SHIBAURA INSTITUTE OF TECHNOLOGY

Automatic Initialization System for Home-based Robotics Service Environment

By

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Declaration of Authorship

I, NUR SAFWATI BINTI MOHD NOR, declared that this thesis titled, ‘ AUTOMATIC INITIALIZATION SYSTEM FOR HOME-BASED ROBOTICS SERVICE ENVIRONMENT’, and the work presented in it are my own. I confirm that:

- This work was done mainly while in candidature for a research degree at Shibaura Institute of Technology, Tokyo.
- Where any part of this has previously been submitted for a degree or any other qualification at this university or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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ABSTRACT

This research introduced an initialization system for robot service in order to support human daily-life activities at every individual home environment. Nowadays, robot service has become significant solution to the rising of elderly people in the sense that robot may help to ease or support their daily routines at home such as bring an object from one place to another or tidy-up the living space as well as storing the objects to the right place. Because of elderly people mostly spend their time at home daily, service robot is expected to co-exist with human so that robot can give assistive service to them. However, robot has to acknowledge the information embedded in the environment itself before introduce the robot service at actual 3D spaces. For instance, information on furniture location and arrangement at home may help the robot to perceive and recognize the object's location that is located on or near the furniture surface. By using sensors attached to the objects in order to identify object's location and along with service robot system itself, it is time and cost consuming to setup database of the first seen environment. This is one of the essential issues of daily life service robot. If the furniture's information can be initialized before introducing robot service, it would be easy and effective to demonstrate it at first-seen environment which suits individual life-styles.

Apparently, vision technology is one way for robot to understand the environment thus obtain required information related to robot service. By using robot-mounted camera, the images for an environment can be analyzed by employing image processing technique. For example, the 3D information of objects in the living environment can be acquired from the point cloud data that is generated by depth camera. The usefulness of these point

cloud data for robot service is that it represents the external surface of an object. In other words, the point cloud is able to describe the shape and corners for objects like furniture in the living space. Meanwhile, exact furniture dimension is crucial whenever to generate robot service to human safely. A reference database which has the actual furniture 3D structure can be used as the information sources thus confirm on the estimation measurements from depth camera. Online database like furniture catalogue contains complete information about a product such as color, size/dimension and assembly instruction. Since online catalogue is updated regularly, it is easy and appropriate to be referred to. As a result, robot is able to perceive human 3D space according to their living lifestyles and preferences especially on the furniture list.

Therefore, by using above ideology, this research is proposing to initialize the first-seen human living environment which implementing consumer-level depth camera such as Microsoft Kinect Xbox as well as the floor layout software, Microsoft Office Visio. The result showed that this initialization system is able to give several number of candidates for the furniture based on its category such as sofa, TV bench and so on from the online catalogue. Besides, this research also develops a system plug-in to link the information from depth camera and online catalogue in one platform for building up the 3D individual environment model.

Finally, the method presented in this dissertation may benefit the robot service by need not to measure furniture dimension to get its physical 3D attributes since information such as size and number of drawers can be automatically extracted from the furniture catalogue. In addition, this initialization system could be a basis to many robot service applications and provide assistive service at every home easily and successfully.

Dedicate to Akio and Hiro.

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Abbreviations

RT	Robot Technology
SOM	Semantic Object Mapping
KnowRob	Knowledge Processing for Autonomous Personal Robot
Kukanchi	Interactive Human Space Design and Intelligence
RFID	Radio Frequency Identification
HRI	Human Robot Interaction
SLAM	Simultaneous Localization and Mapping
FOV	Field of View
ECD	Equivalent Circular Diameter
HMD	Head Mounted Device

Chapter 1

INTRODUCTION

This dissertation proposes and explains the research work on automatic initialization system for robotics service environment at home. This is one of the most important requirements in order to bring Robot Technology (RT) to a living environment such as our home. The main idea of this research is to prepare the initial setup information which is essential and inevitable for robot to introducing service to human at home environment easily. This chapter describes the overview of this research as well as research objectives and goals.

1.1 Research Background

In these recent years, the worrying rise of senior citizens or elderly people in a country has become global issue in world population discussion (Figure 1.1). Reported in 2013, a record-high 30.79 million people or about a quarter of Japan were over 65 years old, increase 1.04 million from previous year according to an estimate released by the Japan government. In addition, the National Institute of Population and Social Security Research expecting 1 in 2.5 people in Japan will be over 65 years old and 1 in 4 people will be over 75 years old by 2060. As a result of this aging situation, the number of older people living alone at home is also increasing.

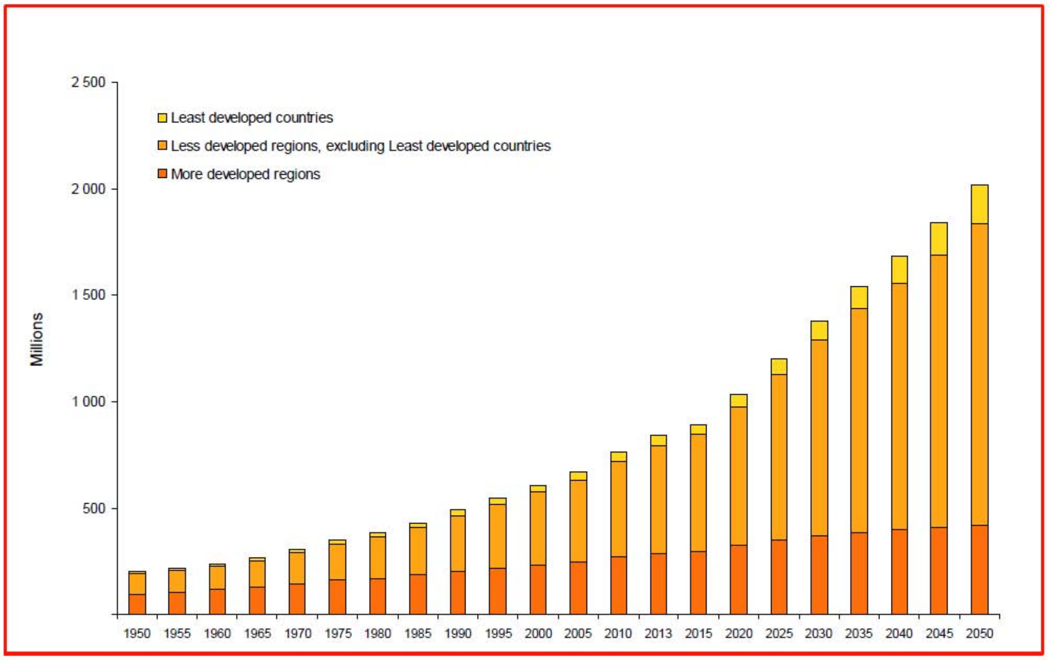
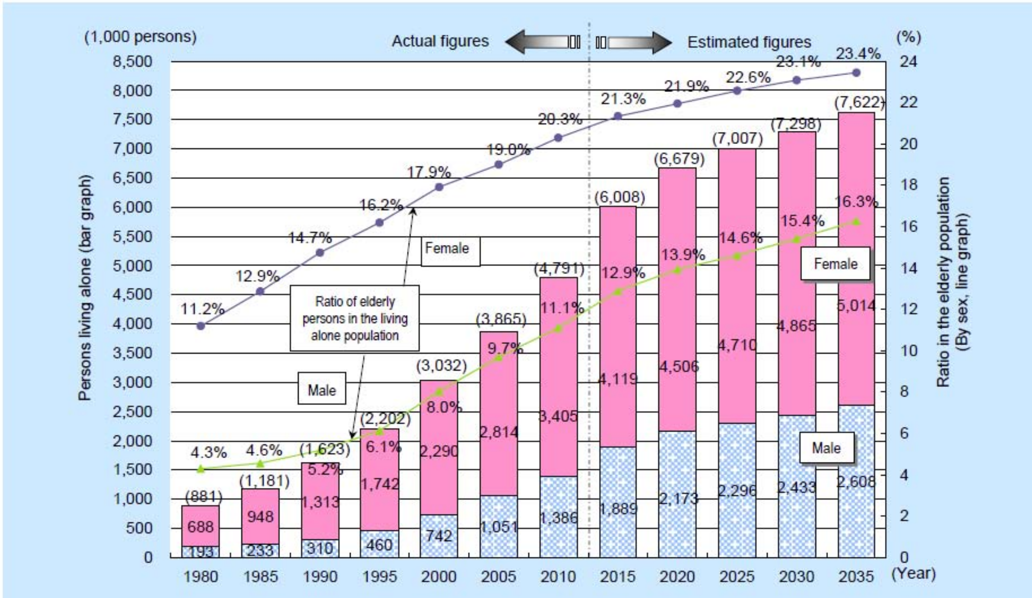


Figure 1.1 Population aged 60 years or over by development region [1]

The increase in elderly people in Japan living alone is remarkable for both males and females as shown in Figure1.2. Percentage of elderly people living alone against the total population of elderly people was 4.3% for males and 11.2% for females in 1980. However in 2010, these numbers turned out to be 11.1% for males and 20.3% for females. To face this aging problem, it is crucial to provide a daily-life support system using service robot to ease and help human especially these elderly people at home so that they can enjoy a more independent life.

Normal individual home environment can be considered as a very dynamic and challenging environment for robot system. This is due to the distributed information or knowledge embedding in the environment depending to variety of individual life-styles. In order to support human daily-life activities at home, the robotic service has to be easily generated and not burden the user.



Source: Ministry of Internal Affairs and Communications "Population Census" till 2010, and after 2015, National Institute of Population and Social Security Research "Future number of households estimates (estimated on January 2013)," "Future population estimates (estimated on January 2012)"

(Note 1) "Living alone" indicates the one-person households of the above surveys and estimates.

(Note 2) In the bar graph, ( ) shows the total number of living alone males and females aged 65 and over.

(Note 3) As a result of rounding, the numbers do not necessarily add up to the total shown here.

Figure 1.2: Trends of elderly persons living alone [2].

Due to robot is expected to co-exist and lives with human, symbiosis between human and robot is very important. Symbiosis is the shared understanding between human and robot. There are many aspects of human-robot symbiosis, but this research focuses on the scenarios where robot is able to understand human activities and provide assistive service when necessary. To realize it, information in human home environment must be populated so that service robot will be able to execute the robotic tasks safely and effectively.

Environmental information can be achieved by an individual home environment model. The generation of three-dimensional model of the environment is an advantage and a key pre-requisite for various robotic systems [3]. For instance, service robot will be able to locate objects in 3D space and knows its correct location to be stored [4]. Hence, an appropriate robotics services can be delivered by the robot to user for their daily life activities referring to object locations in the environment. Specifically to provide a robotics service at home, robotics system needs to be aware and detect the main aspects in each individual house such as floor plan, room type and furniture arrangement. To counter this problem, it will be costly to build every home with RT functionalities like sensor or camera and at the same time along with service robot system itself, it is not appropriate to design different robot software for each house. According to the view point of HRI Laboratory's approach, I extend this approach by proposing the method to initialize the unknown or first-seen living environment thus create 3D environment model contains useful information for robotics service which can be applied at every home. In this research, the 3D information of furniture structure and storing functionalities is measured by using image segmentation method. Based on several algorithms in image processing, the 3D data can be measured as an estimation dataset for robot to determine the exact furniture 3D information.

In the robotic service context, this research defines the word "initialization" as a process to provide initial information about object's location at home environment to the robot before introducing robot service. This process can be done by embedding the useful information to environment map thus make robotic service can be easily realized in human daily-life environment. Also, this initialization system may represent an initialized environment with several candidates of furniture based on data from the depth camera and furniture catalogue. Figure 1.3 illustrates our approach and research positioning. As known, furniture is considered as large and heavy objects in the 3D space which their positions are often unchanged. Due to this, furniture position can be set as 3D referenced coordinates for the robot to locate small objects in the living environment. And since the furniture is static or rarely changed, this initialization of robotics service environment may be done only once or a few times. In addition, by using furniture's catalogue database for this initialization system, crucial information like the position and total numbers of drawers present can be extracted and need not to be measured. Consequently, this initial information of environment setup of furniture could be used in many robot service's applications in order to define the commonsense knowledge for robot like object-place relationship. Hence, robot is able to identify the object's location in 3D space and provide appropriate service in human daily-life intuitively.

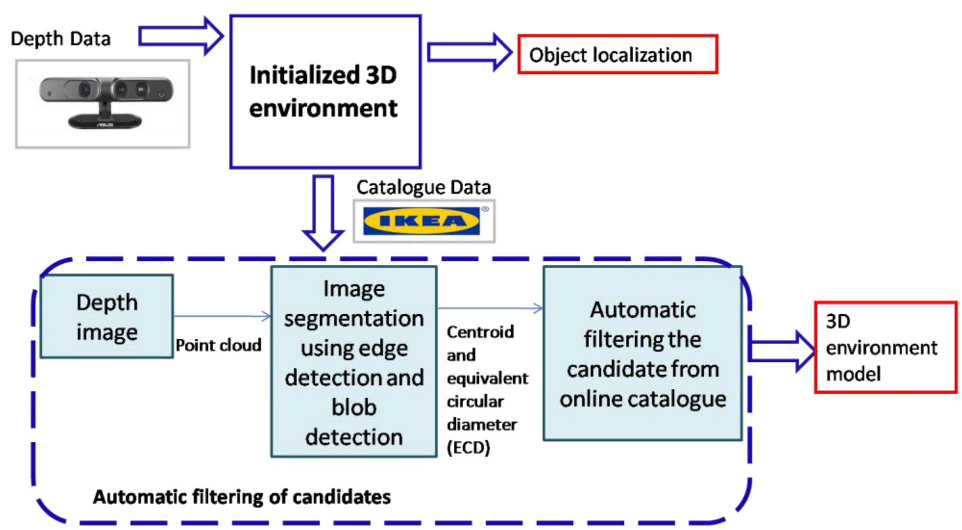


Figure 1.3 Basic idea of the research

1.2 Motivation

Despite the progress made so far in the related research area, little attention has been given to acquire the environment information beforehand and embed it to the environment map. Most of the research realized robotics service in real 3D space by using pre-defined demonstration environment. This method caused problem which it was time consuming as well as costly to setup database for first-seen environment since it involves human intervention as well as many type of sensors. In addition, it will create a messy and tiring setup process especially when the environment is unknown to the robot. Besides, environment map mostly is being used for robot navigation and obstacle detection purpose [5]. Rather than map the free and occupied space, this research develops the initialization system that maps the objects (furniture) in the 3D space. For navigation, the robot just requires information about the unmapped area and either there is obstacle or not in the robot's path. However, in robotic service scenario, 3D location or coordinates of large object like furniture is essential information in the sense that it helps to track small objects in the environment (Figure 1.4). Furthermore, initialization of the environment allows automatic reconfiguration to suit user's preferences [6]. In this way, this initialization system may bring a standard configuration robot system to the complex daily-life environment and can be applied to every house.

How this initialized environment affects human robot interaction in the intelligent space? Service robot needs information of object location in the 3D space.

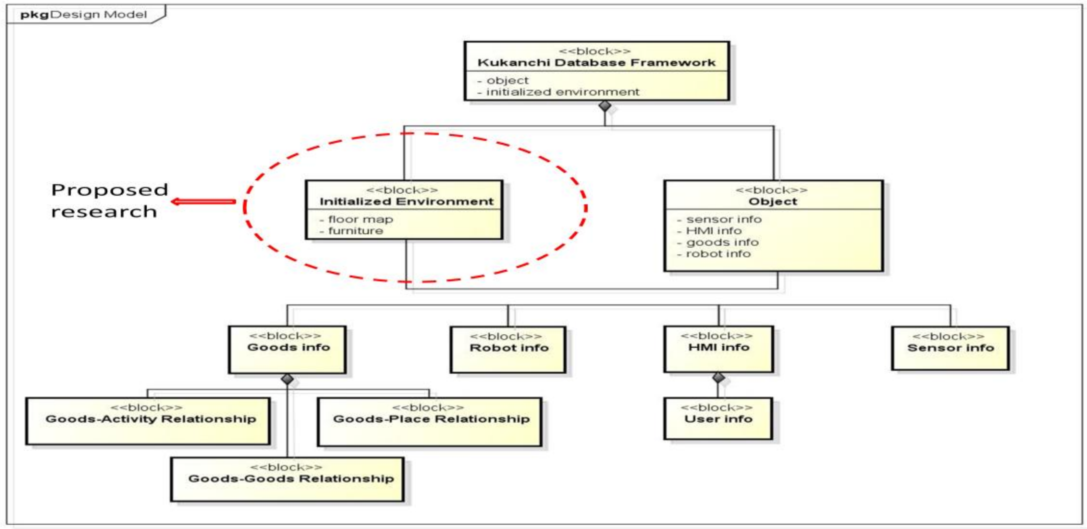


Figure 1.4 Positioning of the research

However, the trend of research activities in human robot interaction field, useful information of the living environment is extracted through distributed sensors thus provides various services to user [7]. From this environment observation or object manipulation, physical objects are manipulated by storing computerized information to the real world. Based on this observed information, robot may know what to do and where to go if user gives request by gesture or other ways. However, this method is not appropriate whenever to apply the concept of intelligent space to every individual homes which is unique. Also, it is difficult to attach sensor to each household furniture and appliances in order to obtain the 3D object information. Instead of using physical sensor to define the objects, a more effective and easier way to initialize the environment for robotic service is needed. Moreover, object database which available online such as furniture catalogue contains 3D attributes which define furniture's size, structure and articulation. This information can be added to the environment map to initialize every individual home efficiently.

