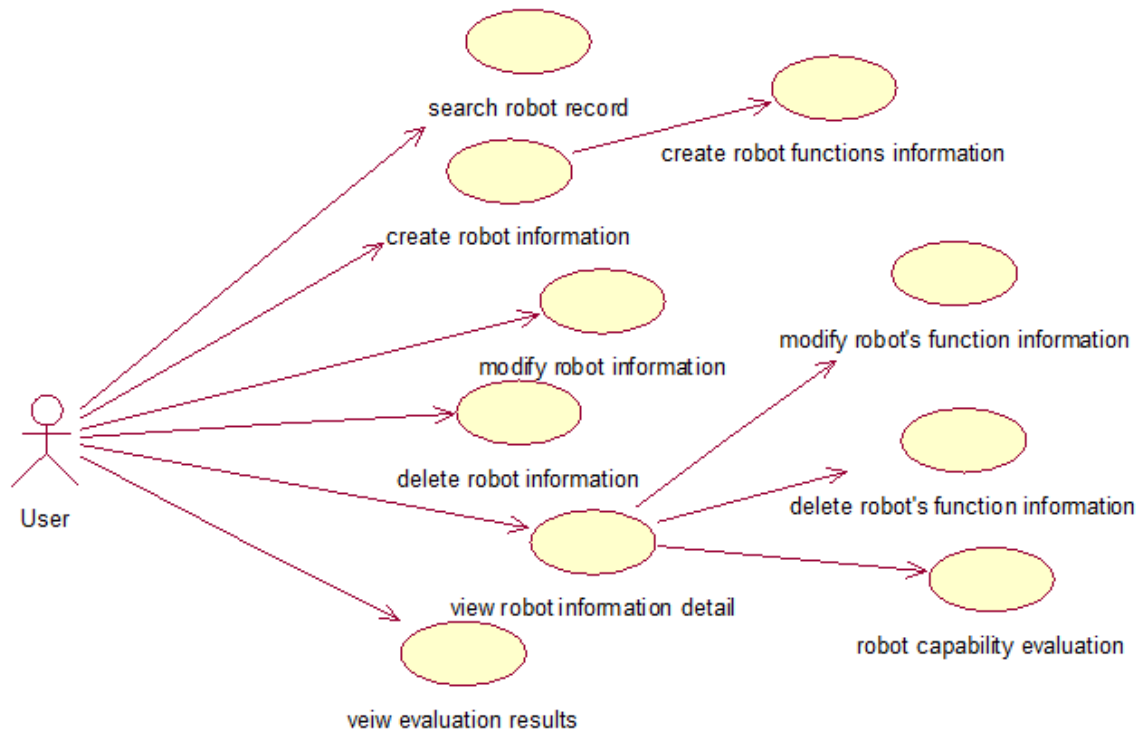
Figure 5-6: Use case diagram for tool

Figure 5-7 Robot list

The robot list (Figure 5-7) shows the robot information that is created in the system by user. In this page, users can find a robot from the system, and can modify its details, as well as read its detailed information and evaluation result. Some explanations are given for Keys in Figure 5-7.

Key:

- Sequence – index number for a robot in the system (auto-generated).
- Robot name – product name (input by user).
- Manufacturer – company name or the place of manufacture.
- High –the height of the product (unit in inch).
- Modify – user can modify or delete the robot's information listed in the table through clicking the "modify" link or the "delete" button.

- Evaluation result – through clicking the "evaluation button" the final evaluation result for a robot can be viewed.

Function detailed information – by clicking the "detail information" details which are already inputted into the software system by the user can be viewed.

Figure 5-8: Robot basic information input

Figure 5-8 shows robot basic information; user can input robot basic information in this page.

Figure 5-9: Robot functions input

The functions input page (Figure 5-9) is used to transfer robots' function descriptions into the system so that users can evaluate these functions by decision making, degrees of freedom, mobility, interaction and system configuration.

sequence	robot name	function type	function details show	Modify	evaluation
1	irobot	mobility	Follow the movements of people	modify delete	1
2	irobot	interaction	Follow the movements of people	modify delete	2
3	irobot	decision making	interprets postures and gestures	modify delete	2
4	irobot	interaction	interprets postures and gestures	modify delete	2
5	irobot	decision making	recognizes environment around	modify delete	2
6	irobot	decision making	distinguishing sounds	modify delete	2
7	irobot	degree of freedom	34 in total	modify delete	5

save Evaluation   return

Figure 5-10: Functions evaluation

This page (Figure 5-10) shows robots' function details, how a user can modify/delete a robot's functions details, and an evaluation of each function. Some explanations are given for Keys in Figure 5-10.

Key:

- Function type – used to identify the type of function details inputted by user which is within the attributes that are defined in the model.
- Function details show – describes function detail information through brief words.
- Evaluation – shows the evaluation results for each function.
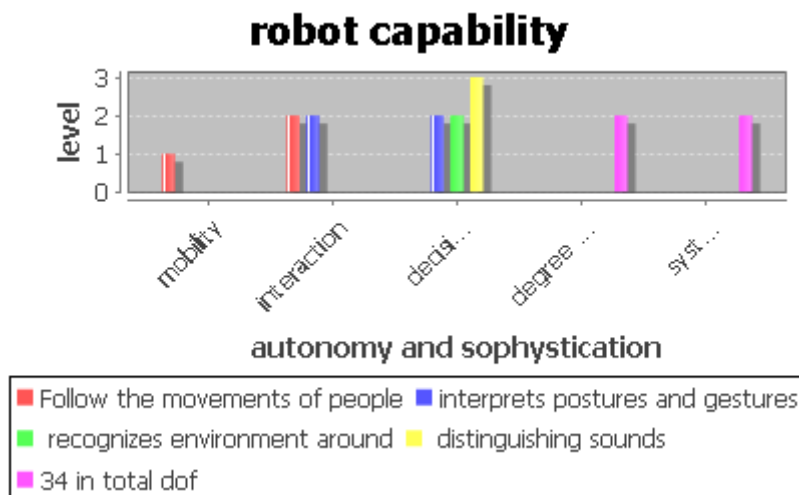
Figure 5-11: Evaluation result

Figure 5-11 shows the evaluation result for robot capability. It shows the distribution of

robots' capability based on mobility, interaction, decision making, degrees of freedom and system configuration; people can also analyse it from an autonomy and sophistication aspect.

5.5 Scenario development

The scenario study here is designed to help stakeholders develop a better understanding of the usage of the tool of ALFHAR. The scenario starts from a dialogue between health professionals and potential human assistive robot users. Then through discussion on the requirement for human assistive robots, the tool may be helpful for them to identify a proper robotic system capable of achieving better decision making.

Scenario one: requirement capture

Persona: Tom, Martin

User group: health professional

Problem: Tom is a health professional. Today one of his customers, Martin, is looking for some robots which can be used to supply some support for his daily life. Martin is about 80, and has some problems with his leg. As Tom is an expert in healthcare, Martin asks Tom for some advice about what kind of robot may be available for him, or at least what kind of functions a robot could perform to support his daily life, so that he can enjoy his life. Martin is living in a detached house, with a large garden. There is also one pet in his house. Through discussion, and considering the real situation of Martin and his living environment, Tom thinks that there are some basic requirements for Martin to live independently.

Martin wants a robot which can help him to move around the house where he lives, which may also involve climbing stairs, making coffee, and communicating with him by voice. Martin also has some chronic diseases; he needs to take medicine at certain times each day. This requires a robot to remind him to take his medicine at the appropriate time. If Martin wants to go to the garden to enjoy the sunshine, a robot should be able to move him from the house to the garden; Martin also wants to be able to control the speed of the robot's movement if possible.

There is in fact a tool, which is expected to evaluate a robot's system capability, including autonomy and system sophistication. Indeed, this may be helpful in the development of a practical requirement. Through the tool, Tom can create a general requirement for Martin, to

confirm whether it meets Martin's requirement. Firstly, Tom reviews the robots which already exist in the system, to ascertain whether they meet Martin's requirement. There may already be robots in existence which meet the requirements of Martin; however, most of them can only meet some part of the required functions. With this in mind, Martin plans to create a new robot requirement; to do this he can click the "create" button to create a requirement for Martin. On this page, Tom must input some basic information for the robot. The robot's name is necessary for this system, whilst other attributes are not vitally necessary at present.

Robot basic information

robot's name	irobot
manufacturer	America
design year	2009
weight	6 (kg)
size	3 (inch)

save   next   return

After this, Tom tries to input the functions required by Martin into the tool.

Generate a evaluation model for a given system.
the evaluation is based on conceptual description for the system.
Each sentence could be considered as some functions / limitation for the system.

please input the robot's nameirobot

please input one description for the system | recognizes environment around

please using a brief words for the function | recognizes environment ar
please select the area that descriptions belongs to:
☑ Decision Making
☐ degree of freedom
☐ mobility
☐ interaction
☐ system configuration

save   more functions   return

From this page, Tom inputs functions that are needed by Martin. For example, if Martin wants a robot which can help him to move around the house where he lives, then Tom can input these words into the textbox area, and using 'moving around house' as an identifier for this function. This function requires decision making, so that the robot can move by itself without collision with pets or other objects; it needs mobility, so it can move from one place

to another; it also needs interaction, so that Martin can communicate with the robot easily; it may also have system configuration, so that Martin can change speed, or the robot can select proper locomotion in different ground conditions. After careful selection, Tom saves these inputs and tries to input more functions by clicking "more functions". After he inputs all of the functions, he then clicks the "return" button which returns him to the front page.

Following this, Tom wishes to assess the extent of the tasks which Martin needs the robot to execute; or to identify what levels of autonomy and sophistication Martin needs to support his daily life. Tom clicks "details information" in the item which it is created by him. This will then display all of the details which he has inputted into the system. On this page, he must verify what levels of decision making, mobility, interaction, system configuration and degrees of freedom Martin needs in order to meet his requirements. As seen in the figure above, Tom clicks "evaluation guider" to view the capability scope for each item. In this way it is very easy for Tom and Martin to make a decision about what requirement they want.

Generally, from this scenario, we can see that the tool can be used to develop requirements easily and quickly for customers who want to purchase a robot system. From another aspect, the tool can be used to capture a robot's system capability by defined levels. It can demonstrate a robot's autonomy level and sophistication level as well. To some extent, we can say that the model for levels of autonomy and sophistication is very helpful for stakeholders to develop their requirements for human assistive robots. There are also details demonstrating how to calculate levels of autonomy and sophistication for human assistive robots. Based on this model, a web-based tool is developed to support the increased applicability of the model.

5.6 Summary

The work in this chapter mainly focuses on how to collect data and information from stakeholders to support the initial ALFHAR model. Through conducting several semi-structured interviews with people, important comments and feedback is received from interviewees; this helps to revise the ALFHAR model and also to develop the evaluation details of the ALFHAR model. Following this there is a demonstration regarding the revised ALFHAR model and its details. There is also a model application analysis whereby the model is applied to two case studies. Based on the model, a web-based tool is developed using JAVA program language. The tool developed here is to support the ALFHAR model to

be used by stakeholders to solve problems. When the tool was developed, a scenario is created to guide stakeholders on how to use this tool to solve their problems.

6 Verification and validation of ALFHAR model

Chapters 4 and 5 present the development of the model for levels of autonomy and sophistication. The model was developed initially from the conceptual logical model, and then through data collection from stakeholders, to support the model development. This chapter presents the model verification and validation. The verification for the ALFHAR model is based on the case study for computer model of ALFHAR. The validation for the model is achieved through several tests of the computer model of ALFHAR, and analyses how the results obtained from participants can ensure that the model is efficient for modelling levels of autonomy and sophistication, and also how stakeholders feel towards this model.

6.1 ALFHAR model verification

Verification is intended to verify that a product, service, or system meets a set of initial design requirements, specifications, and regulations. In this research, the verification work is intended to check that the software tool of ALFHAR meets the ALFHAR model. The verification of the model is done through application of a case study on the software tool of ALFHAR and the ALFHAR model. Through comparing the results obtained from the case study in the software tool of ALFHAR and ALFHAR model, some verification results will be shown in this section.

6.1.1 Case study demonstration

The aim for the model verification is to make sure that the software tool of ALFHAR can reflect the ALFHAR model in the real world.

As described in Chapter 5, the main aim of the ALFHAR model is to evaluate levels of autonomy and sophistication for human assistive robots. The ALFHAR model attempts to evaluate human assistive robots from autonomy and sophistication aspects, which include decision making, interaction, and mechanical ability. The verification here is designed to assess whether or not the software tool of ALFHAR can be used to evaluate levels of autonomy and sophistication for human assistive robots. The research presents a case study in order to ensure that the verification work is carried out in the correct way. The case selected is based on the human assistive robot area, which is the model application area.

Many kinds of human assistive robots already exist in the world. In order to conduct a case study, we choose one of the typical robot examples in order to assess whether or not the model is working.

Case description: the world's first communication robot "Wakamaru" (Shiotani, Tomonaka, Kemmotsu, Asano, Oonishi & Hiura 2006), is a Japanese domestic robot made by Mitsubishi Heavy Industries. It is primarily intended to provide service and assistance to elderly and/or disabled people. Wakamaru can connect to the internet, has a limited speech capability (in both male and female voices), makes eye contact, and has speech recognition abilities. It can move around based on a wheel. Its functions include reminding the user to take medicine on time, and calling for help if it detects that something is wrong. It has high reliability of self-localisation and avoidance of obstacles using sensors, but errors may occur and their frequency increases when there are changes of lighting and location of people.

There are more details on its specifications in Figure 6-1, Figure 6-2, Figure 6-3.

Type	Wheel
Sensors	Self position measurement
	Infrared ray obstacle detection
	Ultrasonic obstacle detection
	Collision detection
Autonomous mobility	Autonomous obstacle avoidance and movement to map-registered locations in a house
Charging	Autonomous movement to the charging station when its power runs down.

