# Replicating Human-like Proxemics Behavior in Approaching Mechanisms of a Domestic Service Robot

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Degree of Master of Science

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Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

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## DECLARATION

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I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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S. M. B. P. Samarakoon Date:

The above candidate has carried out research for the MSc thesis under my supervision.

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Dr. A. G. B. P. Jayasekara Date:

## Abstract

Development of intelligent service robots is a growing research area within the field of robotics. Service robots have been developed to enhance the living standard of people. Users of these service robots are not experts in robotic domain. Hence, they prefer to have human-friendly features in these service robots. These service robots often need to navigate toward their users when accomplishing service tasks demanded by users. Therefore, the ability of a service robot to approach a user in a human-friendly manner would increase the rapport between the user and the robot.

This thesis work has been conducted to enhance human-robot interaction by establishing novel approaching mechanisms that are capable of determining the proper termination distance and direction of a service robot with respect to a user based on the physical behavior of the user. The natural approaching behavior of humans has to be studied in order to implement such human-like navigation abilities in service robots. Therefore, a human study has been conducted for identifying the approaching behavior of a third person toward two persons who are having a conversation. According to the statistical outcomes, the interpersonal distance between the user and the robot at the termination position of an approach does not significantly depend on the positioning of the two persons who are having a conversation. The outcomes of this human study are used to develop the algorithm of the Approach Planner (AP) of the robot in such a way that it can replicate the identified human tendencies to a greater extent. This AP has been implemented on MIRob platform and experiments were conducted by a way of a user study in order to test and validate the behavior of the proposed AP. The experimental results validate that the proposed approaching method of the robot is capable of maintaining the satisfaction of the users during approaches.

The approaching proxemics of a service robot should depend on the physical behavior of a user. In this regard, the thesis proposes a method to decide the approaching proxemics based on the physical behavior of a user. A fuzzy interference system has been designed to decide the proxemics based on the user behavior identified through body parameters. This leads to an effective interaction mechanism initiated by a robot in such a way that the approaching scenario looks more human-like. Experiments were conducted in an artificially created domestic environment and experimental results of the proposed system have been compared with results of a human study. It was found out that the proposed concept is capable of adaptively deciding the approaching proxemics in a human-like manner by assessing the dynamic user behavior.



***Keywords*-Service robotics, Human-robot interaction, Human-centered robotics, Human-friendly robotics, Human-like behavior, Robot approaching, Proxemics**

## DEDICATION

*To my family*

## ACKNOWLEDGMENTS

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Chapter 1

# INTRODUCTION

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Field of service robotics is a rapidly developing area that helps to enhance the living standard of people [1–4]. These service robots play a promising role toward the society and these service robots are used in many service domains such as healthcare [1, 5], entertainment [6, 7], education [8, 9], and guidance [2]. Service robots used for different kind of applications are shown in Fig. 1.1. Furthermore, there are concerns over availability of human caregivers for older people in the near future and these service robots could be used to resolve the implications associated with an aging population [3, 4]. However, most of the users of these robots do not possess much knowledge about robotic domain. Therefore, the users prefer to have human-friendly features in these service robots [10, 11].

Navigation is one of the most important functionalities of service robots since service robots often need to navigate when performing useful services for their users. In the early stages of robotic development, research on navigation had mainly focused on developing low-level navigation functionalities such as obstacle avoiding and localization [12]. Nevertheless, these low-level navigation issues had been almost solved and during the recent years, the attention has been drifted toward developing human-friendly navigation mechanisms [12–14]. Incorporation of human-friendly navigation functionalities to service robots would improve the human-robot interaction since service robots often need to navigate in human populated environments [13, 14].

The ability of a service robot to approach a user in a comfortable and friendly

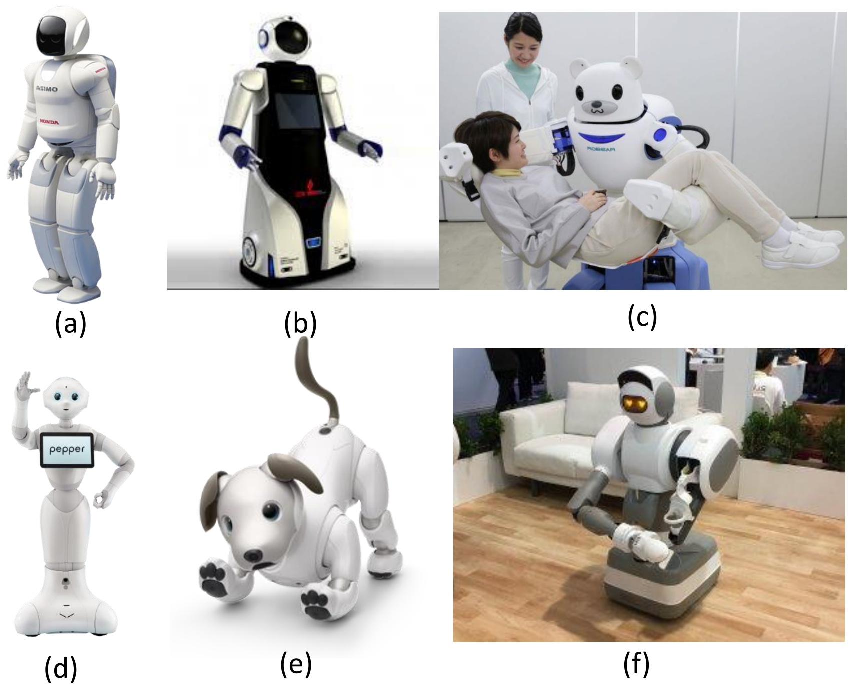


Figure 1.1: Examples of service robots in the present field of robotics. (a) ASIMO robot created for interaction with humans consisting several abilities. (b) S17-7 home service robot. (c) Robear is capable of lifting a patient from a bed into a wheelchair or providing assistance to a patient who is able to stand up but requires help (d) Pepper is a humanoid robot capable of recognizing the principal human emotions and adapting his behavior to the mood of his interlocutor [17]. (e) AIBO is a robotic pet, used for entertainment purposes. (f)Aeolus Robot perform as household robot assistant.

manner would increase the rapport between the user and the robot [13–15]. Furthermore, the navigation action of the robot during the approach should not disrupt nor hinder the ongoing activity of the user [14, 16]. Moreover, the robot should be capable of obeying the social norms when navigating toward the destination position [14, 16].

The approach of a service robot toward a user should be smooth in such a way that it comforts the users in the environment. Human-like behavior and cognitive abilities should be incorporated into the design of robots in order to portray human-friendly interactive features. The ability of identifying user behavior effectively and appropriately responding to user is a major necessity for achieving human-like behavior in service robots. Service tasks often involve interactions with the human user and the robot. Human prefers to maintain different distances with their peers when they are interacting each other in different situations/contexts [18]. Therefore, during such interactions, the robot should maintain an appropriate distance with its user which helps to enhance the rapport between the robot and the user. Furthermore, the robot should be able to approach the user in a direction such that robot's motion would not impede or distract the current activity of the user [19]. Proxemics between two persons depends on the current behavior of the two as well as the context of interaction [20]. Therefore, service robots should be capable of perceiving the behavior of its user and decide proxemics that is appropriate for the current context.

## 1.1 Problem Statement

The approach of a service robot toward a user during domestic service applications is vital to enhance the rapport between the robot and its users. The approaching position of a service robot with a user should be different from one activity to another activity as shown in Fig. 1.2 to have a smooth interaction during the approach. Moreover, the proxemic distance and direction with the user at the termination position of the approach should depend on the physical user behavior.

For example, two different scenarios where a service robot needs to approach a user to deliver a useful task when the user is engaged in two different activities can be considered. In the first scenario, the service robot needs to approach toward the user when he is sitting on a chair. In the second scenario, the robot should approach the user when he is exercising. The comfortable directions of the approach of the robot toward the user are not the same in these two scenarios. Furthermore, the user may prefer a far termination distance in the exercising scenarios than the sitting scenario since a closer proxemic may disturb the exercising. Therefore, the robot needs to maintain two different termination distance and directions with the user during the approach in these two scenarios to improve the smoothness of interaction. However, the termination position of the approach must not solely depend on the type activity engaged by users. For example, a situation, where a user is exercising slowly without much extending limbs and arm, is far more different from a situation, where the user is exercising extensively with far extending limbs and arms. In these two scenarios, even though the activity engaged by the user is the same, the robot should need to maintain different distance and direction during the approach otherwise it may interrupt the user. Therefore, a service robot must be capable of determining the proper proxemic distance and direction with its users at the termination position of an approach based on the physical behavior of the users.

This thesis attempts to enhance human-robot interaction by establishing novel approaching mechanisms that are capable of determining the proper termination distance and direction with a user based on the physical behavior of the user.

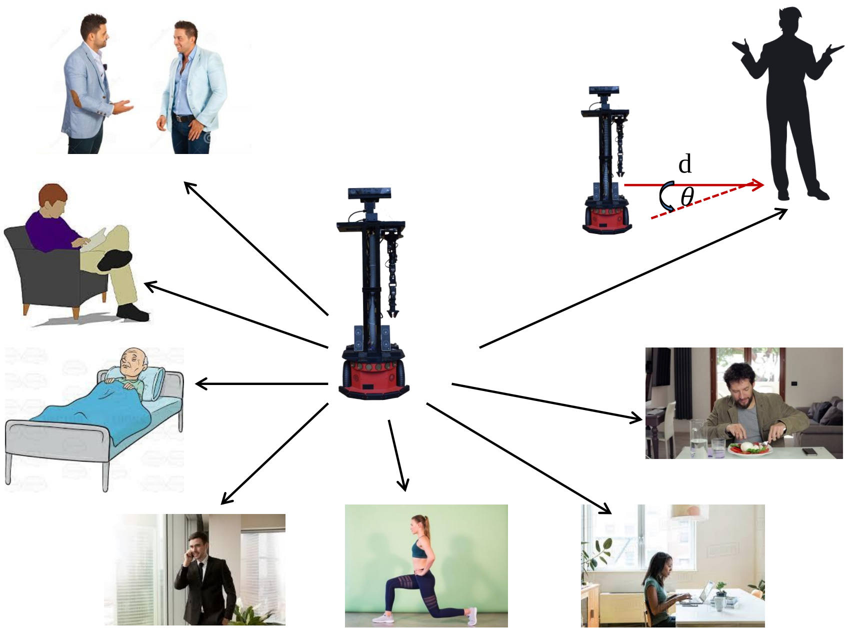


Figure 1.2: Robot observe user engage in different kind of domestic activities. Then robot approach towards the user by maintaining a proper proxemic distance($d$) and direction($\theta$).

## 1.2 Thesis Overview

The thesis is divided in to 7 chapters. Short descriptions of rest of the are chapters are given below.

- Chapter 2 reviews the state of the art approaching mechanisms of service robots. Limitations of the existing systems are discussed and the research gap is explained.
- Chapter 4 includes an overview of the developed system. The functionality of all the modules are briefly described. Furthermore, the details of the hardware platform used for the development is given.
- Chapter 3 contributes a human study conducted for identifying the approaching behavior of a third person toward two persons who are having a conversation. The study has been conducted as three sub studies to identify the parameters that alter the approaching behavior. The key aspects of the approaching behavior of humans have been identified by analyzing the experimental scenarios.
- Chapter 5 proposes a method for human-friendly approaching of a service robot toward a user who is having a conversation with another person. The algorithm behind the proposed approaching method has been designed in such a way that the robot can replicate the natural human tendencies. The experimental results validate that the proposed approaching method of the robot is capable of maintaining the satisfaction of the users during approaches.
- Chapter 6 contributes a method to decide the approaching proxemics based on the behavior of the user. A fuzzy interference system has been designed to decide the proxemics based on the user behavior identified through body parameters. The experimental results of the proposed system have been

compared with results of a human study to evaluate the performance of the system.

- Chapter 7 provides overall conclusion of the developed systems and future directions of the studies.

Chapter 2

# LITERATURE REVIEW

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## 2.1 Proxemics Related Concepts

Human prefers to maintain different distances with their peers when they are interacting each other in different situations/contexts [18]. Four distance zones have been introduced. Furthermore, those are sub divide as near and far phase. It should be noted that the distances vary somewhat with differences in personality and environmental factors. For example, a high noise level or low illumination will ordinarily bring people closer together. The specific distance chosen depends on the transaction; the relationship of the interacting individuals, how they feel, and what they are doing. The four-part classification system used here is based on observations of both animals and men. The classification of proxemic zones given in [18] are shown in Fig. 2.1 and the details of zones are given below.

- Intimate Distance
  - Close Phase: Less than 15cm
  - Far Phase: 15 to 46 cm
- Personal Distance
  - Close Phase: 46 to 76 cm
  - Far Phase: 76 to 122 cm

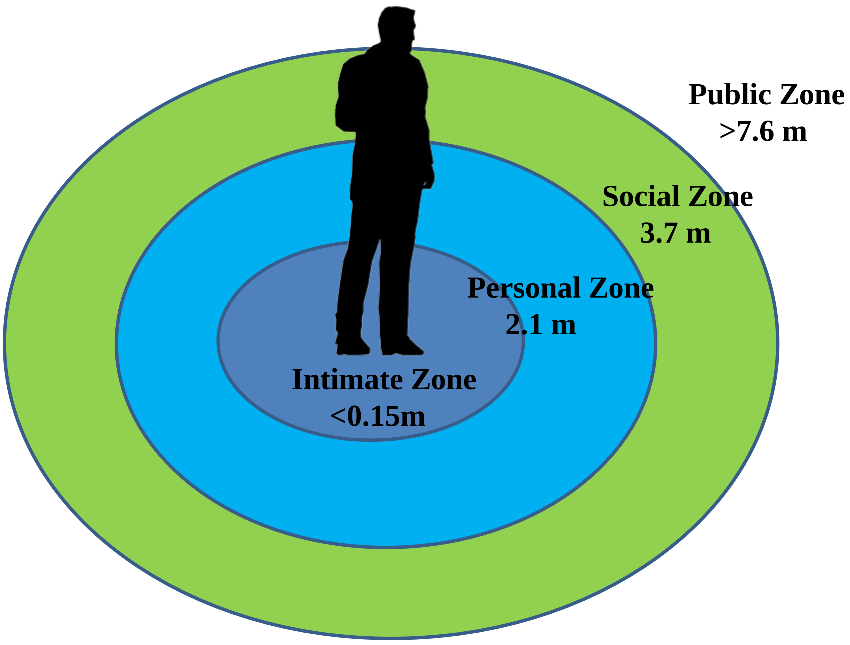


Figure 2.1: Hall's proximity zones.

- Social Distance
  - Close Phase: 1.2 to 2.1 m
  - Far Phase: 2.1 to 3.7 m
- Public Distance
  - Close Phase: 3.7 to 7.6 m
  - Far Phase: 7.6 m or more

### 2.2 User Studies Regarding Robot Approaching toward Users

The information related to the approaching behavior of humans is required to synthesize methodologies for implementing human-like approaching behavior in service robots. Human/user studies have often been conducted to study the human-behavior for implementing human-like interaction abilities in robots for improving human-robot interaction. In this context, a study has been conducted to measure the optimal termination distance of robots approach toward a standing or a seating person who is unaccompanied [21]. During the study, a Nao[1] robot was sent in different approaching directions to evaluate the optimal approach that is accepted by the user. According to the outcomes of the cited study, the robots approaches from the front were preferred over approaches from the side. According to the outcomes of the similar user studies conducted in [22, 23], the humans preferred an approach of a robot from front left or front right over direct front. However, all the above-mentioned studies addressed the problem of positioning robots with respect to one person. Moreover, the studies are limited to investigation of single user scenarios. Therefore, the outcomes would not be valid for a scenario where a couple of persons doing a collaborative task such as having a conversation.

The studies conducted in [16, 24] evaluate the comfort of users when a robot approaches toward a couple of users who are doing a collaborative task such as solving a puzzle game. During these user studies, users were asked to be in different orientations as shown in Fig. 2.2 (a) and asked to play a puzzle game, while a robot was navigated toward them from 8 possible directions as shown in Fig. 2.2 (b). Then, the users were asked to rate their level of comfort for each approach direction. These studies also revealed that approaches of robots from the front are highly comfortable for the users while approaches from the behind are least comfortable. However, the evaluations of these studied were limited to identification of comfortable approaching directions. Moreover, the user comfort variation due to the approaching path or the termination distance has not been studied.

Ruijten and Cuijpers [25] have conducted a user study for analyzing the stopping distance when a robot approaches toward two persons who are having a conversation. A couple of participants were asked to be seated in two chairs positioned as shown in Fig. 2.3. Then, the two participants were asked to have a

[1]www.ald.softbankrobotics.com/en/robots/nao

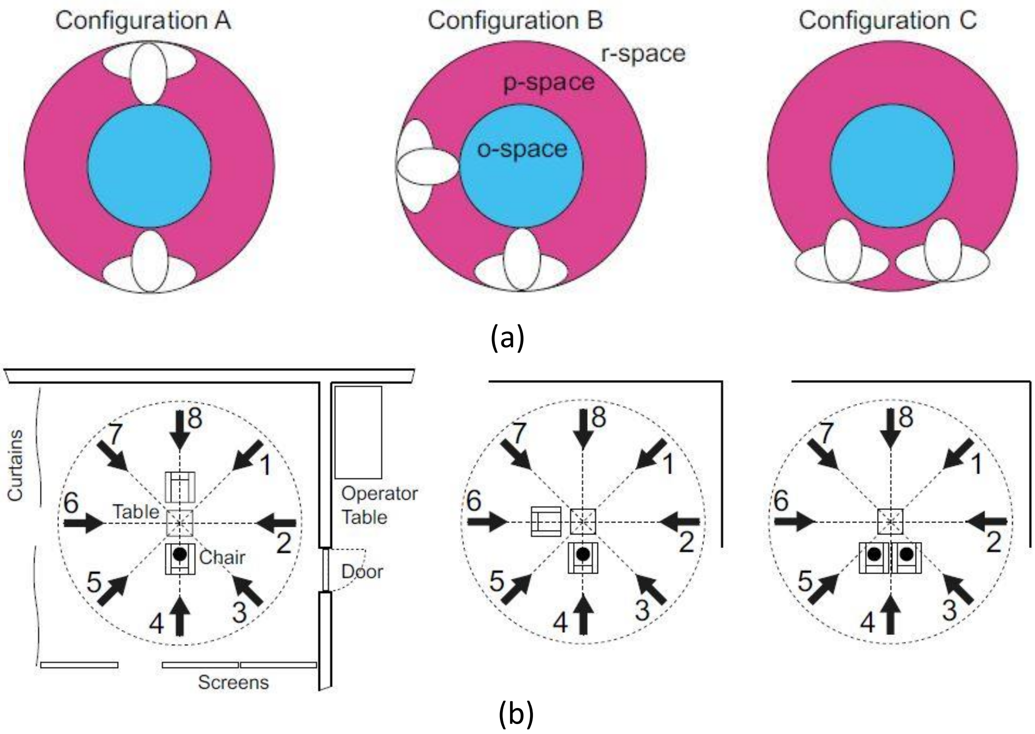


Figure 2.2: (a) Possible seating arrangements of two persons. (b) The experimental space with chairs arranged in configurations and robot approach directions are numbered relative to the positions marked with dots. Extracted from [24].

conversation about their favorite holiday destination. When the two participants were having the discussion, a Nao robot was navigated along a linear path from its start position to the target position. The two participants were asked to indicate the preferred termination distance by pressing a triggering switch given to each participant. Furthermore, the two participants were asked to rate the approach of the robot in a 5-point scale. Similarly, the process was continued by changing the initial position of the robot and target position of approach. The termination distance and the direction of approach preferred by the participants are presented as the outcomes.

