Initial Design, Implementation and Technical Evaluation of a Context-Aware Proxemics Planner for a Social Robot*

Kheng Lee Koay[1], Dag Syrdal[1], Richard Bormann[2], Joe Saunders[1], Michael L. Walters[1] and Kerstin Dautenhahn[1]

[1] University of Hertfordshire, College Lane, Hatfield, AL10 9AB, United Kingdom. {k.l.koay|d.s.syrdal|j.l.saunders|m.l.walters|k.dautenhahn}@herts.ac.uk
[2] Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA, Nobelstr. 12, 70569 Stuttgart, Germany. richard.bormann@ipa.fraunhofer.de

Abstract. Home Companion Robots need to be able to support users in their daily living activities and to be socially adaptive. They should take account of users' individual preferences, environments and social situations in order to behave in a socially acceptable manner and to gain acceptance into the household. They will need to be context-aware, taking account of any relevent contextual information and improve on delivering services by adapting to users' requirements. We present the design, implementation and technical evaluation of a Context-Aware Proxemics Planner which aims to improve a robots' social behaviour by adapting its distances and orientation to the user in terms of interpersonal space, based on contextual information regarding the task, user and the robot.

Keywords: Human-Robot Interaction, Social Robots, Proxemics

1 Introduction

According to Dey et al. [6], a context-aware system uses context to provide relevant information and/or services to the user relevant to the user's task. Much research in the field of context-aware systems originates from the field of ubiquitous computing. For example, Weiser [24] envisioned a scenario in which the computational power (of machines) is available anywhere, embedded within the human environment making information available to users [3]. There are now many location aware systems including intelligent tour guides [1, 19, 4], and many of these depend on the robot knowing where the user is as well as how to physically approach the user for interaction. Context-aware systems are not limited to location-aware systems; Dey et al., [6] introduced a Conference Assistant system which combines time and location contextual information to provide attendees with information related to what is happening in these locations. Context-aware systems are also widely used in the fields of human-computer interaction, artificial intelligence, computer vision [5] and e-commerce [15]. Different researchers

* The work described in this paper was partially funded by the European project ACCOMPANY (Acceptable robotiCs COMPanions for AgeiNg Years). Grant agreement no.: 287624.

define context differently depending on the specific nature of a particular context-aware system.

2 Requirements for a Context-Aware Proxemics Planner

A context-aware proxemics planner for robot home companions should understand users, their everyday activities, and their requirements with respect to the services a robot companion may be able to provide [8]. Current services fall into two main categories: 1) cognitive prosthesis (e.g. reminder functions) and 2) physical assistance (e.g. support in fetch and carry tasks etc.). The target for our robot was that it should be able to provide a variety of notifications, reminders and fetching or carrying tasks, to support independent living of users in a home environment. To achieve this, the robot needs to be aware of a user's activities, their environment and their situation. This contextual information can often be derived from raw sensor data from smart home sensors, and can be converted into meaningful semantic symbolic expressions that describe users' activities, situations and events in their environment [7, 18]. Together these semantic symbolic expressions form the main mechanism that provides the robot with the contextual information needed to perform its tasks. This contextual information can be divided into the following five different categories (i.e. one physical context and four logical contexts) taking inspiration from Mostefaoui and Hirsbrunner [14]:

Physical Context: Contexts that can be measured directly from hardware sensors i.e. drawer is open, doorbell is ringing, light is on, temperature etc.

User Context: User activity, user location, user role, user preferences, user social situation and user permission profile etc.

Robot Context: Robot activity, robot location, robot role.

Time Context: Current time, day, year, month and season etc.

Context History: A time-stamp log of the above contexts which can be used to improve the robot system.

Using this contextual information the robot could in principle take the initiative in assisting its users as well as taking account of users' preferences and overall social situations within these interactions. We use a research and development robot platform (Care-O-bot3®) manufactured by Fraunhofer IPA [17] employing ROS navigation [13] to update a location map in real-time and being able to navigate to any given location, whilst avoiding obstacles and replanning routes. The robot is sited in a naturalistic, sensorised, domestic environment (which we call the *Robot House*) for research into helping elderly persons remain longer in their homes [2, 18]. The Robot House is equipped with over 50 commercially available sensor systems, which sense users' activities at relevant locations, such as the Dining Area, Living Room, Kitchen, Bedroom and Bathroom.