1.3 Goals and Objectives

The main goal of this research is to provide initial information of the object (furniture) location with attributes such as structure and storing functionalities hence to prepare the unknown living environment with this information for delivering robotic service to human. This research also aims to achieve several objectives. The primary objective is

- To initialize human real 3D space with several candidates of furniture by considering unknown or first-seen living environment.

While the secondary goal is

- Object localization for 'Bring Me Something' service generation in the initialized environment

To achieve these objectives, I organize the research work into several parts which each part has their own function as below (Figure 1.5)

- Part 1: Segmentation of furniture occupied area on the floor based on the depth and point cloud image.
- Part 2: Filtering the candidates for furniture by using online catalogue database.
- Part 3: Categorization of 3D space candidates by using ConceptNet5
- Part 4: Representation of individual environment model in Microsoft Office Visio that contains furniture 3D information

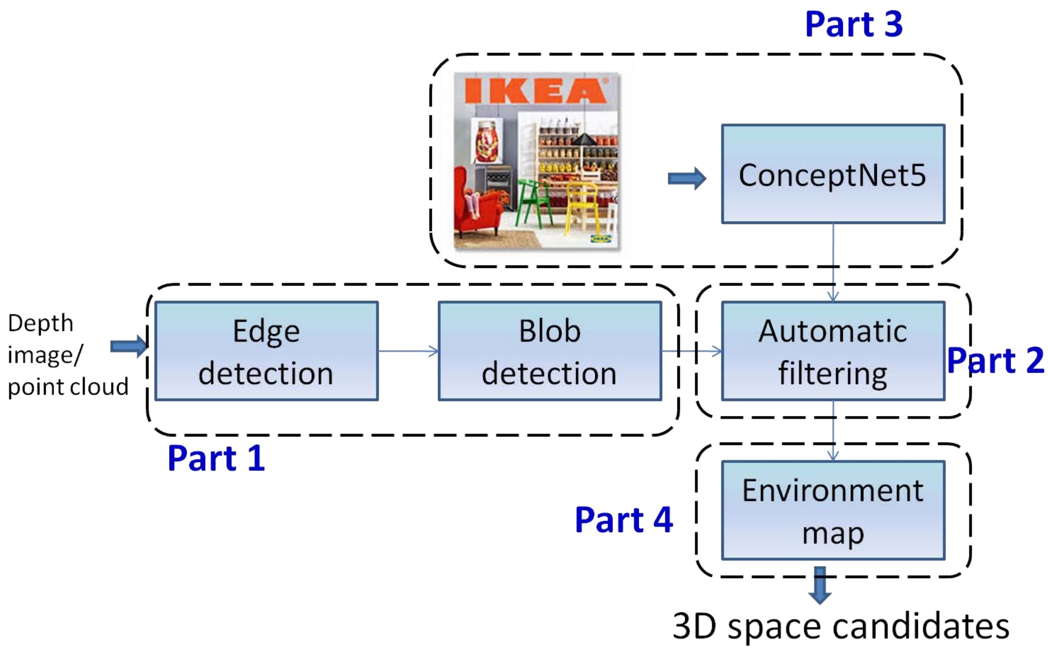


Figure 1.5 The structure of this research

From the set-up goals and objectives, this research hopes to expect these research outcomes

- First, an environment map can be obtained by a robot with depth sensor mounted
- Second, the candidates of a standard individual living environment can be sensed and initialized by using online catalogue automatically.
- Third, natural and intuitive robotics service in actual living environment can be realized from this initialization system easily.
- Finally, this initialization of robotics service environment may be able to reduce the cost and effort to develop intelligent space.

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1.4 Research Scope

The research outcomes will be accomplished by employing the following scope of research (Figure 1.6)

- Sensing the floor map of the 3D space consisting furniture
- Obtaining the 2D occupancy map of the 3D space together with furniture dimensional information
- Filtering the online furniture database to be matched with the data from the depth sensor

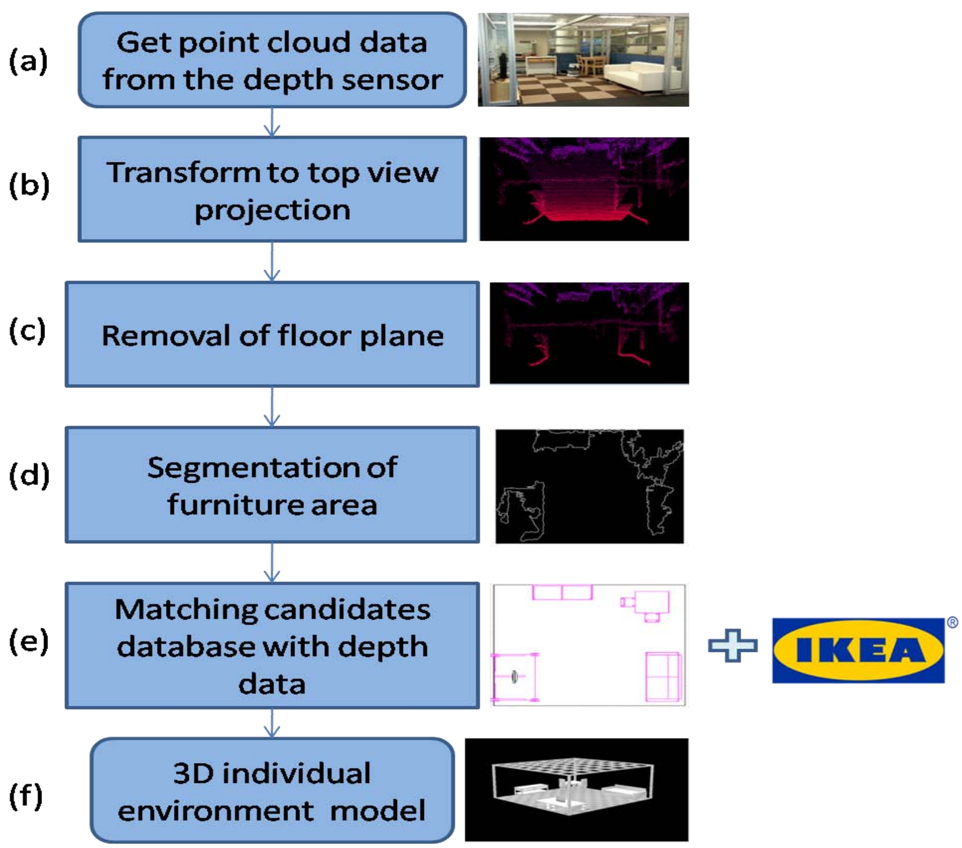

Figure 1.6: Building up of initialization system for robotics service environment

Meanwhile, this research also develops an application known as "Change Detection" that can detect the object new position after pickup by the service robot at its initial position. The application can be describe in the following Figure 1.7 and 1.8.

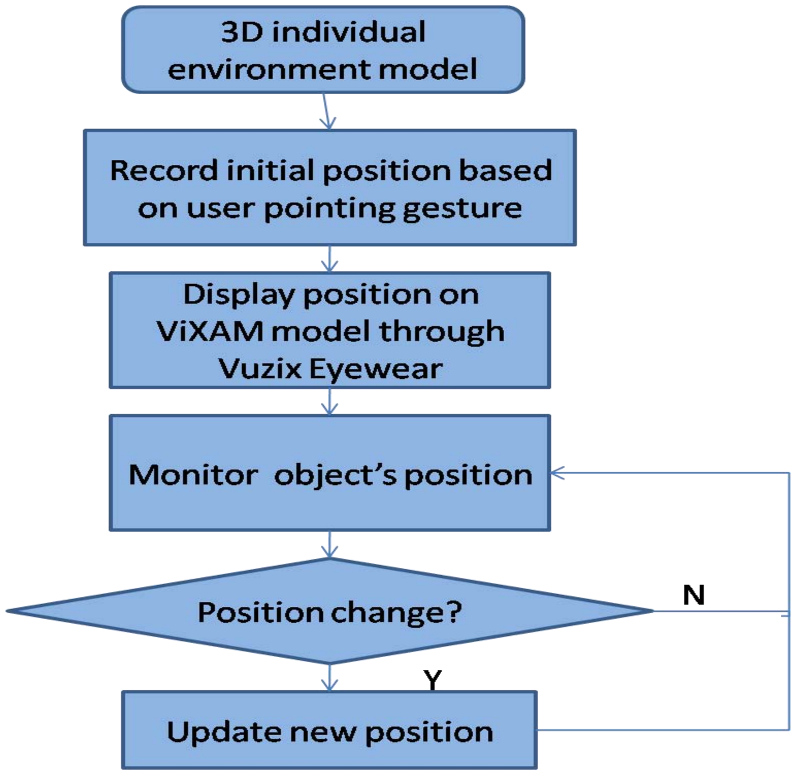

Figure 1.7: Object position monitor in the initialized environment

The remainder of this dissertation is organized into six chapters as follows

- Chapter 1: Introduction – explains the background and gap of knowledge for our research.
- Chapter 2: Literature review – overviews the related research which have been the main reference in this work.

- Chapter 3: Initialization system for robotics service environment – contains the details of our major contribution to construct this initialization system. Also discusses the use of depth sensor and online catalogue to build the 3D environment model.
- Chapter 4: Application of robotic service at home – describes the application which has been built using the initialized environment.
- Chapter 5: Discussion – highlights the idea and usage as well as its significance to human robot interaction.
- Chapter 6: Conclusion and future work.

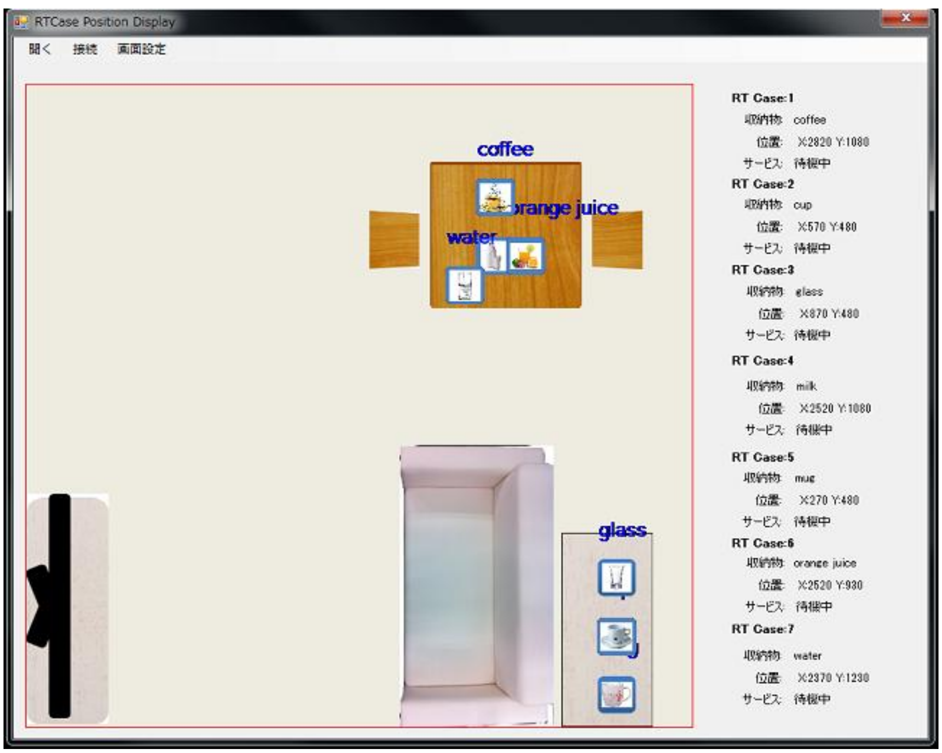

Figure 1.8: Kukanchi Old Object Monitor by Using RTcase

1.5 Assumption

In order to demonstrate the proposed initialization system to the home environment, few assumptions have to be made. They are:

i. Our world contains large and horizontal surfaces on which holding huge objects like furniture.

ii. Furniture can be as the supporting surface and has daily-life objects either in or on them.

iii. Furniture is rarely changed its position.

Chapter 2

LITERATURE REVIEW

This chapter contains some of the current research which related to this work. Although research on initializing of robotics service environment is relatively new, work on 3D modeling of space and environment analysis have been the laborious task of many researchers. Most of the current research deals with information sensing of the environment since it can be populated easily by attaching active or physical sensor into the robot's surroundings. In addition, this thesis will address the knowledge gap in the most related research known as 'Semantic Object Mapping' (SOM) as well as 'Knowledge Processing for Autonomous Personal Robot' (KnowRob). Meanwhile, the environment which has been initialized beforehand may greatly improve the service generation by the robot to user in a natural and intuitive interaction between them.

2.1 Intelligent Space

This research is conducted in the robotics framework known as 'Kukanchi'. 'Kukanchi' is a Japanese word means Interactive Human-Space Design and Intelligence. This framework was developed in our laboratory since 2007 focusing at sensing technology to construct environmental information using sensor networks and RT middleware for integrating robots and sensors. The core idea of ‘Kukanchi’ is the structured environment in which system components is spatially distributed and interconnected through middleware platforms [8]. Figure 2.1 describes this ‘Kukanchi’ concept for human daily living environment. In this figure, two important characteristics of Kukanchi system design are highlighted.

- Distributed system: all system components such as sensors, robots and corresponding software component are designed as part of distributed system. Software components are modularized and interconnected by RT middleware [9]. Home appliances are built as RT devices manipulated by RT components. This architecture provides easy system integration with multiple components which can be acquired from various sources.
- Distributed knowledge: knowledge in Kukanchi is decentralized and embedded into environment using tagging technologies such as RFID, ucode, image marker and etc. based on these tagging technologies, knowledge will be provided to robot only when and where robot needs [10].

Based on the above concept of Kukanchi system, the embodiment of robot can be extended to the whole environment. Furthermore, the whole environment can also be considered as one robot. In this way, a simple mobile robot can interconnect with other RT devices by using this Kukanchi system platform.

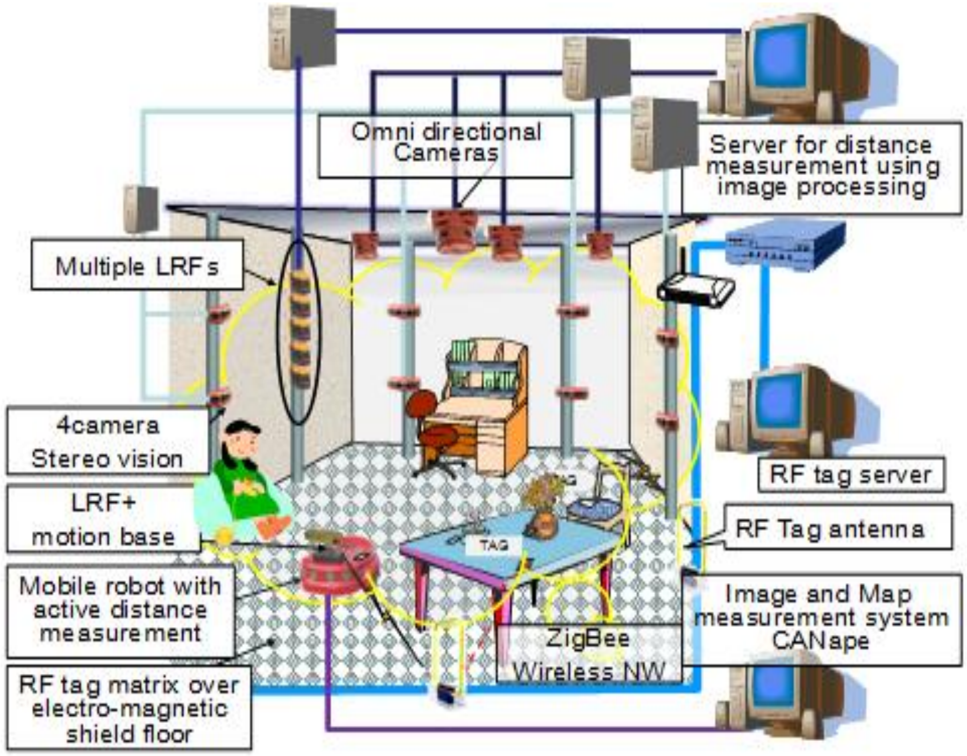

Figure 2.1 Kukanchi system

There are three main components in 'Kukanchi' namely human, environment and robot. Human represent the user at home which is using service robot to assist them in their daily life activities. While, environment defines the 3D living space which intentionally not be designed to accommodate robot together with human. And robot is the agent who provides daily life service to human at home. Therefore, robot needs to interact not only with human but environment as well in order to complete the robot services.

The operation of intelligent space is based on the interaction between these three components (Figure 2.2).

- Interaction between robot and environment: this is the first fundamental issue to help robot exists and functions in human's living space. Robot is required to navigate around user's house [11], avoid obstacles [12], as well as manipulate objects and home appliances [13]. To reduce the robot's burdens, research has been proposing to make environment become more robot-friendly by employing tagging technologies [14] and special design of object's container such as RT case [15].
- Interaction between human and robot: this is the second fundamental issue for robot's usability. Human needs to give command to robot in easy and natural way. Many human robot interactions have been proposed using gesture recognition [16], voice recognition [17] and tablet devices [18]. On top of that, multimodal interaction was also introduced in the intelligent space [19].
- Interaction between human and environment: this is the daily life scenario for human as they interact with objects and surrounding environment based on their needs and intention.