However, the study is limited to few aspects such as variation of stopping distance due to the approaching direction and target position, and some of the possible concerns are not studied. The termination positions were on a fixed path and the participants were only able to select a more suitable one among

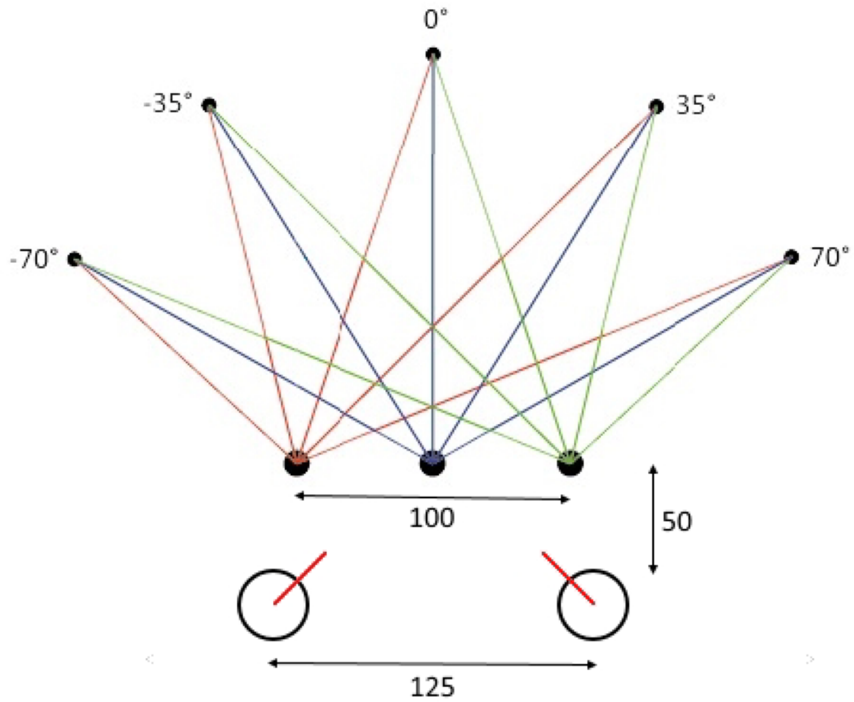


Figure 2.3: This shows the experimental arrangement of the user study conducted in [25]. The circles represent the orientation and the position of the users. Small dots represent the initial positions of the robot. The robot is navigated toward a large dot along the path represented by the line in each case. Reprinted with permission ©2017 IEEE

the available set. Therefore, the selection of the appropriate termination position had been done with restrictive constraints. The position and the orientation of the users were fixed in L shaped configuration defined in Kendon's basic types of F-formation [26] for arrangements of conversational encounters of humans and other possible configurations have not been considered. There are six basic types of F-formation as shown in Fig. 2.4. The variations of the termination distance in accordance to the variation of the position and the orientation of the user have not been studied in here. Furthermore, the robot was navigated in a linear path from its initial position to the target potion. Hence, the study does not reveal the suitable path for the navigation of the robot. In addition to that, this study does not study the behavior of a human participant, who approaches toward a couple of humans such as the social norms followed by the approaching person and greeting during the approach.

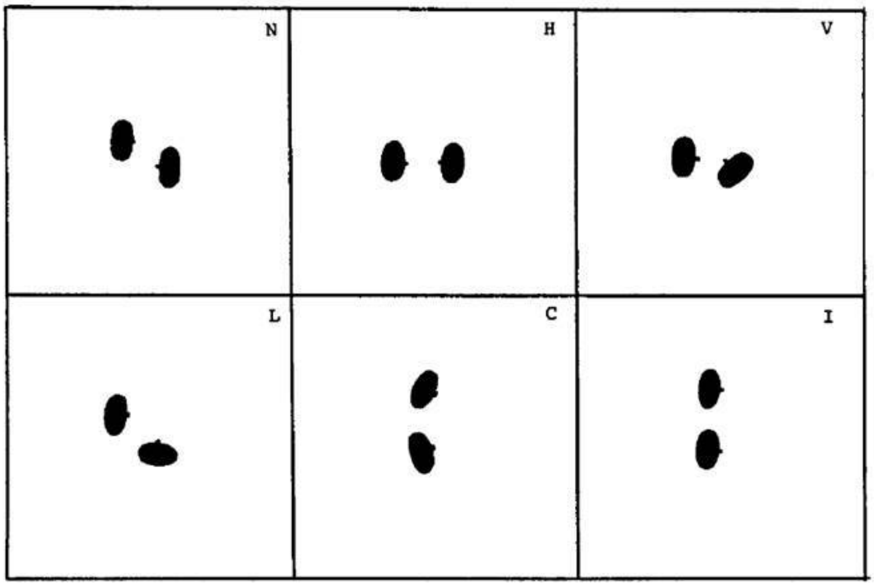


Figure 2.4: Six basic types of F-formation labeled according to their spatial layout. Extracted from [26]

### 2.3 Human like navigation methods

Methods have been proposed for generation of human-friendly trajectories for navigation of robots with their users [27,28]. In [27] analyzed humanhuman interactions and found that human pairs sustained a side-by-side walking formation. They have modeled this interaction by assuming that one needs knowledge from the environment. The model enables a robot to switch between two interaction modes and those are strictly maintains the side-by-side walking formation and in another it walks slightly behind its partner. The results of the experiments were not shown significance for safety impression. Furthermore dynamic environment the human motion pattern might change over a period of time and havent taken into account those motion changes. In [28] introduces a robot social-aware navigation framework to walk side-by-side with people in crowded urban areas in a safety and natural way. The system consist a new robot social-aware navigation model to accompany a person; to extend the Social Force Model. Yet, a better performance has been demonstrated if human interactions are taken into account. However, these methods cannot be adopted for deciding the approach of a service robot toward their users since the contributions of the work are limited to enhancing side-by-side navigation of robots and humans.

## 2.4 Fixed Approaching Proxemics Distances

Service robots those are capable of approaching customers in shopping malls have been developed [29,30]. In [29] the main contribution of the cited work was to develop an effective method to attract the attention of the user for initialization of interaction and less attention has been paid for the improving the human-friendly approaching behavior of the robot. Furthermore, the method considers only a single user of interest. Hence, the approach of the robot may not be friendlier to the other person who is having the conversation with the user of interest. These systems consider only the nearest path to reach the person. Any attention is not given to the behavior of the customer to adapt proxemics while approaching. Fixed approaching proxemics are acceptable for a robot in a shopping mall since the activities carried out by the users are not significantly different. However, it is a downside for a domestic service since users engage different varieties of activities that require different proxemics of the partner. Robot should be more intelligent and human-like to identify domestic user activities and capable of maintain proxemics for better interaction with the user respective to each activity.

## 2.5 Studies Conducted for Maintaining Proxemics Distances

Many studies have been conducted in order to develop methods for maintaining proper proxemics between robots and human users [31–37]. However, these methods have been proposed for maintaining the required distance with a user during different interaction modes/contexts and the way of approaching toward the user is not considered. Moreover, the navigation path of the robot is not of interest for these methods. Furthermore, the methods consider only the user of interest for maintaining the proxemics during interactions and other persons in the environment are ignored. Furthermore, these systems are not capable of considering the human-like behavior such as social norms in deciding the approaching to the user. Hence, the proposed methods would not be effective for approaching a person who is engaged in a activity like having a conversation with another person. In [32], scaling functions have been introduced to alter robot's physical movements based on proximity to a human. However, this system is not capable of altering the proxemics with user based on the behavior of the user. Moreover, these models are not effective for developing a human-friendly approaching method for a service robot.

Furthermore, [36] has a mechanism to understand distancing behavior of people with robots. In this system, robot's behavior is limited to speech and gaze. Activities such as exercising will change postural arrangement of a human from time to time. A method for deciding the approaching based on the user behavior has been proposed in [31]. That system uses a wearable device to detect the user behavior. The proposed system is only capable of deciding the distance between the user and the robot. However, it cannot decide the approaching direction. The robot approaching direction/orientation is also an important factor similar to the distance. The system is capable of deciding the proxemics based on a predefined set of postures categories; standing, sitting, walking and laying. However, it is less effective to have fixed proxemic for each considered posture category. For example, a person doing an exercise slowly and fast can be considered. In this scenario, the posture category is same. Therefore, the system discussed in [31] would give the same response in these two cases. Conversely, the proxemics in these two cases must be different. Therefore, the robot should be capable of determining the approach based on the current dynamic behavior of the user instead of posture category.

## 2.6 Summary

This chapter presented a review of state of the art approaching mechanism that have been developed to improve human-robot interaction. In summary, many systems/concepts have been proposed to develop human-friendly approaching mechanism in service robots. However existing systems have limitations and require improvements to establish human-like approaching behavior. The summary of the state of the art, limitations, and the contributions of the thesis to fill the research gap are depicted in Fig. 2.5

**Existing Approaches**

- Service robot that is capable of approaching users by maintaining fix proxemics.
- Methods for maintaining the required distance with a user during different interaction modes/contexts.
- Scaling functions to alter robot's physical movements based on proximity to a human
- Mechanism to understand distancing behavior of people with robots
- Method for deciding the approaching based on the user behavior

**Research Gap**

- Less attention has given for the improving the human-friendly approaching behavior of the robot.
- Some methods consider only a single user of interest.
- Attention is not given to the behavior of the user to adapt proxemics while approaching.
- Not capable of considering the human-like behavior such as social norms in deciding the approaching to the user.
- System is not capable of altering the proxemics with user based on the behavior of the user
- Less effective to have fixed proxemics for each considered posture category

**Contribution**

- Analyze human behavior related to the approaching in different user activities and environments through a human study.
- Develop an intelligent system for the robot to plan the approach to the user in such a way that the robot can replicate human-like proxemics.
- Train and test the developed robotic system for selected set of domestic activities.

Figure 2.5: Summary of the literature review

Chapter 3

# SYSTEM OVERVIEW

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As explained in Section 1.1, service robots often need to navigate toward their users when accomplishing service tasks requested. Service robots must be capable of maintaining proper approaching proxemics toward a user when he/she engages in a domestic task in order to enhance human-robot interaction. Human-like features in approaching behavior of a service robot will be beneficial in this regard. Therefore, the human-friendly approaching mechanisms proposed in this thesis have been developed based on the natural human tendencies identified through the human studies presented in Chapter 4 and Chapter 6. The functional overview of the developed system is explained in this chapter with details of the used service robotics platform.

## 3.1 Functional Overview

Functional overview of the proposed system is shown in Fig. 3.1. The proposed system evaluates user behavior before approaching the user to determine the most suitable interpersonal distance and orientation to be maintained when completing a service demanded by its user. The system evaluates user characteristics such as joint movements and activity space often considered by humans before approaching another person.

Skeletal Information Extraction Unit (SIEU) acquires vision information as a skeletal representation of the human body in the form of 3D coordinates of feature points. The total body joints which can be obtained from kinect is shown in Fig. 3.2. These feature points are extracted from the Kinect sensor. Behavior of certain body joints which are frequently involved in domestic activities are considered here. The retrieved joint coordinates are fed into the Users' Position and Orientation Identifier (UPOI). The UPOI estimates the positions and the orientations of the people perceived by the robot with respect to the coordinate frame of the available navigation map. The output of Proxemics and Approach Planner Module (PAPM) determines the distance and orientation to be maintained with the user.

Under the PAPM there are two modules and first module is the Approach Planner (AP) which is capable of deciding the approach towards a interested person when he/she engage in a conversation. The second module consists of three sub modules as Fuzzy Proxemics Evaluation Model (FPEM), Data Analyzer (DA) and User Skeletal Information (USI). These three sub modules help to identify user physical behaviors and maintain a proper interpersonal distance and orientation with the robot and the user.

Action Manager is responsible for executing the decisions taken by the PAPM. In addition, it coordinates voice and navigation outputs of the system. It further determines the type of verbal communication required at the moment and the movements to be made by the robot. Furthermore, the AM issues instructions to the Voice Response Generation module, a text to speech converter implemented to generate voice responses of the robot such as greeting and excusing messages. A predefined set of message phrases are stored in the Language Memory for this purpose. Finally, when the robot reaches the user, Voice Response Generation unit will be functional to initiate a conversation with the user.

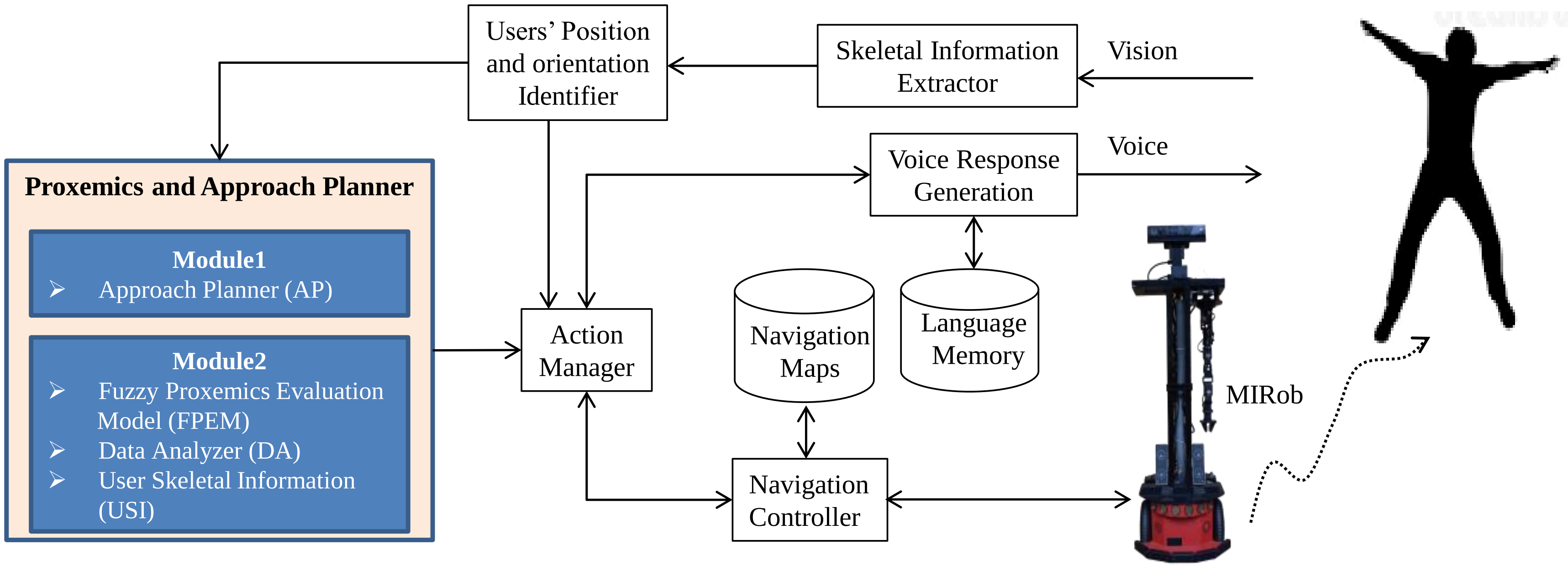



Figure 3.1: Overview of the system

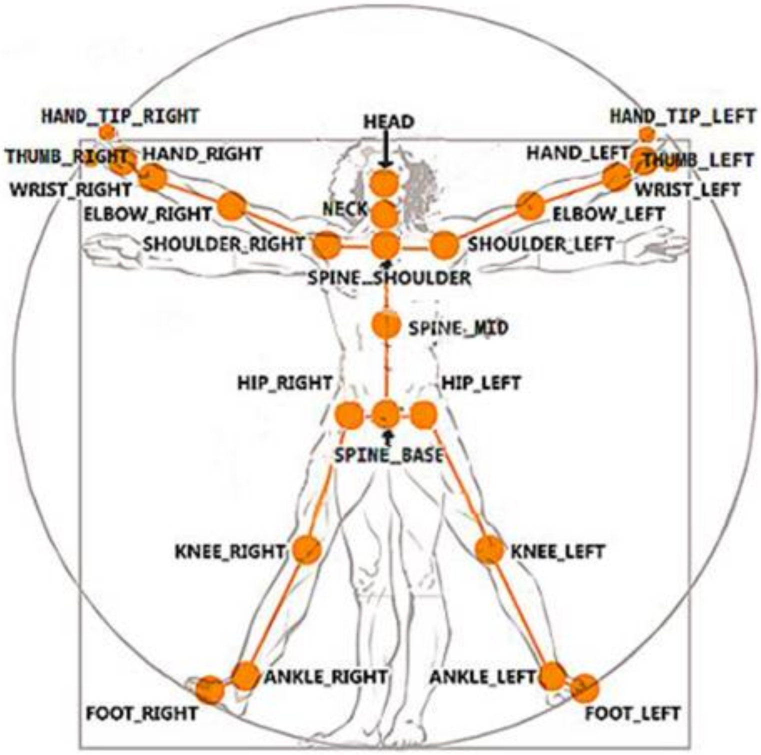



Figure 3.2: Microsoft Kinect V2 is used to track the shown body joints. Selected body joints are used for system development.