3 A Context-aware Proxemics Planner (CAPP)

The Context-Aware Proxemics Planner (CAPP) presented here adapts the robot's distances and orientation in terms of interpersonal space, based on the contextual information of the user and the robot. Previous research [22, 23, 10, 12, 20] has shown that proxemics (i.e. how interactants negotiate interpersonal space) plays an important role human-robot interaction (HRI). Therefore it is essential that a robot takes account of users' proxemics preferences during interactions. Research also suggests that users' proxemics preferences vary depending on their familiarisation and experience with robots [22, 23, 21, 10], and the situation and the context of the interaction. For example, a robot approaching a person who is seated in the living room with the aim of interacting with the user should behave differently depending on the activity the person is currently engaged in and the purpose of the robot that initiated the interaction. If the user is watching TV in the living room, they may not want the robot to approach and stop at their preferred (relative) approach position and orientation as it might block their view of the TV. However, this approach, and interruption, may be appropriate if the robot is presenting urgent information that needs to be acted upon, such as a visitor at the door. The CAPP aims to provide appropriate target coordinates for the robot to approach the user in a socially acceptable manner, and to maintain a suitable interaction distance from the user. It ensures that the robot will always approach a user in a predictable and safe manner. The planner was built as a ROS service [16], independently of the robot's navigation system for portability. A ROS based client needs to provide the user's ID, posture, coordinate (x, y, orientation) in the map, and the robot's task at the target coordinate. Replies from the CAPP service are in the form of ranked target coordinates. If the robot fails to approach the first target coordinate due to unexpected obstacles, the next target coordinate will be used. This process will continue until the robot reaches one of the target coordinates. The CAPP consists of three components: General Proxemics Preferences Based Algorithm, Exceptional Cases Proxemics Preferences Based Algorithm and Location Ontology Based Proxemics Algorithm that work together as illustrated in Fig. 1.

3.1 General Proxemics Preferences Based Algorithm

The General Proxemics Preferences Algorithm was inspired by literature from human-human proxemics and from human-robot proxemics studies [23, 10]. It generates a maximum set of 21 possible target coordinates around the user. These coordinates are arranged in 3 layers of circular configuration, where each layer consists of 7 coordinates. The layers are arranged with 0.4m, 0.7m and 1.5m radius of curvature from the user (see Fig. 2a). The 0.4m and 0.7m interaction distances are reserved for physical interactions such as performing fetch and carry tasks for the user, while the 1.5m interaction distance is reserved for verbal only interactions such as notifying or reminding the user. The default distance for physical interaction is set at 0.7m while 0.4m is reserved for experienced users, and 1.5m distance for users who have no experience interacting with similar robots. Each layer has 7 different robot approach angles from the perspective of the user which are arranged at 45 degrees apart, as shown in Fig. 2a. They are based on previous study [23] which suggested that people may have different preferences for robot approaches, but normally preferred the robot to avoid approaches from behind. The 7 approach angles are ranked from the most