Figure 6-1: Mobility (Mitsubishi Heavy Industries 2012)

Human detection (Sensor combined processing)	Detection of moving persons
	Face detection
Individual recognition	Detects facial characteristics and recognizes two owners and eight other persons.
Voice recognition	Recognizes series of single words necessary for scenarios and word spotting method.
Speech synthesis	Configuration available for reading texts out loud and volume of voice.

Figure 6-2: Communication (Mitsubishi Heavy Industries 2012)

Equipment configuration	Robot main unit	
	Charging station	
	Wireless broadband router	
	Touch panel (option for reception)	
	Computer (option for reception)	
Operating conditions	Indoor barrier-free floor (typical house, with floor unevenness no higher than 1 cm) Room temperature Under daylight or illumination Continuous Internet connection	
Dimensions	Height:	100cm
	Diameter:	45cm
Weight:		Approximately 30kg
Movement	Movement method	Movement on wheels
	Maximum moving speed	1km/hour
Joints	Neck	3 degree freedom
	Arm	4 degree freedom x 2 arms
	Moving part	2 degree freedom wheels
Drive method		DC servo motor
Power source	Battery	Lithium Ion Battery. Operates continuously for up to 2 hours
	Charging	Automatically charged at the charging station
Controller	CPU	Multi processor configuration
	Operating system	Linux
	Robot control architecture	Serial bus connection distributed processing
I/O	Sight	Omni-direction camera x 1 Front camera x 1
	Hearing	Directional microphone x 1 Non-directional microphone x 3
	Touch/Force sensing	Shoulder sensor Hand sensor
	Voice	Speaker
Safety	Structure	Designed for minimum energy consumption and maximum safety. Complies with the Japanese domestic standards of home appliances Safety joint structure prevents finger pinching
	Interlocking	Arm: full axis servo level collision detection (torque monitoring)

Figure 6-3: Hardware specifications (Mitsubishi Heavy Industries 2012)

6.1.2 Case study in ALFHAR model

From the Case description and information in Figure 6-1, Figure 6-2, and Figure 6-3, the evaluation of levels of autonomy and sophistication for "Wakamaru" in the ALFHAR model can be carried out in the following way:

First of all, the ALFHAR model can be used to demonstrate the content of "Wakamaru".

Table 6-1: "Wakamaru"'s description in ALFHAR model

	Wakamaru	
Functions in Wakamaru		Descriptions in Wakamaru
Interaction	Yes	Reminding the user to take medicine on time, and calling for help if it detects that something is wrong.
Decision making	Yes	Reminding the user to take medicine on time, and calling for help if it detects that something is wrong, has high reliability of self-localisation and avoidance of obstacles using sensors.
Mobility	Yes	Follow the movements of people.
Degree of freedom	Yes	Neck, arm, and moving part have 3, 4 and 2 for each component.
System configuration	Yes	Configuration available for reading texts out loud and volume of voice.

According to the evaluation standards in the ALFHAR model, the evaluation results for "Wakamaru" can be as follows:

Table 6-2 Evaluation result of Wakamaru

Interaction		Level 1
Decision making		Level 6
System configuration		Level 2
Mobility		Level 2
Degree of freedom	neck	Level 3
	arm	Level 3
	moving part	Level 2

6.1.3 Case study in the software tool of ALFHAR

To verify the ALFHAR, it must use the software tool ALFHAR to evaluate "Wakamaru" and make a comparison with the results in Table 6-2. As the software tool of ALFHAR is created based on the ALFHAR, the aim of this tool is to make the ALFHAR model more practical in the application. Figure 6-6, Figure 6-7, Figure 6-8, Figure 6-9, and Figure 6-10 show the evaluation standards in the software tool of the ALFHAR model. As shown in Figure 6-6, Figure 6-7, Figure 6-8, Figure 6-9, Figure 6-10, the evaluation standards in the computer software tool are the same as the description in the ALFHAR model. This will generate the same result from the software tool and the ALFHAR model if given the same function. The evaluation process in the computer software tool is based on the robot functions which the user inputs into the system. Users can evaluate each function using the tool and make a proper selection according to the functions described in the case.

CHAPTER 6: VERIFICATION AND VALIDATION OF ALFHAR MODEL

When using the computer model of ALFHAR, it is easy to input each function of "Wakamaru" into the tool, and then make evaluations using the guideline in the tool. The result comes from the computer software tool ALFHAR as shown in Figure 6-4 and Figure 6-5:

sequence	robot name	function type	function details show	Modify	evaluation	evaluation guider
1	wakamaru	decision making	Reminding user to ake medicine on time,	modify delete	6	evaluation guider
2	wakamaru	interaction	Reminding user to ake medicine on time,	modify delete	1	evaluation guider
3	wakamaru	system configuration	Reminding user to ake medicine on time,	modify delete	2	evaluation guider
4	wakamaru	decision making	calling for help when it detects that something is wrong	modify delete	6	evaluation guider
5	wakamaru	interaction	calling for help when it detects that something is wrong	modify delete	1	evaluation guider
6	wakamaru	system configuration	calling for help when it detects that something is wrong	modify delete	2	evaluation guider
7	wakamaru	decision making	move around the house	modify delete	7	evaluation guider
8	wakamaru	degree of freedom	move around the house	modify delete	2	evaluation guider
9	wakamaru	mobility	move around the house	modify delete	2	evaluation guider

Figure 6-4: Wakamaru details information

Key in the Figure 6-4:

- Evaluation guider – by clicking the "evaluation guider" button to enter into an evaluation selection page, the user can choose a proper choice for function evaluation (see Figure 6-6, Figure 6-7, Figure 6-8, Figure 6-9, and Figure 6-10).
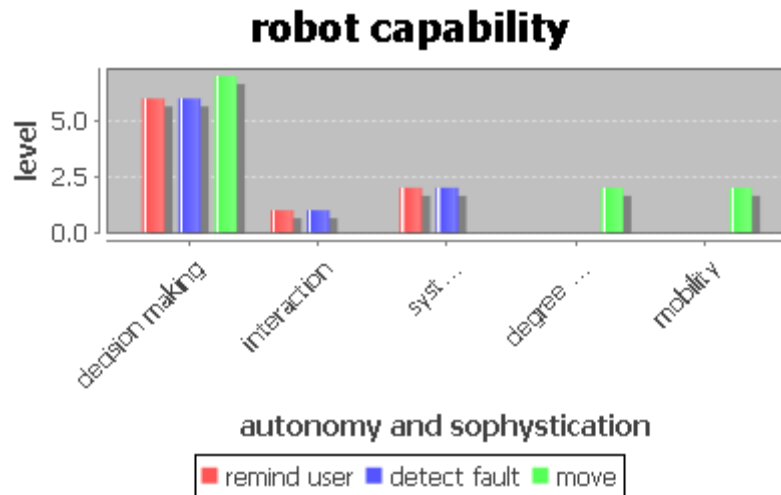
Figure 6-5: Evaluation results

6.1.4 Result analysis for ALFHAR model verification

Figure 6-4 shows the detailed information inputted though the software tool; Figure 6-5 shows all of the evaluation results as seen through the tool. The results from the software tool are based on three main functions of "Wakamaru" that the user inputs into the tool. From Figure 6-5, it is clear that the result from the software tool of ALFHAR is the same as the result in Table 6-2, which shows that system decision making ability is between 6 and 7, interaction ability is about 1, system configuration is 2, degrees of freedom is 2 and mobility is 2. Figure 6-5 shows more evaluation details for each function of the robot system. Through a comparison of results from these two types of model, it is obvious that the software tool of ALFHAR can be considered as a tool for application of the ALFHAR model.

Figure 6-6 Decision making evaluation standards

○ level 1: degree of freedom is 1;1-Dimension, moving forward/backward, or up and down, or left and right

○ level 2: degree of freedom is 3; Two Dimensional (2-D) space, moving forward/backward, up and down, or left and right;

○ level 3: degree of freedom is 6 (configurable); 3-d dimensional space, Heave: Moving up and down Surge: Moving forward and backward Sway: Moving left and right Rotations Yaw: Turning left and right flight Roll: Tilting side to side Pitch: Tilting forward and backward

○ level 4: degree of freedom is more than 6; 3-d dimensional space;

○ level 5: degree of freedom is more than 6; configurable, redundant design; 3-d dimensional space;

[save] [return]

Figure 6-7: DOF evaluation standards

○ level 1: Can move in static environment on a plain ground

○ level 2: Can move in dynamic environment, which involves human beings, living animals on a plain ground

○ level 3: Can move in a static environment on rough terrain around, or stairs, steep hill

○ level 4: Can move in dynamic environment, which involves human beings, living animals on rough terrain around, or stairs, steep hill;

○ level 5: Can move in dynamic environment, which involves human beings, living animals on rough terrain around, or stairs, steep hill, while changing whether condition, like windy, light condition, wet / slip ground, and so on

[save] [return]

Figure 6-8: Mobility evaluation standards

○ level 1: No configuration, just based on original design

○ level 2: Has some agility in system configuration to execute a task (e.g. speed setting, length...)

○ level 3: Has adaptive design for executing tasks in different condition.

○ level 4: Has some agility in system configuration to execute different tasks

○ level 5: Has high agility in system configuration to execute different tasks or in different systems corporation

[save] [return]

Figure 6-9: System configuration evaluation standards

○ level 1: Robot is able to show limited kind of interaction by one type of interaction, like touch, voice, gesture, and do not understand the context of interaction
○ level 2: Robot can learn some limited interaction with humans
○ level 3: Robot can understand some of interaction with humans, and is able to communicate with humans with some kind of interaction
○ level 4: Robot can understand/ recognize the multi-meaning of some interactions; and is able to show some kind of interaction
○ level 5: Robot fully understands whole information supplied from humans, and is able to show some kind of interaction

[save] [return]

Figure 6-10: Interaction evaluation standards

6.1.5 Statement of model verification

The verification of the ALFHAR model in this research is achieved by means of a comparison of results from the case study "Wakamaru" in the computer software tool and the model itself. The computer software tool is created based on the ALFHAR model; the selected case is from the area of human assistive robots, which is helpful for the data analysis in the verification. Through a comparison of these two results from the case study, it can be concluded that the software tool ALFHAR can be considered as a tool for the application of the ALFHAR model.

6.2 ALFHAR Model validation

In engineering, validation is used to confirm that a product or service meets the needs of its users. The ALFHAR model validation is designed to test whether the ALFHAR model created is the right one for stakeholders. The validation work is carried out using several tests on the application of the case study with the ALFHAR software tool. The validation work requires the stakeholder's participation in the research. The involvement of stakeholders helps in understanding how this model is effective with regards to evaluating levels of autonomy and sophistication for human assistive robots. In addition, their suggestions regarding how the model can be improved are invaluable. Based on the results collected from tests with stakeholders, certain conclusions can be drawn in order to assess whether the ALFHAR model meets the stakeholders' needs.

6.2.1 Case demonstration

The test on the tool is done through participants using the tool to evaluate levels of autonomy and sophistication for a given human assistive robot. The participants include people from

robot design company, autonomous systems researcher, and users. The participants are A= user, B=designer, C, D, E, F, G=autonomous systems researcher. They use the web based ALFHAR tool to evaluate the given case by themselves. The case selected here is ASIMO (Advanced Step in Innovative MObility), which is considered as a human assistive robot. There are some function descriptions on ASIMO, which are helpful for further tests.

The main function is demonstrated as follows:

ASIMO can push a drink cart, run across a stage, pour liquid into a paper cup, and hop on one leg.

Figure 6-11: ASIMO (Albanesius 2011)

Its details are described as follows (Albanesius 2011, Obringer & Strickland 2011):

It can serve drinks. Its multi-fingered hands have tactile sensors embedded in the palm and on the fingers so ASIMO can "perform tasks with dexterity, such as picking up a glass bottle and twisting off the cap, or holding a soft paper cup to pour a liquid without squishing it".

It can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface. ASIMO can run approximately 5.5 miles per hour, up from about 3.7 mph in previous iterations.

ASIMO is equipped with "multiple sensors that are equivalent to the visual, auditory, and tactile senses of a human being" so it can detect someone walking towards it and move accordingly.

Coordination between visual and auditory sensors enables ASIMO to simultaneously recognise a face and voice, enabling ASIMO to recognise the voices of multiple people who are speaking simultaneously, which is difficult even for a human being to accomplish.

HEIGHT	4 ft 3in (130 cm)		
WEIGHT	119 pounds (54 kg)		
WALKING SPEED	1.7 mph (2.7 km/hour)		
RUNNING SPEED	3.7 mph (6 km/hour)		
WALKING CYCLE	Cycle Adjustable, Stride Adjustable		
GRASPING FORCE	0.5 kg/hand (5 finger hand)		
ACTUATOR	Servomotor+Harmonic Speed Reducer+Drive Unit		
CONTROL UNIT	Walk/Operating Control Unit, Wireless Transmission Unit		
SENSORS: FOOT	6-axis Foot Area Sensor		
SENSORS: TORSO	Gyroscope & Acceleration Sensor		
POWER	Rechargeable 51.8V Lithium Ion Battery		
OPERATING TIME:	1 hour		
OPERATION	Workstation and Portable Controller		

DEGREES OF FREEDOM (for human joints)

HEAD	Neck joint (Up/Down, Left/Right Rotation)	3 DOF	
ARMS	Shoulder joints (Forward/Backward, Up/Down Rotation)	3 DOF	
	Elbow joints (Forward/Backward)	1 DOF	
	Wrist joints (Up/Down, Left/Right, Rotation)	14 DOF	= 7 DOF x 2 arms
HANDS	4 fingers (to grasp objects) / Thumb	4 DOF	= 2 DOF x 2 hands
HIP	Rotation	1 DOF	
LEGS	Crotch joint (Forward/Backward, Left/Right Rotation)	3 DOF	
	Knee joints (Forward/Backward)	1 DOF	
	Ankle joints (Forward/Backward, Left/Right Rotation)	12 DOF	= 6 DOF x 2 legs
TOTAL		**34 DOF**	

Figure 6-12: ASIMO specifications (American Honda Motor Co. Inc. 2012)

There are also some specifications for ASIMO in Figure 6-12 which are helpful for the evaluation.