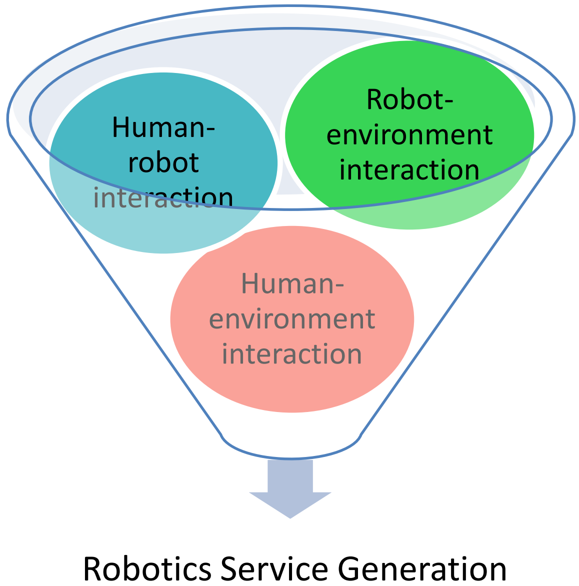

Figure 2.2 Kukanchi's components to generate robotics service

This research will address the issue arises from the interaction between robot and environment thus how it can influence human robot interaction at home. To achieve natural interaction between human and robot, we believe that the environmental information must be created beforehand or in other words, at the early stage of robot interacts with the environment. The domain of the home is worlds away from the laboratory or battlefield where most assumptions and requirements from these domains do not readily translate to the home [20]. This problem has been seen in Kukanchi system framework as user has to predefine every location's information in the environment in order for the completion of robotics service. For that reason, initialization of the environment is proposed in this research.

2.2 Human-robot Interaction and Robotic Services

Human-robot interaction by definition is a study which focuses on interaction between humans and robots. Nowadays, most researchers eventually work on how to deal with interaction problems which will be emerged when a robot is placed in human's daily living environment. This scenario will create a daily life support system by robotics technology in order to help and ease human especially for elderly and handicapped people. This is supported by the fact that the number of elderly people in many countries is increasing every year. For instance, about 42% of Japanese population is predicted to be over 65 years old in 2055[21]. Meanwhile, in Europe the elderly people population of 65 years old or over will increase by 29.5% by 2060[22]. This figure shows that there will be not enough caregivers in future hence many old people will be living alone. Therefore, as a solution, robot is placed in human's house to serve for many purposes such as service robot, entertainment robot as well as communication media (Figure 2.3). While entertainment robot and robot as communication media will improve human psychology and lead to unstressed life, service robot may enhance human's household work. A service robot which can integrate the information in human living environment will solve the physical constraints of human while completing their daily life or household activities. Furthermore, by adopting service robot into human 3D space like home may also improve the quality of life to those who need assistance for handling tasks at home.

For that reason, many aspect of research have been conducted by academician in this field such as study on knowledge database for human-robot environment, study about human-robot interface and many others. All these studies are summarized in the following Table 2.1 to show the recent development or achievement done by other researchers in human-robot interaction field generally and robotic services specifically. By referring to this table, most of the research makes observation of possible interactions might occur between entities like objects, robot and human.

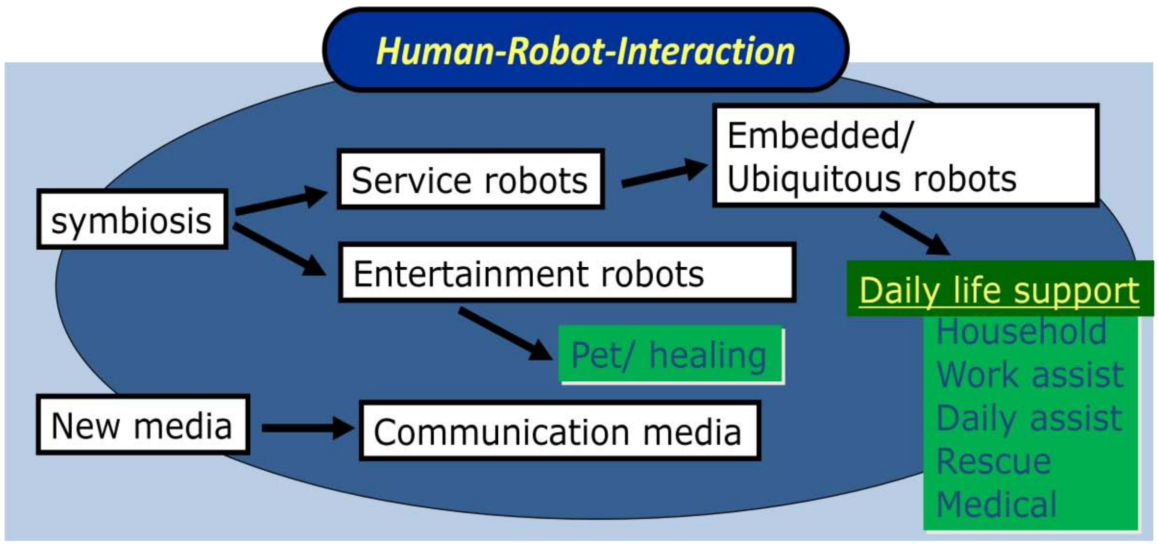

Figure 2.3 The position of robotic service in human-robot interaction

From this observation, knowledge database is created and user interface is developed as well with the target to provide simple robotic service such as bring object from one place to another place. Nonetheless, it is important to address the problem which might happened when bringing the robot to each individual house. In this case, we would like to solve the initialization of the human's living environment itself before any interaction or robotic service take place. For example, when robot enters human' living space for the first time, robot is able to locate the candidates in the 3D space.

Table 2.1: Comparison of recent related research in HRI for robotics service environment

User interface	• Observation of human activities in the 3D space through spatial interface thus provide robotics service based on that observed information[23] • Focuses on interface to gather environmental info based on the place where the robotics service took place[24] • Assist visually impaired person by creating mental maps and provide information to user via sound[25]
Knowledge database	• Study on relationship between objects, location and event to create commonsense for bring something robotics service.[26] • Specifying of appropriate places of daily-life objects for tidy up robotics service.[27]
Distributed sensors	• Focuses on sensory data distributed in the environment to create data management system thus complete the robotics task[28] • Study on self sensing the environment specifically home to sense its contents like furniture and keep track the changes in the environment[29]
Environmental map	• Propose resolution information to describe movement history of humans and object[30] • Using depth camera for robust localization and reliable obstacle avoidance in complex indoor environment [31][32][33]
User model / data mining	• Filtering user information based on motion logs and life logs[34] • Developed Service Proposal System (SPS) to generate 'Tsuide Service' based on service history information and environment information[35]
Modeling language design	• Adoption of certification schemes of modeling language to design dependable intelligent system in uncontrolled environment[36] • Designing robot management system which manages and controls information-structured environment with robots, everyday objects and ambient intelligent system [37] • Development of collaborative design framework for analyzing system behavior [38]
Interaction mechanism	• Developing human-mimetic hand-arm system by applying appropriate grasping force when handling objects in daily-life environment[39] • Developing a common robot service platform based on Web services defined by The RSi Protocol Specification[40]

2.3 Environment Map Generation

The complexity of the environment in which service robots would need to operate and the number of issues that such robots have to overcome pose significant challenges for the development of robot control architecture that can handle them appropriately[41]. This scenario is an example when service robots have to autonomously function in a dynamic environment like 3D space. Any changes in the 3D space may affect the robot's current plan to deliver service to user. Therefore, the robot must be capable of adapting to the new or unknown environment and be able to use the underlying information to generate services as shown in Figure 2.4. Map building of a 3D environment is an important prerequisite for many robotics applications such as object search [42] as well as robot navigation [43]. To make sure the generation of robotics service in living environment, service robot must have the ability to access the environmental information, to move in the space according to the planned path and to localize the target autonomously [44]. To realize this task, robot needs to acquire the environment map where human 'lives' together with the robot.

This environment map can be considered as a model to robot's operation environment that serve as information resources for better task performance [45]. Hence, this research would like to initialize 3D living space for the purpose of robotic service environment by using this environment map. This initialization system aims to provide furniture's 3D information of appearance and articulation to the map thus used with RT ontology to generate robotics services to human at their home. To attain this informational and functional object mapping, firstly this research needs to solve the acquisition of the environment map.

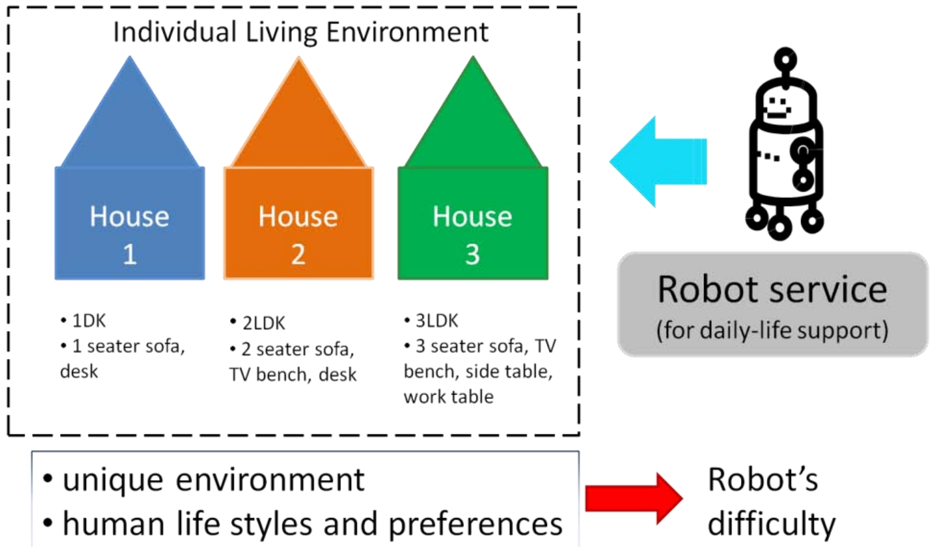

Figure 2.4 Characteristic of unknown environment

For example, automatically providing additional semantic information to the map such as location and type of furniture, are still an unsolved problem [46]. Secondly, based on the environment map, this initialization system has to build up the individual 3D space model which represents the database and knowledge source for robot systems. To attain this environment model, there are two requirements

- First, the main aspect of the environment such floor plan and furniture arrangement need to be detected.
- Second, static objects like furniture need to be initialized by specifying the candidates' properties like name, type and dimension.

To meet the first requirement, research on sensing the 3D space was conducted by other researchers using autonomous robot mounted with laser range finder [47], stereo camera and so on to produce Simultaneous Localization and Mapping (SLAM) [48]. This methodology is widely employed to robotics technology application such as robot localization in the 3D space [49], obstacle detection [50], robot's path planning [51] and so on. However, mostly robots map the 3D space for navigation purpose. Nevertheless, the map may have variety to store and display the information to users which depends on its purpose. Within an unknown environment, robot will build up the map, store its information into an environment representation and display to the users. Besides, the emerging technology in the consumer products like Kinect Xbox and Asus Xtion Pro also become an option to do the environment sensing. These cameras are relatively accurate and provide dense, three-dimensional information directly from hardware which may solve the limitation of high algorithmic complexity in the conventional cameras [52]. Another advantage, this consumer level depth camera capable to capture 3D point cloud data of the real environment to be used for many applications like object recognition, tracking and scene interpretation [53]. In addition, their lightweight property makes it easier to put these cameras on board.

Meanwhile, in order to initialize the real environment with several candidates as to meet the second requirement, an informational database needs to be referred. So far, research done to solve this issue by using a predefined method to demonstrate in real 3D space. Most of the researches done were using physical sensors such as RFID [54], pressure sensors, mechanical switch and RT-Case [55]. Using this type of sensor, information is tagged using a digital memory chip which can be transmitted and used whenever required. For example in a typical RFID system, individual objects are equipped with a small tag. The antenna package on it emits a signal activating the RFID tag so it can read and write data to it. When an RFID tag passes through electromagnetic zone, it detects the reader's activation signal. The reader decodes the data encoded in the tag's integrated circuit and the data is passed to the host computer. The application software on the host computer processes the data. In a situation when robot needs to provide service to human, these tags are used as location tag which is attached to the drawer of the furniture. Then, in the database the structure and position of the drawer is defined manually [56]. This predefined technique suffers from a need for quick database setup and less messy or laborious work whenever to demonstrate in real 3D space. Therefore, it will be great advantage for robot system if the robot can obtain the information automatically especially when robot coming into 3D space for the first time. The closest researches which dealing with this problem is found in 'Semantic Object Mapping' (SOM) and 'Knowledge Processing for Autonomous Personal Robots (KnowRob).

2.4 Semantic Object Mapping (SOM)

Semantic mapping seeks to move the study of robotic mapping beyond two- or three-dimensional occupancy and towards higher-level map constructs like objects, rooms and available actions [57]. Instead of robot maps the free and occupied spaces, the robot will map the objects in the 3D space (Figure 2.5). Even though robotic mapping has been researched widely, little attention given to the acquisition and thus embedding the information in the environment to the map automatically. An early example has been shown by Nüchter et al. [58], in which three-dimensional points in the map are labeled as floor, ceiling or object points. On the other hand, Rusu et al. [59] present the segmentation of objects at close range in tabletop settings, combining heuristic and model-fitting techniques. Meanwhile, Trevor et al. [60] study based on the idea that the observation which flat surfaces such as tabletop tend to support 'interesting' objects.

In all the above mentioned research works, their systems either using Simultaneous Localization and Mapping (SLAM) technique or using consumer-level sensor like Microsoft Kinect RGB-D camera. While the conventional SLAM using sensor like laser range finder and 2D camera, the emergence of low cost and quite accurate 3D camera like Microsoft Kinect has open a new and wide research field related to robotic mapping. Recently, the semantic mapping research has taking advantage of the RGB-D point cloud data from Microsoft Kinect Sensor to add additional information such as objects structure into the map for dealing with generation of robotic services in human daily-life. A point cloud is a set of data points in some coordinate system. In a three-dimensional coordinate system like our living environment, these points are defined by X-Y-Z coordinates thus represent the surface of an object like floor and furniture. Three-dimensional construction using point cloud and Kinect sensor for example may optimize the robotic system to performing SLAM or other environment mapping software. Oliver *et. al* [61] has proven in his research that Kinect data is most valuable to robots with unreliable odometry data or no such information (e.g., unmanned aerial vehicles) and applications where a 3D map is required and precise measurements are not necessary.

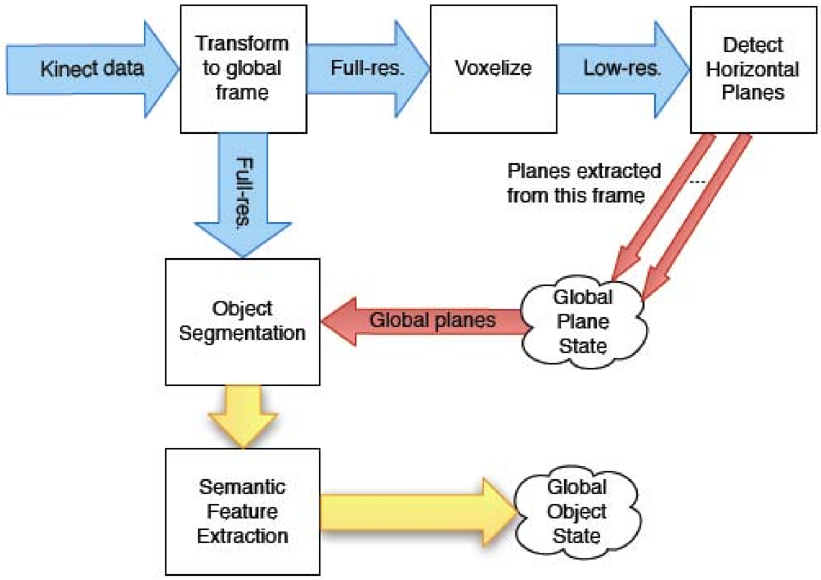

Figure 2.5 An example of approach based on SOM [56]

On the other hand, in object recognition, the usage of point cloud data can reduce the need for labeled training data for classification tasks in robotics. The difference between web-based data and real data collected by a robot is even more obvious in the context of classifying 3D point cloud data [62], which domain adaptation method is applied to the problem of object detection in 3D point clouds. Specifically for indoor living space, environmental data can be populated to scan the floor plane and furniture plane thus create the individual home environment model. While web database such as online catalogue may provide additional information on the environment model so that natural and intuitive robotics service can be achieved in real home environment.

In the context of semantic mapping, Vasudevan et al. [63] and Zender et al. [64] were using SIFT features for object matching while Blodow et al. rely on three-dimensional point features. On top of that, Rusu et al. [65] exploiting the structure of kitchen's environment in order to recognize cabinet handles. In addition, Ekvall et al.

[66] shows a SLAM system that also tracks object poses. This feature-based technique has the limitation such that it requires a high resolution data and an accurate database of objects to be recognized. An alternative to this problem, an approach is seen in [67] as objects in the environment are observed at long distance (low resolution) and does not need access to database of object models. Rather than rely on recognition, they demonstrate it by applying object segmentation which includes easily-computed semantic labels like color and size to build up the semantic mapping. In the meantime, the initialization system in this research depend on attribute-based approach like the two- or three-dimension of the furniture that can be acquired from the occupancy map based on point cloud data from depth sensor. Without need to focus on segmenting the object itself, this research uses the occupied map which describe furniture dimension attribute, applying occupied area segmentation and finally select several candidates for the furniture with the help of online catalogue database. While this research demonstrate in living room environment contains IKEA furniture, the map-object matching is done automatically by computing the Equivalent Circular Diameter (ECD) and centroid in the pre-processing image from 3D Sensor.