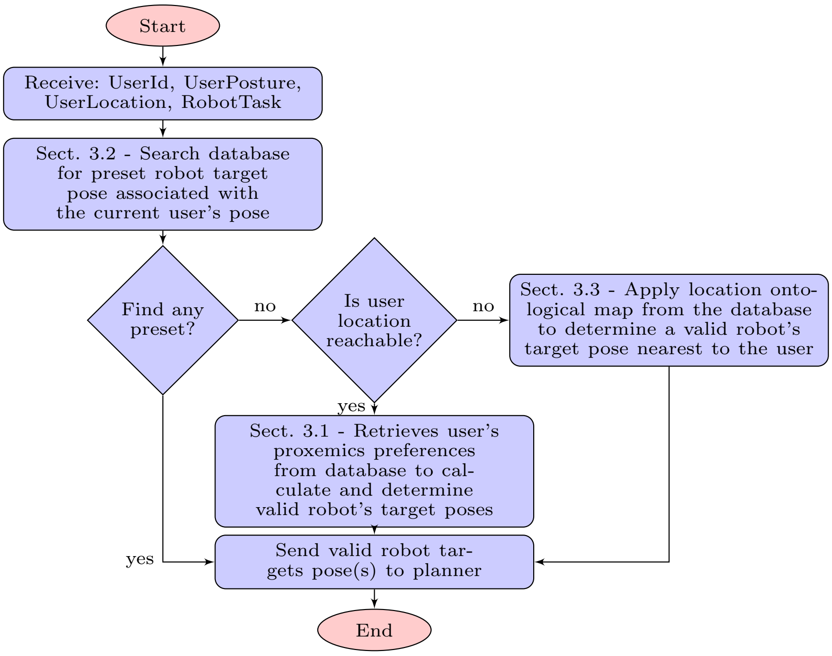
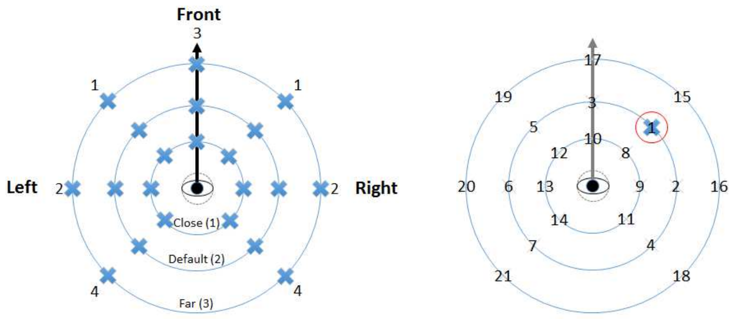


Fig. 1: Algorithm of Context-aware Proxemics Planner

preferred (i.e. 1) to the least preferred (i.e. 4) for each side of the participants as suggested by human-robot proxemics literatures [9, 11].

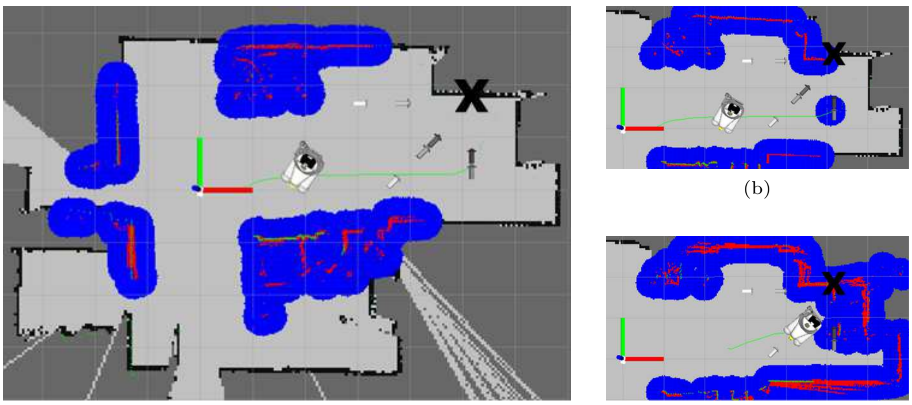
Incorporating the user's proxemics preferences, interaction experiences with robots and the robot's task, the CAPP algorithm utilises the priority data from the approach distance and the approach angle to generate 21 possible target coordinates. These coordinates will be ranked from 1 to 21 for user friendliness (e.g. Fig. 2b) where 1 is most user friendly and 21 being least friendly. The algorithm begin by identifying a distance layer and an approach angle that matches the user's preferences. If the user prefers the robot to approach from their front right with a default interaction distance (i.e. circle X in Fig. 2b) this coordinate will be placed in possible targets list with the highest ranking (i.e. rank 1). It will then determine the next friendliest coordinate around the user that has the same interaction distance to the user and so on until there are 21 ranked target coordinates for the robot around the user (Fig. 2b). The ranked target coordinates then go through an elimination process to verify with a static map of the environment to ensure that they are (a) in the same location as the user, (b) the location can be occupied by the robot and that (c) the coordinates are reachable by the robot from its current location. Only the target coordinates that survive this elimination process are then sent back to the client. This allows the robot to approach a user using the best ranked (i.e. 1 for more human friendly) target coordinate and only use a less desirable ranked coordinate when the best ranked coordinate is not accessible by the robot due to dynamic obstacles.



(a) (b)

Fig. 2: Examples of possible target positions around the user. The layer of circles indicate different interaction distances from the user. (a)The X markings indicate the 21 possible robot positions around the user, (b)an example of the 21 possible robot target positions ranked based on the user's preferences indicated by X.