6.2.2 Data collection and results analysis

Generally, the test on this model is conducted with the participation of several stakeholders'. Through their evaluation of the given case in the research, the results are generated for further analysis. In the test, participants should use the web-based tool for ALFHAR model to evaluate levels of autonomy and sophistication for this case. Participants can input several functions for ASIMO into the tool based on the given information and then evaluate these functions according to the guideline from the tool. Some results have been collected from a

set of tests with stakeholders, whilst they have also provided feedback, which is very helpful for further work on this model.

Table 6-3: Result 1 from test

function			Participants are A, B, C,D, E, F,G; their individual scores are numbers in the table						
			Participant and score						
			A	B	C	D	E	F	G
mobility	a	walk, run, run backward, and hop on one or two legs, walk on an uneven surface	3						
	a	multiple sensors that are equivalent to the visual, auditory, and tactile senses of a human being	4						
	b	Robot is mobile, including stairs. Can cope with slightly uneven ground. Must be hard ground.		3					
	c	Performing Tasks with abilities			4				
	c	It can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface.			4				
	c	detect someone walking towards it and move accordingly			4				
	d	humanoid robot with mobility and dextrous capabilities				3			
	e	walk, run, run backward, and hop on one or two legs, walk on an uneven surface					3		
	e	multiple sensors that are equivalent to the visual, auditory, of a human being, can detect human and environment around					4		
	f	Pushing a drink cart						2	
	f	Walking						2	
	f	Running						2	
	f	Hopping						1	
	f	picking up bottles						1	
	f	manipulating bottle						1	
	f	detect people and react						2	
	g	can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface							4

The results in Table 6-3 are functions generated by participants as well as the evaluation results given by them on the right column. The functions listed in Table 6-3 are those related to **mobility** in a participant's mind. For mobility, some people demonstrate walk, run, hop and others together that relate to the movement of robot. Some other people evaluate a robot system's mobility from the single function of movement, such as walk, run, hop, and so on.

The result from multi-function evaluation is between level 3, and 4, whilst the result from single-function evaluation is between 1 and 2. Through analysis, the difference within evaluation results from single function and multi-function aspect is due to the fact that single function can only fit into low levels of mobility in the evaluation, and cannot satisfy levels 3 and 4. On the other hand, people also feel slightly confused by the choice of level 3 or level 4 as they feel that the information supplied in the case study is sufficient for them to make a clear decision.

Table 6-4: Result 2 from test

		function	Participant and score						
			A	B	C	D	E	F	G
decision making	a	walk, run, run backward, and hop on one or two legs, walk on an uneven surface	6						
	a	multiple sensors that are equivalent to the visual, auditory, and tactile senses of a human being	4						
	a	multi-fingered hands move	4						
	b	Can manipulate small objects and re-orientate precisely.		6					
	b	Robot is mobile, including stairs. Can cope with slightly uneven ground. Must be hard ground.		6					
	b	robot can perform persistent perception (visual, auditory), but not yet understand speech		5					
	c	Performing Tasks with abilities			6				
	c	Coordination			6				
	c	Recognition of the human and environment			7				
	d	humanoid robot with mobility and dextrous capabilities				4			
	e	walk, run, run backward, and hop on one or two legs, walk on an uneven surface					6		
	e	multi-finger hands perform tasks					6		
	e	multiple sensors that are equivalent to the visual, auditory, of a human being, can detect human and environment around					6		
	f	picking up bottles						4	
	f	manipulating bottle						4	
	f	detect people and react						7	
	f	recognise the voices of multiple people						4	
	f	recognise a face						4	
	g	detect people and environment							6
	g	Coordination							6

The functions related to **decision making** are generated by participants in Table 6-4. The main results in this table are from level 4 to level 7. Through participants' feedback, it is clear that they feel as if it is a bit difficult to make a choice between level 4 and level 6 as there are not enough details in the case, although the distance between different levels of decision making is clear enough for them. The ASIMO robot can perform tasks with different requirements, and any case where there is confusion about its behaviour is related to human command. Manufacture support may be needed in order to get enough information for the study.

Table 6-5: Result 3 from test

		function	Participant and score						
			A	B	C	D	E	F	G
interaction	a	walk, run, run backward, and hop on one or two legs, walk on an uneven surface	1						
	a	multiple sensors that are equivalent to the visual, auditory, and tactile senses of a human being	3						
	a	multi-fingered hands move	1						
	b	Can manipulate small objects and re-orientate precisely.		2					
	b	robot can perform persistent perception (visual, auditory), but not yet understand speech		1					
	c	Performing Tasks with abilities			1				
	c	detect someone walking towards it and move accordingly			2				
	c	Coordination			1				
	c	Recognition of the human and environment			1				
	d	humanoid robot with mobility and dextrous capabilities				2			
	e	walk, run, run backward, and hop on one or two legs, walk on an uneven surface					1		
	e	multi-finger hands perform tasks					1		
	e	multiple sensors that are equivalent to the visual, auditory, of a human being, can detect human and environment around					3		
	f	detect people and react						1	
	f	recognise the voices of multiple people						1	
	f	recognise a face						1	
	g	serving drinks							1
	g	can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface							3
	g	detect people and environment							3

Table 6-5 displays functions related to **interaction** and its evaluation comes from participants in the test. The data in the table shows that the interaction level for ASIMO is between level 1 to level 3. In the evaluation standard, level 2 requires that a "robot can learn some limited interaction with humans", and level 3 requires that a "robot can understand some of interaction with humans, and is able to communicate with humans with some kind of interaction". However, in some cases it is difficult to identify what interaction capability ASIMO possesses. In actual fact, people in the test admit that sometimes they cannot make a choice as there is a lack of information in the case. On the other hand, interaction mainly consists of human robot interaction in the model; people in the test suggest that the interaction for a robot system should also include robot-environment interaction and robot-robot interaction, the 'interaction' evaluation standard sometimes fails to fit into the function they described.

Table 6-6: Result 4 from test

		function	Participant and score						
			A	B	C	D	E	F	G
system configuration	a	walk, run, run backward, and hop on one or two legs, walk on an uneven surface	4						
	a	multiple sensors that are equivalent to the visual, auditory, and tactile senses of a human being	3						
	a	multi-fingered hands move	4						
	b	Can manipulate small objects and re-orientate precisely.		4					
	b	Robot is mobile, including stairs. Can cope with slightly uneven ground. Must be hard ground.		4					
	c	Performing Tasks with abilities			4				
	c	detect someone walking towards it and move accordingly			4				
	c	Coordination			4				
	c	Recognition of the human and environment			3				
	d	humanoid robot with mobility and dextrous capabilities				2			
	e	walk, run, run backward, and hop on one or two legs, walk on an uneven surface					4		
	e	multi-finger hands perform tasks					4		
	e	multiple sensors that are equivalent to the visual, auditory, of a human being, can detect human and environment around					4		
	f	picking up bottles						1	
	f	manipulating bottle						4	

	f	detect people and react						3	
	f	recognise a face						1	
	g	serving drinks							2
	g	can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface							3
	g	Coordination							3

Table 6-6 shows functions which are related to **system configuration** in the model and evaluation results from participants. Robot system configuration is about resource relocation, components configuration, and adaptive design. The results in Table 6-6 shows that the level for system configuration is mainly between 3 and 4. There are also some functions in level 1 or 2 in some people's mind. From their feedback, it seems that there is still not enough information for them to make a choice for levels of system configuration in some functions. However, through analysis, people may occasionally not choose the proper selection in the evaluation as the levels of system configuration for their function do not fit into the case. This may be due to the time limitations in the test, or due to the fact that they do not clearly understand the evaluation stand with regard to system configuration, or have not fully read the content in the case. For example, the function "picking up bottles", in the case where the robot hand can also pick up soft paper, and so on; from this point of view, the level of sophistication for this function is about 4.

Table 6-7: Result 5 from test

		function	Participant and score						
			A	B	C	D	E	F	G
degree of freedom	a	walk, run, run backward, and hop on one or two legs, walk on an uneven surface	4						
	a	multi-fingered hands move	4						
	b	Can manipulate small objects and re-orientate precisely.		5					
	b	Robot is mobile, including stairs. Can cope with slightly uneven ground. Must be hard ground.		3					
	c	Performing Tasks with abilities			4				
	c	It can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface.			4				
	c	detect someone walking towards it and move accordingly			4				
	c	Coordination			5				

d	humanoid robot with mobility and dextrous capabilities				3			
e	walk, run, run backward, and hop on one or two legs, walk on an uneven surface					5		
e	multi-finger hands perform tasks					4		
f	Walking						4	
f	Running						4	
f	Hopping						1	
f	picking up bottles						4	
f	manipulating bottle						4	
f	detect people and react						5	
g	can walk, run, run backward, and hop on one or two legs, as well as walk on an uneven surface							4

Table 6-7 shows how **degrees of freedom** for ASIMO are evaluated by participants in the test. In this table, it is evident that the degree of freedom covers 1 to 5 depending on the function they describe in the test. For a robot's mobility, its DOF is approximately 4 or 5. More information is needed about the case so that people can make a definite choice on level 4 or level 5 in the test, namely whether ASIMO has configurable / adaptive design in its mechanism. There is also level 1 for function "hopping" in participant's evaluation. Through analysis, it is interesting to find that with the function "hopping", the robot can only move up and down. If we consider the function "hopping" as part of movement, the "hopping" can also be considered to have level 5 of DOF as ASIMO can walk, run and hop; the multi-functions are based on its legs, and "hopping" is part of system configuration.

6.2.3 Feedback from stakeholder

In addition, there is some feedback from stakeholders, which is crucially important for the model's improvement.

For the evaluation standards descriptions, participant C comments that the description on interaction is not very clear, as for robot interaction, it can be interpreted as any interaction with the outside world, not just humans. In the decision making evaluation standards, participants also seemed confused with regards to this: whether the evaluation standard for decision making ability is for human being or robots? In fact, with regards to the evaluation standard, the robot decision making ability is about how much (and to what extent) decision making is made by robots or human beings, or how much robots are controlled by human beings. Decision making ability can be considered from both the robot and human aspect. For example, if humans control the robot's decision making, then this robot has a low level of

decision making; on the other hand, if a human does not need to send a command to the robot, the robot can execute tasks by themselves, and in this way the robot has high level of decision making ability.

On the other hand, all of the participants have commented about the details of the selected case. They occasionally find it difficult to make proper decisions through the model as there is not enough information given in the case to support them in making a choice.

Generally, the evaluation scope description for each evaluation type is good; participants can make a proper choice from the given standards in most situations.

6.2.4 Statement of model validation

The validation of the ALFHAR model in this research is achieved through the test case "ASIMO" in the software tool ALFHAR with several participants. The results from tests show that the ALFHAR model can work well for evaluation levels of autonomy and sophistication for human assistive robots when given sufficient information in the case. On the other hand, the test is only based on one case, and further conclusion could be drawn were more tests conducted on other case studies and with more participants.

6.3 Evaluation result reliability analysis

In terms of reliability of an evaluation based on the ALFHAR model and the instantiation of the framework in the computer software tool, there is a question of how to ensure that the evaluations are considered to have a certain level of reliability.

Generally, the validation for this research is based on a small sample of participants using the computer software tool of ALFHAR to evaluate a given case study. Each participant generates a set of functions of human assistive robot from the given case study, and then evaluates levels of autonomy and sophistication for these functions; there is no cross-testing between participants to see whether they agree with each other on the evaluation result for the functions generated by each participant. The limitation of this validation process is that it has not so far arranged for participants to evaluate the same function using the ALFHAR model. This causes some uncertainty about the reliability of the evaluation result. An ideal validation activity for the model would require statistical validity.

Statistical validity is defined as:

"The degree to which an observed result, such as a difference between two measurements, can be relied upon and not attributed to random error in sampling or in measurement." (Barefoot Proximity 2012)

To execute a statistical validation of the model / tool, there are several issues that need to be considered. First of all, for statistical validity, a proper sample size should be defined according to practical issues; although a larger sample size will make the analysis result more accurate. It is worth noting that this survey should not be conducted with random sampling, because, clearly, a certain level of technical expertise is required to make the judgements necessary to validate the assessment tool. The technique that is recommended for further validation of the tool is an approach such as mini-Delphi, whereby a small number of technically able participants score the same set of functions independently and are then presented with the overall results. They are then asked to score the functions again, but in the knowledge of the scores of the overall sample. Through this an agreement on the scores can be obtained. If agreement cannot be reached, then that is a signal to the researcher that further refinement of the assessment criteria and scoring tables is required. Given the number of criteria (7) that must be evaluated, it is considered that at least 20 participants should be canvassed, but the distribution of these across relevant backgrounds (academic, industry, end-user) will be the most significant factor.