Navigation Controller(NC) handles low-level controlling functions such as localization and maneuvering based on information of the environment acquired by sensory input unit. It can calculate a collision-free path from its initial position to a given destination position. The required navigation maps are created using Mapper3 Basic provided by Adept MobileRobot and the maps are stored in Navigation Maps database.

### 3.2 Physical Overview

The proposed concepts have been implemented on MIRob platform [38] as shown in Fig.3.3. Pioneer 3DX mobile robot platform used as the base of the MIRob. The robot consists of two sonar sensor arrays one in the front and one in the back. Eight sonar sensors, which have sensitivity range from 10 cm to 5 m, consist with each sonar sensor array. The base can carry a payload of up to 17 kg and the maximum speed is 1.2m/s. Total height of the MIRob is 110 cm and Cyton Gamma 300 manipulator is installed on the robot to handle objects. The manipulator has 7- DOFs and 1 DOF gripper. Kinect version 2 motion sensor is mounted with a pan-tilt unit.

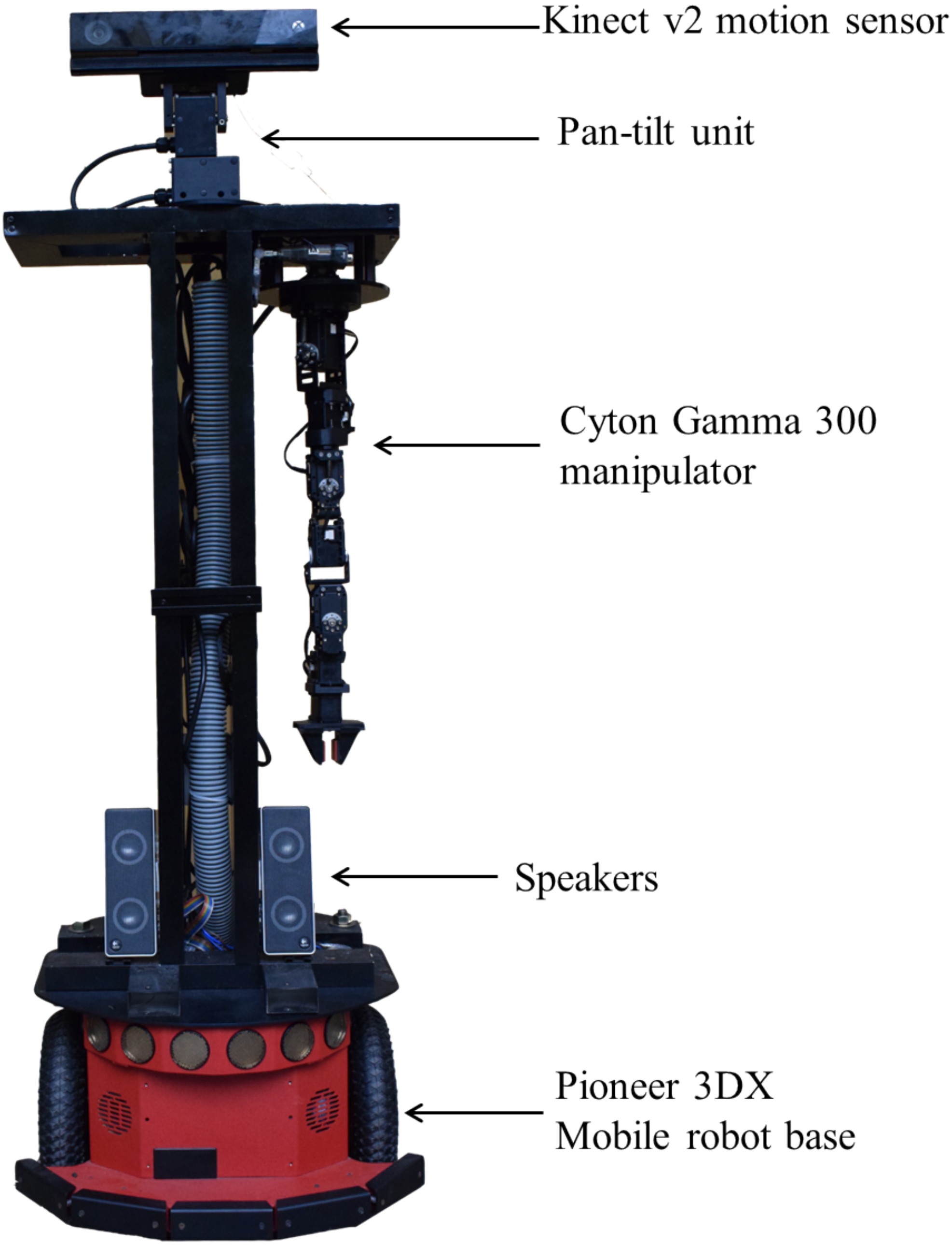



Figure 3.3: Moratuwa Intelligent Robot (MIRob).

Chapter 4

# IDENTIFYING APPROACHING BEHAVIOR OF A PERSON DURING A CONVERSATION: A HUMAN STUDY

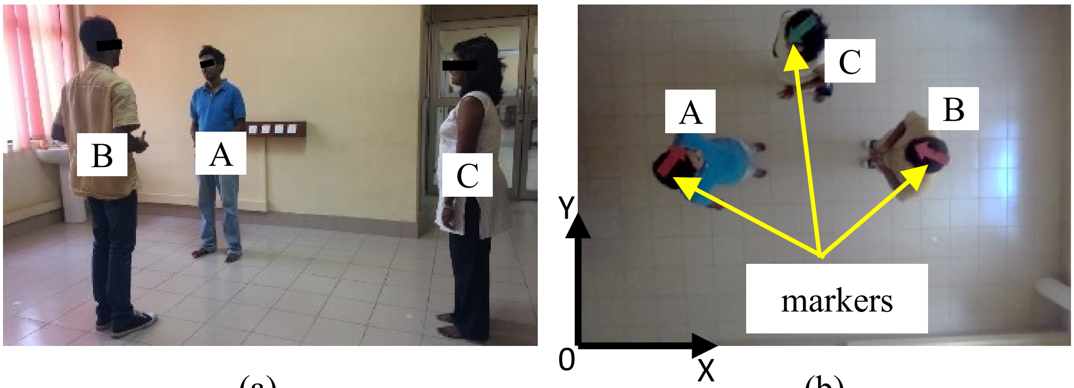
---

The chapter presents about a human study conducted for identifying the approaching behavior of a person toward two persons who are having a conversation. The human study has been conducted as three sub studies to identify the approaching behavior. In study 1, dependency of approaching in accordance with the orientation of the two persons who are having the conversation has been studied. Effects caused to the approaching due to the variation of the initial position of the approaching person have been studied in study 2. The variation of the approaching in accordance with the distance between the two persons who are having the discussion has been studied in study 3.

## 4.1 Study Design

The goal of the study is to identify the approaching behavior of a third person toward a person who is having a conversation with another person. The main intention of the study is to gather information necessary for implementing a human-like approaching mechanism for a domestic service robot. The recommendation and guidelines given in [39] have been considered when designing and conducting the experiments to minimize the subjectivity of the outcomes.

Three human subjects were used for a particular scenario as shown in Fig. 4.1(a)




(a) (b)

Figure 4.1: (a) An explanation of experimental scenarios is given here. The persons 'A' and 'B' are having a conversation while the person C approaches toward the person 'A' for having a conversation interaction. The approaching behavior of 'C' is expected to be replicated on a service robot based on the outcomes synthesized in this study. (b) A frame captured from the overhead camera during an experimental case is shown here. Markers are fixed on the heads of the human subjects as shown for increasing the accuracy of tracking process and also to measure the orientations. All the measurements were taken with respected to the marked origin. It should be noted that the image shown here is cropped for displaying only the interested area.

during each run of the test cases. The persons annotated as 'A' and 'B' are having a conversation while the person annotated as 'C' is approaching toward the person 'A' for having a conversation. The behavior of person 'C' is the interest of the study since the approaching mechanism of a service robot should be capable of replicating the behavior of person 'C'. Eight human subjects, whose age is in between 24-28 years (M =25.9 and SD =1.2 ), participated as the approaching person (Person 'C'). The subjects participated as 'A' and 'B' were the same for all the test scenarios. The topics of the conversations between 'A' and 'B' were related to popular sport events such as recent Cricket tournaments. This would ease the interaction of the third person (i.e., 'C') with 'A' and 'B' since the topic of the conversation is well sociable. All the participants were graduate students of the university and all of them have South Asian cultural backgrounds. Furthermore, participants who had previous experience with interacting each other were chosen for the study as the participants. This decision was taken since a domestic service robot would most probably interact with familiar person and the intention of the human study was to gather information required for implementing an effective approaching mechanism for a domestic service robot.

The size of the environment considered for the human study was 3.45 m in width and 4.95 m in length. Furthermore, there were no any other objects/obstacles in the considered environment and hence, the outcomes of the study are not altered due to the effects caused by objects/obstacles in the environment such as congestion issues. This was desired since the scope of the study was limited to the identification of the approaching behavior of a person in an unconstrained environment.

An overhead camera mounted on the top of the room was used to capture the motion of the subjects during the experimental scenarios. The video streams have been recorded with a resolution of 1080P with a frame rate of 60 frames per second. It should be noted that the camera had been calibrated to minimize the radial distortion. Markers with a shape of arrowhead were clipped to the heads of the human subjects during the experiment for the sake of increasing the tracking ability as well as to measure the orientation variations. A frame captured through the overhead camera during an experimental scenario is shown in Fig. 4.1(b). Markers with two colors were used: for 'A' and 'B' red color and for 'C' green color. The markers used for the tracking purpose are also annotated in Fig. 4.1(b). The captured video streams were analyzed offline using Kinovea[1] software.

[1] www.kinovea.org

## 4.2 Human study 1: Effects of the Approaching due to the Orientation of the Two Persons

### 4.2.1 Procedure

The idea of this study is to understand how the participants alter their approach toward the two persons who are having a conversation, depending on their orientation. Therefore, different orientations of 'A' and 'B' should be considered while the other factors are kept constant. Person 'A' and 'B' asked to be located in given fixed locations. The distance between those two locations was chosen 120 cm to have the distance between 'A' and 'B' in the border of Hall's [40] personal distance and social distance. Then, 'A' and 'B' were asked to be in nine orientations shown in Fig. 4.2. The orientations of 'A' and 'B' were selected to cover most of Kendon's basic types of F-formation [26] defined for arrangements of conversational encounters of humans. Each subject participated as 'C' was asked to approach to 'A' in all of the nine cases. The initial position of the 'C' was the same for all the cases. Similarly, the experiment was repeated for all the subjects participated as 'C'. The movements of 'C' have been captured and analyzed for all the cases.

### 4.2.2 Results

The traced path of 'C' for all the test cases are marked on the maps shown in Fig. 4.2. Most of the time the termination position of the 'C' was inside the field of view of the person 'A' (for this analysis horizontal field of view of a human has been considered as 190° based on [41]). Furthermore, there was a higher probability of having the termination position within the peripheral vision field of 'A' (peripheral vision range is 120° [41]). This phenomena can be clearly visible in the cases shown in Fig. 4.2 (a), (b), (c), (d), (g), and (h). However, there are cases where 'C' is not within the vision field of 'A'. For example, in the cases e,

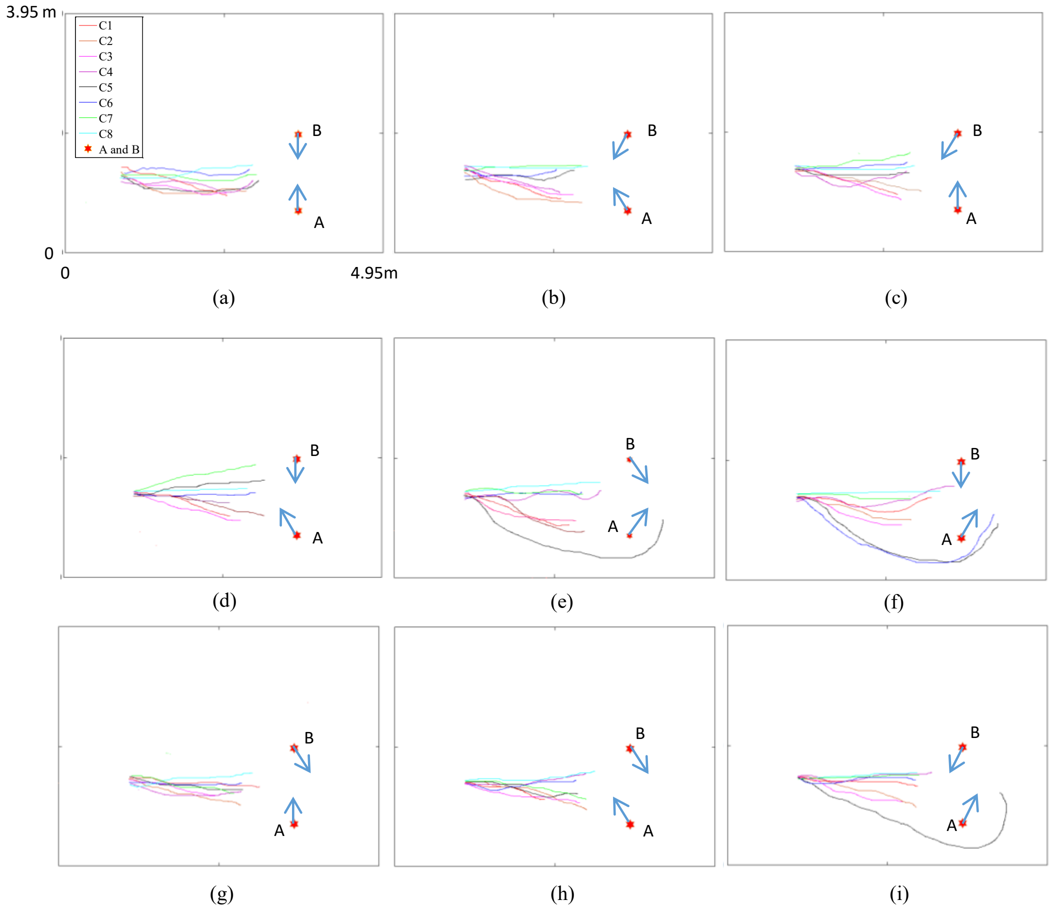



Figure 4.2: The traced paths of human subjects participated as 'C' in study 1 are shown here. The distance between 'A' and 'B' was kept as 120 cm throughout the study 1. The orientations of the 'A' and 'B' in each case are marked with arrowheads. (a),(b),(c),(d),(e),(f),(g),(h) and (i) are the distinct cases considered for the study.

f and i, participants 'C1', 'C2' and 'C3' are not inside the vision field of 'A'. In those situations the orientation of 'A' was little backward to 'C'. Captured videos of those cases have been further examined to find out the possible factors for the deviation. According to the analysis, it was found out that, 'A' has changed the orientation during the termination because 'C' grabbed the attention from 'A' by speaking or knocking to the person 'A'. Furthermore, in all the test runs included in the study, subjects participated as 'C' have not approached 'A' in such a way that the movement hinders the ongoing discussion between 'A' and 'B'. This phenomena is typically considered as a social norm.

Then, the effects of the orientation of ‘B’ for the approaching behavior of ‘C’ have been examined. Cases a,c and e are considered since the orientation of ‘A’ was the same and the orientation of ‘B’ was changed. The paths of ‘C’ in the cases are almost similar. Therefore, it can be concluded that the change of the orientation of ‘B’ does not effect the approaching behavior of ‘C’.

The distance between ‘A’ and ‘C’ at the termination point of the each test run has been calculated for the analysis since it will be useful for developing the approaching mechanism for a service robot. The mean distance between ‘A’ and ‘C’ calculated for each case is plotted in Fig. 4.3(a) with error bars. Furthermore, box plots of the distance values are shown in Fig. 4.3(b) to provide better visualization to the reader about the distribution. The significance of the

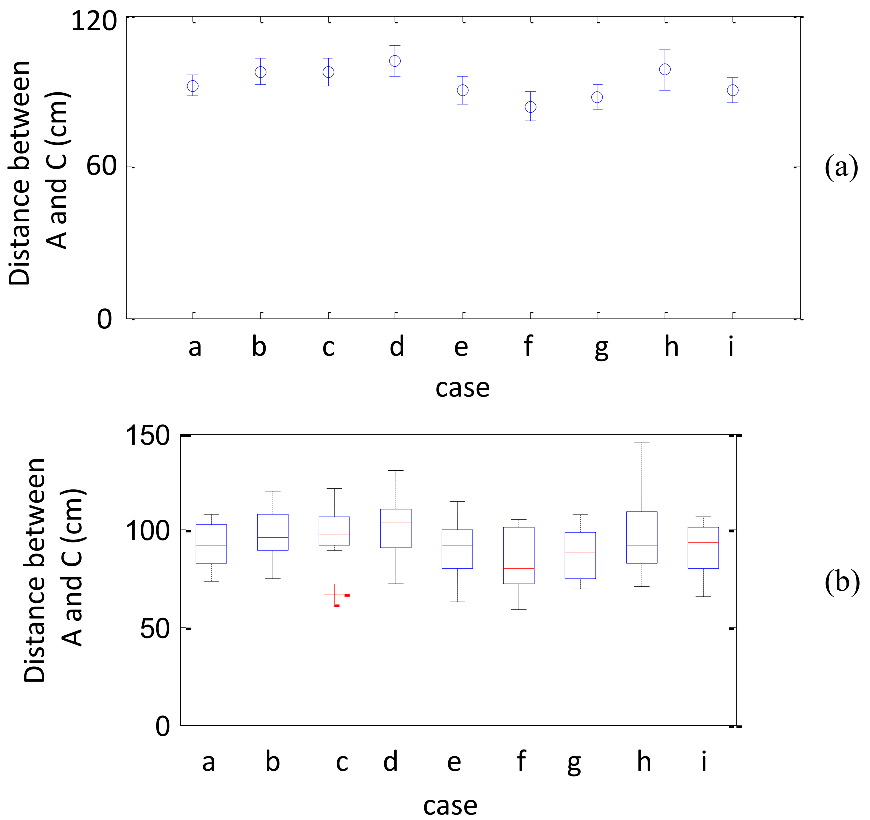



Figure 4.3: (a) shows the mean distances between ‘C’ and ‘A’ at the termination positions during study 1. Error bars represent the standard error. (b) shows the box plots of the same for case a, b, c, d, e, f, g, h, and i. The box plots have the usual notation; box: inter quartiles, horizontal line:median, whiskers: minimum and maximum, and plus sign: outliers

results has been analyzed using one-way ANOVA test. According to the test statistics, there is no statistically significant difference (F = 0.68, P = 0.57) between the distances obtained in the cases. Therefore, it can be concluded that the termination distance between ‘A’ and ‘C’ does not depend on the orientations of ‘A’ and ‘B’.