2.5 KnowRob

KnowRob is a knowledge processing system particularly designed for autonomous personal robots [68]. KnowRob describes the idea of let the robot doing the ‘right thing’ to the ‘right object’ in the ‘right way’. Hence, the knowledge processing act as resource that works directly on the data structures used for robot control such as 3D environment model and symbolic representation. It is specifically designed for autonomous robots that are to perform everyday manipulation tasks. Based on several sensors like RFID, laser range finder, cameras and magnetic sensor attached to kitchen environment, perception module creates 3D environment maps, track human motions and record log data of robot's activities. This may explain the scenario when a robot is looking for objects in order to deliver service to human at home. Service robot needs to locate objects for a task it is about to perform. An example shown by Tenorth et al. which by combining the environment map with encyclopedic and commonsense knowledge, the robot can query for objects by their functionality (Figure 2.6). For instance, the encyclopedic knowledge returns the concept 'Oven' as object used for heating or boiling and the semantic map locates an oven and in order to operate the oven, the robot has to know which part to manipulate to cause a heating/boiling process.

Rather than dealing with data structures from the perception system that involves computation of observation system and loading observations into knowledge representation of the environment map, this research focus on filtering the candidates automatically by combining the point cloud data with online database like IKEA catalogue into single layout software such as Microsoft Office Visio. In Microsoft Office Visio, the 3D environment model can be created applying custom stencil which have the furniture attributes like number of drawers in the cabinet as well as position of each drawer on the furniture structure. This information will be helpful for service robot to approach the objects in the 3D space thus bring the objects as requested by user.

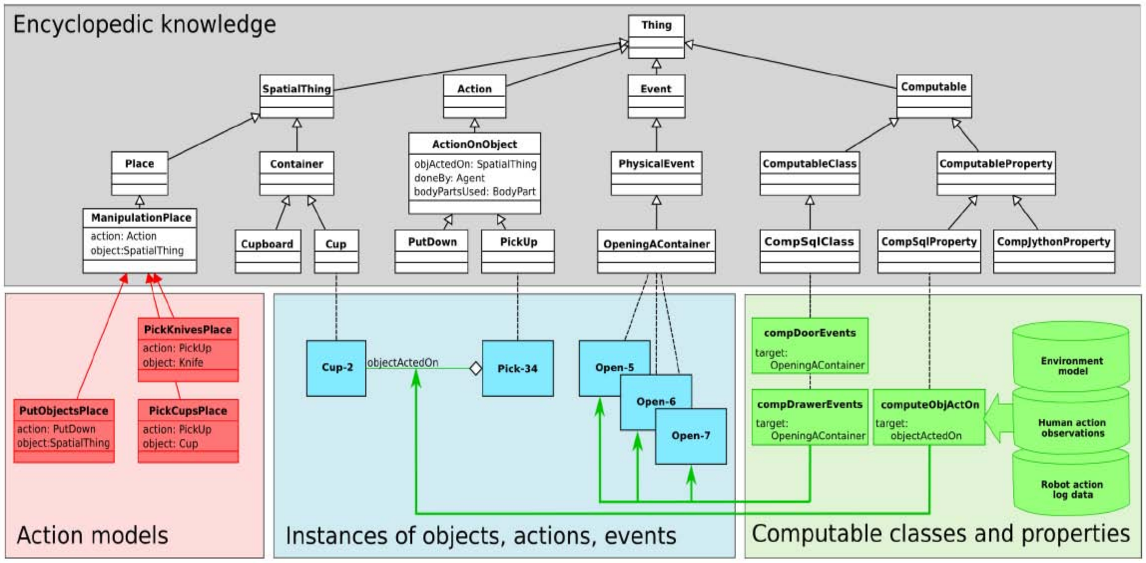

Figure 2.6 The KnowRob perception module.[68]

2.6 Summary

Approach presented in this thesis would like to overcome the drawback of using predefined method to demonstrate robotic service environment in real 3D space. This research also using online database to match the furniture 3D information to the point cloud data and presents several candidates for the 3D space. Rather than using object recognition which requires training dataset, this research applying segmentation algorithm to image from depth camera and measure the dimensional values to be matched with online catalogue. Moreover, this initialization for robotic services at home focus on automatically filtering the candidates and build up the 3D environment model. Finally, this research allows the addition of object structural information (furniture) to the 3D environment map (robotic map) with minimal effort. The following Table 2.2 illustrates the comparison of this research with others on some characteristics.

Table 2.2: Comparison of semantic map research

	Rusu et al.	**Mason et al.**	**Tenorth et al.**	**This research**
Sensor	Laser range finder (robot-mounted)	3D depth camera (robot-mounted)	RFID, laser range finder, magnetic sensor (sensor-equipped environment)	3D depth camera (robot-mounted)
Mapping method	Object recognition and classification	Object segmentation	Perception system (robot log data, human motion tracking and environment information)	Occupied area segmentation and blob detection
Semantic map	Encyclopedic knowledge (Hierarchically structured object)	Attribute-based (color and size) and trained dataset	Encyclopedic knowledge (Action-related concept)	Attribute-based (occupancy size) and online catalogue
Representation	Multi-dimensional tuple	Plane tracking and removal	Computable predicates	Plane tracking and removal

Chapter 3

INITIALIZING THE ENVIRONMENT FOR ROBOTICS SERVICE

This chapter describes in detail our approach to initialize the robotics service environment and how the candidates are filtered automatically. The main parts of this chapter are

- Building the 2D occupancy map based on data from depth sensor
- Filtering candidates from online furniture database based on 2D and 3D data
- Build up of 3D individual environment model

As in chapter 1, the initialization of service and generation of real living environment model is significant to many robotics systems such as daily robotics service at home. This characteristic becomes the requirement if robotic service is needed in every individual home. In the first part of this work, a floor projection map of Kukanchi 3D space is obtained by mounting depth sensor on the robot.

3.1 System

Based on the depth and point cloud data, we can create a static environment map which is consisting furniture candidates. The occupancy map of the space floor is drawn by using floor layout software such as Microsoft Office Visio. To conduct the experiment, I use the consumer level depth sensor, Asus Xtion Pro live as the depth camera. On top of that, a low-cost personal robot kit, TurtleBot 2 running open-source software like OpenNI and OpenGL are used. Figure 3.1 describes the hardware configuration showing depth camera setup on the TurtleBot 2. One of the objectives of this research is to determine the floor plane or top view projection map of the 3D space. This approach is applied to indoor living space and therefore I use depth camera mounted on the robot to capture the depth map of the floor. The advantages of taking depth data is that, it may provide useful information such as the furniture three-dimensional properties or attributes like its size (width, length and height).

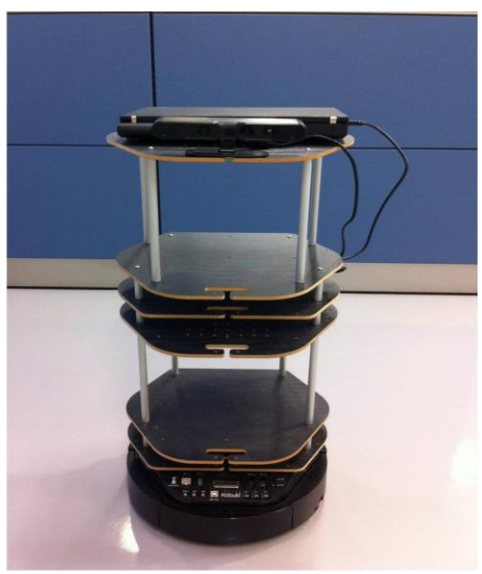

Figure 3.1: System hardware

3.1.1 Segmentation

From the depth map, this research measures the point cloud data based on OpenNI built-in calibration. To obtain the top view floor projection, I apply transformation matrix including two times of translation matrix and a rotation matrix. I mount the depth camera on the robot with distance of 72cm from the floor. While to produce the floor projection, the robot position is fixed at 200cm from location defined as [0,0,0] reference point. Also, this research applies a perspective projection with depth camera Field of View (FOV) 58 degree vertical. Figure 3.2 illustrates in detail the 3D coordinate setup of the depth camera. The camera is positioned at [0, 720,-2000] and aimed at [0, 0, 3000] in the world coordinates. In other words, the depth camera is looking in the positive z direction.

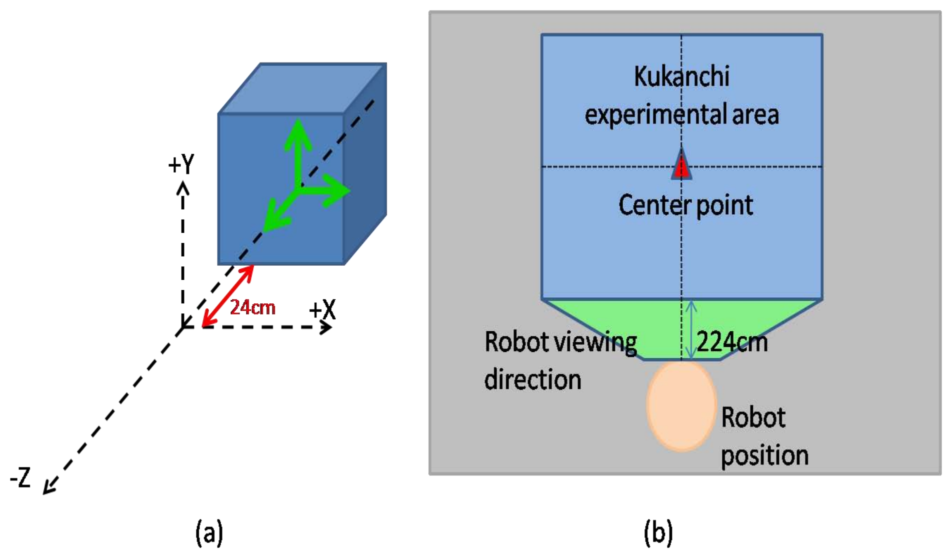

Figure 3.2: (a) Coordinate system (b) Robot positioning

Meanwhile, this research specifies the upright direction of the depth camera in the positive Y-axis which fixed it to be perpendicular to the viewing plane. Once get the top view of the floor projection, the ground plane that the robot standing on is estimated. The ground plane which is the floor as the surface where huge object such as furniture lying on can be represented by 3D coordinates. During the calibration process, I clear the floor from any object except for furniture in the FOV of the depth sensor and capture a single instantaneous point cloud.

The procedure to get top view floor projection, this research uses a simple algorithm to remove the points belong to the floor plane. By referring to [4], the equation of floor plane in the camera coordinate system can be represented as followed

$$\rho_z = -\alpha\rho_x - \beta\rho_y - \delta \qquad (1)$$

where (ρ_x, ρ_y, ρ_z) are the 3D coordinates of a point on the floor plane. Once α, β and δ have been calculated, the floor plane may be determined thus remove it so that only the furniture occupancy area can be seen on the floor. Figure 3.3 shows the point cloud image of the 3D space with and without the floor plane.

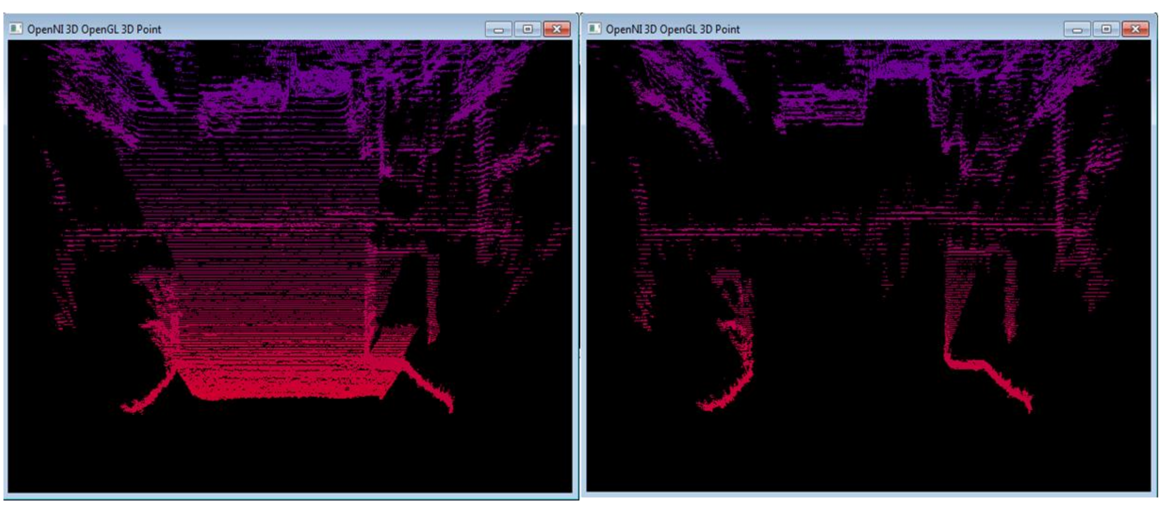

Figure 3.3: 3D point cloud image with floor plane (left image) and without floor plane (right image)

From the point cloud data of depth sensor, these two depth images are analyzed and applied image processing algorithm to segment the area of candidates. To get these candidates' area, the size of the floor plan is measured beforehand and the depth images are converted to gray scale image. After that, Sobel edge detection was applied where the edges of the image are detected with a threshold value of 0.5. Sobel edge detector will highlight regions in the image that have high spatial gradients. In addition, Sobel operator performs a 2D spatial gradient measurement on an image and emphasized regions with high spatial frequency correspond to edges. This Sobel edge detection algorithm produced a binary gradient mask image. This binary gradient mask image contains objects in the 3D space that have been partitioned. However, this image does not accurately represent the contour of the candidates' area. By using a structuring element in the longitudinal direction, the binary gradient mask image is expanded thus produced dilated gradient mask image. Then, small objects in the binary image are removed by controlling the pixel value of the objects. Finally, the image is smoothened to obtain final segmented image which contains only candidates' area. Figure 3.4 illustrates the steps involved to segment the depth image. Also, this research is using Sobel edge detector due to its characteristic which less sensitive to noise compared to other edge detector.

After that, the segmented image is analyzed with Hough transform algorithm to identify lines of each candidates in the image. Since by using Sobel edge detector is not enough to remove the unwanted objects in the image, this research add Hough transform algorithm to recognize the furniture's occupied area. It is important to obtain accurate occupied area since it will be used to measure the 2D data in order to match with database in online catalogue thus generate several candidates automatically. The following Figure 3.5 shows the segmented image describing shape and size of the candidate's occupancy area on the floor.

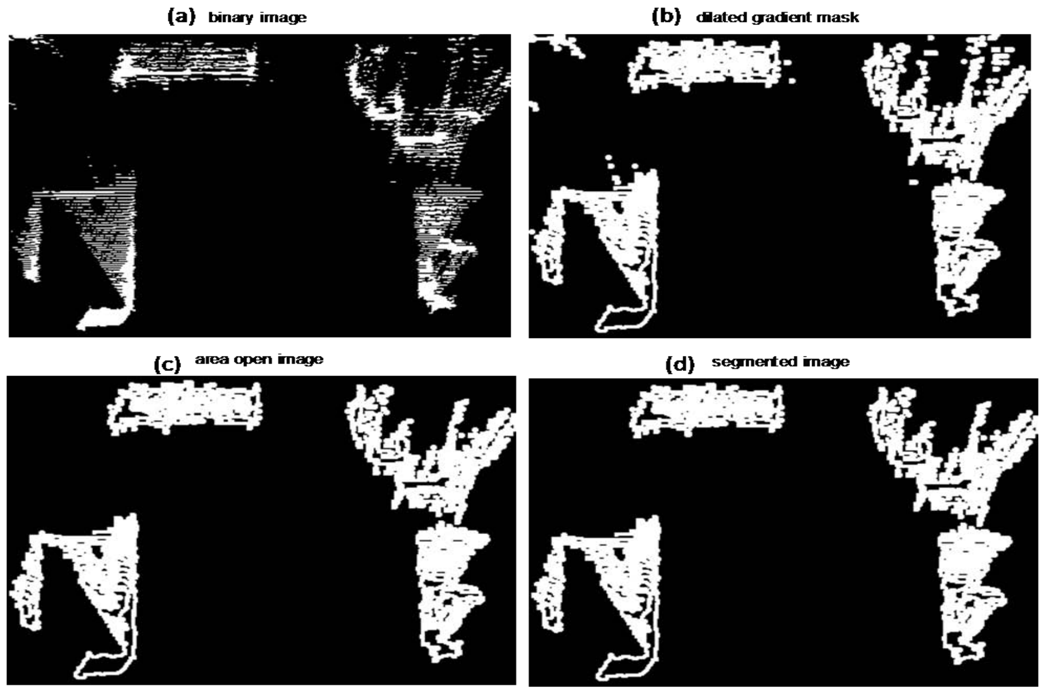

Figure 3.4: Segmentation process of the depth image. (a) binary image (b) dilated gradient mask image (c) removes small objects (d) final segmented image

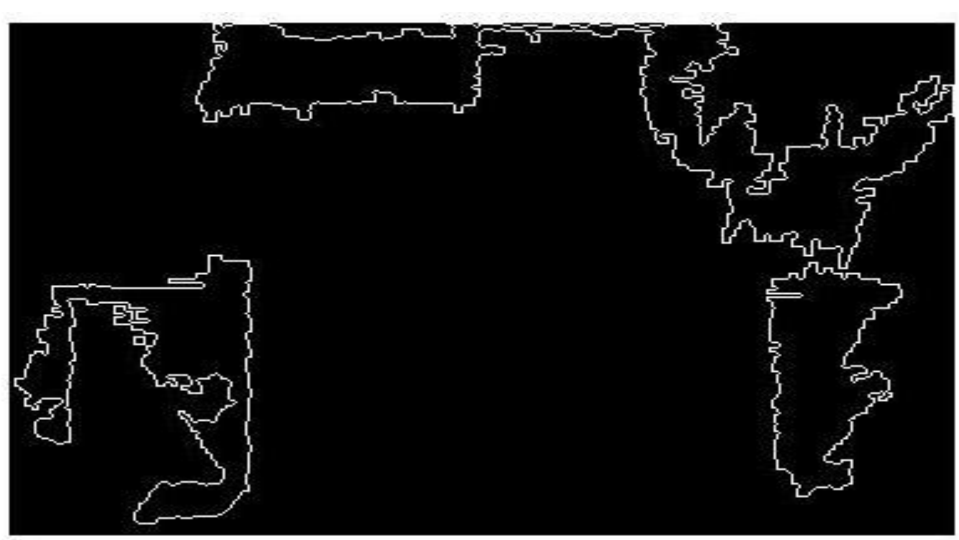

Figure 3.5: The segmented image showing the candidate's occupancy area

3.2 Object Association

Several candidates of furniture in the 3D space are passed to the object association by using a filtering method. This object association reflects or returns the result of matching data from catalogue database to actual measured of occupied area in the segmented image. An attribute-based approach is using to filter the candidates automatically and hence produce the semantic map with furniture 3D structural information. By using blob detection algorithm to measure 2D size of occupied area, this initialization system can filter the database based on width and depth values.