The process of statistical analysis for the model validation can be considered as follows:
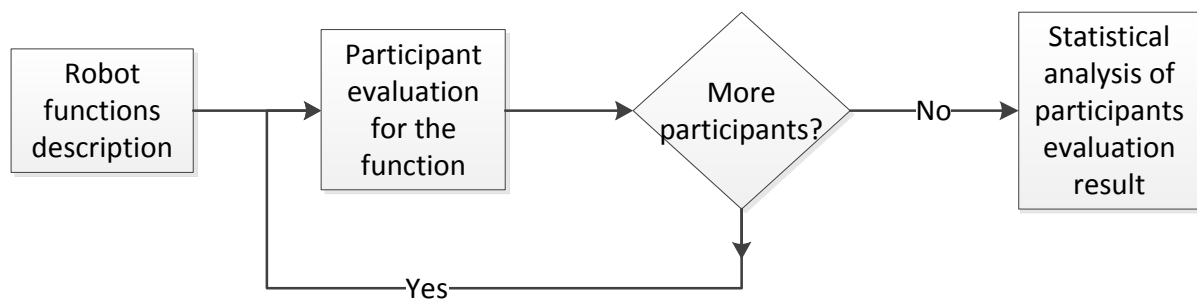
Figure 6-13: Statistical analysis process for the model validation

According to the Figure 6-13, to calculate a certain level of the model / tool reliability, a sample of technically competent people score the same individual functions with a significant percentage in agreement, this would give a validity of X % for the model / tool. For example, if there are 20 participants who are domain experts in autonomous systems joined in for the model validation, and in the robot functions description: "Can manipulate small objects and

re-orientate precisely", 16 participants of them score '5' in degree of freedom and 4 participants score '4' in degree of freedom based on the ALFHAR model. According to the statistic, the ALFHAR model has 80% reliability in the evaluation of degree of freedom aspect, but with an error of approximately 20%. Significantly larger samples are required to achieve an error closer to 1%, but these would probably not be feasible. The reliability analysis for other dimension within the model is considered as in the same way. From this process it can help the research to gain the reliability of the model / tool.

6.4 Summary

Generally, the ALFHAR model is implemented with verification and validation. There is also an analysis on how to ensure the model / tool has some level of reliability. The verification work is achieved through case studies in the software tool ALFHAR and the ALFHAR model. The results in the verification show that the software tool of ALFHAR can be used to evaluate levels of autonomy and sophistication on behalf of the ALFHAR model. The verification process is very helpful for the ALFHAR model validation; as after the model verification, the software tool of ALFHAR model can be used to support the model validation in the test which makes model validation easy. It is also much more convenient to communicate with stakeholders through the tool. The validation work is achieved using case studies on the software tool ALFHAR with several stakeholders participating. The validation results show that the ALFHAR is efficient in evaluation levels of autonomy and sophistication to some extent. The validation step is necessary in the research in order to show that the model is helpful for stakeholders in the real application. Through verification and validation, as well as receiving feedback from stakeholders to identify the good as well as deficient aspects of the ALFHAR, it is clear that there is great scope for further research work.

7 Findings and conclusions

Having created the model, model verification and validation, the results obtained in the test in Chapters 5 and 6, this chapter discusses all the results in the context of the current literature whilst also considering the implications of the results and any limitations of the research. There are also some guidelines for further research and a final summary for the entire research project.

7.1 Introduction

The main aim of this research is to develop a generalised model for levels of autonomy and sophistication for autonomous systems. Through a literature review, the research has identified that there is a gap in the existing frameworks for human assistive robots with regards to identifying characteristics through which classification will be possible. Some of these gaps are:

- Much of the research activities in autonomous robots which try to identify the characteristics of autonomous systems are mainly in the area of defence.
- There is an urgent requirement for the development of autonomous, domestic service robots.
- The existing frameworks, such as the ALFUS framework for autonomous unmanned systems do not adequately cover such domestic applications.

In light of the gaps highlighted above, the present research seeks to create a model for evaluating levels of autonomy and sophistication for human assistive robots.

7.2 ALFHAR model and key results obtained

The development of the ALFHAR model is described in Chapters 4, 5 and 6. It is created to evaluate levels of autonomy and sophistication for human assistive robots. The specific issue for this model is whether or not it can be effectively used for human assistive robots. The model is developed through interaction with a set of designers, engineers and researchers in the area of autonomous systems.

Through testing the computer model ALFHAR model, it is interesting to find that ALFHAR can work well in the human assistive robot area, but not other areas; it focuses on the

autonomy and sophistication aspects of the human assistive robot, which includes decision making, mechanical ability, and interaction. The performance of the model depends on how functions of autonomous systems are described by the user. For example, if one multi-function can be described in 3 sub-functions, the evaluation results from multi-function and sub-functions may be different based on the ALFHAR model. The reason for this problem is because a multi-function is normally more complex than its sub-function. People simply consider levels of autonomy and sophistication of human assistive robots from macroscopic and microcosmic aspects. The results in the Chapter 6 also show that to use the ALFHAR model properly, enough detailed information should be supplied with regards the selected autonomous system, which will be helpful for the evaluation.

7.3 ALFHAR model in the TLM

As discussed in the literature review, TLM is a very important issue for human assistive robots. The ALFHAR model created here is to support the TLM of human assistive robots. The ALFHAR model has been verified and validated in Chapter 6. The following section presents an analysis of how this model can fit into TLM processes in human assistive robots' lifecycles. Through analysing the content of the ALFHAR model, the main aim of this model is to evaluate levels of autonomy for human assistive robots. One can use this model as a guideline for selecting a proper autonomous system based on their requirements. From this point of view, the ALFHAR model can fit into the concept stage of CADMID lifecycle model. Designers can also use this model to validate whether the product they designed meets the requirement or not; in this way the ALFHAR model can support the demonstration stage in the CADMID model. When an autonomous system is in the in-service stage, a user can experience benefits from the evaluation results of the ALFHAR model which can help them understand the capability of autonomous systems which they have contact with. This is especially helpful when people initially use a robot system and are not familiar with the capability of the system.

Generally, the ALFHAR model can fit into CADMID model in several aspects. The ALFHAR model can support concept, design, and in-service stage in the through life management of autonomous systems. It may also be related to access, manufacture and disposal depending on how people use this model. From the discussion above, it is evident that the ALFHAR can be considered as partly supporting the through life management of human assistive robots.

7.4 Limitations of this study

The development of the ALFHAR model starts with a logical model analysis of the concept of autonomy, before a set of interviews are carried out to support the model's development and revision. In the model verification and validation, some cases studies are conducted to support the verification and validation. There are also several tests on the ALFHAR model. Through providing an overview of the development of the ALFHAR model, although the theory was developed as a scientific endeavour, the methods used during the research also have some limitations. For example, the semi-structured interview has been used in the research to collect data and information. Although there are many suggestions from designers, more contributions may be required from users to identify how the ALFHAR model can be helpful for their work. On the other hand, when using a case study in the test, the detail of the case seems to not supply enough information for participants during the test. There must be more information supplied from product manufactures or designers for the test.

The sample sizes used for both semi-structured interviews and the ALFHAR model test could be increased in future studies to make the results collected in this research more reliable. Whilst the number of people participating in this study can provide confidence for the research itself, the model's accuracy with regards to its real application could be improved were more information to be collected from additional participants.

7.5 Further work

This research has shown that the ALFHAR model can be considered a general model for levels of autonomy and sophistication for human assistive robots. A computer tool for this model has been developed. One suggestion from the test shows that if the tool includes a guideline on the cost evaluation for different levels of autonomy and sophistication, this will make the model much more attractive. This is also fairly related to the through life management of autonomous systems. Further work which can be done is based on the limitations of this research. Indeed more stakeholders could participate in this future research, so as to make the research results more accurate and credible.

As identified in the thesis, there are several opportunities for deeper theoretical study, such as ontology regarding autonomous systems, safety standards in the domestic robot area, and so

on. These works will be extremely helpful for the further development of autonomous systems in the domestic area.

7.6 Final conclusion

To conclude, this research has generated a model to support the through life management of autonomous systems. Through identifying the current existing models in classification of levels of autonomy and their deficiency, an ALFHAR model is developed to evaluate levels of autonomy and sophistication in the human assistive robot area. A web-based tool for ALFHAR is created to support the application of the ALFHAR model. In terms of meeting the objectives originally set out in Chapter 1, Table 7-1 presents an overview of each objective, where and how it was met.

Table 7-1: An overview of objectives distribution

Objective	Where	How objective was met
To identify information and knowledge requirements for autonomous system	Chapter 2	A report about literature reviews for this research is produced, and also identifies the research area.
To identify Stakeholders	Chapter 2	A map shows the stakeholders in this research and their relationships.
To generate the research requirement	Chapter 2	Through literature and interviews with stakeholders, a set of research requirements and research questions are generated.
To develop framework	Chapters 4&5	ALFHAR model is developed through logical modelling, interview, case study, and scenario. The ALFHAR model is expected to be a generalised model for levels of autonomy and sophistication for human assistive robots. Due to the time limitations, the framework development does not include the ontology development and guidance for designers.
To create a tool	Chapter 5	A web-based tool is developed to support the ALFHAR model in the real application.
To measure benefits	Chapter 6	Through verification and validation of ALFHAR model, there is an analysis of the strengths and weakness of the ALFHAR model based on data collected in the test.

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Appendix I: Classification of levels of autonomy for human-assistive robots

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Abstract *As the development of more advanced autonomous systems gathers pace, so the need for an agreed ontological framework becomes imperative to assist in the design, manufacture, and in-service support of deployed systems. A number of researchers have proposed frameworks, but analysis of these has indicated that they tend to be specific to particular application domains and/or particular types of system. Of particular concern is the failure of such frameworks to adequately address the 'through-life' management aspects of autonomous systems. The ALFUS framework (Huang, et. al., 2005) for instance, has been developed to classify unmanned systems across a range of applications but, nonetheless, is mostly applicable to vehicular systems and does not adequately represent important aspects associated with human-assistive robots. In this paper, we critique the ALFUS framework with respect to human-assistive robots and use the analysis to propose a framework approach that will better support definition of systems characterized by substantial physical human interaction and in which through-life support (e.g. upgrades, maintenance) may be represented. The approach we propose will be the basis upon which wider considerations (such as ethical dimensions) could be incorporated within the framework leading, eventually, to a design support tool that will better enable life-cycle planning to be built into the designs of human-assistive (and other) robots.*

INTRODUCTION

In recent years a number of research activities in autonomous robots have sought to identify characteristics through which classification will be possible. Examples include Huang, Messina et al. 2004, Huang, Pavek et al. 2005, Visnevski, Castillo-Effen 2009; the

characteristics through which classification is proposed have mainly concerned autonomy, adaptability, and machine cognition, etc. Much of the research has focused on defense applications, for which significant human-robot interaction is comparatively low. Indeed, defense robots are generally used in hostile environments in place of humans to reduce the risk to human life; the so-called dirty, dull, or dangerous environments. But increasingly, robots are being seriously considered for applications in which the interaction with human beings includes significant physical contact. For instance, a high priority driver for such applications is as a means to support the welfare of an increasingly aged population. In fact, there is an urgent requirement for development of autonomous, domestic service robots. The existing frameworks for autonomous, unmanned systems do not adequately cover such domestic applications. Although the ALFUS framework (Huang, Messina et al. August, 2007) is one of the most comprehensive, it does not allow proper distinction between different levels of autonomy for the case of human-assistive robots; the work reported herein, therefore, critiques the ALFUS framework for human-assistive robots, and then seeks to extend its basic structure to be more generally applicable. It is acknowledged that ALFUS was created with unmanned vehicles in mind, but as one of the most comprehensive frameworks, the lack of extensibility to the human-assistive case is informative.

BACKGROUND

There are significant differences between the application of autonomous robots in the defense area and those in the domestic area. Consider the level of autonomy for Unmanned Air, Ground, surface, or Underwater Vehicles (UXV) used for defense purposes. Huang, Pavek, et. al., (2005) propose evaluation through consideration of environmental difficulty, human interface, and mission complexity. A higher level of autonomy implies that the UXV will accomplish more complex missions, be resilient in a wider range of environments, and require fewer human-robot interactions to achieve the mission. But for a human-assistive robot, a higher level of autonomy may be associated with greater complexity due to an increased number of human-robot interactions, working in cluttered environments in close proximity to human beings, but remaining safe at all times. The complexity of communication is also significantly higher than for a UXV.

The rules governing the human-robot interaction are very different between these applications. Expressed in an extreme sense, a domestic robot must interact with humans in

an entirely safe (do no harm) manner, whereas for a defense robot (UXV) the purpose may be to deliver violent effect. TABLE 1 provides a comparison between these two domains. Although not all UXVs are associated with defense, in general this has been the main application area that has driven their development so far.

The strongly contextual nature of the interactions means that the development of a generally applicable framework, that is also usable and useful, is a major challenge.

Nowadays, there are a great many unmanned systems in use with varying (although mostly very low) autonomous capabilities. Different areas of application require different information and knowledge and this has led to various frameworks, some of which we briefly review below.

Table 1 COMPARISION BETWEEN DEFENSE ROBOT AND DOMESTIC ASSISTIVE ROBOT.

	Defense robot	Domestic assistive robot
Definition	'The application of the science of robotics to military uses, such as remotely piloted vehicles, automated ammunition and supply handling, and the like'	'A service robot is a robot which operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations'
	(The Encyclopedia.com 2010)	(SRI Consulting Business Intelligence 2008)
Typical applications	UXVs: Surveillance, mine detection, kinetic effects, search and destroy	Unitary application: cleaning, porterage, monitoring, Telemedicine Pharmacy Automation (Healthcare)
aims of application	Inhospitable and dangerous environments / persistent tasks	Replace human-beings in repetitive tasks
Safety considerations	Avoid human proximity, correct identification of targets, occupation of separate spaces (e.g. airspace), remote piloting	Fail-safe, predictable behaviors, prescribed actions
communication	wireless communication (infrequent comms)	advanced sensors-vision, touch, voice, etc. (continuous comms)
standards	Engineering standards, legal restrictions on area of operations	Engineering standards
Operational	Domain experts operate and	Generally non-expert users

responsibility	control the robot	
Human robot interaction	higher level of autonomy, lower degree of human intervene	human robot interaction happens during the whole application

As discussed above, there are several frameworks for the evaluation of unmanned systems; three widely used frameworks are:

1) *ALFUS framework (Huang, et. Al., 2004)*: used to describe characteristics of unmanned systems and evaluate levels of autonomy of unmanned systems.