Figure 3 shows an example of a robot using the algorithm to approach a user seated at X. The valid ranked target coordinates were plotted around the user. Note the most preferred target (highest ranked) is marked with a darker coloured arrow than a least preferred target which is marked with a lighter coloured arrow. In this example, the user prefered a frontal approach with a close interaction distance (see Fig. 3a). As the robot approached its initial target position and discovered that the target was no longer valid due to the presence of an obstacle (see Fig. 3b), it proceeded to use a lower ranked target position which allowed it to successfully approach the user (see. Fig. 3c)



(a) (b) (c)

Fig. 3: An example of valid target coordinates (arrow) around the user's position marked X. The robot is shown in the centre of the image and the blue areas are expanded obstacles that the robot avoids. (a) The robot navigates toward the darkest arrow, (b) robot encountered obstacle at the initial target coordinate, (c) Robot switch to the next target coordinate and successfully approach the user.

3.2 Exceptional Cases Proxemics Preferences Based Algorithm

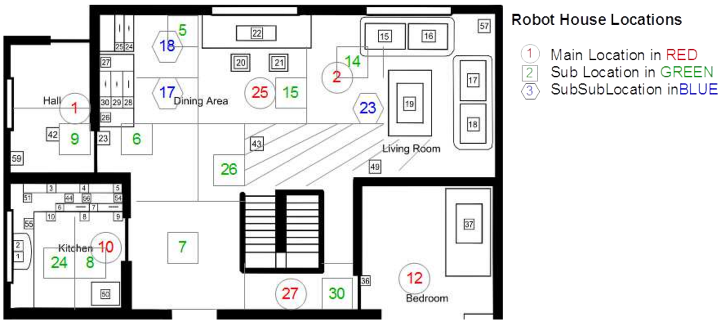
The Exceptional Cases Proxemics Preferences Based System deals with special cases such as when the user is in engaged in specific activities or at different locations. For example, the user can specify that the robot should be in a specific position and orientation when the user is watching TV (activity based) or when the user is in the kitchen (location based). There are two ways the user can set these preferences; one is to set a preferred target coordinate for the robot based on the user's location, the other is to set the preferred coordinate based on the activity of the user (e.g. contextual information [7]) deriving from sensory information. The Exceptional Cases Preferences algorithm will then utilise the contextual information from the user's location or that of the sensors triggered by the user to send the robot to these specific coordinates.

3.3 Location Ontology Based Proxemics Algorithm

The Location Ontology Based Proxemics algorithm deals with cases where it is not possible for the robot to approach the user at their location. This can be because there is no valid path for the robot to approach the user (e.g. the user is behind a doorway that is too small for the robot to go through), or the robot cannot go into a small confined area such as a kitchen. In these situations, it is neither feasible to use the General Proxemics Based Algorithm nor the Exceptional Cases Proxemics Preferences Based Algorithm unless an exceptional case was pre-set by the user for the location. This algorithm uses the user's location information to search for a target coordinate that is located at a reachable location closest to the user's current location. For example, if the user is in the Kitchen (see Fig. 4a), the algorithm will search the hierarchical location table Fig. 4b for the Kitchen object. Knowing that the Kitchen is not a valid target for the robot (see Fig. 4b row 11, column ValidRobotLocation), it will search for the closest location that is valid for the robot (i.e. Kitchent Entrance) and retrieve its coordinate for the robot.

4 Technical Evaluation of the Context-Aware Proxemics Planner

A technical evaluation (formative study) was conducted to examine the efficacy of the CAPP. The technical evaluation focused on how well the planner would perform and adapt to a user's preferences within the constraints of a domestic environment. We identified three locations of interest, the Kitchen, Dining room and Living room. These were locations where the robot would be likely to approach the user for interaction. It is important that the planner can cope with different users, taking into account their interaction experience with robots and proxemics preferences. Table 1 shows the evaluation conditions diagram that was developed to cover all the conditions highlighted above. There are two main conditions, the first condition is a situation when there are no unexpected obstacle in the environment while the second condition concerns a situation when there



(a) Visual mapping of location ontology of Robot House Map.