3.2.1 Filtering of Candidates

The attribute-based approach describes the using of furniture 2D size on the occupied area which can be obtained from the segmented image before. Figure 3.6 explains the process to filter the candidates based on these 2D measured values.

Figure 3.6: Automatic process to filter the 3D space candidates.

Blob detection is used to detect region in an image that differ in properties such as brightness and color by comparing to areas surrounding those region. Meanwhile, a blob is a region which the properties are constant or varies within a prescribed range. These information obtain from blob detection can be used as a complementary information about the previous segmented image which cannot be obtained from Sobel edge detector as well as Hough transform. In this research, the blob detection is applied to measure the blob's centroid and Equivalent Circular Diameter (ECD). The candidate filtering algorithm finds the matching data IKEA online catalogue by referring to furniture's width and depth. From the segmented image obtained by Hough transform, numbers of blob is detected and recognize. For easy visualization, each blob is labeled with different color that describes the number of furniture present in the actual living space. Figure 3.7 shows the result from the blob labeling process.

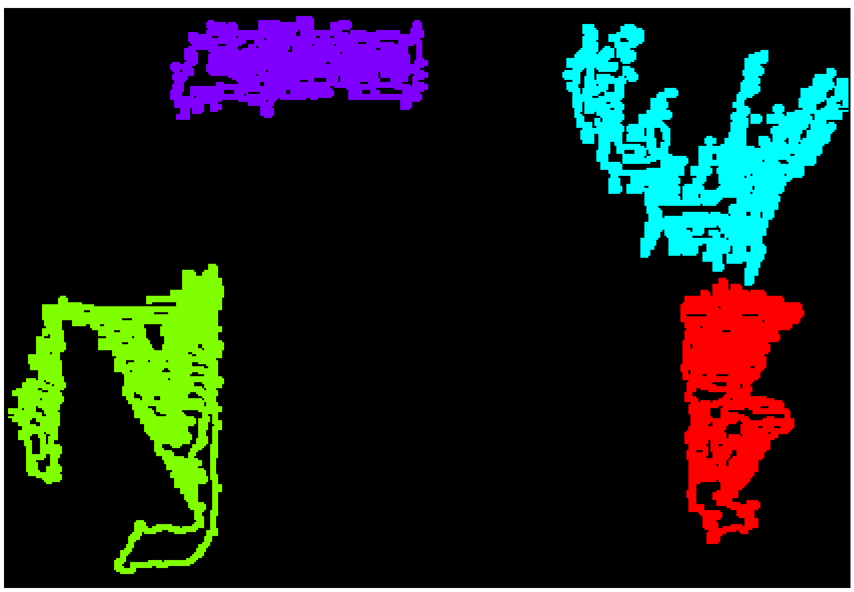

Figure 3.7: Pseudo colored labels of each blob.

To measure the blob's centroid and ECD, the boundary of the blobs have to be detected in order to trace the furniture occupied region on the floor. Figure 3.8 shows the blobs with boundary traced algorithm. After that, the size of the blobs is determined by indicating its two significant attributes which are centroid and ECD. In other words, the boundary of each blob is used as the maximum value or limit for each attribute.

Figure 3.8: The blob's boundary image

3.2.2 Filtering Result Based on 2D Data

It is important to validate the candidate data which are obtained from the point cloud data as well as depth data. This analysis is needed in order to set the threshold of candidate's filtering algorithm from online database like IKEA catalogue. Thus, to validate the camera image data acquired, few additional experiments were conducted to analyze the accuracy of experiment data versus actual data gathered from furniture catalogue. In these experiments, we divided into two steps. First, the data is read from another position of the robot and secondly, I swapped the furniture position in the 3D space. The result which contains 2D data of the candidates are then plotted and compared to the actual one. Figure 3.9 until figure 3.12 illustrates the result of these experiments for all the candidates in the 3D space.

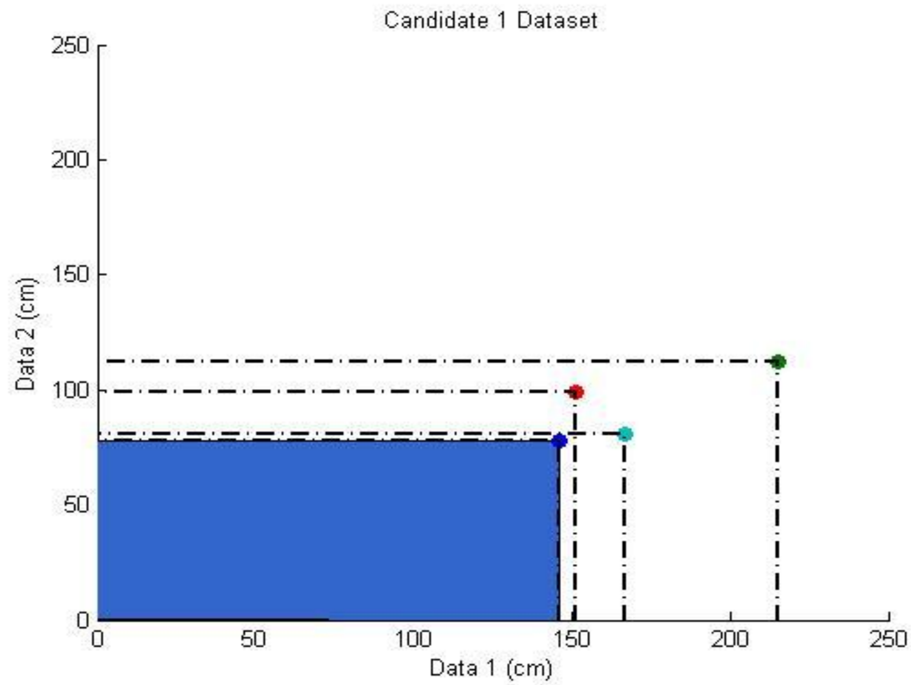

Figure 3.9: 2D plot of all data for candidate 1

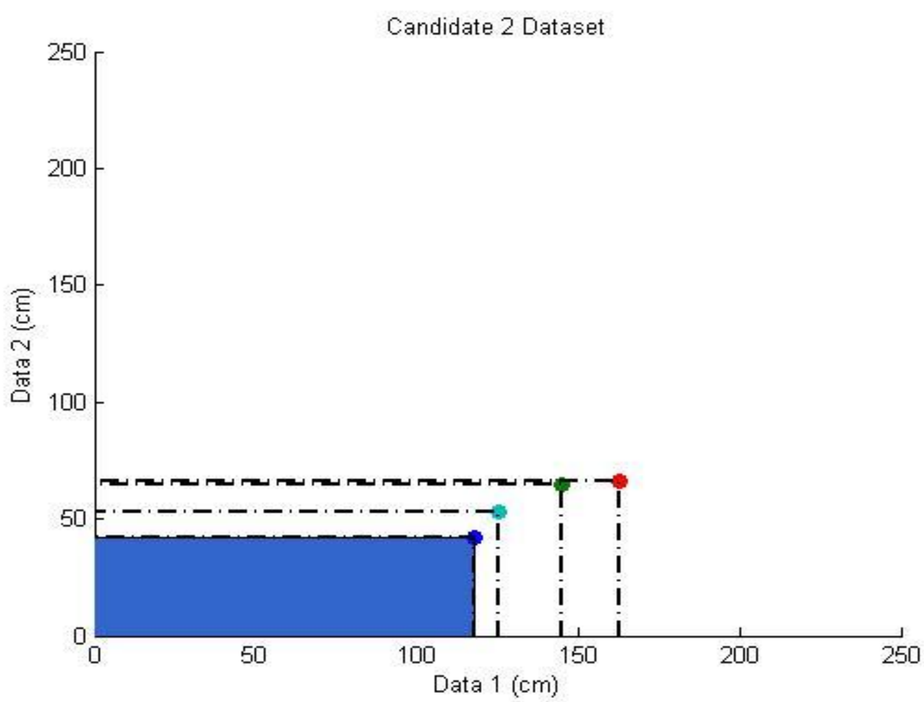

Figure 3.10: 2D plot of all data for candidate 2

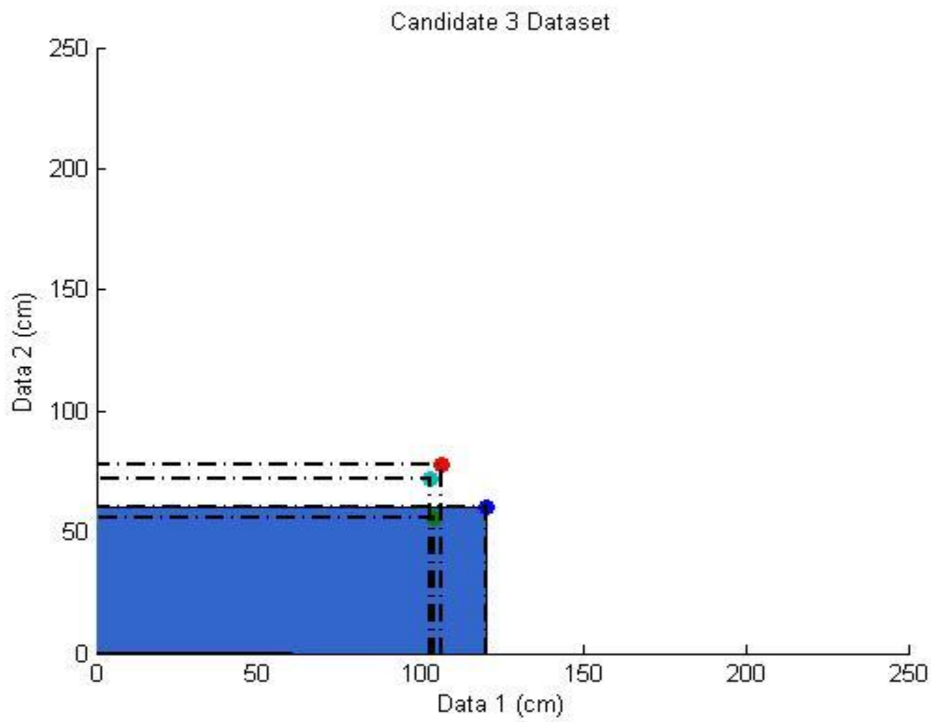

Figure 3.11: 2D plot of all data for candidate 3

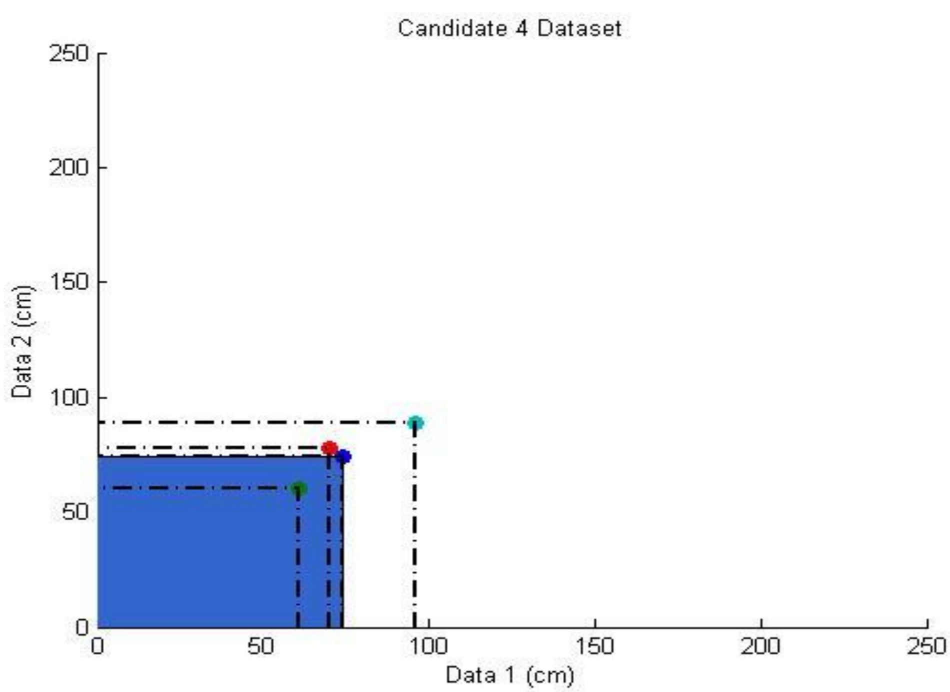

Figure 3.12: 2D plot of all data for candidate 4

Based on the above graphs, the 'Data 1' in the x-axis represents the first data given by the depth camera while the 'Data 2' in the y-axis represents the second data given. 'Data 1' and 'Data 2' resemble the width and length of the candidates in the online catalogue database. The area under the graph shows the occupancy area of the candidates on the floor. The blue rectangular area shows the actual 2D size of the candidates in the online catalogue. While the other three 2D plots show the experiment data from the depth camera. The plot with 'light blue mark' is the actual or calibration position of the furniture and 'red mark' is the position when I swapped the furniture. Meanwhile, the 'green mark' is the data at a different robot position in the 3D space. Table 3.1 shows the measured and actual value of furniture in the 3D space based on this experimental analysis. In candidate 1 dataset, the accuracy of the experiment data varies from 5% to 50% for both 'Data 1' and 'Data 2' which 'Data 2' much more accurate than 'Data 1'. Also, in candidate 2 dataset, the same accuracy applied as candidate 1 dataset. Meanwhile, candidate 3 dataset, the accuracy much better which varies from 2% to 23% of error. Finally, in candidate 4 dataset, the percentage of error can be seen varies from 2% to 20%. Same as candidate 1 dataset, 'Data 2' has better accuracy compared to 'Data 1' in candidate 4 dataset. This result is also has been analyzed with respect to each dataset for width and length values in the catalogue. From figures 3.13 and 3.14, the width dataset experiences high percentage error compared to depth dataset.

Finally, based on this experiment to validate the depth camera data, the initialization system is able to list down several candidates out of total number of furniture in the catalogue database. Using the result of this analysis, the candidate's filtering algorithm is set to filter the catalogue database with a maximum limit of 20%

from the camera data. It means this initialization system finds and matches the camera data to catalogue data by 20% above the blob size and 20% below the blob size. Equation 2 and 3 describe the threshold to blob's centroid and ECD of filtering algorithm. In conclusion, regardless the size of online catalogue database, robot may extract several candidates that match with the 3D living environment measurement data.

$$Filtered\ data1:$$

$$data1 \geq centroid - (20\% * centroid)\ \&\ data1 < centroid + (20\% * centroid) \qquad (2)$$

$$Filtered\ data2:$$

$$data2 \geq ECD - (20\% * ECD)\ \&\ data2 < ECD + (20\% * ECD) \qquad (3)$$

Table 3.1: Comparison of candidate's 2D size

	Measured		Actual	
	Width (cm)	Length (cm)	Width (cm)	Length (cm)
Candidate 1	192.1895	85.6677	146	78
Candidate 2	120.8367	50.0772	118	42
Candidate 3	192.1895	74.4987	120	60
Candidate 4	74.5	74.5	74	74

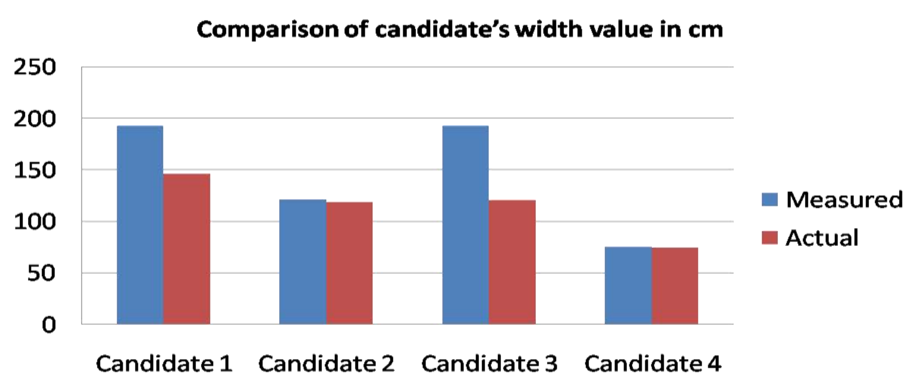

Figure 3.13: Data accuracy based on width value.