2) *Systems Capabilities Framework (SCF)* (Visnevski, Castillo-Effen 2009b): illustrates relationships between cognitive, adaptive and simple reactive systems.

3) *Autonomous Control Logic (ACL)* (Sholes 2007): uses metrics to characterize autonomy by establishing a peer-reviewed set of universal metrics for autonomous control.

These frameworks have wide application in UXV areas, but do not address classification of levels of autonomy for human-assistive robots. Through comparison, the ALFUS framework is considered the most applicable, as the main context and definitions can be used to evaluate levels of autonomy for unmanned systems. The ALFUS framework consists of three main components: terms and definitions, a detailed model for autonomy levels, and the summary model for autonomy levels, which is generated from the detailed model (Huang, Messina et al. August, 2007). The detailed model includes three main axes: environment complexity (EC), mission complexity (MC), and Unmanned System (UMS) human independence (HI), see Fig.1. EC in the detailed model covers the outside environment in most situations; the UMS HI is dependent on how the UMS is able to sense, perceive, analyze, communicate, plan, make decisions, and act. MC is based on task, co-operation, planning, and perception. Generally speaking, ALFUS can properly demonstrate characteristics of unmanned systems in the defense area. Some researchers have satisfactorily applied the ALFUS framework to evaluation of autonomy of ground vehicles (McWilliams, G. T., Brown, M. A., Lamm, R. D., Guerra, C. J., Avery, P. A., Kozak, K. C., and Surampudi, B. 2007). At present, it seems that there is still no application of the ALFUS framework in the domestic service area. We present two simple case studies below of domestic robots to test the applicability of the ALFUS framework to this type of application. The results are based on applying the framework as described in the open literature.
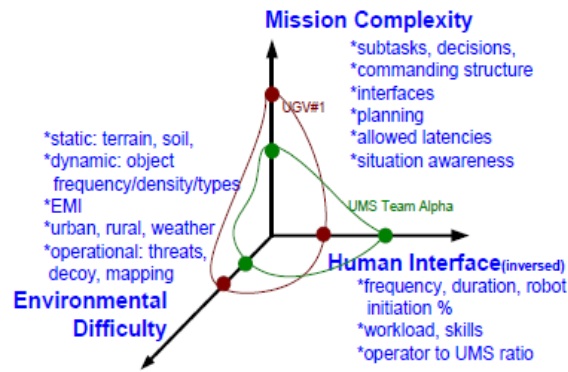
Fig. 1 ALFUS detailed model (Huang, Pavek et al. 2005)**.**

CASES STUDY 1

There are, already, many different kinds of autonomous robot used in a variety of domestic applications. Two of these are used to analyze how the applicability of the ALFUS framework.

Case one: the world's first communication robot "Wakamaru" (Shiotani,S., Tomonaka,T., Kemmotsu,K., Asano,S., Oonishi,K. and Hiura,R. 2006), is a Japanese domestic robot made by Mitsubishi Heavy Industries. It is primarily intended to provide service and assistance to elderly and/or disabled people. Wakamaru can connect to the internet, has a limited speech capability (in both male and female voices), makes eye contact, and has speech recognition abilities. Its functions include reminding the user to take medicine on time, and calling for help if it detects that something is wrong. It has high reliability of self-localization and avoidance of obstacles by sensors, but errors may occur and their frequency increases when there are changes of lighting and location of people.

Here we apply the ALFUS framework to demonstrate mission complexity, environment complexity, and human independence for Wakamaru. Details are shown in TABLE 2.

The analysis indicates that for each of the ALFUS axes of mission complexity, environment complexity and human independence various levels of complexity are identified. The mission complexity includes values from simple to highly complex, as do environment complexity and human independence. Even if a weighted scoring system were employed, the final value for each axis would be ambiguous.

Table 2 CASE STUDY: WAKAMARU.

	mission complexity	environment complexity	human independence
Service /assistance to elderly	Vary from simple to complex	Vary from simple to complex	high human dependence for activity, low for decision making
Service /assistance to disabled	Vary from simple to complex	Vary from simple to complex	high human dependence for activity, low for decision making
internet	simple	simple	
limited speech	complex		n/a
eye contact	Complex, depends on EC		complex
speech recognition	very complex	affected by environment noise	high human dependence for communication
remind take medicine	simple	Simple	high human dependence for activity, low for decision making
call for help is	simple	complex	high if response is monitored
detect something is wrong	complex	complex	could be high or low
high self-localization	learned - cannot easily change environment	constrained to simple environment	high
obstacle avoidance	complex - must avoid harm to human	constrained to simple environment	n/a
sensors affected by lighting	robot simple	only simple environments	n/a
changes to people location	cannot, therefore robot simple	only simple environments	High

Also mission complexity is not independent of environment complexity and is constrained by it, and vice versa.

Thus, the ALFUS framework does not have appropriate coverage to evaluate this human-assistive robot in several aspects. For example, the ALFUS descriptions for environment complexity do not include the domestic environment; the domestic environment definitions should include aspects such as roughness of various floors, softness of objectives, fragile objects, etc., the complexity of environment for the domestic instance is highly related to the number of humans and other dynamic activities. Another aspect is that the human robot interactions happen all the time during this application, the ratio of human participation is

difficult to calculate and has little or no meaning in this context. Also, humans may not give any decision making or commands to the robot, but just receive advice and service from robot.

Case two: Toyota Partner Robot, a series models of domestic robot (TOYOTA MOTOR CORPORATION 2003). The walking model has bipedal locomotion; it walks on two legs similar to a person. It is able to use its hands to carry out a wide variety of tasks. The aim of this design is to supply assistance and elderly care.

Here we use mission complexity, environment complexity and human independence to analyze the Toyota Partner Robot in TABLE 3.

Table 3. CASE STUDY: TOYOTA PARTNER ROBOT

	mission complexity	environment complexity	human independence
walking	complex, dependent on environment complexity	dependent on floor type	high
service elderly	complex, dependent on environment complexity, and its mobility	complex, dependent on floor type, human	high human dependence for activity, low for decision making
assistance	vary from simple to complex, dependent on its mobility.	complex, dependent on floor type, human	high human dependence for activity, low for decision making

In this example, the level of autonomy as measured by the framework is highly dependent on the robot's mobility. Many researchers are interested in robot's mobility, at present. The humanoid walking type for a robot is more attractive, but more difficult than a vehicle. The complexity of environment will depend on roughness of floor, inclination of floor; mission complexity will depend on the weight of object, the balance of burden on the robot; in this case the classification of the environment is less ambiguous. However, human independence is not obvious in this situation. When applying ALFUS framework to analyze the level of autonomy for this robot, we find that it is difficult to evaluate through EC, MC, and HI according to the detailed model in the framework. The bi-pedal mobility of this robot can contribute its high level of sophistication and a certain level of autonomous decision making in this type of mobility. It is more difficult for robot to move by bipedal locomotion because of the need to consider its stability and mobility in a wide area.

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Through these two case studies, we conclude that the descriptions within the detailed model of ALFUS are not suitable for classification of domestic service robots. This is not an entirely unexpected result, because the ALFUS framework was originally designed for UXVs, but it does highlight the difficulty of a generally applicable framework for classification of autonomous systems. There is, thus, a need for a framework that can be applied to domestic service robots.

Although the current level of autonomy in domestic robots is still very low, it can be reasonably anticipated that the levels will increase. As this occurs, there are many aspects that must be considered in order to reduce safety risks. This consideration underpins the research into through-life management of autonomous robots that this work on classification supports.

ARGUMENTS

Firstly, through comparison and analysis, the framework mentioned above cannot cover domestic assistive robot properly; although it is widely used in the UXV area and has been proved well. The ALFUS model evaluates levels of autonomy by environmental difficulty, mission complexity and human interface, which represent appropriate, but not sufficient dimensions for domestic robots. Communication for UXV applications is usually through platform control. The vehicles capture information in the front line and send it back to the control platform by wireless signal; then experts in this area operate the platform and interpret the information for decision making. Domestic service robot is designed to assist human being in their daily activities. Robots will stay in close proximity to human beings; the communication style will also be different from defense robots. In the ALFUS framework, human robot interaction will affect the level of autonomy. The higher the level of autonomy of unmanned systems, the fewer the number of human robot interactions. However, for domestic service robot, no matter how high the level autonomy is, there will still need to be a high number of human robot interactions; the robot's behavior should still be under human's supervision/permission. The communication can be separated into a set of levels dependent on the level of sophistication the decision making power of the robot. Also, as domestic robots stay close to human beings, the safety issue will be the most important factor under the human's consideration. Only a robot with adequate safety strategies can possibly be accepted by the public. The level of autonomy for domestic service robots is influenced by safety

issues. That is to say that autonomy may be restricted precisely to reduce the risk of unsafe action.

Secondly, for domestic service robots, the mission complexity does not necessarily match the ALFUS definition, because it derives from the complexity of the communications. As the communication between humans and robots is directly through voice, vision, touch, remote control, etc, different types of communication will be attributed to different levels of sophistication. As a result, this will result in different levels of autonomy based on the different types of communication. For example, if a robot cannot interpret what a human says, then it can only receive limited messages from the human beings, and its behavior will be constrained by the limited choices of its function selection. If the robot can interpret what humans say, then this can help it to make decisions more conveniently and quickly. Communication complexity is not catered for at all in the ALFUS framework, and others similar to it.

Thirdly, as shown in the roadmap for service robots (Fig. 2), at the moment, the development of autonomous systems in the area of domestic assistive robot is still at an early stage. Future robots in the service area should have the ability to demonstrate useful decision-making and communicate effectively with human beings. From this prediction, the level of decision making and communication will be parts of the contribution to the autonomous systems. The behavior of the system should be human friendly and under human ethical constraint.
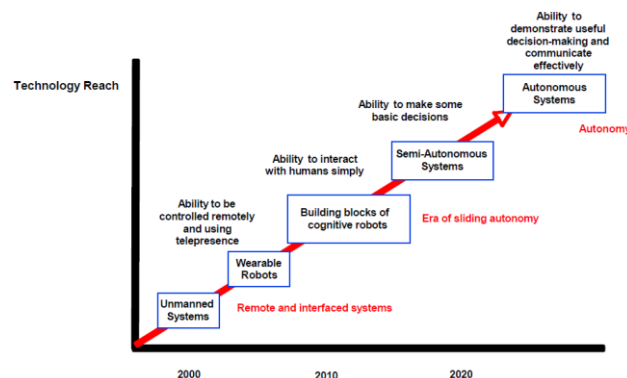
Fig. 2 Technology roadmap: service robotics (SRI Consulting Business Intelligence 2008)**.**

Last but not least, from the through-life aspect, there is still no framework for autonomous systems in domestic assistive robot area. Research being conducted by the author will create an integrated framework to supply through life management for autonomous systems. During the whole life cycle of autonomous systems, several issues need to be considered, for

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example: safety, reliability, security, maintainability, which is also related to different levels of autonomy.

CURRENT AIMS

A draft framework for autonomous systems in domestic service area is shown in _{Fig. 3}, which considers several aspects in order to evaluate the levels of autonomy of domestic assistive robot; and other aspects which can be used to evaluate the through life management of autonomous systems.

Generally, the high priority aspects of human-assistive robots are safety, communication and mobility. To supply assistance and service for the elderly or disabled, those three aspects should be included within the framework for evaluation of levels of autonomy. The different safety level, communication type and mobility will contribute to different levels and degrees of autonomy in the framework in _{Fig. 3}.

Mobility: the mobility of robots can range from non-mobile to powerful locomotion, and there are also different types of locomotion to be considered.
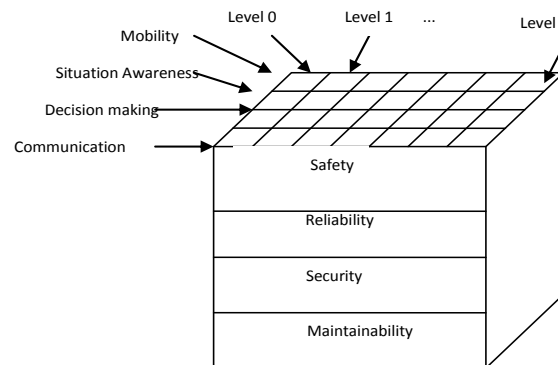
Fig. 3 Initial Framework for human-assistive robot.

"Situation Awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"

For robot systems, situational awareness is dependent on many different aspects, such as sensing capabilities, recognition of objects and/or environmental features, projection of likely changes etc. The complexity of the task is dependent on the environment and upon the mission complexity.

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Decision making: the ability of robot's decision making will be a significant factor in determining the level of autonomy. The level of decision making can be from non-decision making ability to autonomous decision making. We will also consider ethical issues, safety problems, etc as the evaluation of robots' decision making ability.

Communication: communication will happen during the application of human-assistive robot. The level of robot comprehension of the content of communication and what types (modes) of communication are available will be included in identification of levels and degree of autonomy of domestic service robot.

The safety issues have already been discussed by many researchers. Generally, robot safety can be categorized into six types, which are general safety; human-factors; safety standards; safety methods; accidents; safety systems (Dhillon, Fashandi et al. 2003). The weight of safety will be considered to contribute to levels and degree of autonomy for autonomous systems. TABLE 4 shows more details of the draft framework.

A number of interviews with researchers have been carried out to test the draft framework against their design activities. Further interviews are planned to test the framework further. Initial results suggest that the draft framework has appropriate coverage, but insufficient granularity to accurately describe the systems so far examined. The next stage of the research will aim to increase the granularity appropriately to provide an unambiguous means of classification.

CASE STUDY 2

Using the "wakamaru" robot as the example, we evaluate the application of the draft framework.