#	locationId	name	where	xCoord	yCoord	orientation	ValidUserLocation	ValidRobotLocation	closestValidRobotLocation
1	1	Hall	0	0	0	0	0	0	0
2	9	Living Room Entrance	1	0	0	0	1	0	6
3	8	Living Room Entrance	10	0	0	0	1	0	7
4	7	Kitchen Entrance	25	-0.027	-1.8	-176	1	1	7
5	6	Hall Entrance	25	-0.53	-0.01	159	1	1	6
6	5	ChargingStation Area	25	-0.5	1.8	-90	1	1	5
7	4	Bathroom	0	0	0	0	1	0	7
8	3	Office	0	0	0	0	0	0	0
9	2	Living Room	0	3.63	0.74	0	1	1	2
10	0	UH Robot House	0	0	0	0	1	1	0
11	10	Kitchen	0	0	0	0	1	0	7

(b) LocationOntology table in the Robot House database

Fig. 4: Location Ontology of Robot House. a)The hierarchical labelling of locations are shown using colour label while small black numbered square boxes indicate the location of sensors. b) LocationOntology table used by the algorithm to locate valid robot coordinates.

is an unexpected obstacle in the environment. As shown, within each condition, there are three different factors: Location, User, and Robot task.

The *Location* factor looks at the planner adapting to different environment configurations in a domestic environment, in this case the Kitchen, the Dining room and the Living room (Sofa location A and Sofa location B). The *Users* factor looks at the planner adapting to different user preferences (i.e. right handed approach or left handed approach) and different interaction experience with robots. The *Robot Task* factor looks at the planner adapting to different tasks carried out by the robot during interaction (i.e. Notification or Fetch and Carry tasks).

Overall we have 40 different configurations for the technical evaluation. During the experiment, we conducted 3 trials for each configuration for consistency purposes. This resulted in a total of 120 trials. The trials were conducted over a period of four days. The first two days involved all the trials for the environment with no dynamic obstacle condition. The second two days involved all the trials for the environment with dynamic obstacle condition.

Two virtual users were created for the experiment. First user had a preference for the robot to approach from the right hand side, while the second user had a preference for the robot to approach from the left. For the experiment, the robot always started its approach to the user from its home position. The

Table 1: Evaluation conditions and the algorithms applied to each condition

Robot Task	Location	Algorithm	User				Dynamic Obstacle	
			Handedness		*Experience*			
			Left	Right	Non-expert	Expert	With	Without
Fetch & Carry	Dining Room	General	✓	✓	✓	✓	✓	✓
	Living Room Sofa A	General	✓	✓	✓	✓	✓	✓
	Living Room Sofa B	General	✓	✓	✓	✓	✓	✓
Notification	Dining Room	General	✓	✓	–	–	✓	✓
	Living Room Sofa A	General	✓	✓	–	–	✓	✓
		Exception (Sensor)	–	–	–	–	–	✓
	Living Room Sofa B	General	✓	✓	–	–	✓	✓
		Exception (Sensor)	–	–	–	–	–	✓
	Kitchen	Exception (Location)	–	–	–	–	–	✓
		Ontology	–	–	–	–	–	✓

experiment involved an experimenter and an actor. The actor's job was to act as the user to sit at one of the locations during the experiment. The user's sitting location varied depending on the configurations of the specific trial being conducted. During the experiment, a video camera was setup to record the robot's behaviours. Screen capture tools were also used to capture the outputs from the Navigation System, the CAPP, the standalone client as well as the visual display from ROS's 3D visualization tool. This allowed us to collect all the data necessary for improving the system.

4.1 Results

Overall, the results show that the robot successfully approached the user in all of the 120 trials conducted to evaluate the performance of the CAPP, coping with 40 different configurations (3 trials each) in the Robot House. The results indicated that on average, the CAPP took less than 30ms to provide ranked target coordinates in response to the standalone proxemics client request. The experiment also revealed that the idea of the Context-Aware Proxemics Planner providing ranked target coordinates is useful to ensure that the navigation system has other options to reach the user in the cases of unexpected situations as encountered during the experiment. There were a total of 30 occurrences where the robot could not reach the first target coordinates (position or orientation) due to phantom obstacles detected by the laser scanner or due to inaccurate localisation. However, in 24 of the occurrences, the robot was able to reach the user with second target coordinates, in two of the occurrences the robot was able to reach the user using the third target coordinates, in three of the occurrences the robot was able to reach the user using the fourth target coordinates, and in one occurrence the robot was able to successfully reach the user using the fifth target coordinates.