## 4.3 Human study 2: Variation of the Approaching in Accordance to the Initial Position of the Approaching Person

### 4.3.1 Procedure

The core idea of this section of the study is to recognize approaching behavior with respect to the initial position of ‘C’ when ‘A’ and ‘B’ are engaged in a conversation. Study was carried out considering five initial positions as shown in Fig. 4.4 for covering all the possible cases. The distance between ‘A’ and ‘B’ was maintained 120 cm for all the five cases as similar to human study 1 to have the distance between ‘A’ and ‘B’ in the border of Hall’s [40] personal distance and social distance. For the case shown Fig. 4.4 (c) and (d) person ‘C’ was approaching to ‘A’ in the direct backward and the direct forward directions respectively. For those two cases the size of the created environment was not sufficient. Therefore, positions of ‘A’ and ‘B’ were changed as shown Fig. 4.4 (c) and (d). ‘A’ and ‘B’ were having a face-to-face conversation (i.e., orientation similar to case a of human study 1) and person ‘C’ was asked to approach toward ‘A’. Similar to the study 1, the movement of ‘C’ has been traced and analyzed.

### 4.3.2 Results

The traced path of ‘C’ for all subjects in the test cases are marked on the maps shown in Fig. 4.4. Similar to the study 1, the final positions of ‘C’ was

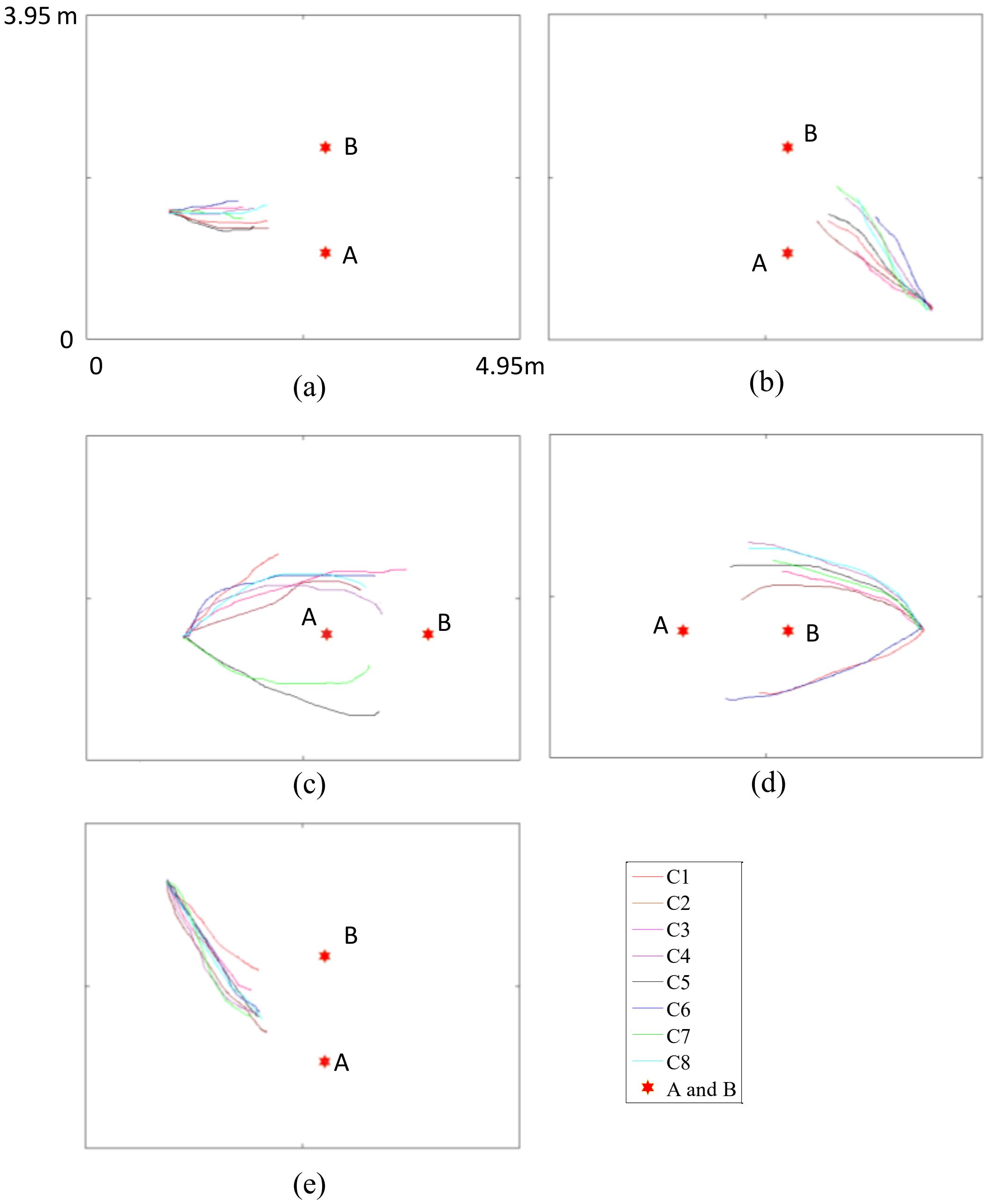



Figure 4.4: The traced paths of human subjects participated as 'C' in study 2 are shown here. The orientation of 'A' and 'B' was similar to that of case (a) of the study 1. The initial positions of 'C' was different in (a), (b), (c), (d), and (e).

always within the field of view of 'A' in this study too. Based on the results of case a and e, it can be observed that if the initial position of 'C' was in the left (with respect to 'A') then the final position of 'C' is also in the left side (with respect to 'A'). Vice versa of this can be shown with the results of case

b. Since in Fig. 4.4 (b) initial position of the 'C' was right side of the person 'A' and the final position of 'C' was also the right side of person 'A'. If there were no discrimination of the side of the initial position of 'A' (for example case c and d), the final positions of 'C' cannot also be discriminated based on the side. This implies that the approaching person (i.e., 'C') usually chose the closer destination position. When the initial position of 'C' is on back of 'A' (i.e., in case c), except for one person (i.e., 'C1'), termination positions were inside the vision filed of 'A'. The deviated test run of the subject was separately analyzed to get an idea about the reasons for the change in approaching behavior. That subject got the attention of 'A' by excusing, that changed the orientation of 'A'. In all the test cases, the subjects act as 'C' has not crossed in between 'A' and 'B' obeying social norms. Then, similar to the study 1, distance between 'A' and 'C' at the termination positions was calculated for each run of the cases and analyzed. The mean value variation of the distance between 'A' and 'C' is shown in Fig. 4.5(a) with error bars. The distributions of the distances are given as box plots in Fig. 4.5(b). In order to test the significant of the results, one-way ANOVA test was carried out. According to the test statistic, there was no statistically significant difference in the distances ($F = 1.48$, $P = 0.23$) between the cases. This implies that the distance of the termination does not significantly depend on the initial position of the approaching person.

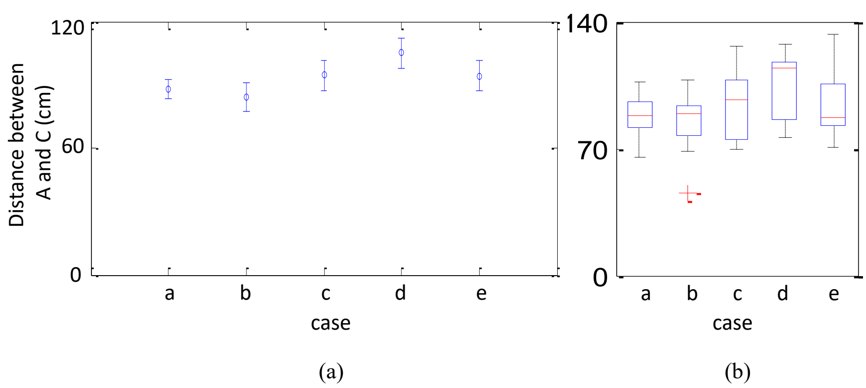



Figure 4.5: (a) shows the mean distances between 'C' and 'A' at the termination positions during study 2. Error bars represent the standard error. (b) shows the box plots of the same for case a, b, c, d, and e.

## 4.4 Human study 3: Variation of the Approaching in Accordance with the Distance between the Two Persons

### 4.4.1 Procedure

Study 3 was conducted to analyze the variation of the approaching behavior with the distance between 'A' and 'B'. The distances between 'A' and 'B' for test cases were chosen as 77 cm, 135 cm, 200 cm and 278 cm. The traced path of 'C' and corresponding positions of 'A' and 'B' are shown in Fig. 4.6. The distances between 'A' and 'B' were chosen to cover the range from far phase of personal distance to close phase of social distance defined by Hall [40]. The position of 'A' was fixed and the position of 'B' was changed in each case for having the above-mentioned distances between 'A' and 'B'. Initial position of the 'C' was kept fixed for all cases. In this scenario, 'A' and 'B' were having face-to-face conversation (i.e., orientations similar to the case a of study 1) and 'C' approaches toward 'A'. As similar to the previous studies, the movements of 'C' have been captured for the analysis.

### 4.4.2 Results

The traced path of 'C' for each of the considered test cases are marked on the map shown in Fig. 4.6 According to the experimental results, final positions of all the subjects participated as 'C' are within the vision field of 'A' in all the test runs. In most of the test runs, the final positions of 'C' were closer to 'A' than 'B'. During the experiment, it was observed that the subjects participated as 'C', excused from 'A' and 'B' when starting the interaction with 'A'.

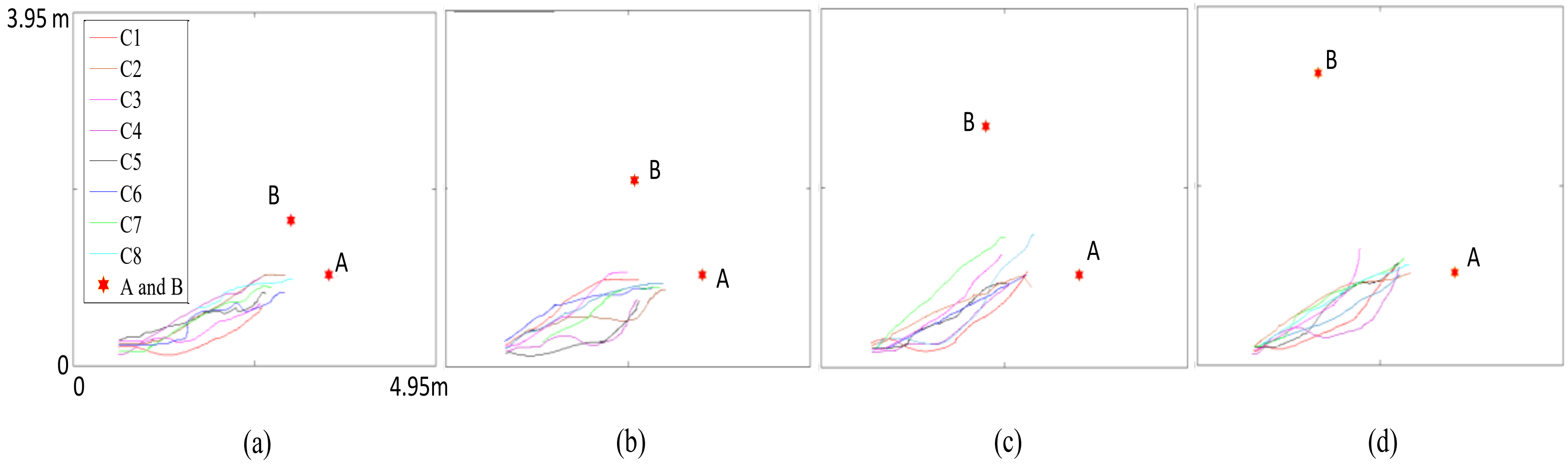



Figure 4.6: The traced paths of human subjects participated as ‘C’ in study 3 are shown here. The orientation of ‘A’ and ‘B’ was similar to that of case (a) of the study 1. The distance between A and B in each case was; (a): 77 cm, (b): 135 cm (c): 200 cm and (d): 278 cm

However, when the distance between 'A' and 'B' is increased the frequency of excusing by 'C' from 'B' is decreased. Furthermore, the subjects obeyed the social norm that they should not position in the middle of 'A' and 'B' in such a way that it hinders the ongoing discussion.

The distances between 'C' and 'A' at the termination positions have been calculated from the traced paths. The distance variation between 'A' and 'C' with the distance between 'A' and 'B' is given in the graph shown in Fig. 4.7(a) The box plots of the distances obtained are shown in Fig. 4.7 (b) for better visualization of the variations. In order to analyze the significance of results, one-way ANOVA test was conducted. According to the test statistics, there is no statistically significant difference (F = 0.68, P = 0.57) in the distances between the cases. This implies that the distance between 'C' and 'A' does not significantly depend on the distance between the two persons who are having the discussion.

## 4.5 Outcomes of the Human Study

The human study was conducted to identify the behavior of a person approach toward two persons when they are engaged in a conversation. The overall results were analyzed and the following key facts related behavior of the approaching

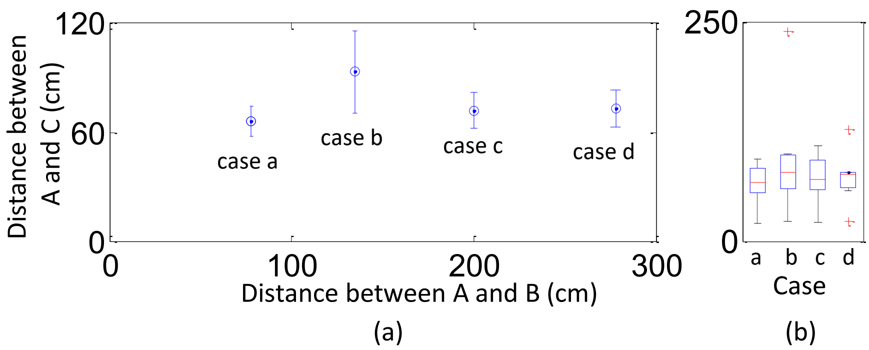



Figure 4.7: (a) shows the mean distances between 'C' and 'A' at the termination positions during study 3. Error bars represent the standard error. (b) shows the box plots of the same for case a, b, c, and d.

person have been discovered.

1. Most of the time ‘C’ approaches to the vision field of ‘A’ (if fact 4 is not violated). The initial orientation of ‘A’ affects the termination position of ‘C’ while there is no effect from the orientation of ‘B’.

2. The termination distance between ‘C’ and ‘A’ has been found to be independent from the orientations and the distances between ‘A’ and ‘B’. Furthermore, the termination distance does not depend on the initial position of the third person (i.e., ‘C’).

3. The approaching person prefers to choose the closer termination position to its initial position which satisfies fact 1, 4 and the required termination distance.

4. Most of the times approaching person obeys the social etiquette: a third person should not go in between two persons who are having conversation in such a way that it hinders the ongoing discussion.

5. The approaching person excuses the other two when initiating the interaction.

Since the termination distance does not significantly depend on the orientation of the two person, distance between the two person and the initial position of the approaching person, an average termination distance was calculated considering all the test cases. The mean value of the termination distance was 91 cm with a standard deviation of 22 cm. Preferences of proxemic behavior depends on the cultural backgrounds of the people [42]. The conducted study presented in this work has also contributed for identifying the proxemic behavior of Sri Lankan people (South Asian culture) during conversational interactions. Hence, the outcomes such as termination distance would be greatly beneficial for developing proxemic models for the targeted population, since these details of the targeted population is not available in the literature.

The conducted human study would be important for the development of intelligent service robots that possess human-like behavior. The key capabilities of the robotic system that require realizing the approaching behavior has been synthesized based on the outcomes of the human study. The navigation planner of a service robot should be designed in such a way that it can follow the above mentioned key facts (except fact 5) when approaching toward two users who are having a conversation. Therefore, these facts should be developed in an algorithmic way to implement them in a robot. A rule based approach would be a feasible solution for this. However, it would be a challenging task. In addition to that, the interaction management functionality of the robot should be capable of generating vocal expressions such as greeting and excusing messages at the correct occasions when the robot approaches to the users. The robotic system should be capable of identifying the exact locations and orientations of the two persons who are having the discussion (i.e., 'A' and 'B'). Furthermore, it needs to estimate the vision filed of 'A' to decide the destination position. Usage of RGB-D sensors such as Kinect that facilitates the human skeletal tracking would be a suitable option to realize the identification process of the users and their orientations by the service robot. Therefore, it would be a promising approach to implement human-like approaching mechanism in service robots based on the outcomes of the study.

The two persons engaged in the conversation task is a static situation. Since the achieved results show that the distance of the subject 'C' does not significantly change at all. There may be variations in the termination distance for different task/behavior of subject 'A'. Therefore, investigation of effects due to the dynamic behavior of humans is proposed for future work.

### 4.6 Summary

This chapter presents about a human study that was done in order to understand the approaching behavior of a third person toward two persons who are having a conversation. The study has been conducted with three sub studies and the first study aimed at identifying effect the orientation of the two persons having the conversation. The second study has been conducted to observe the change of approach behavior due to the initial position of the person and final study has been conducted to identify the approach behavior by varying the distance between the conversation carrying two persons.