In our framework, the level and degree of autonomy will also depend on the complexity of domestic environment, failure frequency, communication understanding. In this framework, robot safety will be put into a significant place. The failure frequency of the robot will be considered as a total weight when calculate the general autonomy of wakamaru. There will be more research about the details in a metrics table to find out how the new details description work in the human-assistive robot. In some conditions, we may use ethics to evaluate its ethical behaviour as the autonomous behaviour should also be constrained by these considerations.

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Taking mobility as an example, the following parameters should be considered:

Type of locomotion: this could range from simple (wheeled, caterpillar), through moderately complex (segway), to highly complex (bi-pedal, quadrupedal). In each case the complexity enables more complex environments to be made available for operations.

Weight of unit and payload are also concerned with locomotion management

This framework is still under development. Interview results have so far indicated that its coverage is appropriate, but that its granularity at the low-autonomy level must be increased. Future work will address this.

CONCLUSION

Currently, this research is trying to supply knowledge management support for through life management of autonomous systems. The research in identifying levels of autonomy in domestic service robot will supplement (or extend) other frameworks in this area in order to adequately account for through-life considerations. This is essential for supporting designers in the task of designing robot systems for maintainability and assured future safety. As the research in domestic assistive robot is still at an early stage, the output of the current research will be helpful for the future development of autonomous systems in this area. Future research will focus on the safety and communication matters for domestic assistive robot, and other matters related to the whole life cycle of autonomous system, such as standards, reliability, and ethical issues.

Table 4 INITIAL DETAILED FRAMEWORK FOR HUMAN-ASSISTIVE ROBOT.

Level	Level Descriptor	Mobility	Perception/Situation Awareness	Decision Making	Communication
0	Remote control	No mobility; control by human being.	Reactive data collection, capture environment data by robot automatically.	N/A	show environment data via telemetry
1	Pre-programmed	Automatic moving: one dimension; two dimensions;	Perception through pre-load experience and knowledge.	pre-programmed	Can communicate with human within its pre-programmed knowledge lib. The communication way can be tactile,

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		three dimensions.			gesture, voice, Telepathic communication
2	human guidance	control by human being: object avoidance	has some ability to capture its environment information, and can accept human's intervene during application	Make some decision making and has some learning ability.	Need human's guidance to finish a task; has some basic ability of communication
3	self-detection	object avoidance and route planning	Detect self-health condition.	Making decision under safety self-health condition. Can cope with emergency and not hurt human being.	Show/ warn self-health condition to human/expert/engineer; has a middle level of communication
4	robust response to potential emergency	object avoidance and emergency protection	projection of current environment situation	making decision to protect itself and not hurt human	Show warning information/ give advisement for human to avoid danger; has robust understand during communication.
5	multi-task	object avoidance and emergency protection	Comprehends its situation and the importance of task, can accept multi-task.	making decision based on the task urgency	Share information with user by possible type of communication; strong ability of understand during communication.
6	multi-robot cooperation	object avoidance and route planning	Aware other robot's capability and cooperate with each other to finish a task.	Can make decision within multi-robots scale, and achieve task in an efficient way.	Communication among robots, human to select a task executer, needs external supervision; high level of understand during communication.
7	multi-robot cooperation	object avoidance and route planning	Aware other robot's capability and cooperate with each other to finish a task.	Can make decision within multi-robots scale, and achieve task in an efficient way.	Communications among robots, human distribute cooperation with other robot; high level of understand and communication ability.
8	Human-like				

Appendix II: Prepared Questions and information in the semi-structure interview

Stage 1: aim for understanding the background and design process in the autonomous system area.

1. Can you describe one of your projects that related to autonomous systems' design?
2. What is the requirement of this project?
3. What is the process of design for this project?
4. Is there any standard about this design? What standards have you use in this project? (Design standard, safety standard, etc)
5. How to achieve some required level of autonomy? How do you know that the level is satisfied for the requirement?
6. In this level of autonomy, what kind of safety issues have you considered? Is there any standard for design in this project?
7. What is the main application of autonomous systems in domestic area? How is it different with defence robot?
8. If the robot has learning ability, what is the strategy of safety issues?
9. What is the main difficulty for research in the domestic service robot?
10. Have you seen the Toyota partner robot? Is it possible to combine its mobility with other intelligent robot to develop a higher intelligent humanoid robot in the near future?
11. What is the ethic issue you considered in the autonomous systems? As the ethic issue is a difficult point for robot, it has links to human robot interaction, decision making, etc.
12. Can you envisage when the requirement of this project increases the autonomy level, the hardware can still support the function? What are the constraints between situation awareness and decision making?
13. How environment complexity will affect the levels of autonomy? E.g. if change its environment, what will happen for the system?
14. What kind of application the robot will do in your consideration? What will the environment

15. Learning capability: the area/extend of learning capability, what will be the learning capability affect robot's behaviour forward?

16. Human robot interaction analysis: what factors will affect human robot interaction: mobility? Communication? Safety?

Stage 2: capture information for the model created in the research

1. When talking about levels of autonomy, what do you put into consider? How do you evaluate levels of autonomy when one to know how well the autonomous the design is.

2. What is the main important factor for autonomy in your opinion?

3. Can you describe level of autonomy that currently involved in your research? The learning behaviour: how important the learning behaviour is in the home robot? What we can do to predict the safety problem for its learning behaviour?

4. What will change when people change the application of robot into multi-robot interaction? Is it possible to do this?

5. Multi-robot interaction: what is the current application of multi-robot interaction in human assistive robot?

6. Can you envisage what will the future's human assistive robot be like? Or how autonomy it will be? According to the current development of autonomy in robotics.

7. What is the main characteristic and trend of the current robotics development?

8. What is the safety aspect for user when applying human assistive robot?

9. Do you think autonomy and sophistication can be used to describe human assistive robot's capability entirely? Is there any other word / description that can be used to describe autonomy?

10. What is your consideration about conception of human assistive robot?

Part of interview information

Dialogue 1:

HF:	From your point of view what does autonomy mean for robot system? How can we say that a robot has some kind of autonomy ability
RW	The more decision making on your behalf, the high level of autonomy it will be.
HF:	From your point of view, when talking about autonomous system, from which aspect will you describe that the system has some levels of autonomy or has some autonomy ability?

RW:	Thinking about a control system, make decisions to turn on the radiator, maintain a target, that I would say the term radiator has some autonomy. The move decision that system is made on your behalf, the higher autonomy it is. For example, a heating system, changes its setting because of the weather and time. That would be high level of autonomy, in terms of a robot system, it will have control system, decision making, and how much robot can do, without choosing outside as human do next.
HF:	In your description, there are some words that autonomy is covered. One is decision making
RW:	Maybe the number of the control route, almost, if you have a number of control route, you will have a high level of autonomy.
HF:	yes, when I do some literature, one of the definition for autonomy is described as follows: … my research is based on this definition, and
RW:	Yes, from defence area, it is about the authority that you want to achieve. There is about 6-7 level of autonomy, from machine that you are directly control to, a machine is simply told to go out there, and do the job, and back when the job is done. That is almost the definition. My view is, you can use that definitions, but only some of it works.
HF:	Yes, maybe you cannot design a robot exactly just based on this kind of standard. Sometimes you should design with mix-functions
HF:	another point of view, is if we try to measure autonomy from those attributes, like decision making, in your experience, from which aspect is high level, and which low level
RW:	If you think about the autonomy in a machine tool down the road, if the machine tool could tell that some part is broken, then it would not have autonomy but it will have decision making.
RW:	Here is my plan, and I have some decisions over here, if an event happens, I will think about the decision, whether or not it is in the plan. It is like layer, and the layer below, the more layers it is, the more complex the system it is.
HF:	From your point of view, how about the sensors, how does it related to levels of autonomy? Sometimes the sensors are more complex, or the configuration is more complex. How does this relate to autonomy? Or are there any relationships between these?
RW:	I think you cannot have autonomy without having some sensors. Actually, robot will have sensors in decision making but not the main activity. For example, in a machine, the sensors is used to track the movement of machine, and detect the tool is broken by another sensor, this sensor does not help the machine, it help tell that something happen. So in a simply autonomy machine, actuator sensor provide sensor, proceed sensor to autonomy.
RW:	for example, in a todal robot, it goes out and move around, if the battery goes flat, it will make decisions to go back to charge it. Then it will have some levels of autonomy and decision making.
HF:	Does that mean if a robot system want to be high level autonomy, then it will be more sensors?
RW:	It will have more sensors that you think to do the job. It will have some sensors redundancy. It will also have some additional sensors for other roles.
HF:	When consider about the sensor ability, I just consider about the number of sensor.

RW:	Yes, the number of sensors, the type of sensors, overlap of sensors, if you have two different sensors, measure the same thing, and then the overlap is there, with a vision, you have two eyes to give a better focus of objects. But if you image a robot, it might have two different type of camera, high revolution deep camera, and a low revolution dept camera, this will provide different type / quality of information. that give robot more capability
HF:	so if we want to say something about levels of autonomy, then we can talk about this from numbers, types, overlap / configuration
RW:	And also I want to say that the way that sensors are used. For example, we use vision sensors for detect object, use vision for balance, use vision to avoid object. We use smell to detect risk, danger, and use smell to detect good or bad. Again sensor has a set of roles. And also that sensors used in different level. In a complex system, multi-sensors use in multi-level in different way.
HF:	As you said, sometimes the vision can use to detect danger, and smell can also be used to detect danger, what may happen if these two different types of sensor that use in the same time to detect danger, but result in a different way. What will happen? Or what will robot do base on such kind of information? How about the decision making? Which decision will be taken?
RW:	That is the sensors problem of robot system. If sensors are disagree, how to make decisions. We do not know. I do not have answers
HF:	ok
RW:	But I have to say that a highly autonomous system, it has to deal with that kind of situation and responsible with that.
HF:	In your company, does the product you designed have any levels of decision making?
RW:	Not really, as the product in our company is mainly robot hand, it has low level of decision making; normally it is based on human control.
HF:	So normally the decisions are come from human beings?
RW:	Or from the software I will use in the robot system. The physical application that like remote control, human hand, grove…
HF:	In this research, we try to describe human assistive robot from two aspects: autonomy and sophistication aspect. For example, if one robot has low level autonomy, but high level of mechanical ability. Then if we use this model to describe this robot, then we can say that this robot has some high level of sophistication, but low level of autonomy.
HF:	When talking about the mechanical ability, from which aspects will you describe that this robot has some mechanical ability?
RW:	it might not have sophisticate interface, it might only do a few thing, but useful aspect considering the sophistication aspect…..
HF:	Do mobility should be part of the system? Include in the design?
RW:	Certainly, normally I will use the robot do not move. But they have movements. I think a robot whether it can move around or not is less relevant to how much it can change to the world. It is about how many robots can change the world. If a robot can make many changes in one place, that is the capability of robot. If a robot can make less changes, but can move to other places, that is the less capability robot.
HF:	Do you think moving ability is part of mechanical ability or not?
RW:	yes, you can take robot like car on a mobile platform,

RW: If you take mobility for example, has move, rotation… 5 dimension, if look at the configuration of robot, the sum of degree of freedom. It is the dimension .that some of them. ….degree of freedom is 19…. Sophistication of configuration is 19. Using degree of freedom as one of the evaluation for sophistication.

RW: If a robot is moving on the ground here, a parallel is moving in this direction, another is.. It is about two degree of freedom. It could get anywhere on this space.

HF: The model I want to describe is like this model. …mobility /mechanical ability should be in the same dimension. Autonomy aspect is from decision making and sensors ability. Interaction, not sure what is sophisticate? Or from which we can say that they are sophisticate? Like vision, touch, speech, and so on. In your experience, which are more

HF: complex?

RW: Like speech, understanding speech is highly context dependent. Speech is both rich communication, and depends on the context around. But then understand touch is as well. If I touch you, it also may have many means depend on the context. A robot could speak or communicate without standard context, but normally I would get wrong or miss-understand. A robot with very limited speech ability but with a high level understands of context of the speech, will be useful and practical. And if a robot is very good at speech and bad in understand the context of speech, if you think about a robot translator. The interest thing is when robot does not understand about the context of speech, because they miss-understand the space around them. And I think a robot to be completely complex, and then it has to understand the context as well as having the communication ability.

HF: So if a robot has a good speech but low level in understand the context, does that mean the robot is low level in autonomy?

RW: Low level in sophistication. Autonomy is something else. Remember that the system can hold conversation with you, it is not necessary at all autonomous. It may not make any decision simply at all the conversation with you.

HF: So in this point of view, normally is jus related to sophistication.

RW: yes,

HF: and, I want to clarify that if we want to describe autonomy, then we can describe it from decision making ,sensors,

RW: I think I would only look at it from decision making. Where the decisions were made. By the human or by the robot. The fewer decisions made by human, the more autonomous the robot it is.

HF: So not quite related to the sensors?

RW: Sensors will be necessary for decisions to be made, but I think you could describe these two, how decision is made. We can be told how autonomy it is without knowing how it did that. It is very orthogonal capability.

RW: If I say tell a robot to go out, find a mine, measure the type, and location of mine, and back to tell me. We can say that robot is pretty autonomous. You do not need to know how robot did that. Like robot in undersea using sonar, or flying robot using radar, no matter by radio or other sensors. Any of those were work, what happen is that we build a robot performing a task with levels of autonomy.

HF: so if we want to judge autonomy level of robot, we will do not need to know how much sensors or which sensors is used.

RW: I think you can be very precise but fairly autonomy without a set of sensors.

HF: Interesting. Before I do not get in touch with people in industry enough

HF: in your experience, the situation awareness , how much does it related to decision

making

HF: When making decisions, then there should be some data and information.
I wonder the term: situation awareness is the wrong term. Why situation awareness is used, but I think that term is used in a particular way of thinking about decision making. I do not know machine make decision in the same way. The machine has to understand the context, which maybe the same as situation awareness. But machine will have

RW: something other we think of situation awareness in order to make decisions.