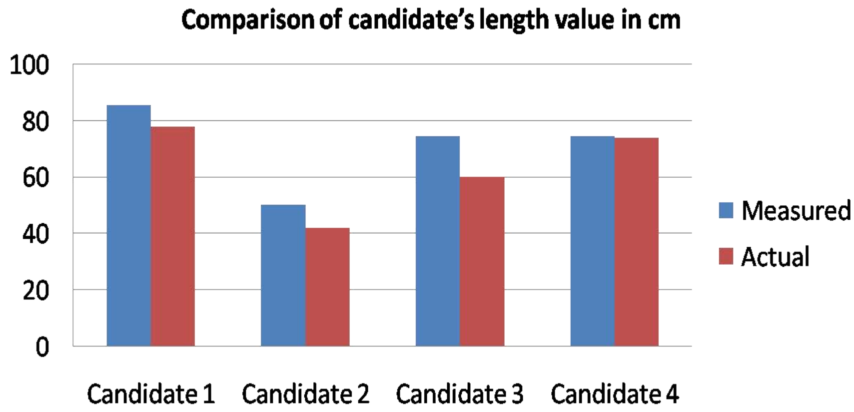

Figure 3.14: Data accuracy based on length value.

3.2.3 Filtering Result Based on 3D Data

As the 3D data can be easily obtained from the depth camera, the analysis on filtering result of 2D dataset is compared with the 3D dataset. The measured 3D dataset has additional information of furniture which represents the depth of furniture above the floor plane. By applying 3D filtering, candidates of furniture from IKEA catalogue are extracted based on width, length and height of the furniture. In order to get the input measured data for the furniture height, the average value of camera's depth array values is calculated. It can be described as in the following equation.

$$B = mean\ (A, dim) \qquad (4)$$

Where;

B is the resulting average

A is the depth's array to average

dim is the dimension to average over

Meanwhile, the 3D data for the furniture based on camera's measurement and actual dimension in IKEA catalogue is illustrated as in Table 3.2 and Figure 3.15.

Table 3.2: Comparison of candidate's 3D size

	Measured			**Actual**		
	Width (cm)	Length (cm)	Height (cm)	Width (cm)	Length (cm)	Height (cm)
Candidate 1	192.1895	85.6677	83.0982	146	78	72
Candidate 2	120.8367	50.0772	68.4728	118	42	51
Candidate 3	192.1895	74.4987	67.3421	120	60	74
Candidate 4	74.5	74.5	95.4444	74	74	75

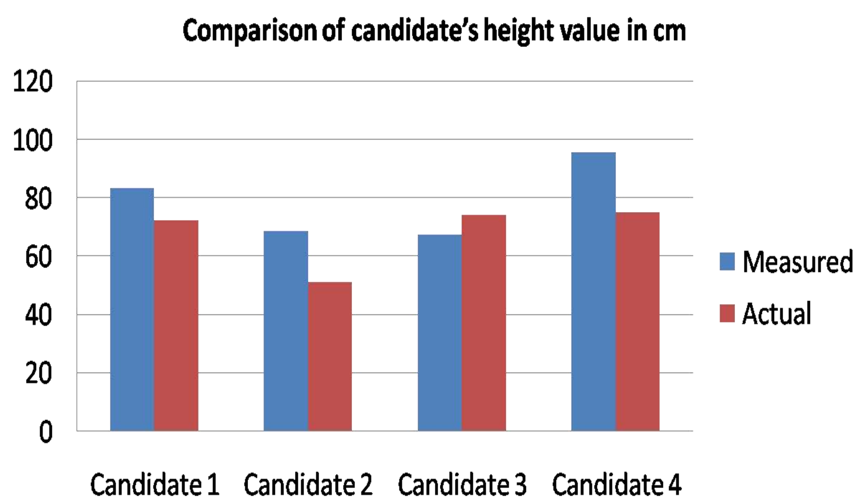

Figure 3.15: Data accuracy based on height value

3.2.4 Categorization of 3D Space Candidates

In order to initialize the robotic service environment, the candidate's name and type should be properly categorized. A more general name and type of these candidates should be assigned to make sure this initialization system can be applied to every home. To solve this problem, by using Conceptnet5, the candidates in the living room are categorized. Conceptnet5 is one of the biggest databases available to show the relationship between object, place and activity. Conceptnet5 uses a semantic network with a large number of concepts interconnected by relations. Therefore, by using Conceptnet5 database, this study extracts the information of its two relations:

- *AtLocation*: represent the spatial relationship between objects and spaces. This relation is used to find the list of common objects or candidates at the specific locations. For example, objects available in living room.
- *IsA*: represent the general information of certain object. This relation is used to find another name for a specific object. For example, 'work table' and 'coffee table' can be considered as 'table' in general.

Table 3.3 shows some sample objects which can be found in living room using *AtLocation* relation in conceptnet5. From this information generated by Conceptnet5, the type of furniture in IKEA online catalogue is categorized accordingly hence present appropriate and general name of the candidates for robotics service environment.

Table 3.3: Result using *AtLocation* relation

No.	Object
1.	Table
2.	Couch
3.	Sofa
4.	Human
5.	Chair
6.	Coffee table
7.	Carpet
8.	Tv set
9.	Cabinet
10.	cup

Meanwhile, Table 3.4 shows the *IsA* relation for object 'table'.

Table 3.4: Result using *IsA* relation

Object
Coffee table
Work table
Desk
Breakfast table
Conference table
Tea table
Booth
Console

There are four categories of candidates in our actual robotic service environment as follows:

i. Sofa: include all types of sofa which available in catalogue such as two-seater or three-seater sofa. Also either it is armchair or not.

ii. TV bench: include all types of TV sets.

iii. Cabinet: include all types of table which to store objects such as side table or display cabinet.

iv. Work table: include all type of table with chairs.

Furthermore, Table 3.5 shows the final result of this automatic filtering process. It describes the number of candidates before and after the automatic filtering. The first filtering is using the ‘width’ dataset only while the second filtering is using ‘width’ and ‘length’ dataset. At this stage, this output result of our 3D space initialization system capable

1. To list down several numbers for each candidate in the 3D space.
2. To include the actual furniture in the candidate’s list.
3. To show properties of the candidates in the 3D space like 3D appearance of furniture which also include its articulation such position of drawers and compartment on each furniture.

Table 3.5: Number of furniture candidate after each filtering.

Candidate’s Name	Total Number	Filtered by 2D dataset	Filtered by 3D dataset
Sofa	207	119	119
TV Bench	9	7	7
Cabinet	13	8	2
Work table	9	2	1

Meanwhile, figure 3.16 gives some of the example of filtered furniture. The 'green-box' furniture in the figure describes the actual furniture installed the in the 3D living space. In this way, robotics system is able to locate and identify huge objects like furniture installed by the user in 3D space.

Figure 3.16: Example of filtered furniture using 3D dataset.

3.2.5 Evaluation

To evaluate the algorithm of filtering technique presented in this research, an experiment is conducted. For this dataset's analysis and evaluation, the demonstration's environment image is captured from another robot's position. And this new depth and point cloud dataset is analyzed with the same segmentation and filtering algorithm previously. For the evaluation purpose, the comparison between new and previous filtering result is studied from two perspectives which are 2D candidate's filter and 3D candidate's filter. Table 3.6 describes the number of candidates which have been filtered down for each furniture category. This new robot-mounted camera's position is located at [0, 720, 0]. Figure 3.17 and 3.18 show the total number of candidates for furniture which have been filtered according to 2D and 3D filtering of both robot positions.

Table 3.6: Number of furniture candidate at another robot position

Candidate's Name	Total Number	Filtered by 2D dataset	Filtered by 3D dataset
Sofa	207	1	1
TV Bench	9	4	1
Cabinet	13	1	1
Work table	9	2	2

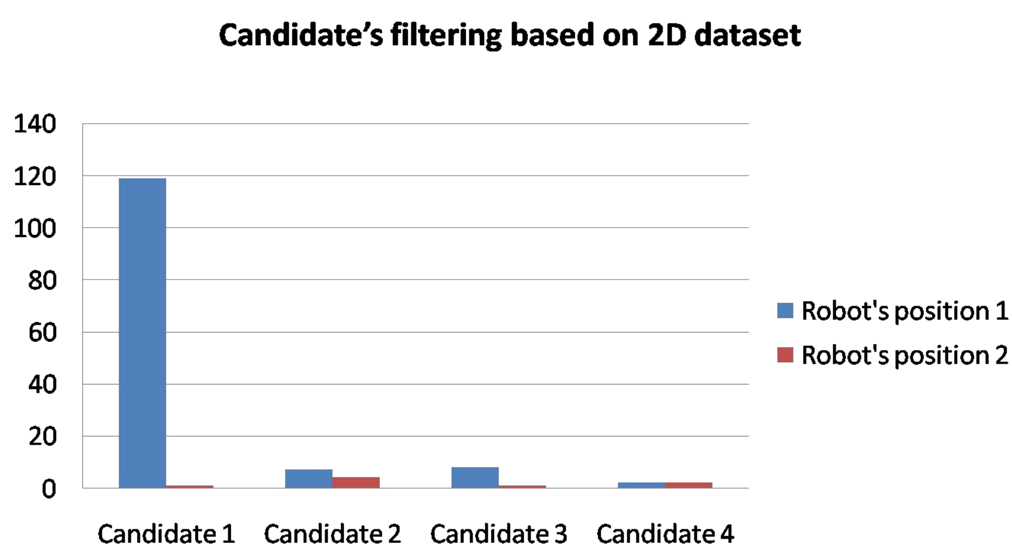

Figure 3.17: Comparison of 2D filtering result for different robot position in the living room

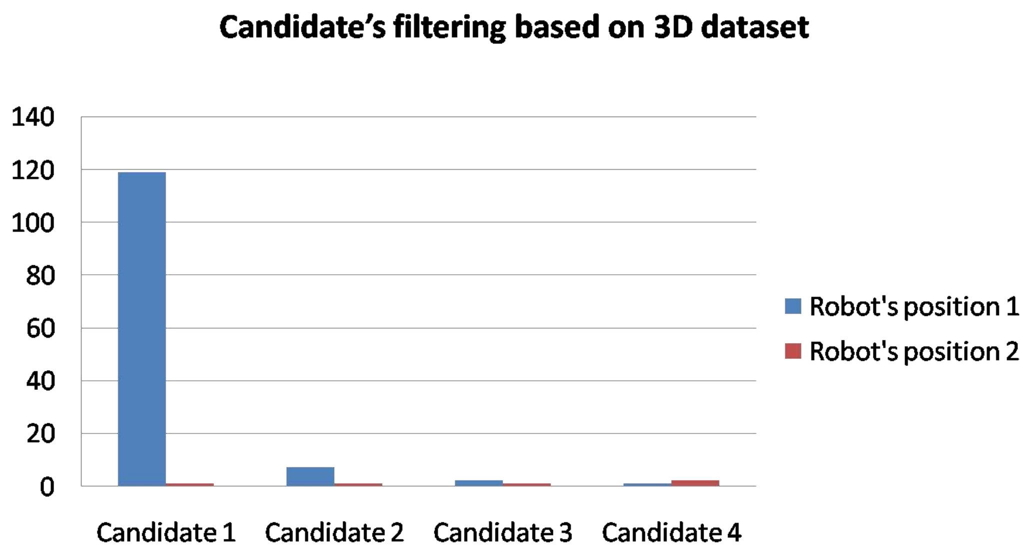

Figure 3.18: Comparison of 3D filtering result for different robot position in the living room

Meanwhile, the ratio of candidate's number with respect to 2D and 3D filtering process is calculated for each category of furniture. This ratio given in Table 3.7 illustrates the relative values of current robot position compared to its prior position previously. From this ratio analysis, it can be concluded that

i. The 2D filtering process is able to give a small list of candidates for the robot.

ii. By employing 3D filtering algorithm, the number of candidates for furniture at certain position in the 3D space is improved.

iii. Two factors which affected the filtering algorithm are the furniture position in the living environment as well as robot position.

iv. While furniture is rarely changed its position, robot position to capture the image is crucial in order to initialize the 3D space.

Table 3.7: Ratio of filtering result (2D and 3D) belongs to each candidate's category.

Candidate's Name	Robot position 1	Robot position 2
Sofa	1 :1	1:1
TV Bench	1:1	4:1
Cabinet	4:1	1:1
Work table	2:1	1:1

3.3 Representation

Also in this research, the filtering result which is candidates of furniture is mapped onto the environment layout. This part was done by using Microsoft Office Visio platform. The importance of this representation of candidates on the floor layout map is that, additional semantic information of furniture which is useful for robot service can be embedded together onto the map. This is the fundamental characteristic of initialization system for robot service environment. In addition, as human live together with robot, they may revise the furniture location shown on the map to correct environmental information retrieved by the robot. To achieve the objective of this research, the filtering result is embedded to the floor map by generating 3D environment model from the 2D floor occupancy map. For easy mapping the information from the depth camera with furniture online catalogue, this research also developed a plug-in for Microsoft Office Visio to link all the measured and estimation from robot with the actual database in the same platform. With this plug-in, the initialization system is able to manage and categorize its candidates into several categories of furniture by creating custom stencil.

3.3.1 Map Construction

From the 3D point cloud data obtained by depth camera, this research builds the 2D floor occupancy map layer by using Microsoft Office Visio. Then, we superimpose the floor map layer to the 3D point cloud layer to build up the furniture layer of the tested living environment. The significant of using 3D depth camera such as Asus Xtion Pro Live is the ability of this sensor to examine the height or depth of objects. This functional ability is useful to determine the floor plane of our 3D space. While the 3D point cloud is needed to find coordinates points which belong to the floor which differentiate between floor and candidates' area. Figure 3.19 illustrates the number of candidates available in our developed 3D space known as Kukanchi.

Figure 3.19: Kukanchi experimental area

To build up the 2D occupancy map (Figure 3.20), firstly two images were superimposed in order to map the depth data on the segmented image obtained. This step is to make sure the physical layout and arrangement of the actual experimental area. In Microsoft Office Visio platform, based on the imported segmented depth image and depth data, I filtering the IKEA furniture database to find the approximately matching candidates in the experimented living space. Once the filtering procedure is done, the 2D occupancy map can be created of the several filtered candidates. Later, the information can be used to create the 3D environment model showing the candidates position the living space. This study created three layers to superimpose these images thus produce an informational individual environment model. I name these three layers as depth layer, occupancy layer and furniture layer. The description of each layers as follows:

- Depth layer: layer consisting raw depth image and also the final segmented image.
- Furniture layer: in this layer, the candidates are selected based on the depth layer information and filtering the matching IKEA database. The furniture stencil is drawn based on three dimensional data of furniture from IKEA online catalogue.
- Occupancy layer: layer consisting floor plan of the 3D space and show the occupancy area of the floor which specifies the area to place the candidate. This layer is determined by the furniture information in the furniture layer.

By using superimpose technique, we not only may confirm on the layout structure but at the same time, we are able to recognize distinct features if any.

3.3.2 Furniture 3D Properties and Custom Stencil

To create the individual living environment model, this research using of Microsoft Office Visio and ViXAM 3D viewer functionalities to generate 3D model for IKEA furniture. To realize this step, I create plug-in using Microsoft Office Visio 2010 API. Mainly, there are three plug-in which needed for our initialized robotics service environment. First, ViXAM that allows 3D view of the actual living space with candidate's properties. Secondly, IKEA website which provides a hyperlink to online catalogue with specific list such as 'modular sofa', 'dining sets' and 'side or coffee tables'. Lastly, intelligent space setup plug-in gives access to depth layer, occupancy layer and furniture layer. Figure 3.21 shows the created plug-in as menu command in Microsoft Office Visio 2010. In addition, IKEA custom stencil is prepared for the purpose of furniture layer creation. The stencil is drawn according to its actual dimension provided in the IKEA online catalogue.