The movements of the approaching persons have been traced and analyzed to identify the key characteristics of the approaching behavior that would be useful for implementing human-like approaching behavior in a service robot. The future directions for implementing human-like approaching behavior in service robots have been synthesized based on the outcomes of the human study. The future work that can be done in order to improve the human-study has also been presented. Therefore, outcomes of this work will be beneficial for improving human-robot interaction of service robots.

CHAPTER 5

# REPLICATING NATURAL APPROACHING BEHAVIOR OF HUMANS FOR IMPROVING ROBOT'S APPROACH TOWARD TWO PERSONS DURING A CONVERSATION

This chapter proposes a method for smooth approaching of a service robot toward a user who is having a conversation with another person. The proposed method has been synthesized based on the natural approaching behavior of humans identified through a human study. The proposed approaching method is capable of obeying the social norms and maintaining proper stopping distance and direction with the person of interest. Therefore, the proposed work would be useful in improving the rapport between service robots and its users since the robot frequently encounters such approaching scenarios when performing service tasks. The Approach Planner Module(APM), which is in the Proxemics and Approach Planner Unit(PAPU) responsible for navigating the robot toward the person of interest in a human-friendly manner. This is done by an algorithm that has been designed based on the natural approaching behavior of humans in similar situations identified from the human study discussed in chapter 4.

## 5.1 The Approach Planner (AP)

The AP is responsible for planning the approaching of the robot toward the person of interest (defined as 'U'). The human tendencies related to approaching listed in chapter 4 section 4.5 have been utilized in the algorithm for planning the approach. Algorithm 1 has been designed to decide the termination position of the approach (defined as $P_T$) in such a way that the robot can replicate the considered natural human tendencies.

An example scenario for third person approaching toward a person of interest during a conversation is shown Fig. 5.1. $P_U$, $P_P$, $P_R$ and $\theta_U$ are taken as inputs

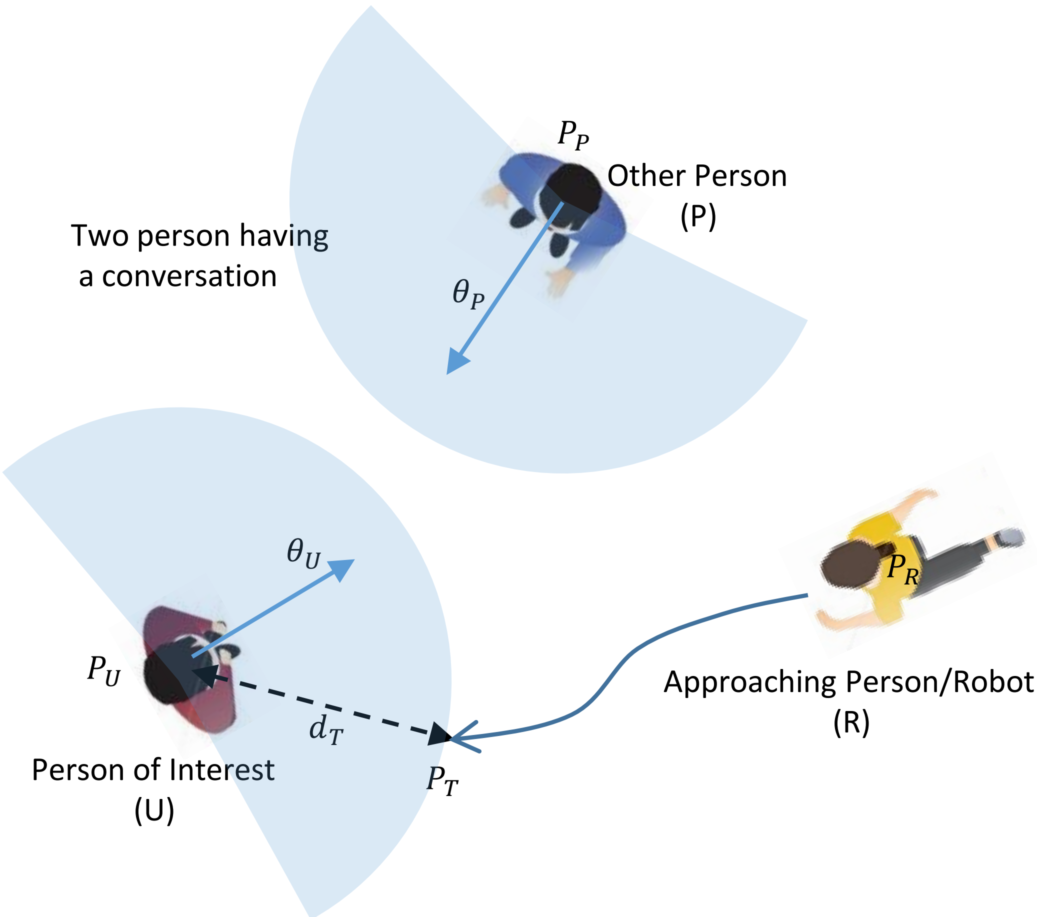



Figure 5.1: This illustrates an example situation where a third person (i.e., 'R') approaches toward a person of interest (i.e., 'U') who is having conversation with another person (i.e., 'P'). The position of 'U' and 'P' are considered as $P_U$ and $P_P$ respectively. The starting position of 'R' is considered as $P_R$ and the termination position is $P_T$. $\theta_U$ and $\theta_P$ are the heading angle of 'U' and 'P' respectively. The shaded areas represent the vision field of 'U' and 'P'. The distance between 'R' and 'P' at $P_T$ is defined as $d_T$. The natural behavior of 'R' is replicated by the robot.

**Algorithm 1** Selection of $P_T$

INPUT: $P_U$, $P_P$, $P_R$, $\theta_U$
OUTPUT: $P_T$

```
d_T = TERMINATION_DISTANCE(discussion)
{Area_VFU} = VISION_FIELD_OF_U(θ_U)
{Area_FFA} = AREA_FORBIDDEN_FOR_APPROACH(P_U, P_P)
Area_For_Approach, {Area_FA} = {Area_VFU}-{Area_FFA}
loop
    Find: position, P̂ : P̂ ∈ {Area_FA} and |→(P_U P̂)| = d_T
    if ¬(→(R P̂) crosses →(P_U P_P)) then
        P_T ← P̂
        return P_T
        Break
    end if
end loop

function VISION_FIELD_OF_U(θ_U)
    Vision_Range_U = [θ_U − ΔV, θ_U + ΔV]
    return Area_Within_Field_Of_View_Of_U
end function

function AREA_FORBIDDEN_FOR_APPROACH(P_U, P_P)
    return Area_Between_P_U_and_P_P_based_on_Margin_Of_ΔF
end function

function TERMINATION_DISTANCE(User_Behavior)
    switch User_Behavior do
        case discussion
            Defined_Distance = D_Discussion
        case reading
            Defined_Distance = D_Reading
        ...
        ...
    return Defined_Distance
end function
```

of the algorithm since the approaching depends on those parameters. The output of algorithm 1 is the termination position of approach ($P_T$). After deciding $P_T$, the AP issues instructions to the Navigation Controller (NC) to perform the navigation toward $P_T$. In order to ensure the obeying of fact 4 of the considered human tendencies, the forbidden area calculated during the execution of Algorithm 1 (i.e., $\{Area_{FA}\}$) is given as a forbidden region for temporary inclusion in the navigation map. The NC then performs the navigation considering the data available in the navigation map. When the robot approaches toward $P_T$, the AM makes necessary arrangements to generate voices responses for excusing (e.g., "excuse me") and greeting (e.g., "hello"). The robot's orientation at $P_T$, $\theta_T$ is set in the direction of $\overrightarrow{P_T P_U}$ for facing the robot's front toward the user.

The field of view of 'U' is defined considering the vision range of humans. Hence, $\Delta V$ that delimits the calculation of vision filed of 'U' in Algorithm 1 is defined as 95° based on [41]. However, when searching $\hat{P}$, higher priority is given to the peripheral vision range. $\Delta F$ that delimits the forbidden area for approach is taken as 1 m considering approximately two times of shoulder breadth of men (According to [43], 50th percentile value for men is 49.1 cm). Algorithm 1 has been defined with possible future extension of the work and hence the function of deciding $d_T$ has been defined in such a way that $d_T$ depends on the current user behavior. However, the ongoing user behavior in this work is limited to having a discussion with another person. Therefore, the user behavior is always considered as "discussion". According to fact 2 of the considered human tendencies, $d_T$ is independent from $\theta_U$, $\theta_P$, $|\overrightarrow{P_U P_P}|$ and $P_R$. Therefore, $D_{Discussion}$ is assigned 91 cm based on the mean termination distance identified from the human study presented in chapter 4.

The inputs of Algorithm 1 except $P_R$ (i.e., $P_U$, $P_P$ and $\theta_U$) are estimated from the skeletal data retrieved from the Kinect motion sensor of the robot. $P_R$ is estimated from the localization algorithm of the NC of the robot.

## 5.2 Results and Discussion

### 5.2.1 Experimental Setup

A user study has been conducted to evaluate the behavior and performance of the developed approaching mechanism of the robot. In order to minimize the subjectivity of the experimental evaluation, the user study has been designed and conducted by paying due attention to the recommendations given in [39] for conducting user studies for evaluating human-robot interaction.

The user study was conducted with 10 participants (male = 6 and female = 4) whose age is in between 25–38 years (M = 26.9 and SD = 4.1). All the participants were either graduate students or staff members of the university and all of them have South Asian cultural backgrounds. Furthermore, the participants are different from the participants of the human study presented in chapter 4. For a particular experimental case, two persons were selected randomly from the pool of participants. At the start, two different short video clips (not related to robotics) were shown to each selected subject separately. Then, they were instructed to be in selected case positions and asked to discuss about the video clips that they saw. This strategy was chosen based on [35] since this supports them to have a natural conversation. One person among these two is randomly selected as the person of interest and the robot is instructed to approach toward the person of interest (i.e., 'U') when he/she is having a conversation with the other person ('P'). It should be noted that the instruction to initiate the approach of the robot is manually triggered through an external signal given via a remote terminal. This approach of initiating the navigation is justifiable since the core contribution of this work is limited to a development of a human-friendly approaching mechanism. The navigation data of the robot and the parameters of the users perceived by the robot during the approach have been recorded for the analysis. Similarly, fifteen different cases were created by arranging the positions and orientations of ‘U’, ‘P’ and ‘R’. Snapshots taken during an experimental case are shown in Fig. 5.2.

After completion of each case, ‘U’ and ‘P’ were asked to rate the following statements in 5 point Likert scales.

- **Q1:** The stopping position of the robot felt comfortable.
- **Q2:** Final orientation of the robot seemed good.
- **Q3:** Approach of the robot did not disturb the ongoing conversation.
- **Q4:** Robot obeyed social norms.
- **Q5:** How satisfied are you with the overall approaching behavior of the robot ?

The possible feedback ratings for Q1, Q2, Q3 and Q4 were 5-*Strongly Agree*, 4-*Agree*, 3-*Neutral*, 2-*Disagree* and 1-*Strongly Disagree*. For Q5, the possible feedback ratings were 5-*Strongly Satisfied*, 4-*Satisfied*, 3-*Neutral*, 2-*Dissatisfied* and 1-*Strongly Dissatisfied*. When the given rating for a particular question statement was either 1 or 2, further clarification questions were asked from the participant who gave that ratings to get more insights.

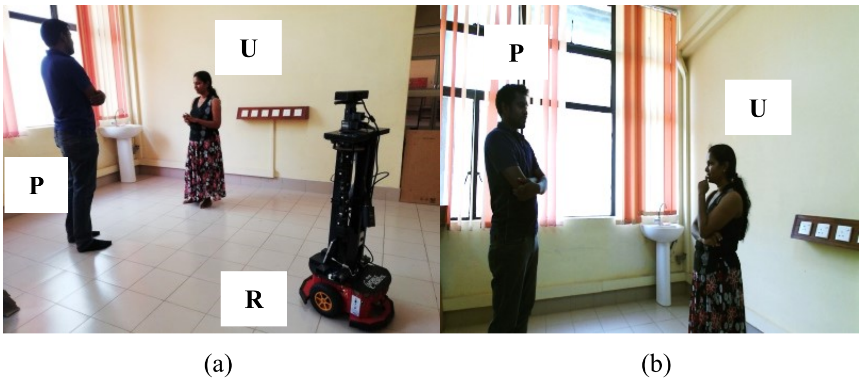



Figure 5.2: (a) shows a third person view of an experimental case. (b) shows the view of the scenario perceived by the robot through Kinect sensor.

### 5.2.2 Operation of the Robot

The basic operational behavior of the proposed robotic system is explained in this section based on the sample experimental results. The positions and orientations of 'U', 'P' and 'R' during execution of the first five experimental cases are marked on the map shown in Fig. 5.3 and the corresponding numerical data are given in Table 5.1 as sample experimental results to provide concise idea about the operation of the robot to the readers.

In case 1, the robot's starting position (i.e., $P_R$) was 'R1' (marked on the map shown in Fig. 5.3) where X and Y coordinates were 99 cm and 45 cm with respect to the marked origin. The heading of the robot at this instance was 84°. After the robot was triggered to initiate the approach toward 'U', the positions and orientations of 'U' and 'P' perceived by the robot through Kinect sensor were (223 cm, 306 cm, 180°) and (88 cm, 360 cm, -25°) with respect to the origin of the navigation map. These positions and orientations of 'U' and 'P' are marked on the map as 'U1' and 'P1'. Then, the robot moved to position 'T1' (134 cm, 258 cm, 40°) considering 'T1' as the termination position ($P_T$) based on the developed approaching method. The position 'T1' is within the field of view of 'U' and $|\overrightarrow{P_T PU}|$ (i.e., $d_T$) was 101 cm. The reason for small deviation for $d_T$ was the robot navigation controller is set to consider a tolerance upto ±10 cm in achieving a goal position. The heading of the robot at $P_T$ was 40°, which aligned

Table 5.1: Sample Experimental Results

| Case $i$ | $U_i$ (X,Y, $\theta_U$) | $P_i$ (X,Y,$\theta_P$) | $R_i$ (X,Y, $\theta_R$) | $T_i$ (X,Y, $\theta_T$) |
|---|---|---|---|---|
| 1 | (223,306,180) | (88,360,-25) | (99,45,84) | (134,258,40) |
| 2 | (268,248,-122) | (118,77,52) | (51,338,-45) | (179,220,7) |
| 3 | (79,36,109) | (42,168,-34) | (232,407,-132) | (121,112,-134) |
| 4 | (256,314,128) | (139,345,1) | (46,90,58) | (186,259,31) |
| 5 | (160,423,-114) | (84,443,-65) | (120,167,84) | (156,336,88) |

The positions are given with respect to the coordinate system marked on the map shown in Fig. 5.3. The units are in (cm, cm, degrees) format. The heading angles are measured with respect to the positive X-axis in counter-clockwise direction.

the front of the robot toward 'U' as expected. Therefore, the operation of the robot in this case was similar to that was expected in the design stage. Similarly, all the sample cases were analyzed and it was found out that the behavior of the robot was similar to that was designed to possess.

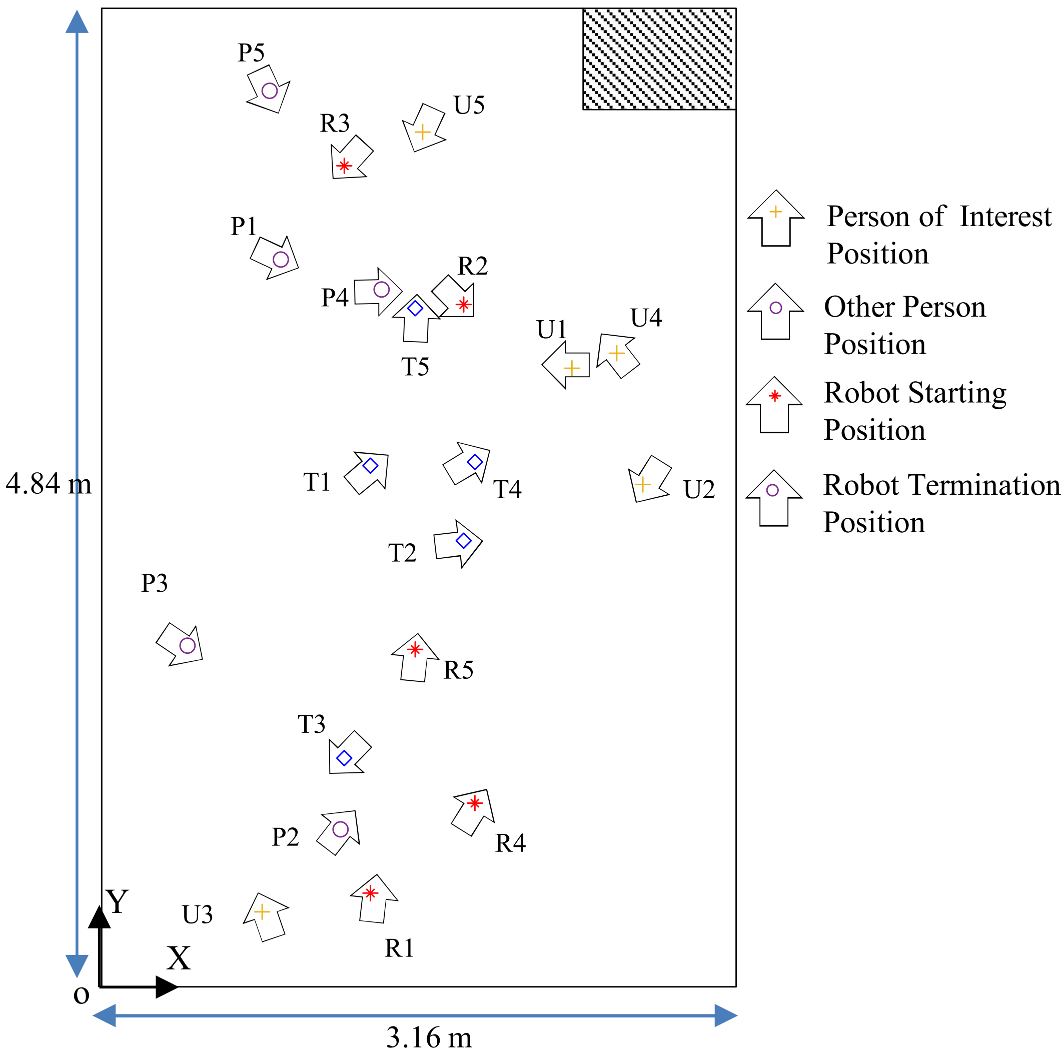



Figure 5.3: The positions and orientations of 'U', 'P' and 'R' during first five cases of the experiment are marked on the map. The map is drawn to scale. However, it should be noted that the markers are not drawn to scale and do not reflect the actual size of the robot and the people. The corresponding position data are given numercally in Table 5.1

### 5.2.3 Analysis of User Ratings

The feedback of the users (both 'U' and 'P') given to the question statements in the survey has been analyzed in order to evaluate the performance of the developed approaching method. The ratings obtained from 'U' and 'P' for the five question statements during the whole experiment are visualized in the plot shown in Fig. 5.4.