HF: when a machine do a decision making, normally based on the data from sensors, and process it into some information, formulate,

RW: Yes, compare with inside data, if something different, not like what I want, then I will do something different. That is the decision being made. The number of ne.. Level we doing that, it is the autonomy level we define decision making..

RW: Whether or not having situation awareness, may or may not matter. It is a convenient term for someone else with you.

HF: Yes, normally maybe from human factors point of view.

RW: Human can consider a few type of things at the same time, and robot can consider all the things at the same time, may not matter, we may think about the way machine make decisions.

HF: In future, robot may have some moving ability. Before we talk moving ability, we talk it from degree of freedom, how about the navigation / localization, I am not sure is it part of freedom or not?

RW: I can say that localization will be useful for intelligent system, but it will not be necessary.

RW: a robot with very simple navigation but very high level autonomy

HF: if a robot has navigation in mobility, does it mean that the robot is more sophistication? Not sure, it depends on sophistication. The sophistication is about the presentation of robot with user, user's feel about robot. It depends on how they interact with robot

RW: depend on the navigation.

Dialogue 2:

HF: my research project is about knowledge management support for through life management of autonomous system

PM: Knowledge management, through life management, autonomous system. Ok

PM: So really what you looking at are when giving an intelligent system, you are looking at the data, information, and you are looking at life cycle setup, and so on.

HF: and most of the situation is based on the human assistive robot area

PM: so really area are robot that interact with human beings, personal robot, what even be include application like clean hotel room robot,

HF: just that can supply service to human beings,

PM: Industry robot is that include in your area or not really.

HF: Not really, the most of the research is focus on future's human assistive robot. I mean that robot may have high level autonomy

PM: yes, you may get that level.

PM:	there are lots of systems in industry that are robots that are highly autonomous with some degrees of human operate
HF:	And currently I am focus on development of a generalized model for levels of autonomy for human assistive robot. The model is proposed to evaluate how much autonomy a robot has.
PM:	ok
HF:	And from this part of interview, I try to understand whether the model is good enough to evaluate autonomy or not.
PM:	Ok I can give you my project that you can do, and I can give my view that what you are looking for. The areas we work here are certainly closed to your interest. But I would say they are not exactly too. ...Some of the work we did is very much both autonomy or robotic, but not lots of it. i just try to get a project started with collaboration in Moscow, Russia. The subject is about autonomous system in mechanical robot system. That is very new idea; we have done some work before.
HF:	So in your experience, what does autonomy mean for a robot? How can we say that a robot has some levels of autonomy?
PM:	possibly it is the ability of a robot or a machine to insure() information from environment, and based on that, information makes decision, or call reaction, but it would normally be make those decisions just fit the goal or task
HF:	When I do this research, I also do some literature view; one of the definitions of autonomy is like here… autonomy is ums…
PM:	Well, that is more comprehensive, but fundamentally, you use sensor objects to scan environment, take information, and that might be vision sensor, laser, it might be radar sensor. Data or information will allow it to move or avoid object. It might be very high level, or it might be very simple. And typically industry robot its application may be very simple.
PM:	The project might be constrained with interaction, cleaning operation in a house, sensor to environment. Move
PM:	Sensors ==collect information, analyse information, moving. The input is the knowledge/ information of environment. In terms of autonomous system, it is depends on how designer…….
PM:	you are trying to catalogue different types of autonomy
HF:	I am trying to describe autonomy in some formal words.
PM:	Interest. Challenges
HF:	Here, I draw a map based on the definition, and try to understand what autonomy of a robot mean for user or customer. As in this map, some of components are related to sophistication. Some are related to autonomy.
PM:	.. Not exactly consider the type of device, if you take mobility for example, move between 2d. The degree of autonomy there is at very high level. The complex of unmanned machine / your autonomous machine, you need to define. The human motion. That want to be put into simulate. And autonomous machine want to interpret this behaviour, even there is no purpose about what i am doing.
HF:	Yap, for example, if you are speaking to robot, but then use gesture to show another information, then robot may not catch up your meaning.

PM:	Human use vision, smell, touch, ear... To pick up information from outside environment, a robot only has limited range of sensors; it might be vision, it might be radar... Its level of perception defends on sensor information. The full information is really limited. Not exactly, as you have done research in robotic... very difficult. I think you have got a difficult task.
PM:	I want to say that the physical complexity of a device itself must be one element that the way you define your autonomy
PM:	the level of autonomy / the scale of autonomy will be great
HF:	So there may be two aspects to describe human assistive robot: one is from physical aspect, another is from ...
PM:	I think what you call mechanical ability could be one.
HF:	In my previous idea, the mechanical ability is mainly considered about payload. Like heavy / light object
PM:	an issue of scale, like industry robot, small industry robot, only has certain ability of payload, or you can have a much larger machine, which is identical in form, and the way of control, but particularly larger, but it does not mean any degree of autonomy, both structure require the same level of autonomy. I am not really thought about this before, as it is not my area directly. Both you are looking for the some degree of physical structure for a form of a device, some degree has influence some sophistication or levels of autonomy.
HF:	From my project aspect, I am trying to describe autonomous system from autonomy aspect and sophistication aspects two aspects for the system.
HF:	Like mobility, mechanical ability, we will consider more about sophistication. For moving ability, some of its attributes are related to autonomy, and some of them are related to sophistication. For example, for mobility, it can have navigation, speed. The navigation is more related to autonomy, and the speed is more related to sophistication. For example, if there are two robots, which has the same navigation, but different speed, the faster will have higher sophistication, and the same level of autonomy.
PM:	Would you mean faster will be more sophistication? I have thought about this.
PM:	For example, you could think a car with a big engine, then it will go with more power, but it cannot necessary more sophistication. A robot may have a drive motor, then another one, it may have bigger motor, with the same structure, and then it will accelerate /decelerate more quickly. But I am not sure it will be more sophistication.
HF:	In your mind, the mobility. The measure of mobility in mobility are from which aspect
PM:	Mobility in robot is an issue of mechanical configuration, the degree of freedom, the number of joints, but also redundant, design redundant for the flexibility. Like snake robot,
PM:	Sophistication that related to mobility: one thing is about redundant, but nothing to do with speed. It is more about configuration flexibility.
HF:	One example could be: a robot has several type of mobility, for a plain ground, the wheel will move much quicker. And for stairs, the bipedal type will be more convenient.
PM:	yap
HF:	then in future's domestic robot, it may have several types of mobility integrated within one robot, and makes the application more convenient.

PM:	Could be. There is argument, that robot are more likely to be cost-effective, and also efficient. In terms just taking one task. Example of domestic robot, just like vacuum cleaner, all it does is just navigation, plan the services, identify when to recharge it, and can do its task very effective. And because of the type of device it is, it can be manufactured sufficient value, cost-effective. Again, it needs high degree of autonomy, but only to do the task.
PM:	It cannot do any damage to furniture, to pets, or humans, so it needs high level of safety, again which it need to be autonomy, but it should be a specialised device.
	Another issue is.
HF:	Some people say that in future environment, one possible solution for robot will be that a set of robot will work together to achieve some goals, they need to corporate with each other.
PM:	Cooperative, coordination. Which again define another level of sophistication / autonomy required, because not only look at their own behaviour; they have to corporate with other robot. that is really agent / software engineering
HF:	One aim of this model is also trying to consider about: if we can this kind of model to evaluate levels of autonomy for robot, then in some stage of its lifecycle, it may be used to corporate with other robot. If we know how much autonomy it is and its autonomy's composition, then it will be easier for user to make decision whether they can corporate or not.
PM:	Yap. If you talk about domestic robot, at the moment, I cannot think there is a wide application where you want robot to corporate together, in industry robot, there are many examples where you want robot to corporate with each other. There is good example, like consumable, you want one component into another, one machine should execute very accurate to put one component into another component.
PM:	A very critical need to corporate. …. Very high speed conveys system….
PM:	In domestic area, I am not sure it will be applied. There probably an example, but I cannot think one.
HF:	In my mind, in the future, some robots may have speech ability, they may communicate with each other to achieve a task.
PM:	I think if they have such ability, they will communicate with the user, rather than with robot. Interesting questions.
HF:	Yap, in this research, I just feel that it is a bit abstract..
PM:	yes
HF:	Also, in your description, you have many words cover with sensors, I mean if we try to measure sensor ability, is it possible to measure it in a general way? For a robot system, how can we say that this robot has powerful sensor ability?
PM:	I would thought what you probably look at is in a way, the term depends on the vision,… in terms of action or decision, you need to process that information together, to come out a more reliable action ,based on a number of sorts of information. And certainly the machine will derive information from lots of different way. It should be much more reliable. The machine will use one sort of information to make decision, and that get an element… it is ability of taking more supportive information. Those sensor devices may be intelligent device in their own right, and take physical measurement, and turn out to useful information, which can be used for decision making.

HF: So the sensor ability is also related to sophistication?

Mechanical sophistication, in terms of configuration. You also got sensor sophistication, in terms of degree of range sensing. Are they high revolution sensors? Are they low revolution sensors? How does information integrated? Then to make a formal decision. It was not my area. What may be interest is to speak to some computer scientist. For the particularly information about Artificial intelligent domain. They have a well development of definition. The ability to make decisions. Or

PM: decision making ability as well.

PM: For defence area, when you take information, knowledge, which then informs your actions? Which will go for the whole process of analysis, and so on?

PM: How measure, I do not know. Possibly they have some formal definitions. Or you may already speak to computer scientists.

HF: When you talking about autonomy, most of situation you will consider about decision making, how do you think that decision making relate to sensor awareness……

Decision making. A measurement of autonomy. Element of robot make decision. The rest will decide how robot behaves. Lots of work around is just about decision making. They just get certain information. Gather information --process information --->decision making. It is definitely not my area. But decision making is critical to

PM: autonomy and level of autonomy...

HF: speed not related to sophistication

PM: speed could be

HF: mechanical ability, not related to speed

Not exactly. Speed could be. But it is more related to configuration. The sophistication of mechanical system. The combination of mechanical system. Power

PM: available, it is critical important factor for robot system

yes, the aim of robot is to supply service for human beings, the mechanical ability is

HF: the way to carry out task

PM: yes

HF: move ability / mobility

PM: that would be part of mechanical ability

HF: Ok. It will be integrated together

PM: Mobility, it is mechanical design. It will constraint what robot can do

Sensors ==collect information, analyse information, moving. The input is the knowledge/ information of environment. In terms of autonomous system, it is

HF: depends on how designer…….

Sensors are the input for decision making. It is critical role. But that only one component for decision making. Another aspect is supervision for the control. For high level autonomy, robot may need to identify task that would be high level autonomy. Because it can..The autonomy is about the ability to identify task, it is not

PM: told by human command. it is based on its own decision

HF: For robot system. From which aspect you think it is sophistication

PM: I suspect, it is from decision making. Look at some of the definition

Appendix III: Tool requirement specification

1 User:

Through stakeholder analysis, the users in this tool are mainly designers in the area of robotics and customers who wish to use robots to assist with their daily life.

2 ALFHAR Tool overview

2.1 User requirement

The computer software tool of ALFHAR is considered to be used as a tool for evaluation of levels of autonomy and sophistication, which should evaluate a human assistive robot's capability from decision making, mobility, interaction, degree of freedom, and system configuration aspect. The evaluation criteria in the tool should be the same as the description in the ALFHAR model, and can be selected from the tool during the evaluation.

2.2 Benefits from this tool

1. User can save time on the evaluation of capability of human assistive robot using the tool instead of the ALFHAR model, and it will make the evaluation process more conveniently and easily.
2. The tool will supply a great support for verification and validation work in the current.
3. Make the evaluation stored easily and convenient for update.
4. Support the ALFHAR model in a wider publication.

2.3 Summary of system capability

The ALFHAR tool will provide the following capabilities to users:

- Search evaluation history through the tool.
- Create new evaluation, which includes robot information input, its functions description input.
- Update or delete robot information / its functions information
- Do an evaluation based on the robot functions description in the tool.
- Update evaluation
- View an evaluation through graphic figure.