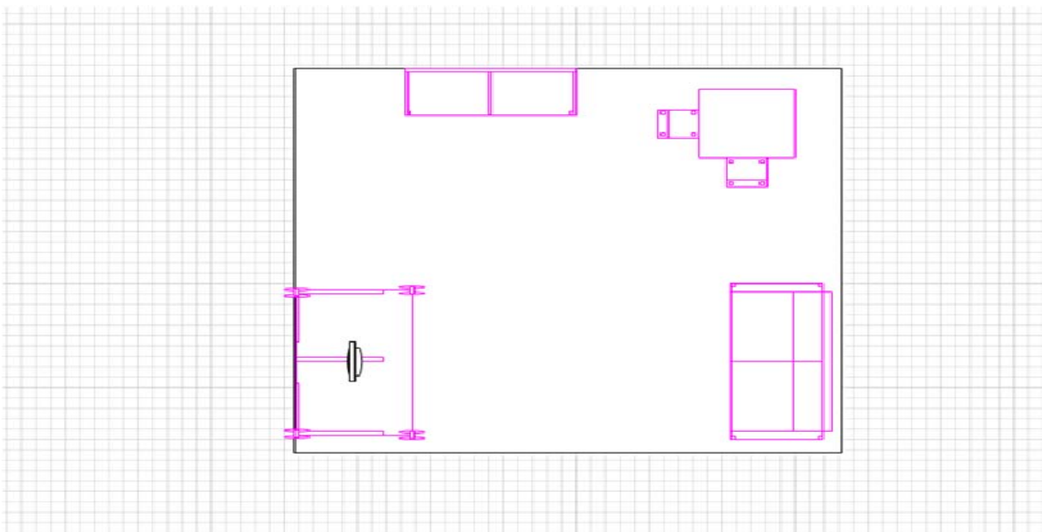

Figure 3.20: 2D occupancy map showing the candidate's area

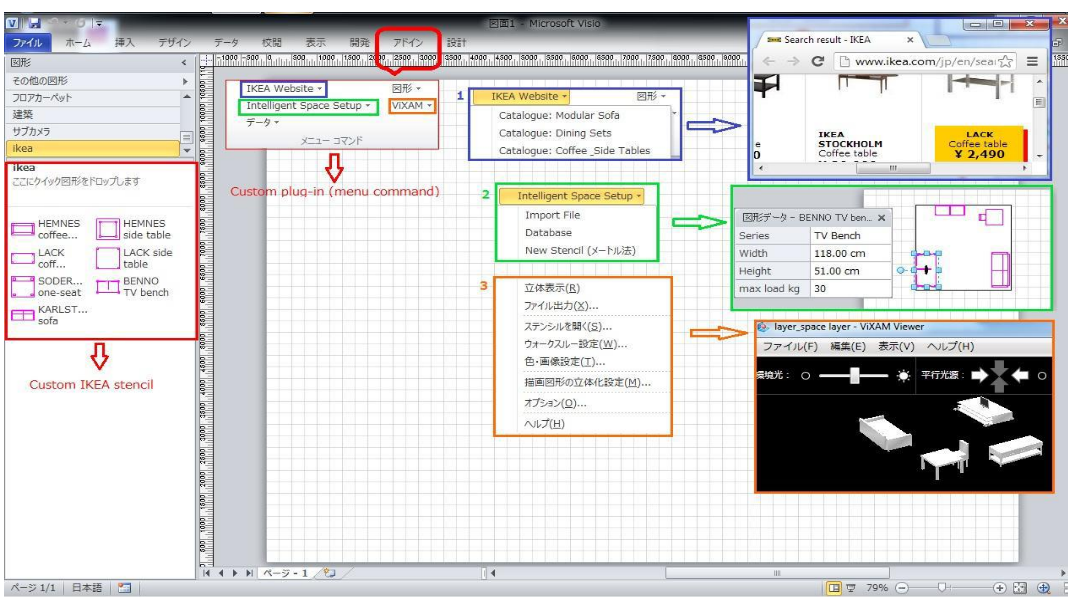

Figure 3.21: Creation of new plug-in Visio to link online catalogue, furniture space layout and 3D viewer layout.

To determine the layout of furniture in actual living space, we drag the furniture shape from the stencil to the rectangular areas in the occupancy floor map. Finally, after determination of furniture candidates, this study visualizes the 2D floor occupancy map into 3D environment model as shown in figure 3.22. This figure describes the 3D position and location of the furniture with the embedded necessary information from the online catalogue.

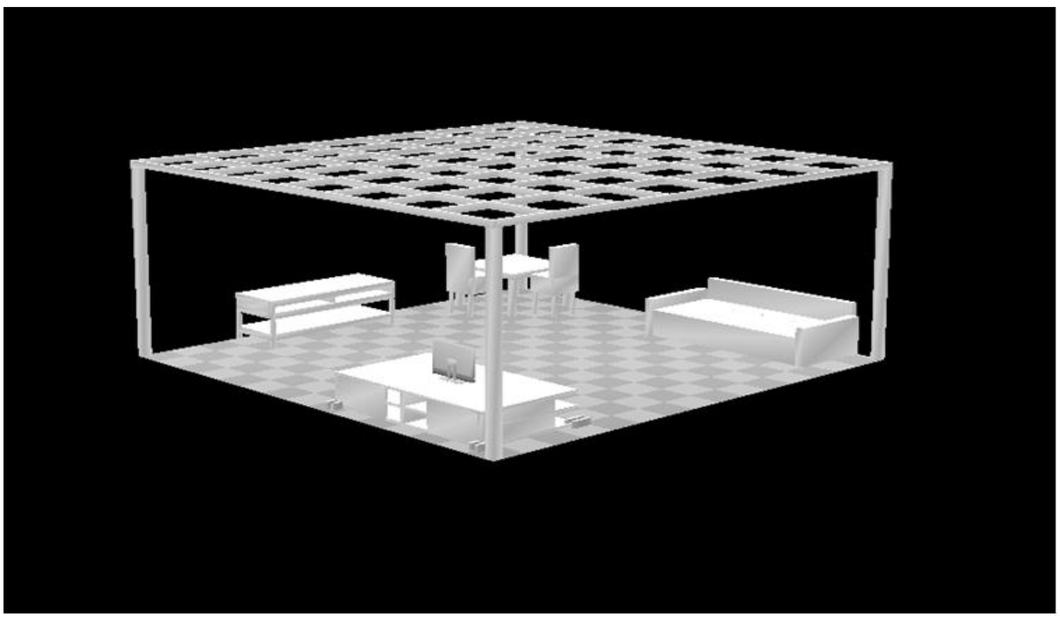

Figure 3.22: 3D environment model from the ViXAM 3D viewer.

Chapter 4

APPLICATION FOR ROBOTICS SERVICE AT HOME

In robotic service environment scenario especially daily-life 3D space, human robot symbiosis is expected. In this regard, human and robot should have mutual understanding about the environment they live in. User interface is a tool which realizing both human and robot perceive the environment condition in the same way. To make sure robot service is delivered correctly and safely, the interaction between user and robot should occur. As an example, human request the robot service and confirm the service by employing user interface. Mostly, user interface for robot service environment has the capabilities to execute robot task naturally as well as provide feedback information to user. These two characteristics may smooth the robot service generation as well as not burden human as user especially elderly people to give order to robot at their own living environment.

This chapter presents the integration of the developed initialization system of the 3D living space with robotics service scenario of ‘bring service” (Figure 4.1). Based on the initialized 3D environment, robot system is able to use the furniture 3D information to identify the exact location of objects in the 3D space. In addition, the generation of robot service can be visualized in the 3D environment model which provided with initial or prior information of first-seen or unknown environment. Two applications of user interface is developed in order to demonstrate the robot service of bring object from its original position to the user. The first application is using user pointing gesture to provide robot what object to be pick-up by estimate user hand pointing direction. The second application is employing an eyewear to augment the 3D environment model that is built based on initialized environment onto the actual robot service scenario in 3d space. It can be summarized as follows:

1. Augmented reality feedback system to view the initialized 3D space using Vuzix 920ar Wrap Eyewear.
2. Object localization in 3D space based on user pointing gesture.

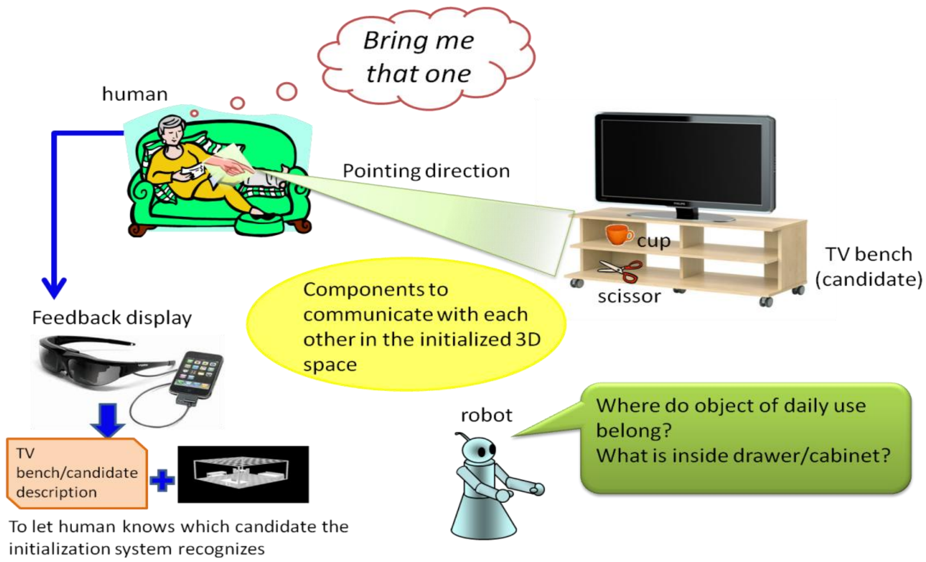

Figure 4.1 Robotic service scenario of 'Bring Service'

4.1 Augmented Reality Feedback System

4.1.1 Introduction

An interactive user interface device has become a phenomenon in our daily life nowadays. From an initially built for gamers like Kinect Xbox, people has started to bring these gaming devices into their daily life such as to assist robotics services at home. This is occurs due to the device's functionality which are abundant and easy to be learnt as well as its reasonable price in the market. Using this gaming based device has brings our daily life up to a whole new level environment and satisfaction. In this way, people can access to information easily and interactively. Head mounted device or HMD also an example of gaming based device that has been used widely by normal person daily. Since it is equipped with camera and microphone, make it suitable and appropriate for many applications in robotics service at home. Some examples of HMDs applied to academic research are Google glass and Vuzix Eyewear. Earlier, a research done in [16], they used PDA to provide convenient portal so that the user can view the augmented world quickly. An advantage of HMD based user interface such that it comes with 6DOF tracker that can detect movement and orientation of user's head.

Augmented reality also has become people attraction recently. Many applications employ or apply this technology such as healthcare system using augmented reality to show virtual objects in real environment thus help the user to relax while deep breathing [15]. Meanwhile, research in [69] work on displaying virtual information of outdoor area occluded by buildings known as 'Mobile Outdoor Augmented Reality'. Therefore, in our research we created a feedback system to our robotics services space initialization system such that the users can augmented their view of 3D space with virtual information display on the Vuzix Eyewear. In robotic 'bring' service, daily-life objects is put into RT-Box for easy robot handling and pickup. It is contains one object for each RT-Box. By using RT-Box, the object inside cannot been seen by user eyes if the user is sitting quite far from it. Therefore, this feedback system will help user to get the information of RT-Box location in the 3D space as well as what object inside the RT-Box itself. In this way, the feedback system will assist people to retrieve the information needed for robot service.

4.1.2 Marker-based augmented reality

This feedback system is designed such that it can display information of the furniture installed by the user interactively. Therefore, for that purpose, an HMD based user interface is used as shown in Figure 4.2. By using Vuzix Eyewear as this HMD based user interface, this study augmented virtual information on the real furniture image. The virtual information displays the information of RT-Box exact location at furniture and let user knows what object inside it. In addition, this feedback system also acts as database storage of intelligent space.

The application of this feedback system using augmented reality technology is based on the detection of custom marker attached to the furniture. Figure 4.3 shows the custom marker used for the augmented reality feedback system. This marker is attached to the furniture so that it is visible to user's view. The augmented reality application has been created using flash, flare3d and flar toolkit developed by a Japanese named Saqoosha. Flare3d and flar toolkit provide the libraries to build an augmented reality application in flash platform. To augment the virtual information on Vuzix eyewear screen of what user sees in 3D space, this research embedded marker pattern file and camera parameter file into flash develop software. The main algorithm to overlay information on real furniture which we see through theVuzix Eyewear consists of several main steps.

1. Setup single marker detector
2. Setup the 3D camera and determine the display plane
3. Get the camera capture using bitmap
4. Get the overlay information to camera capture using pivot method

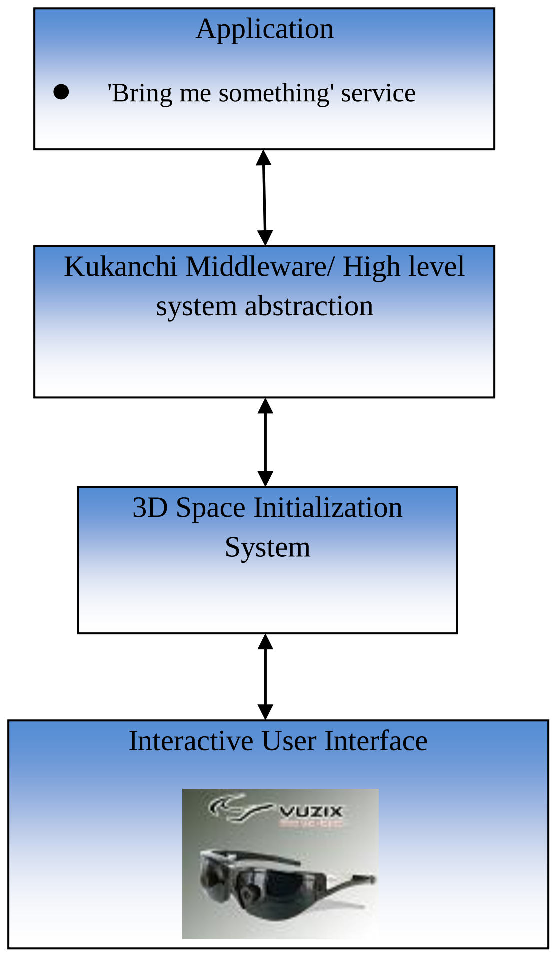

Figure 4.2. Architecture of HMD based feedback system.

As for the hardware part, we connect Vuzix eyewear to the laptop to run the application in Flash Develop Software. Figure 4.4 shows a user wearing Vuzix eyewear in our Kukanchi 3D space.

Figure 4.3. Custom marker to augment the virtual information.

4.1.3Viewing candidate’s information

When user needs to get the information of the furniture in their 3D space, user has to see through the vuzix eyewear to find the attached custom marker on furniture (Eg: Side table). As in the Figure 4.4 shows the experiment setup, user wants to know what object is inside the drawer at the side table. Once the custom marker was detected by the 3D camera, user can see the detailed information of object’s location on the Vuzix eyewear display (Figure 4.5).

Figure 4.4 A HMD based augmented reality for furniture in 3D space.

Figure 4.5. An augmented reality application for furniture in 3D space.

4.2 Locating Object in the 3D Space

Robotics service always deal with objects and human in order to generate active service especially in human daily life. Locating an object in the 3D space is the preliminary step for a barrier-free environment for service robot. The practical way to locate object for a robotics service environment, is by translating user input request.

To give a service request to the robot, it is a common practice for user to pointing by using hand. However, a problem that may arise from this scenario is to estimate the object location in the 3D space or in other words 3D object localization [32]. The second application focuses on displaying the location of object in the 3D space using the initialization system for robotics service environment as well as pointing gesture and RT Ontology. The main idea of this application is to utilize the initialized robotics service environment with candidates of furniture as the reference position of locating small objects like cup or remote control.

In this robotics service scenario, user points to an object location to order the robot to get the object and bring it to user [26]. The change of the object's location is viewed and displayed in the 3D environment model of the initialization system through Vuzix Eyewear. Also, to realize the 'bring' service, a simple recognition system to estimate user pointing direction is developed. To resolve the ambiguity due to closed objects, user pointing information is combined with RT ontology to complete the robotics task.

4.2.1 Estimation of hand pointing direction

In this study, pointing gesture is defined by a movement of user's arm to a target object in the 3D space. The line of arm including three joints which are shoulder, elbow and hand. By using Kinect Xbox API and OpenNI, the system will automatically detect user's 3D coordinates or arm's joints. The shoulder joint is significant to be tracked because we differentiate the pointing posture either sitting or standing based on the height of the shoulder. Figure 4.6 shows the experiment setup to estimate user pointing direction.

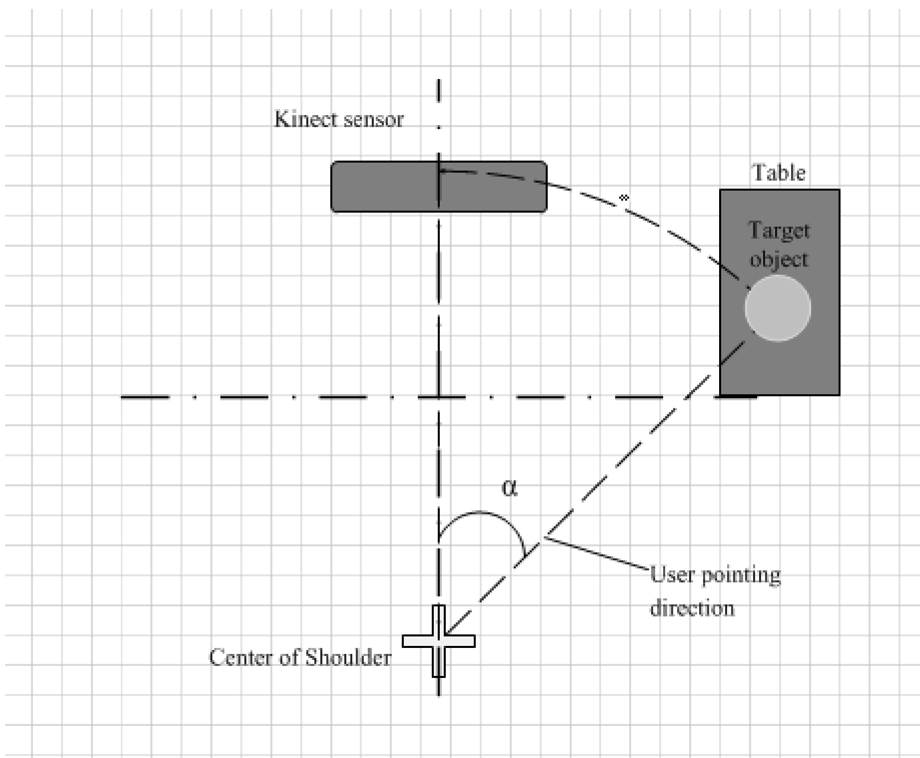

Figure 4.6 Setup to estimate pointing angle.