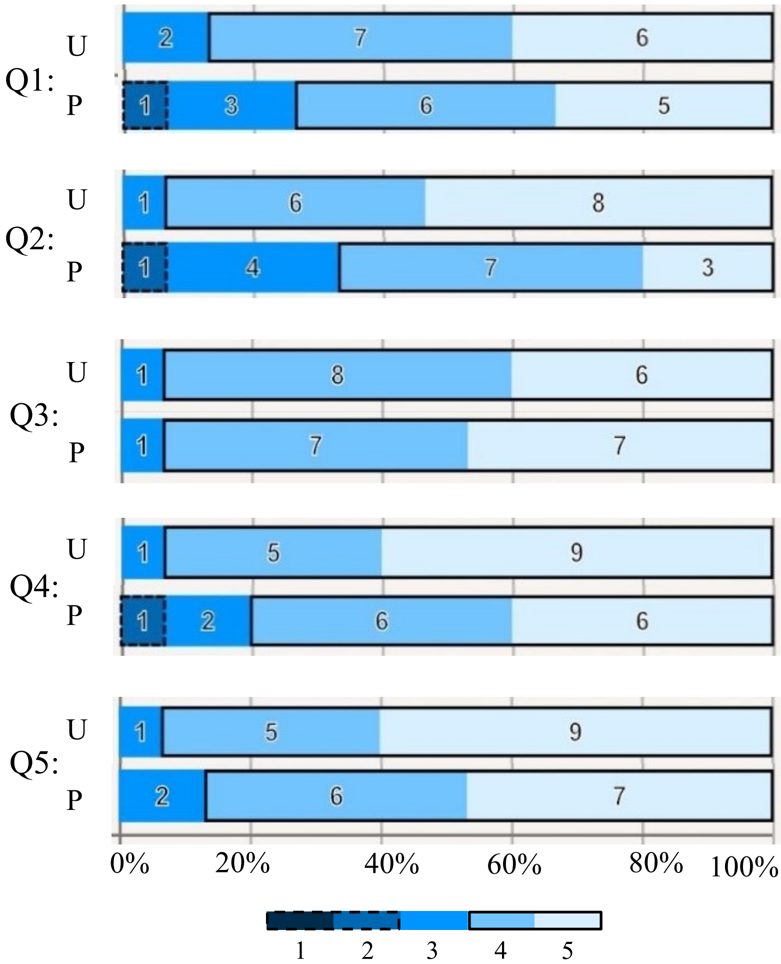



Figure 5.4: The ratings obtained from 'U' and 'V' for each question statement through 5 point Likert scales are plotted in here. The feedback categories are discriminated by color shades. The linkage between color shades and corresponding feedback categories are shown in the key given at the bottom of the figure. The number of feedback received for a particular category is annotated on top of the strip which represents that particular category. Furthermore, above neutral categories (i.e., 5 and 4) and below neutral categories (i.e., 2 and 1) are bounded together by boxes with solid lines and dashed-lines respectively.

Cronbach's alpha has been calculated to measure the internal consistency of the items included in the questionnaire. It was found out that the reliability coefficient is higher than 0.9 for all the scenarios; 'U' only (0.95), 'P' only (0.95), and both 'U' and 'P' (0.94). This confirms that the questionnaire is well acceptable for the evaluation.

The first question (i.e., Q1) evaluates the comfort of the user with respect to the stopping position of the robot (i.e., selection of $P_T$ by the robot). The mode of the ratings received from the person of interest (i.e., 'U') is *Agree*. The percentage of ratings received in the agreeing categories (i.e., combination of *Strongly Agree* and *Agree*) is 87% while number of ratings received for disagreeing categories (either *Strongly Disagree* or *Disagree*) is zero. This implies that $P_T$ decided by the system is comfortable for the person of interest (i.e., 'U'). The mode of the ratings given by 'P' is also *Agree*. The percentage of agreeing categories is 73%. However, one case received a rating of *Disagree* yielding to combined disagreeing ratings to 7%. However, the agreeing percentage is more than 10 times larger than the disagreeing percentage. This confirms that $P_T$ decided by the system is comfortable for 'P' too.

The second question statement (i.e., Q2) assesses the agreement of the two persons about the orientation of the robot at the termination position $P_T$ (i.e., $\theta_T$). *Strongly Agree* is the mode rating revived from 'U' for Q2. The percentage ratings received in agreeing categories is 93% while no case has a rating in disagreeing categories. This implies that $\theta_T$ decided by the system is agreeable to 'U'. For 'P', the mode rating category is *Agree*. The percentage of rating received for agreeing categories is 67%. One case has been rated as *Disagree*. The percentage of rating received for disagreeing categories is 7% which is quite smaller with respect to percentage receival of agreeing ratings. Therefore, this indicates that $\theta_T$ decided by the system is affable for 'P'.

The third question (i.e., Q3) assesses the agreement of the two person to the statement, "Approach of the robot did not disturb the ongoing conversation".

The mode rating received from 'U' is *Agree*. In 93% of the cases, 'U' agreed (either *Strongly Agree* or *Agree*) that the robot's approach did not disturb the ongoing conversation while no case received a disagreeing (either *Strongly Disagree* or *Disagree*) rating. The mode rating received from 'P' is *Strongly Agree* and *Agree*. 'P' agreed (either *Strongly Agree* or *Agree*) in 93% cases that the robot's approach does not disturb the conversation. Therefore, these feedback ratings confirm that the proposed approaching method does not hinder the ongoing discussion between the two persons that is necessary for a human-friendly behavior.

The fourth question (i.e., Q4) evaluates the agreement of the two persons to the fact that the robot obeyed social norms during the approach. According to the mode rating, 'U' strongly agrees that the robot obeyed the social norms during its approaching action. 93% of cases received either *Strongly Agree* or *Agree* rating while no case received either *Strongly Disagree* or *Disagree* rating from 'U'. The mode rating received from 'P' is *Strongly Agree* and *Agree*. 80% of cases received ratings in either *Strongly Agree* or *Agree* categories while only one case received disagree rating (i.e., 7% ) from 'P'. Therefore, it can be concluded that the proposed method is capable of obeying the social norms during the approach to an acceptable level of the users.

The fifth question (i.e., Q5) evaluates the satisfaction of the two persons toward the overall approaching behavior of the robot. If modes of ratings are considered both 'U' and 'P' are *Strongly satisfied* with the overall approaching behavior of the robot. 93% of feedback received from 'U' is in the side of satisfaction (either *Strongly Satisfied* or *Satisfied* categories) while the number of dissatisfaction ratings (either *Strongly Dissatisfied* or *Dissatisfied* categories) are zero. 87% of cases received either a *Strongly Satisfied* or *Satisfied* rating from 'P' while no cases received a dissatisfaction rating. When the feedback received from 'U' and 'P' is considered as a single entity, the mode rating is *Strongly Satisfied*. The percentage of ratings received in the satisfaction side (either *Strongly Satisfied* or *Satisfied*) is 90% while dissatisfaction fraction is null. Therefore, it can be concluded that the overall approaching behavior of the proposed method is capable of satisfying the users.

Overall, it can be seen that the satisfaction of 'P' is slightly lower than that of 'U'. This would be due the fact that the algorithm of the proposed approaching method pays more attention to 'U' than 'P'. Moreover, the design of proposed method is more centric toward 'U'.

*Disagree* rating has been received in three instances. Those were received from the feedback of other person (i.e., 'P'). Further analysis has been conducted for those instances. Those three instances are based on two experimental cases; instances of Q2 and Q4, both are from a one case and instance of Q1 is from a different case. In the instance of Q1, the participant acted as 'P' felt that the position was a little bit closer to himself. However, this kind of disagreement for the final position of the robot (i.e., $P_T$) was given by only one participant for a single instance (only one instance out of a total of 30 instances). According to the clarification of the situation of the particular participant related to the instances of Q2 and Q4. The reason behind the disagreement for the final orientation of the robot (i.e. $\theta_T$ decided by the system) was that the robot backside is slightly directed toward 'P' and the connecting wires of the devices attached to the robot were visible to the participant. In the instance of Q4, the reason was that the robot does not show any friendly reaction such as a smile toward the participant. Furthermore, the orientation of the robot at the termination position (i.e. $\theta_T$) also influences the decision for the feedback even though it was separately evaluated by Q2. However, the robot used for the experiment was a mechanoid type robot and it does not possess abilities in showing friendly facial features such as smiles. Furthermore, the core contribution of the work presented in this paper is limited to the development of a smooth navigation method for robot approach toward two people who are having a conversation. Therefore, addressing of such issues is proposed for future development.

### 5.3 Summary

This chapter proposed a method of smooth approaching of a service toward a user who is having a conversation with another person. The main strength of the proposed concept is the proposed approaching method is capable of replicating the natural approaching behavior of humans.

The proposed approaching method has been synthesized based on the outcomes of a previously conducted human study for identifying the natural approaching behavior of humans. The Approach Planner (AP) is responsible for executing a human-friendly approach toward the users. The algorithm of the AP has been designed in such a way that the robot approach is capable of replicating the considered human tendencies. The parameters required for the evaluation of the algorithm are derived from the skeletal information perceived though Kinect sensor attached to the robot. Furthermore, the parameters related to the environment and the robot are obtained from the Navigation Controller (NC) of the robot.

The proposed approaching method has been implemented on MIRob platform and a user study has been conducted to evaluate the satisfaction and the comfort of the user in relation to the approaching behavior of the robot. User feedback given in 5 point Likert scales for a set of question statement has been used to evaluate the user satisfaction and the comfort. According to the obtained experimental results, the proposed concept is capable of satisfying and comforting both persons involved in the interaction.

The ability of a service robot to approach a user in a comfortable and friendly manner would increase the rapport between the user since service robots often need to approach toward their users when rendering the services. Therefore, the proposed method would be useful in enhancing the human-robot interaction of service robot.

Chapter 6

# PROXEMICS AND APPROACH EVALUATION BY SERVICE ROBOT BASED ON USER BEHAVIOR IN DOMESTIC ENVIRONMENT

Intelligent service robots are used at a significant level to uplift the living standards of domestic users. These robots are expected to possess human-friendly interactive features. Service robots should be able to provide a variety of tasks to support independent living of users in domestic environments. Therefore, a service robot often needs to approach users to execute these services and the approach toward the users should be human friendly. In order to achieve this, proxemics planner of a service robot should be cable of deciding the approaching proxemics based on user behavior. This chapter introduces a method to decide the approaching proxemics based on the behavior of the user. A fuzzy interference system has been designed to decide the proxemics based on the user behavior identified through body parameters. This leads to an effective interaction mechanism initiated by a robot in such a way that the approaching scenario looks more human-like.

## 6.1 Rationale Behind the Proposed Method

In domestic environments, users are engaged in activities involving movements which fan out over a number of points in space. When an outsider reaches that person during such an activity, his/her proxemics depends on parameters such as the movements of body parts that are visible to the outsider while reaching. An example of such a scenario is shown in Fig. 6.1. The user and the approaching person locations are marked on a time-line for the ease of explaining behavior of both approaching person and user with respect to time. Here, the user is observed by the approaching person for time $T_{ob}$ and he takes another $t_r$ s to approach the user. For a human time $T_{ob}$ is a very small value. In the first instance, i.e. at $T$ = 0 s, approaching person catches a glimpse of the user.

The user's postures and approaching persons position at different occasions during the period of observation are shown in Fig. 6.1. Movements of two body joints; wrist and foot, change considerably during this activity. During that period, wrist position changes as $P_1$, $P_2$ and finally $P_3$. In the same way, foot locations change as $P_4$, $P_5$ and $P_6$. Final approaching proxemics between the two person is denoted by $d$ and the direction of the approach with respect to the user is denoted by $\theta$. Here, in this case as the user has fast movements in legs and arms, the approaching person keeps a certain distance in between and does not reach the user from front where frequent movements are observed. Therefore, the approaching person reaches from a side where movements are minimum. The proposed system has been implemented in such a way that it can replicate this kind of natural phenomena to a greater extent.

## 6.2 Selection of Behavior Characteristics

In order to enhance human-robot coexistence in the domestic environment, human approaching scenario is planned in the proposed system. User evaluation criteria is based on the factors which are most favorable to judge the proxemics efficiently. Proposed system takes movements and invasion of space into account to decide upon how to reach a user to deliver a particular service. Movements are monitored along joint trajectories and farthest locations of joints are tracked in order to determine their motion within a period of time. Body joints which

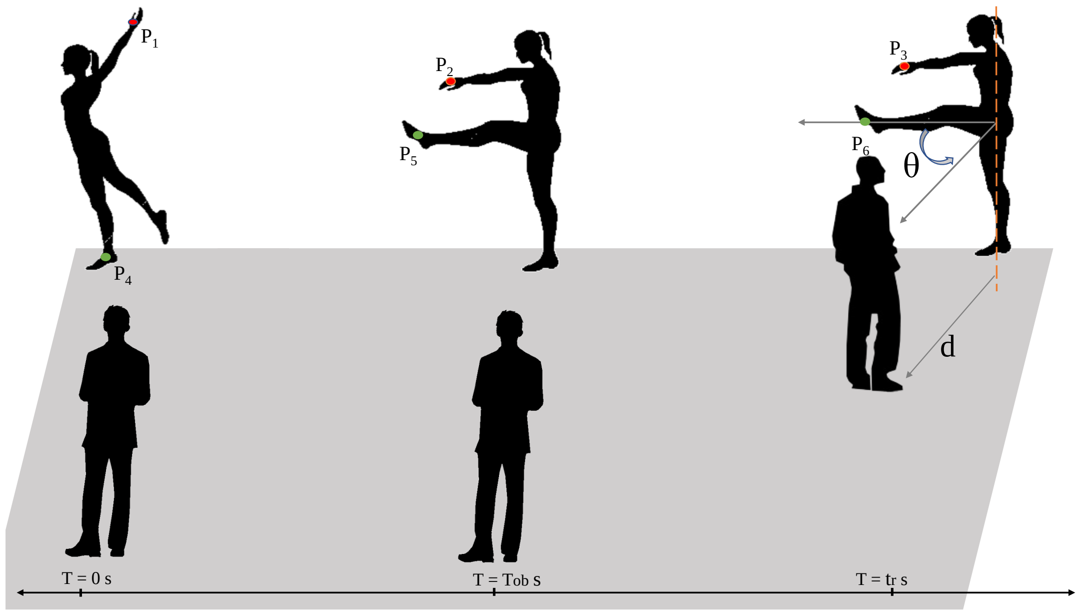



Figure 6.1: A person approaches a user engaging in an exercise. Time is considered as T= 0 s when the approaching person starts observing the user. Interpersonal distance achieved by the approaching person is marked as $d$. The orientation of approaching person with respect to the user is denoted by $\theta$. Motion of the left wrist and left foot in each time is observed. $P_1$-$P_3$ are user's wrist locations while $P_4$-$P_6$ indicate foot locations.

are critical in deciding whole body motion are considered during this scenario.

To achieve the decision-making criteria explained in the Section 6.1, the robot must have the capability to monitor user behavior. In the proposed concept, user behavior is analyzed based on the movements made by body joints marked in Fig. 6.2. Two parameters are considered as behavioral changes made by the user. These are the distance to the considered joint from the vertical extended across the spine base joint as in Fig. 6.2(b) and the speed of that joint. These two parameters are calculated from vision information extracted by the SIEU. User skeletal Information (USI) and Data analyzer are consist under the module 2 as shown in Fig. 3.1. Values of these two parameters during each second are stored in the USI by the Data Analyzer until the end of total period of observation.

Vision system extracts joint details as Cartesian coordinates with respect to coordinate frame of Kinect sensor. Joint locations are converted to distance by

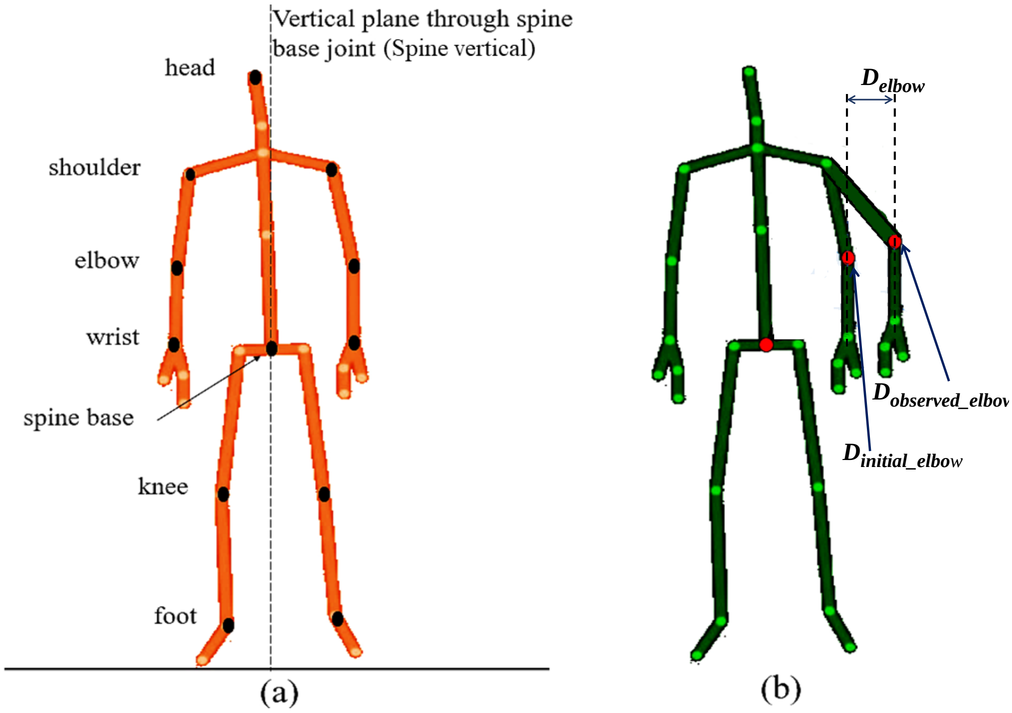



Figure 6.2: Skeletal representation of body joints used for the analysis. (a) Only the named joints are used for behavior monitoring. Both right and left sides of the body are analyzed. Distance from the vertical that goes through the spine base joint to a particular joint is used to calculate joints which are farthest from the body during an activity. (b) Obtaining of $D_i$ is explained here considering $i$ as elbow hence difference between initial location and observed location of elbow is taken as $D_{elbow}$

the Data Analyzer. As the observation progresses, these parameters are stored in the (USI) memory. Here, $i$ denotes the set of joints considered by the system.