3 Functional requirements

A general functions in this tool is described through use case in Figure 1. There are more details on what those functions mean in this tool.
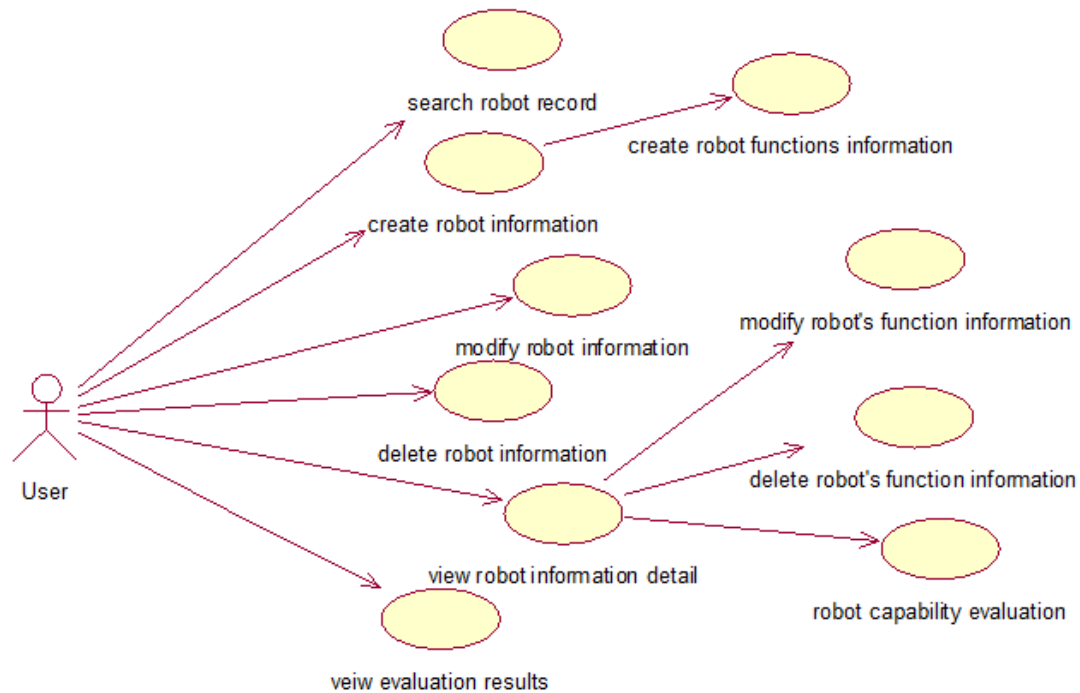

Figure 1: Use case diagram for tool

The functional flow diagram is shown as Figure 2:

APPENDIX III
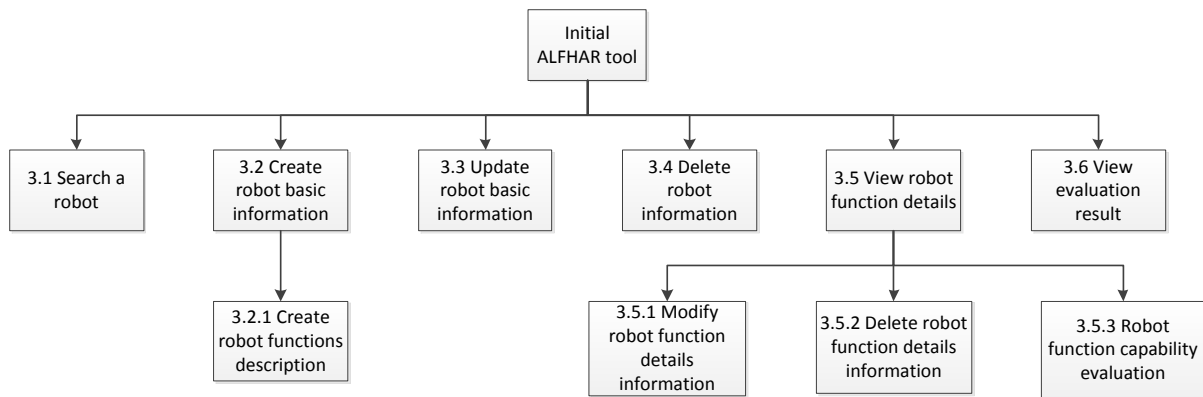
Figure 2: Tool functional flow diagram

3.1 Search a robot

The system should allow user to search a robot to find any evaluation related to this robot in the tool.

3.2 Create robot basic information

The system should allow user to create new robot information within the tool, which is the object that will be evaluated by this tool. The information must include robot name.

3.2.1 Create robot functions description

The system should allow user to input functions details related to the created robot information that is to be evaluated by this tool. User can choose some proper evaluation dimensions that link to the input functions.

3.3 Update robot information

The system should allow user to update robot information in the tool

3.4 Delete robot information

The system should allow user to delete robot information from the tool.

3.5 View robot function details

The system should allow user to view robot functions detail which was created by user.

APPENDIX III

3.5.1 Update robot functions description

The system should allow user to update functions details in the tool, also the links to some proper evaluation dimensions.

3.5.2 Delete robot functions description

The system should allow user to delete functions details in the tool.

3.5.3 Robot function capability evaluation

The system should allow user to create evaluation for the robot functions details in the tool. User can input scores directly in the tool or they can do an evaluation through evaluation support, which will list all of evaluation criteria within the dimension in the evaluation.

3.6 Show evaluation result

The system should allow showing a graphic figure for user on the whole evaluation results of each function.

Appendix IV: Source code for the web-based tool

```java
/**

 * create a new robot*

 */

public void saveAsrobot() {

        dataItemId.setValue(this.getAsrobotBO().getName());

        if (this.checkName()) {

            System.out.print("Robot is already exist");

        FacesContext.getCurrentInstance().addMessage("form1:uname",

                    new FacesMessage("name is exist."));

        } else {


            try {

                Asrobot ar = new Asrobot();

                ar.setName(this.getAsrobotBO().getName());

                ar.setHigh(this.getAsrobotBO().getHigh());

        ar.setManufacture(this.getAsrobotBO().getManufacture());

                ar.setWeight(this.getAsrobotBO().getWeight());

                ar.setYear(this.asrobotBO.getYear());

    this.asrobotservice.saveOrUpdateAsrobot(this.getAsrobotBO());

            } catch (Exception e) {

                e.printStackTrace();

            }
```

```java
		}

	}

	/**

	 * save robot functions

	 */

public void saveAsrobotFunctions() {

		if (this.getRodetailBO().getFunctionDetail() == null

				|| this.getRodetailBO().getFunctionDetail().length()
<= 0) {


	FacesContext.getCurrentInstance().addMessage("form2:function1",

				new FacesMessage("please input functions
details"));

		} else if (this.getRodetailBO().getAbbrCode() == null

				|| this.getRodetailBO().getAbbrCode().length() <= 0)
{

			FacesContext.getCurrentInstance().addMessage(

					"form2:abbrcode",

					new FacesMessage(

							"please input brief code for the
functions"));

		} else {


			try {

				int a = selectItemValue.size();

				for (int i = 0; i < a; i++) {
```

```java
                        System.out.print("select item is 1"

                                + selectItemValue.get(i));

                        String r =
String.valueOf(selectItemValue.get(i));

                        Asrobotdetail detailbo = new Asrobotdetail();

        detailbo.setRobotName(this.getAsrobotBO().getName());


        detailbo.setFunctionDetail(this.getRodetailBO()

                                .getFunctionDetail());

                        detailbo.setTypeCode(r);

                detailbo.setAbbrCode(this.getRodetailBO().getAbbrCode());

                this.asrobotservice.saveOrUpdateAsrobotdetail(detailbo);

                    }

                } catch (Exception e) {

                    e.printStackTrace();

                }

            }

        }

        /**

         * go to standard select page

         * @param standardList selected item in the list

         * @return string

         */

        public String gotoStandardSelect() {

            this.rodetailBO = (Asrobotdetail) this.dataTable.getRowData();
```

```java
String par1 = this.rodetailBO.getTypeCode();

this.standardList = new ArrayList<SelectItem>();

        this.dataItemId.setValue(this.rodetailBO.getId());

if (par1.equalsIgnoreCase("decision making")) {

    this.standardList

                    .add(new SelectItem("0",

                            "level 0: Whole task done by
human except for actual operation"));

    this.standardList

                    .add(new SelectItem("1",

                            "level 1: Human asks robot to
suggest options and human selects"));

    this.standardList.add(new SelectItem("2",

                    "level 2: Robot suggests options to human"));

    this.standardList

                    .add(new SelectItem("3",

                            "level 3: Robot suggests options
and proposes one of them"));

    this.standardList

                    .add(new SelectItem("4",

                            "level 4: Robot chooses action &
performs it if human approves"));

    this.standardList

                    .add(new SelectItem("5",

                            "level 5: Robot chooses action &
performs it unless human disapproves"));
```

```
                    this.standardList

                            .add(new SelectItem("6",

                                    "level 6: robot chooses action,
performs it & informs human"));

                    this.standardList

                            .add(new SelectItem(

                                    "7",

                                    "level 7: Robot does everything
autonomously, understands its environment thoroughly"));

            } else if (par1.equalsIgnoreCase("degree of freedom")) {

                    this.standardList

                            .add(new SelectItem(

                                    "1",

                                    "level 1: degree of freedom is
1;1-Dimension, moving forward/backward, or up and down, or left and right
"));

                    this.standardList

                            .add(new SelectItem(

                                    "2",

                                    "level 2: degree of freedom is 3;
Two Dimensional (2-D) space, moving forward/backward, up and down, or left
and right; "));

                    this.standardList

                            .add(new SelectItem(

                                    "3",
```

```java
                                            "level 3: degree of freedom is 6
(configurable); 3-d dimensional space, Heave: Moving up and down Surge:
Moving forward and backward "

                                            + "Sway: Moving left
and right Rotations Yaw: Turning left and right flight"

                                            + " Roll: Tilting
side to side Pitch: Tilting forward and backward "));

                this.standardList

                        .add(new SelectItem("4",

                                "level 4: degree of freedom is
more than 6; 3-d dimensional space; "));

                this.standardList

                        .add(new SelectItem(

                                "5",

                                "level 5: degree of freedom is
more than 6; configurable, redundant design; 3-d dimensional space; "));

        } else if (par1.equalsIgnoreCase("mobility")) {

                this.standardList.add(new SelectItem("1", "level 1: Can
move in static environment on a plain ground"));

                this.standardList.add(new SelectItem("2", "level 2: Can
move in dynamic environment, which involves human beings, living animals on
a plain ground"));

                this.standardList.add(new SelectItem("3", "level 3: Can
move in a static environment on rough terrain around, or stairs, steep
hill"));

                this.standardList.add(new SelectItem("4", "level 4: Can
move in dynamic environment, which involves human beings, living animals on
rough terrain around, or stairs, steep hill;"));

                this.standardList.add(new SelectItem("5", "level 5: Can
move in dynamic environment, which involves human beings, living animals on
```

```java
rough terrain around, or stairs, steep hill, while changing whether
condition, like windy, light condition, wet / slip ground, and so on"));



                } else if (par1.equalsIgnoreCase("interaction")) {

                    this.standardList.add(new SelectItem("1", "level 1: Robot
is able to show limited kind of interaction by one type of interaction,
like touch, voice, gesture, and do not understand the context of
interaction"));

                    this.standardList.add(new SelectItem("2", "level 2: Robot
can learn some limited interaction with humans"));

                    this.standardList.add(new SelectItem("3", "level 3: Robot
can understand some of interaction with humans, and is able to communicate
with humans with some kind of interaction"));

                    this.standardList.add(new SelectItem("4", "level 4: Robot
can understand/ recognize the multi-meaning of some interactions; and is
able to show some kind of interaction"));

                    this.standardList.add(new SelectItem("5", "level 5: Robot
fully understands whole information supplied from humans, and is able to
show some kind of interaction "));

                } else if (par1.equalsIgnoreCase("system configuration")) {

                    this.standardList.add(new SelectItem("1", "level 1: No
configuration, just based on original design"));

                    this.standardList.add(new SelectItem("2", "level 2: Has
some agility in system configuration to execute a task (e.g. speed setting,
length...)"));

                    this.standardList.add(new SelectItem("3", "level 3: Has
adaptive design for executing tasks in different condition."));

                    this.standardList.add(new SelectItem("4", "level 4: Has
some agility in system configuration to execute different tasks"));

                    this.standardList.add(new SelectItem("5", "level 5: Has
high agility in system configuration to execute different tasks or in
different systems corporation"));
```

```java
        }

        return "standard_list";

    }

    /**

     * draw a map for evaluation result

     *

     */

    public String drawChart(HttpSession session) throws Exception {

                    this.asrobotBO = (Asrobot)
this.dataTable.getRowData();

        List<Asrobotdetail> arlist = new ArrayList<Asrobotdetail>();

        arlist =
this.asrobotservice.findAsrobotdetailbyName(this.asrobotBO.getName());

        DefaultCategoryDataset dataset = new DefaultCategoryDataset();

        if (arlist.size() != 0) {

            for (int i = 0; i < arlist.size(); i++) {

                this.rodetailBO = arlist.get(i);

                if (rodetailBO.getTypeCode().toString().equals("1"))
{

        dataset.addValue(Integer.valueOf(this.rodetailBO.getLevel()),

        this.rodetailBO.getAbbrCode(), "decision making");

                } else if
(rodetailBO.getTypeCode().toString().equals("2")) {

                        dataset.addValue(Integer

    .valueOf(this.rodetailBO.getLevel()),
```

```java
                                                        this.rodetailBO.getAbbrCode(),
"degree of freedom");

                        } else if
(rodetailBO.getTypeCode().toString().equals("3")) {

                                dataset.addValue(Integer


        .valueOf(this.rodetailBO.getLevel()),

                                                this.rodetailBO.getAbbrCode(),
"mobility");

                        } else if
(rodetailBO.getTypeCode().toString().equals("4")) {

                                dataset.addValue(Integer


        .valueOf(this.rodetailBO.getLevel()),

                                                this.rodetailBO.getAbbrCode(),
"interaction");

                        } else if
(rodetailBO.getTypeCode().toString().equals("5")) {

                                dataset.addValue(Integer


        .valueOf(this.rodetailBO.getLevel()),

                                                this.rodetailBO.getAbbrCode(),

                                                "system configuration");

                        }

                }

        }

        String fileName = "";

        // title
```

```java
        StringBuffer title = new StringBuffer();

        title.append("title");

        // dataset

            CategoryDataset dataset1 = dataset;

        // dataset

        // create chart

        JFreeChart chart = ChartFactory.createBarChart("robot
capability",

                    "autonomy and sophystication", "level", dataset1,

                    PlotOrientation.VERTICAL, true, false, false);

        CategoryPlot plot = chart.getCategoryPlot();

        CategoryAxis domainAxis = plot.getDomainAxis();


    domainAxis.setCategoryLabelPositions(CategoryLabelPositions.UP_45);

        ValueAxis valueAxis = plot.getRangeAxis();

    chart.getRenderingHints().put(RenderingHints.KEY_TEXT_ANTIALIASING,

                    RenderingHints.VALUE_TEXT_ANTIALIAS_OFF);



        FileOutputStream outStream = null;

        try {

            ChartRenderingInfo info = new ChartRenderingInfo(

                    new StandardEntityCollection());

            fileName = "/servlet/DisplayChart?filename=";

            fileName += ServletUtilities.saveChartAsPNG(chart, 400,
250, info,
```

```java
                        session);

        } catch (Exception e) {

            e.printStackTrace();

        } finally {

            try {

                // outStream.close();

            } catch (Exception e) {

                e.printStackTrace();

            }

        }

        this.setFileName(fileName);

        return fileName;

    }
```