To determine the user's pointing direction, this research estimates the pointing angle from user's arm to center of shoulder during hold state. In the experiment, while pointing user has to hold the arm for 3 sec while pointing to a direction. The estimated pointing angle, α is measured by using (5)

$$\alpha = \tan^{-1}\frac{hand.x - shoulderCenter.x}{hand.y - shoulderCenter.y} \qquad (5)$$

For the analysis, this study measured the angular error of pointing direction during sitting and standing posture for several object positions as shown in Table 4.1. From this result, calculate the average angular error for each predefined angle. Figure 4.7 illustrates the measured angular error for sitting and standing posture. Based on these result, it can find that there is bigger angular error difference between sitting and standing at small pointing angle below 50 degree. In addition, it is clearly seen that the estimation of user's pointing direction has the accuracy below four degree of error.

Table 4.1: Object positions in pointing direction estimation experiment

Position	Angular	Distance (m)	Height (m)
1	30	2.05	0.8
2	40	2.30	0.8
3	50	2.62	0.8
4	60	2.53	0.8
5	70	2.26	0.8
6	80	2.13	0.8

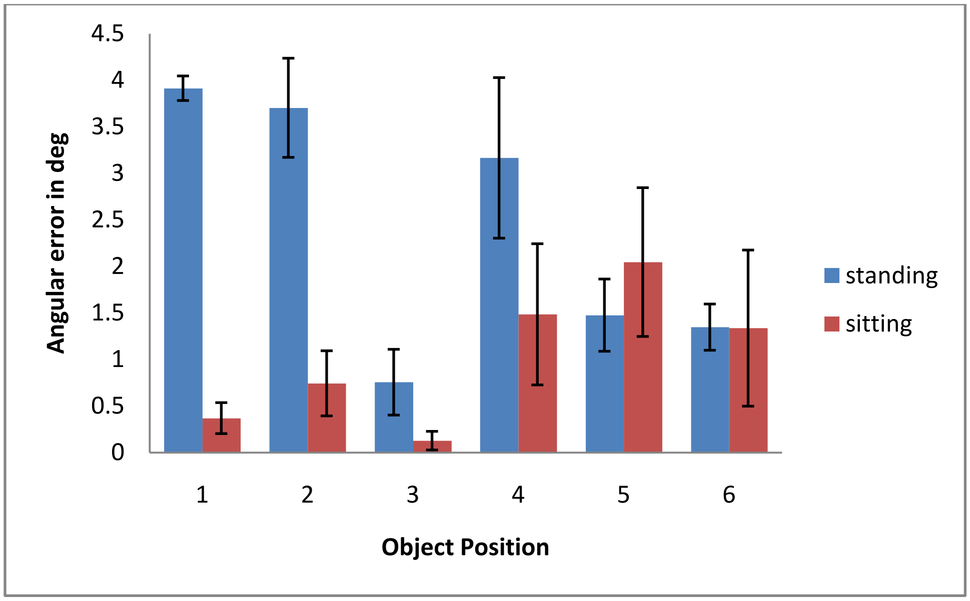

Figure 4.7. Angular error of user's pointing direction. (The solid bar and thin bar on top of it indicates mean and standard deviation respectively.)

4.2.2 Evaluation and Comparison

In order to choose the best pointing gesture tracking algorithm, this research conducted an evaluation and comparison study with the research work in [70]. The different method of tracking user pointing direction is evaluated by finding the least MSE. In [70], the pointing direction is estimated based on the angle between the pointing arm and center of user's head (Figure 4.8). From the calculated MSE, method of using center of shoulder instead of center of head has the least MSE for both sitting and standing posture. Therefore, we may conclude that the method that we use is more appropriate and accurate for pointing angle estimation in 3D space. Furthermore, the difference in MSE for standing and sitting mode is smaller while using center of shoulder method. This small difference indicates the validity of the method and it gives better performance than the other one. Table 4.2 shows the calculation of MSE for the angular error for both methods.

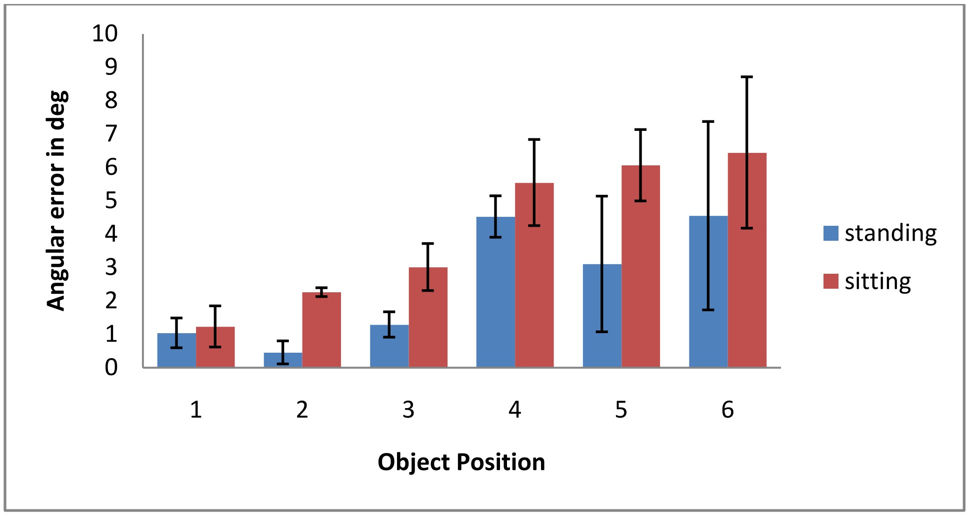

Figure 4.8 Pointing angular error based on hand-head center tracking. (The solid bar and thin bar on top of it indicates mean and standard deviation respectively.)

Table 4.2 Comparison of Mean Squared Error (MSE) in unit of degree

Method	Standing	Sitting
Hand-shoulder center (This research)	7.27	1.48
Hand-head center (Other research)	8.95	20.76

4.3 Object's Location Monitor

Using the developed user's pointing tracking algorithm, we intend to display the change of object's location in the 3D space before and after the robot delivers the service to user. This display is seen through head mounted device Vuzix Eyewear on the initialized environment model ViXAM viewer. To monitor the object's location, user pointing direction is considered as the estimated initial and final location. For the demonstration purpose, experiment need to be done for a scenario where user requests the robot to bring the target object to another location in the living space. In this case, firstly user will point to the target object and secondly user needs to point to the new location where robot should bring the object to. The experiment scenario is described as follows.

1. The user picks a bottle of water and put it on the work table. Then user goes to sofa.
2. The user points his arm to a cup on the cabinet and after a while user pointing again to the work table. This is to order the robot to bring the cup from the cabinet to work table. On the cabinet there are other objects beside cup which are pen and TV remote.
3. Initial cup location is shown on the display of 3D ViXAM viewer.
4. The robot recognizes the user pointing direction and command. Robot chooses the best candidate object based on RT ontology service reasoning.
5. The robot brings the fetched object to work table using the object map of initialization system
6. Final cup location is shown on the display of 3D ViXAM viewer.

Chapter 5

DISCUSSION

The research in this dissertation has solved several important problems in initializing real 3D environment for the purpose of robotic services at home. The main contribution proposed in this research is initializing unknown human living environment specifically home by embedding and mapping furniture 3D information from online database to 3D space environment layout for robot service purpose. This initialization system may be needed when robot service is conducted in complex real world scenarios instead of laboratory setups. The usage of online catalogue as the reference database to filter the candidates of human's 3D space may benefit the robotic service itself as the furniture 3D structure and storing functionalities is determined automatically without need of trained dataset from sensor or image recognition algorithm [45-46]. Rather than actively exploring the environment [45-46], this research focused on segmentation of depth and point cloud image from static robot's position in the 3D space and extracted the knowledge about the furniture properties and attributes from online catalogue. In addition, the size of the living environment can provides a variety of objects such as many types of furniture and to recognize them as well as to build the database is time and cost consuming. Therefore, the size of database like online furniture's catalogue can be easily initializes the first-seen environment regardless its room's dimension. This characteristic is able to improve robot service at home in the sense that it can be applied to each individual home with less effort to setup the database for the first-seen or unknown environment. By initialize the unknown 3D space with several candidates of furniture, service robot should be able to identify object's location which is positioned on the furniture surface or in the furniture storing place. This chapter discusses the contribution made of the proposed methodology.

5.1 Mapping Environmental Data from Depth Camera with Catalogue Database

Specifically for first-seen or unknown environment such as human 3D living space, robot needs ability to understand and perceive thus initialize what robot sees before provide daily-life support to human. Therefore, it is crucial for robot system to obtain the initial knowledge of the environment in order to provide robot service effectively and safely. Before generate robot service, robot needs to know the locations of objects in the environment. While daily-life objects are always been placed on the surface like floor or on top of furniture, it is essential to initialize the robot service environment with several candidates of furniture. In this research, a plug-in of Microsoft Office Visio is developed to connect furniture catalogue (eg. IKEA) with sensory data and create 3D individual environment model from the floor layout and object mapping. Introduction of the existing online catalogue into the popular layout software (Microsoft Visio) is effective by combining with measured furniture data and automatic image processing with some segmentation algorithms.

As the implementation of depth sensor which mounted onto the service robot is quite common for robot system, the 3D point cloud data gives the advantage for robot to obtain the object (furniture) 3D position without need to recognize or measure the furniture's dimension. Based on the point cloud data obtained from the depth sensor, the 3D structure of the furniture can be extracted from the catalogue database because the point cloud shows the external surface of furniture and hence describe furniture's shape and corner. The mapping of point cloud data to width, length and height of the furniture in the catalogue is able to filter down several matching candidates for the living environment automatically. This initialization system is capable to give the candidate's 3D size as well as its structural and storing information in the actual space that can overcome functional problem when introducing robotics service into individual living environment.

However, one big issue for robot service to identify objects in the environment is due to occlusion problem. This is proved by the evaluation experiment done in this research where robot is positioned at two different locations in the 3D space in order to capture the image of furniture in living environment. The point cloud obtained in the second robot's position is applied to the first robot's position and redo the initialization process again to see the improved result like the number of candidates which able to be filtered down from the catalogue. By analyze the result based on 2D and 3D filtering algorithm, it shows that the 3D filtering technique employing the point cloud data mapped to the furniture 3D (width, length, height) has improved the 2D filtering technique. This hypothesis is supported by the number of candidates resulting from the filtering process. This initialization system that employ 3D point cloud data is able to reduce the numbers of furniture available in the catalogue database into its category like sofa, TV bench, cabinet and work table including the actual furniture located in the 3D space itself. Many of robot service demonstrations showed the functions by using pre-defined environment which unable to give the initial information beforehand had caused the robot system faces a messy and laborious work. Therefore, the technique presented in this thesis in order to initialize the 3D living space with some candidates may overcome the limitations in previous research work.

To incorporate the actual human daily living space for service robot, this research is significant to enhance the human-robot interaction when delivering daily life service in unstructured environment like home. Other research related to intelligent space and robotic service only used sensory data such as RFID technology to detect huge and static object like furniture. However, that approach is not practical if we want to realize daily life robotic service in actual home individually. Therefore, an initialization system in this research is defined as

- A system which provides initial information of the unknown environment especially objects like furniture prior to robot service generation by the robot.
- The initial information of the furniture that is required by the robot to deliver daily-life service to human in 3D space are furniture 3D size/position as well as its structure database for storing functionalities such size/position of drawers, shelf and compartments available with the furniture itself.

This initialization system for robotic service has solved the limitations addressed in the previous research as stated below [27]

- RT-Case event detection – in some area which ultrasonic sensor is not suitable for positioning, the location of furniture is obtained by using location tag and predefine the position of each location in database. With the wireless RFID reader which attached to RT-Case, the system can imply and reference the position of the RT-Case from the location tag.
- RT-Shelf structure and position – RT-Shelf was attached with location tag in each tray slot. In the database, the structure and the position of the shelf has been defined. The system implies RT-Case position from the RT-Case storing and takes to events.

Therefore, human intervention to predefine the position of furniture location and structure is not needed anymore. That knowledge will be obtained by robot itself when enter the actual home for the first time and need not to measure the furniture in advance. It can be easily extracted from the online database like catalogue in order to initialize 3D space for robotic service.

5.2 Robotic Services for Elderly People at Home

This research is conducted to meet the goal which is to provide daily-life support to human at home environment especially for elderly people. Since elderly people might have constraints to manage their daily-life activities, robot service is provided so that their needs can be achieved. This research demonstrates the developed initialization system for robotic services environment by employing the user interface in order to realize bring service. The application of these user interfaces is developed to show the generation of bring service of object from its original position to the user. By implementing natural interface like pointing gesture, user may point to object position thus gives the robot pointing direction estimation of the object. However, since objects might be close to each other in the environment, user hand pointing is not enough to identify which object is pointed. Therefore, to have an intuitive human robot interaction for robot service at home, RT ontology is applied as to incorporate the commonsense knowledge for robot in the living environment like home. With this idea in mind, the initialization system proposed in this research may improve the robot service as it provides initial knowledge like furniture arrangement and position to the robot in the unknown 3D space. The combination of this initialization system with RT ontology may improve the robotics service to be more intuitive and effective whenever to apply at every individual home.

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Summary

This research is the first work to initialize human daily living environment such as home for robotic service purpose. Since service robot faces problem to acknowledge the essential and inevitable information for robot service such as object's location in the 3D space, this research proposes a process to give initial setup information about object's location known as initialization system that requires no object search, inspection and recognition. The initialization system which has been introduced in this research not only gives several candidates for human living environment but at the same time may overcome the disadvantages of a predefined method which has been widely practiced when to demonstrate robotic service in actual 3D space.

The initialization system which is proposed in this research implements the 2D area segmentation to the image captured by depth camera. Based on the 3D point cloud data available in the depth image, candidates of furniture in the living space are automatically filtered by mapping those data with online database like IKEA catalogue. The filtering process of the living room's candidates involves Sobel edge-detection and blob detection algorithm to analyze and recognize candidate's occupancy area on the floor. From the blob detection on the depth image, total numbers of furniture available in the living room is identified and it will measure the centroid and ECD for each blob which these values to be matched with width and length of furniture in IKEA catalogue. The filtering process is divided into two parts which are 2D filtering and 3D filtering. In 3D filtering, the depth dataset from camera is used to match with the height value of furniture in the IKEA catalogue. From the 3D filtering result, the number of candidates for the living space in 2D filtering is successfully reduced. This evaluation shows the effectiveness of this filtering method that based on segmentation and point cloud data as well as online database.

On top of that, a plug-in to Microsoft Office Visio is developed in this research in order to represent the filtering result into floor layout map. With this plug-in, the filtering result can be connected to IKEA catalogue by using custom stencil which contains structure and storing functionalities information of the furniture. The embedded of this essential information of furniture for robot service into the floor layout map also known as semantic mapping. The advantages of this initialization for robot service at home are it may support independent living in real 3D space as well as 3D information from catalogue such as position and number of drawers can easily extracted and need not to be measured.

The research work also has described two important characteristic of the initialization system.

- The furniture online database/ catalogue, IKEA was filtered based on the depth camera data. This filtering process finds the candidates automatically for the 3D space which include the actual furniture installed.
- The living environment map with initial information of furniture's location and structure was done by using Microsoft Office Visio to obtain the 3D environment model. To get this 3D environment model, a plug-in is developed in Microsoft Office Visio platform to link point cloud data to IKEA online catalogue and finally create the custom stencil of the candidates.

As a conclusion, an application is developed to show the usefulness of the initialization system. The "Change Detection" application is implemented by incorporating the initial object's information in human living environment obtained from the initialization system during "BRING" service. When robot is asked to bring an object from one position to another, the requested object will change its location. Therefore, the 3D information of furniture may infer the location of daily-life objects whenever robot brings them to another place.

6.2 Future Work

In summary, the initialization system presented in this research can gives a broad direction for future work. One idea is to use the initial information of object's location for tidy-up robotic service. As an example, the tidy-up robotic service in [55] is using object-place commonsense knowledge to generate an intuitive service. However, robot needs to identify object's location in actual environment before delivering the service and provide the daily-life support to human. Therefore, by using the result of the initialization system, robot can detect and recognize the object in real 3D space thus generates robotic service in a more effective way.

In general, the initialization system could be a basis process to demonstrate robotic services in actual human living environment which is known as unique and unstructured.

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1 Journal(s)

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2. Nur Safwati Mohd Nor, and Makoto Mizukawa, "Ubiquitous User Interface System for Human Robot Interaction in Living Space", *Proc. of The Seventh South East Asian Technical University Consortium (SEATUC2013) Symposium*, March 5-6, 2013, Bandung, Indonesia

3. Nur Safwati Mohd Nor, and Makoto Mizukawa, "The Importance of Natural User Interface System in Intelligent Space Called Kukanchi", *Proc.of Intensive Workshop in conjunction with The SEATUC2013 Symposium*, vol.3, March 5-6, 2013, Bandung, Indonesia.

4 Domestic Conference(s)

1. Nur Safwati Mohd Nor, and Makoto Mizukawa "Pointing-Based User Interface in 3D Space", *Japan Society of Mechanical Engineers, Robotics and Mechatronics Conference 2012 (ROBOMEC2012)* Proceedings (CD-ROM), May 27-29, 2012, Hamamatsu, Japan.