$i$=\{$head$, $spine\ base$, $right\ shoulder$, $right\ elbow$, $right\ wrist$, $right\ knee$, $right\ foot$, $left\ shoulder$, $left\ elbow$, $left\ wrist$, $left\ knee$, $left\ foot$\}

Each joint in human body is situated from a certain distance from aforementioned vertical when an ordinary posture is considered. Therefore, to measure the deviation of joint location during an activity, the difference between initial location and observed location is taken as $D_i$ for $i^{th}$ joint as represent in (6.1). Here, initial location is referred to as the location of that particular joint when an ordinary standing posture of an average human is considered. This is explained in Fig. 6.2 (b).

$$D_i = D_{observed\_i} - D_{initial\_i} \tag{6.1}$$

Ordinary average value for the distance to a particular joint when the user is in his/her standard standing posture is denoted by $D_{initial\_i}$. This value may slightly deviate from user to user. Therefore, an average for each joint, $D_{initial\_i}$ is considered in the study. $D_{observed\_i}$ is the distance to observed joint location from the vertical.

The other parameter calculated at each information extraction stage is the speed of $i^{\text{th}}$ joint which is denoted by $\dot{\theta}_i$ and calculated as in (6.2).

$$\dot{\theta}_{i\{t=T\}} = \frac{D_{observed\{t=T\}} - D_{observed\{t=T-\delta_t\}}}{\delta_t} \tag{6.2}$$

All the values of $D_i$ and $\dot{\theta}_i$ are stored by the Data Analyzer. At the end of $T_{ob}$, these values are compared with each other to select maximum values recorded for $D_i$ and $\dot{\theta}_i$.

$\delta_t$ is considered as one second.

$\dot{\theta}$ = max$\{\forall\dot{\theta}_{i\{t=j\}}$ | $i$ = head, spine base, right shoulder,..,left foot; $j$ =1,2,..., $T_{ob}\}$

$D$= max$\{\forall D_{i\{t=j\}}$ | $i$ = head, spine base, right shoulder,..,left foot; $j$ =1,2,..., $T_{ob}\}$

Here, $D$ stores the magnitude of the maximum deviation of joint location from its original position.

### 6.3 Fuzzy Proxemics Evaluation Model (FPEM)

This module is inside of the Proxemics and Approach Planner Unit as in Fig3.1.Maximum distance, $D$ and the joint speed, $\dot{\theta}$ are used as the inputs to evaluate a user situation to decide the approaching proxemics. These two parameters are analyzed at information processing stage. Due to the vagueness in interpretation, these are used as fuzzy variables. FPEM uses a Mamdani type fuzzy inference system to evaluate these two parameters to decide the proxemics to be kept with the user. FPEM takes the maximum distance and the joint speed as input and triangular membership functions are used to represent inputs and the output of the model. Output of this system is the proxemic distance determined for the current user situation. This is denoted as $d$. Centre of area method is used for the defuzzification of this output. Corresponding membership functions of the inputs and the output are shown in Fig. 6.3. Rule base of this fuzzy inference system is given in TABLE I. The rule base is defined using the natural tendency in considered occasions. Labels VL, L, M, S and VS in the output denote fuzzy labels 'Very Large', 'Large', 'Medium', 'Small' and 'Very Small' respectively. Labels S, M and F in $\dot{\theta}$ denote 'Slow', 'Medium' and 'Fast' respectively while S, M and L in $D$ represent 'Small', 'Medium' and 'Large'.

There are many points that the robot can navigate to achieve $d$ between the robot and user. Therefore, the direction by which the robot approaches the user has to be considered. As in the example explained in Section III-A, the robot should move to an appropriate position farthest from the zone where the movements are maximum. However, the approaching zone should be within the field of view of the user for convenience. Such criterion is used to achieve $d$ determined by the FPEM.

Here, the density of activity area of the farthest joint at $t$ s is analyzed during $T_{ob}$. Activity area is found by dividing the space around the person into smaller regions and analyzing the frequency of visits by each joint into each re-

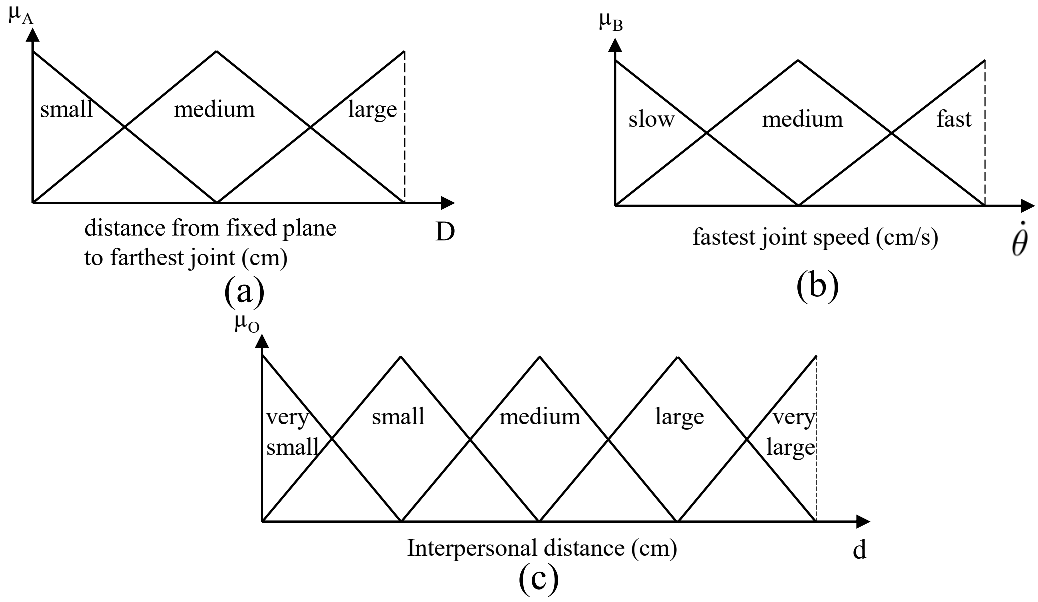



Figure 6.3: (a) and (b) represent input membership functions corresponding to distance from fixed plane (spine vertical) to the farthest joint (i.e., $D$) and fastest joint speed (i.e., $\dot{\theta}$). (c) represents the output membership function which corresponds to the interpersonal distance to be kept with a user at the termination of an approach.

Table 6.1: Rule Base of the Fuzzy System

| Input Memberships | | $\dot{\theta}$ (cm/s) | | |
|---|---|---|---|---|
| | | **SL** | **M** | **F** |
| $D$ (cm) | **S** | VS | VS | S |
| | **M** | M | M | L |
| | **L** | L | L | VL |

gion. Frontal space around the user is divided into $n$ zones with the length of $L$ cm (since approaching position should be within the field of view of the user). Each smaller region is called an 'activity zone' and the zones with maximum number of joint visits are considered to have the highest activity density. Therefore, it is favorable for the robot to reach the user from the zone with farthest and more appropriate zone for both safety and decency of behavior. Hence the user approach scenario looks more human-like in both aspects; maintaining a proper interpersonal distance as well as a direction. In order to simplify the implementation complexity, the space is divided into 6 zones (i.e., $n = 6$). These zones are shown in Fig. 6.4. If a zone is detected with the maximum activity, the robot

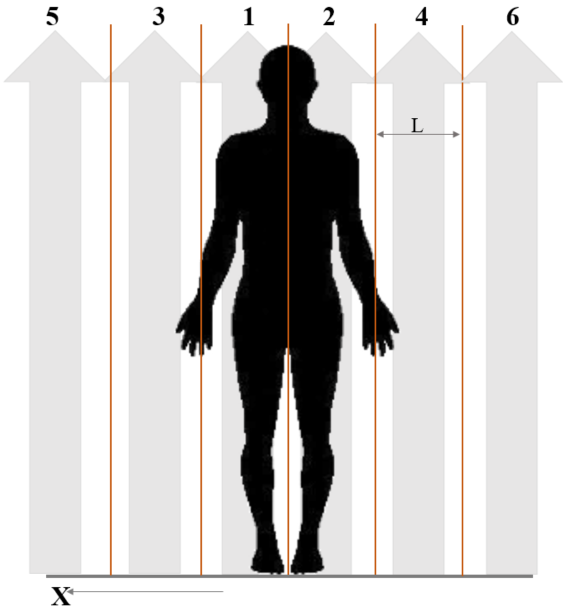



Figure 6.4: Division of visible space around the user is shown. The area is divided into 6 regions called 'activity zones'. Width of a single zone is marked as $L$.

is instructed to reach from the farthest but most appropriate zone. Therefore, if the maximum activity zones are 1,2,3,4,5 and 6, appropriate reach zones are defined as 6,5,4,3,2 and 1 respectively.

## 6.4 Experiment and Results

### 6.4.1 Experimental Setup

The experiment was conducted in an artificially created domestic environment. A human study has also been carried out in order to compare performance of the proposed system against natural behavior of humans. In order to avoid the subjectivity of the evaluation, due attention has been paid to the guidelines suggested in [39] for conducting user studies for evaluating human robot interaction.

### 6.4.2 Human Study

Human activities can be described as spatiotemporal evolutions of different body postures. Therefore, domestic applications can be sub-categorized depending on behavior. Four tasks that domestic users frequently engage in were selected for the experiment to analyze proxemic behavior of humans. These tasks were exercising, reading a book, making a phone call and working on a laptop. The reason for selecting these especially is that these tasks involve many types of postures including standing, sitting and laying.

The human study has been conducted with the participation of 10 healthy human subjects (mean age- 24.6 years and SD- 1.9 years). All the participants were graduate students of the university and all of them have South Asian cultural backgrounds. The arrangements of the experimental scenario are shown in Fig. 6.5.

Three persons were selected to perform the same task for a single observer. The observer was asked to stand in given initial position (as marked on Fig. 6.5) and asked to approach toward the person engaged in the task. The observer's approach to each person was recorded. It is assumed that the observer approaches the person to deliver a task previously demanded by that person. In the same way, the experiment was repeated for 10 observers.

The first set of experiments was conducted for a user working on a laptop. Initial position coordinates of the user were chosen as the origin. For explanation purposes, a user is denoted by 'U' and the observer is denoted by 'P'. Initial positions of 'P' and 'U' during this occasion are shown in Fig. 6.5 (a). Second set of experiments was conducted for the situation where a user is reading a book while sitting in a chair. In general, people tend to be in relax sitting position when reading a book. Therefore, we asked participants to sit with relaxing posture. An obstacle free environment was chosen for the other two tasks as shown in Fig. 6.5 (b). In the exercising task, same exercise was performed by all the participants.

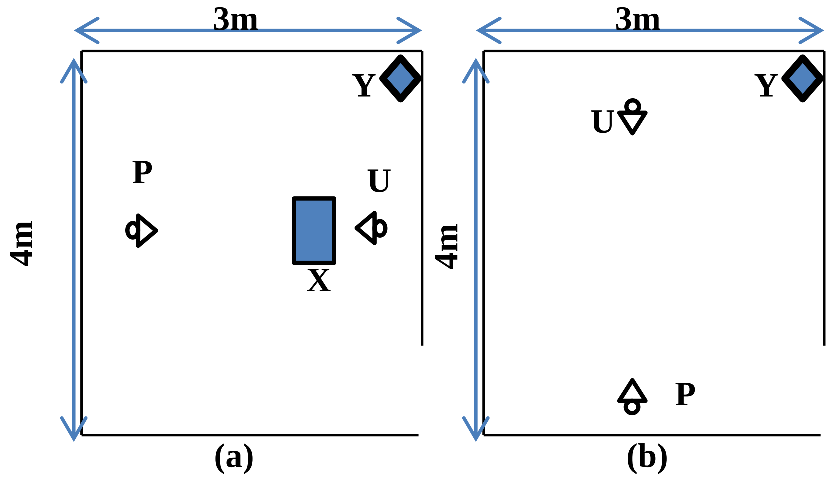



Figure 6.5: (a) Represents the space arrangement when a person is working on a laptop while sitting on a chair and the arrangement for reading a book is also same as this hence for that table X removed and U is sitting in a chair. (b) Represents the space arrangement when a person is involve in activities, exercising and making a phone call. P symbolize the initial position of the observer. U, X and Y symbolize the user, table and sink respectively.

Final task was making a phone call and during this situation, 'U' used a mobile phone while standing. The room size was fixed in all the cases. The number of participants in the human study were 10 and each participant had three different runs for each task. Therefore, the experiment has conducted with an effective sample size of 30 for each task.

### 6.4.3 Experiment

An experiment to evaluate robot's behavior was carried out with the participation of 10 persons (of age with mean- 26.9 and SD-1.70). All the participants were graduate students of the university and all of them have South Asian cultural backgrounds. It should be noted that the participants for these experiments were completely independent from the participants of the human study discussed in section 6.4.2. Each person was allowed to perform the same set of tasks used for the human study. This includes exercising, making a phone call, reading a book and using laptop. The robot was initially placed in a predefined location in the map similar to the observations of the human study. Distance and direction with a user at the termination position of the robot's approach were recorded. An explanatory video of the experiment can be found in the supplementary multimedia attachment[1]. Experiment results for several persons are shown in TABLE II. Two occasions during the experiment are explained. Ten seconds was chosen for $T_{ob}$ and 25 cm was used as $L$ during the experiment because the average length from vertical to shoulder of an average person is nearly 25 cm and many body joints lie around 25 cm from the vertical during most of the tasks. The Limits for the farthest joint distance and maximum speed were taken as 115 cm and 110 cm/s. These limits were determined experimentally by observing data collected by the system when monitoring user behavior. Maximum proxemics that could be obtained was taken as 1.8 m in order to maintain a comfortable situation.

### 6.4.4 Results and Discussion

Distance and orientation by means of reached activity zones have been analyzed during the experiment. Results obtained for several persons are given in TABLE II. Situations of user 1 and user 3 are shown in Fig. 6.6. These situations are used to explain the operation of the proposed system.

In the first occasion, as in Fig. 6.6(a), the user was exercising so that his right and left legs are mostly engaged. Forward movements make zones 1 and 2 as maximum activity zones. Out of them, 1 has been recorded by the system as the maximum activity zone, due to the highest number of joint locations within the zone. The distance to the farthest joint: right leg was 79 cm and joint speed was 94 cm/s. The system gives a output distance of 1.229 m. The decided direction to reach is zone 6 since the system observed maximum number of movements from the user's right. Therefore, the robot approaches the user from left, keeping a distance of 1.229 m. The same user is in Fig. 6.6(b) and he was reading a book while sitting and with his left leg forward. Therefore, left knee was the farthest

[1]Available in the attched CD

joint during this occasion. It was 64 cm away from the vertical. The maximum speed movement was recorded in right wrist as 46 cm/s. The system output was 0.970 m approaching from user's left from which speedy movements are less. In (c), the user was on phone with his left hand on hip. Therefore, the farthest joint was left elbow in a deviation of 51 cm from the original position. He had a maximum joint speed of 47 cm/s which resulted in a distance output of 0.828 m to be reached in zone 3. Zone 4 was recorded as the maximum activity zone as the user makes a maximum number of movements in zone 4 due to his left elbow movements. In (d), the user was working on his laptop in an ordinary sitting posture. Due to movements made while typing, right wrist recorded farthest location from the body, with a deviation of 50 cm and a speed of 48 cm/s. After evaluation, an interpersonal distance of 0.830 m was obtained as the output. Therefore, robot approached the user from his left where least number of fast movements were recorded, keeping a distance of 0.83 m.

The second occasion is regarding user 3 in TABLE II. This is shown in Fig. 6.6 (e)-(h). In (e), the user was exercising her hands. As the hands are wide open into either side of the user, wrists are the farthest joints. Out of them, left wrist recorded the maximum deviation, which was 71 cm. Fastest movement was made by her head at a speed of 89 cm/s. This is due to bending to sides while exercising. Therefore, the interpersonal distance for this occasion was 1.188 m which should be approached from zone 1. This is due to fast movements on right and left sides while movements on the front were minimum. In (f), the user was reading, with her right leg stretched forwards. Therefore, farthest joint was right leg, at a distance of 101 cm. The fastest movement was made by her left wrist at a speed of 22 cm/s. The user behavior resulted a distance of 1.211 m. Therefore, maximum activity zone was 4 in which left wrist was identified. In (g) the user was making a call while standing. She was in a standing posture with the right foot little forward. Therefore, the farthest joint was right foot, which was 27 cm deviated and due to movements in left hand, a maximum joint speed of 20 cm/s was recorded. This caused the robot to approach from user's left where movements were less. In (f), the user was working on her laptop with her left foot slightly in front. Therefore, the farthest joint was 44 cm deviated and joint speed was relatively low, i.e. 15 cm/s. This caused an output of 0.769 m achieved from zone 5.

A maximum interpersonal gap was recorded when the user was exercising where fast movements were incurred. A least number of movements are recorded while reading. Therefore, interpersonal gap kept by the robot was low unless there are stretched body parts due to relaxing postures. The interpersonal gap was minimum in many occasions when the user was in a phone call. This was due to the fact that the user's attention was on the call, and the joints movements and stretching were small. As a whole, while sitting, slow movements and farthest joints were recorded. In contrast, while standing, fast movements were observed with relatively low deviations in joint locations. This fact was sometimes violated when the user's task was exercising. The reason for this was that speeds and movements vary depending on the type of exercise and there are numerous exercises a user can choose. Making a phone call is a confusing task where behaviors adopted during the task strongly depend on the individual. As such situations were perceived by the robot only with respect to movements, interpersonal distances obtained for the same task by different users were deviated considerable from each other.

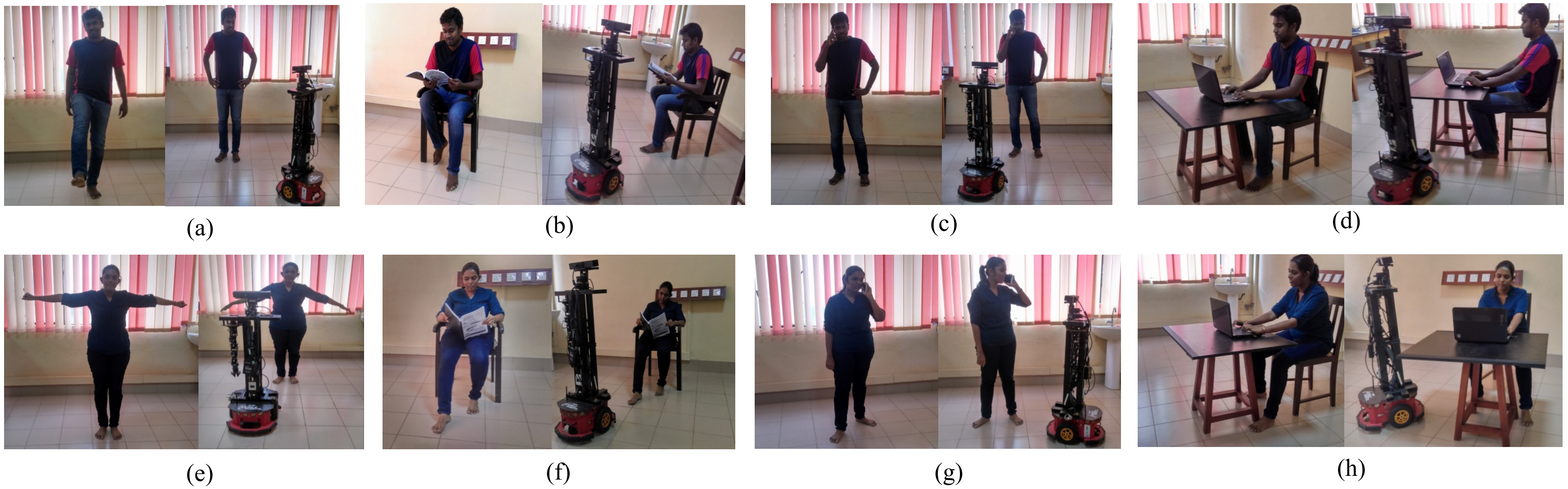



Figure 6.6: This shows experimental situations of user 1 and user 3 given in TABLE II. (a) Left: User 1-Standing/engaged in exercise, Right: robot approach with an interpersonal distance of 1.229 m within zone 6. (b) Left: User 1-Sitting/reading, Right: $d$ = 0.970 m within zone 4. (c) Left: User 1-Making a call, Right: $d$ = 0.828 m within zone 4. (d) Left: Using laptop, Right: $d$ = 0.830 m within zone 3. (e) Left: User 3-Standing/engaged in exercise, Right: robot approach with an interpersonal distance of 1.188 m within zone 1. (f) Left: User 3-Sitting/reading, Right: $d$ = 1.211 m within zone 3. (g) Left: User 3-Making a call, Right: $d$ = 0.641 m within zone 6. (h) Left: User 3-Using laptop, Right: $d$ = 0.769 m within zone 5.

Table 6.2: Results of the Experiment

| User | Activity | Joint with fastest movements | Farthest joint | $D$ (cm) | $\dot{\theta}$ | $d$ (m) | Maximum activity region(zone) | Orientation (zone) |
|---|---|---|---|---|---|---|---|---|
| 1 | Standing: engaged in exercise | right leg | right foot | 79 | 94 | 1.229 | 1 | 6 |
| 1 | Sitting: Reading | right wrist | left knee | 64 | 46 | 0.970 | 3 | 4 |
| 1 | Standing: Making a phone call | left elbow | left elbow | 51 | 47 | 0.828 | 4 | 3 |
| 1 | Sitting: Using laptop | right wrist | right wrist | 50 | 48 | 0.830 | 3 | 4 |
| 2 | Standing:engaged in exercise | left elbow | left wrist | 42 | 67 | 0.859 | 3 | 4 |
| 2 | Sitting: Reading | head | right foot | 58 | 8 | 0.909 | 1 | 6 |
| 2 | Standing: Making a phone call | left elbow | left elbow | 54 | 33 | 0.866 | 4 | 3 |
| 2 | Sitting: Using laptop | left wrist | right knee | 35 | 43 | 0.700 | 4 | 3 |
| 3 | Standing:engaged in exercise | head | left wrist | 71 | 89 | 1.188 | 6 | 1 |
| 3 | Sitting: Reading | left wrist | right foot | 101 | 22 | 1.211 | 4 | 3 |
| 3 | Standing: Making a phone call | left wrist | right foot | 27 | 20 | 0.641 | 1 | 6 |
| 3 | Sitting: Using laptop | head | left foot | 44 | 15 | 0.769 | 2 | 5 |
| 4 | Standing: engaged in exercise | head | left shoulder | 27 | 48 | 0.641 | 2 | 5 |
| 4 | Sitting: Using laptop | right wrist | right elbow | 52 | 57 | 0.873 | 1 | 6 |
| 5 | Sitting: Reading | left foot | left knee | 62 | 49 | 0.954 | 1 | 6 |
| 5 | Sitting: Using laptop | left wrist | left knee | 36 | 68 | 0.828 | 4 | 3 |
| 6 | Standing: engaged in exercise | head | right elbow | 53 | 36 | 0.848 | 3 | 4 |
| 6 | Sitting: Reading | right knee | right knee | 39 | 2 | 0.733 | 3 | 4 |
| 7 | Standing: Making a phone call | head | right elbow | 51 | 12 | 0.835 | 3 | 4 |

### 6.4.5 Comparison of robot and human behavior

The proxemics obtained from the proposed concept have been compared against the proxemic distances obtained from the human study for each activity. The mean values of the proxemics obtained from the experiments with the robot and the human study are plotted in Fig. 6.7 for the considered four tasks. Furthermore, box plots of the gathered data are shown in Fig. 6.8 for better visualization of the distribution. Positive and negative outliers can be seen in the box plots for results of the human study and the robot. The existence of outliers for experiments of this kind is natural due to different human behaviors. In exercising, the mean values of the approaching distance of the robot and the human study are 73.15 cm and 77.27 cm respectively. The difference between the two means is not statistically significant ($P = 0.87$) according to the t-test. The same phenomena can be observed for the other tasks except making a phone call. Therefore, it can be concluded that the behavior of the proposed system is not significantly different from the natural behavior of humans in all the tasks except the task, making a phone call. In the instance, making a call, the difference between the robot's proxemic distance and the proxemic distance obtained from the user study is statistically significant ($P < 0.05$). The reason for this difference is that making a phone call is a confusing task to be recognized only with movements and it involves various movements which are unique to each person. In addition to that, humans adopt different habits during a phone call while sitting and standing. Furthermore, even though the difference is statistically significant, the difference between the proxemic distances obtained from the human study and the robot is not large (according to Cohen's d value [44]). Therefore, this sort of slight deviations did not cause adverse effects to the overall performance of the system.

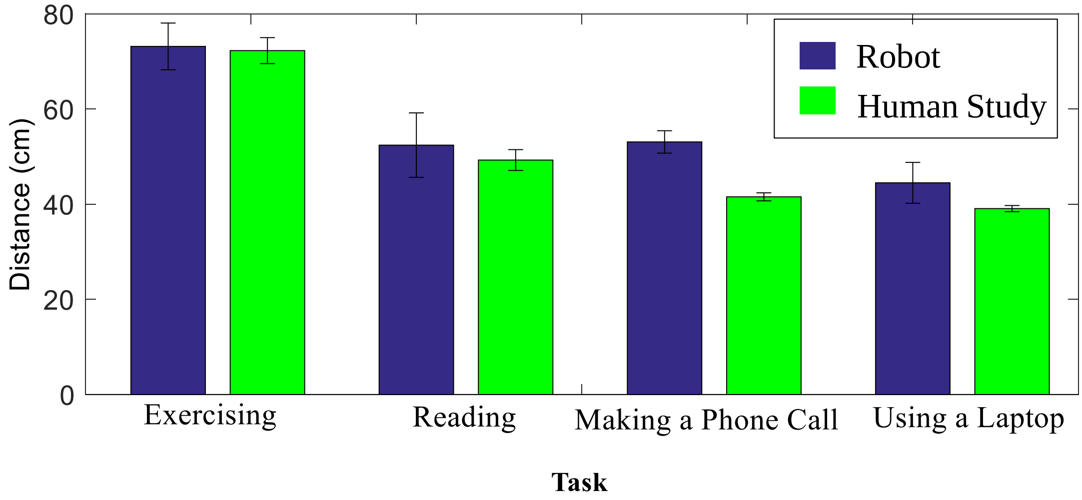



Figure 6.7: The mean values of proxemic distance obtained from the human study and the proposed system for the considered four task are plotted here with error bars. The error bars represent the standard error.

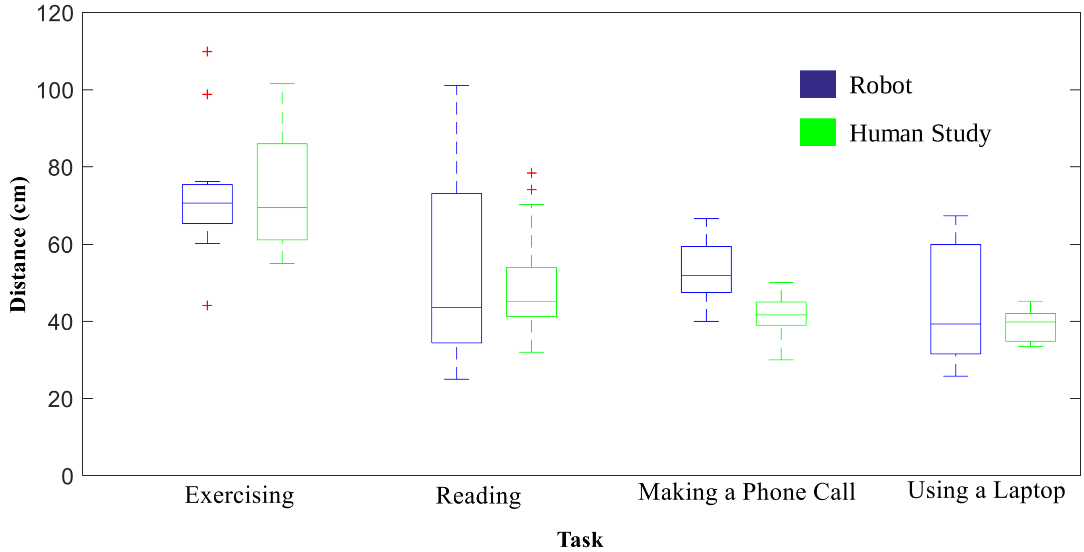



Figure 6.8: Box plots of the proxemics for the four tasks are shown here.The box plots have the usual standard notation; box: interquartile range, horizontal line:median, and whiskers: minimum and maximum. The maximum length of the whiskers is limited to $2.7\sigma$ any outliers are marked with plus sign.

## 6.5 Summary

A method has been proposed to decide the approaching proxemics of a service robot toward a human user by considering the proper spatial orientation and personal space of the user. The proposed concept is capable of determining a suitable termination position when approaching a human. The termination position of an approach toward a user is decided by Fuzzy Proxemics Evaluation Model (FPEM) which perceives and analyzes the user behavior.

The FPEM has been designed with a fuzzy inference system that evaluates the skeletal information of the user. The speeds and the distances of movements of joints are considered by the FPEM to decide the appropriate proxemics. The evaluation model has been designed in such a way that the system is not required to identify or classify the current behavior of a user (e.g., reading, exercising, eating, etc.) to decide the approaching proxemics. Moreover, the system could be used to determine approaching proxemics for most of the user activities without having prerequisites such as learning for classifying activities. Therefore, this capability makes the operation of the robot more flexible and improves the interaction.

In order to evaluate the performance of the proposed system, experimental results of the system have been compared against results of a human study. According to the comparison of results, the proposed concept is capable of replicating the natural human behavior to a greater extent. Therefore, the proposed system proved to be a convenient mechanism to determine comfortable termination distance and direction during an approach of a service robot in a domestic environment. The major improvement of the proposed system over the existing approaches is its ability to adaptively decide approaching proxemics in a human-like manner by assessing the dynamic user behavior. The ability of the system in replicating the natural human behavior would increase the overall interaction between the robot and the user.

Chapter 7

# CONCLUSIONS

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This thesis attempts to enhance human-robot interaction by establishing novel approaching mechanisms that are capable of determining the proper termination distance and direction with a user based on the physical behavior of the user. At the beginning, a human study was conducted in order to identify the human way of approaching toward an interested person during a conversation. The study was conducted under three sub studies as; effects of the approaching due to the orientation of the two persons, variation of the approaching in accordance to the initial position of the approaching person and variation of the approaching in accordance with the distance between the two persons. Approaching person data was analyzed to identify the key characteristics of the approaching behavior. The future directions are implementing human-like approaching behaviors in service robots based on the outcomes of the human study. Therefore, outcomes of this work will be beneficial for improving human-robot interaction of service robots.

The Approach Planner (AP) is designed using the outcomes of the human study of the approach behavior of a person during a conversation. The proposed method aim is to have a way of smooth approaching of a service toward a user who is having a conversation with another person. The foremost strength of the proposed concept is the method is capable of replicating the natural approaching behavior of humans. The AP is responsible for performing a human-friendly approach toward the users. The algorithm of the AP has been designed in such a way that the robot approach is capable of imitating the considered human tendencies. The parameters required for the algorithm are derived from the skeletal information perceived though Kinect sensor of the robot. Furthermore, the parameters related to the environment and the robot are obtained from the Navigation Controller (NC) of the robot. A user study has been conducted to evaluate the satisfaction and the comfort of the user in relation to the approaching behavior of the robot. User feedback given in 5 point Likert scales for a set of question statement has been used to evaluate the user satisfaction and the comfort. According to the obtained experimental results, the suggested method is capable of satisfying and comforting both persons involved in the interaction.

The two persons engaged in the conversation task is a static situation. Since the achieved results show that the interpersonal distance between the approaching person and the interested person does not significantly change at all. There may be variations in the termination distance for different task/behavior of subject interested person/user. As the next research step a method has been proposed to decide the approaching proxemics of a service robot toward a human user by considering the proper spatial orientation and personal space of the user when engage in different kind of tasks. The method is capable of determining a appropriate termination position when approaching toward a user/interested person. The termination position is decided by Fuzzy Proxemics Evaluation Model (FPEM) which perceives and analyzes the user physical behavior. The FPEM has been designed with a fuzzy inference system that evaluates the skeletal information of the user. The appropriate proxemics is decided by the FPEM by considering the speeds and the distances of movements of joints. The evaluation model has been designed in such a way that the system is not required to identify or classify the current behavior of a user (e.g., reading, exercising, eating, etc.) to decide the approaching proxemics. Furthermore, the system can be used to decide approaching proxemics for most of the user activities without having prerequisites such as learning for classifying activities.

Experimental results of the system have been compared against outcomes of a human study in order to evaluate the performance of the proposed system.

According to the comparison of results, the proposed concept is capable of replicating the natural human behavior to a greater extent. The system proved to be a convenient mechanism to determine comfortable interpersonal distance and direction during an approach of a service robot in a domestic environment. The major improvement of the proposed system over the existing approaches is its ability to adaptively decide approaching proxemics in a human-like manner by assessing the dynamic user behavior.

In general, following can be concluded based on the thesis work.

- When a third person approaches toward two persons who are having a conversation, approaching proxemics does not significantly depend on positioning of the two person.
- User comfortability/satisfaction toward a service robot can be improved when natural human-like proxemics behavior is replicated on a service robot.
- Fuzzy logic can be used to determine approaching proxemics distance in human-like manner based on dynamic user behavior.
- Movement speed and displacements of body joints of an user can be used to determine the appropriate approaching proxemics.

## 7.1 Future Directions

The proposed concepts do not consider constraints imposed due to the arrangement of the environment such as positioning of obstacles and size of the room, and the systems are not capable of adapting to the environment. However, the capability to adapt the approaching proxemics based on the environment is also necessary for real world usage of a service robot. Therefore, the adaptation of approaching proxemics based on both user behavior and environmental constraints is proposed for future work.

Proxemics preferences may be depend on person to person; therefore the adaptation of proxemics toward user (personalization)would be beneficial in improving user comfortability. It would be interesting for future work to consider such adaptations.

## LIST OF PUBLICATIONS

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1. **S. M. B. P. Samarakoon**, H. P. C. Sirithunge, M. A. V. J. Muthugala, and A. G. B. P. Jayasekara, "Proxemics and Approach Evaluation by Service Robot Based on User Behavior in Domestic Environment," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Madrid, 2018, pp. 8192-8199.

2. **S. M. B. P. Samarakoon**, M. A. V. J. Muthugala, and A. G. B. P. Jayasekara, "Replicating Natural Approaching Behavior of Humans for Improving Robot's Approach Toward Two Persons During a Conversation," in *27th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, Nanjing, 2018, pp. 552-558.

3. **S. M. B. P. Samarakoon**, M. A. V. J. Muthugala, and A. G. B. P. Jayasekara, "Identifying approaching behavior of a person during a conversation: A human study for improving human-robot interaction," in *2018 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, Miyazaki, 2018, pp. 1972-1978.

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