5 Discussion and Conclusion

The studies above also indicate that various enhancements to the proxemics planning would be desirable e.g. by reducing the distance the robot has to travel when approaching the user. Using the robot's pose to determine whether it is closer to the user's left or right side would allow the algorithm to select the optimum path towards the target while maintaining the same approach orientation (i.e. 45 degree to the right or 45 degree to the left). This extension would both provide optimality in the path taken and indicate to the user that the robot was intelligently making decisions while respecting the user's preferences. Similarly the CAPP system uses a circular shaped proxemics zone which causes the distance between the robot and the user appear differently depending on the target location of the robot (i.e. distance between user and robot for the same proxemics zone is further when the robot is in front of the user then when at the side of the user). This could be improved by using a modified ellipse shape zone to ensure that the robot maintains the same user reachable distance around the user. In conclusion, the developed context-aware proxemics planner, which operates independently of the robot navigation algorithm, allow users to personalise the robots' proxemic behaviour across different contexts. Results from a technical formative evaluation have shown that the developed context-aware planner successfully and reliably utilised the user preferences and contextual information to provide suitable, socially acceptable ranked target coordinates allowing the robot to approach the user in a socially acceptable manner.

References

1. Abowd, G.D., Atkeson, C.G., Hong, J., Long, S., Kooper, R., Pinkerton, M.: Cyberguide: A mobile context-aware tour guide. Wireless Networks 3(5), 421–433 (1997)
2. Amirabdollahian, F., Bedaf, S., Bormann, R., Draper, H., Evers, V., Pérez, J.G., Gelderblom, G.J., Ruiz, C.G., Hewson, D., Hu, N., et al.: Assistive technology design and development for acceptable robotics companions for ageing years. Paladyn, Journal of Behavioral Robotics pp. 1–19 (2013)
3. Baldauf, M., Dustdar, S., Rosenberg, F.: A survey on context-aware systems. Intl. Journal of Ad Hoc and Ubiquitous Computing 2(4), 263–277 (2007)
4. Cheverst, K., Davies, N., Mitchell, K., Friday, A., Efstratiou, C.: Developing a context-aware electrocnic tourist guide: Some issues and experiences. In: Proc. of the SIGCHI conf. on Human Factors in Computing Systems. pp. 17–24. ACM Press, New York, USA (2000)
5. Crowley, J.L., Coutaz, J., Rey, G., Reignier, P.: Perceptual components for context aware computing. In: Borriello, G., Holmquist, L.E. (eds.) Proc. of the 4th Intl. Conf. on Ubiquitous Computing (UbiComp '02). pp. 117–134. Springer-Verlag, London, UK (2002)
6. Dey, A.K., Futakawa, M., Salber, D., Abowd, G.D.: The conference assistant: Combining context-awareness with wearable computing. In: Proc. of the 3rd Intl. Symposium on Wearable Computers. pp. 21–28. San Francisco, CA (1999)
7. Duque, I., Dautenhahn, K., Koay, K.L., Willcock, I., Christianson, B.: Knowledge-driven user activity recognition for a smart house. development and validation of a generic and low-cost, resource-efficient system. In: Proc. of the 6th International Conference on Advances in Computer-Human Interactions. pp. 141–146 (2013)
8. Kim, Y., Mutlu, B.: How social distance shapes human–robot interaction. International Journal of Human-Computer Studies 72(12), 783–795 (2014)
9. Koay, K.L., Sisbot, E.A., Syrdal, D.S., Walters, M.L., Dautenhahn, K., Alami, R.: Exploratory Studies of a Robot Approaching a Person in the Context of Handing

Over an Object. In: Proc. AAAI - Spring Symposium. vol. 28, pp. 26–28. Multidisciplinary Collaboration for Socially Assistive Robotics Stanford University, Palo Alto, California (2007)
10. Koay, K.L., Syrdal, D.S., Walters, M.L., Dautenhahn, K.: Living with robots: Investigating the habituation effect in participants? preferences during a longitudinal human-robot interaction. In: Proc. of IEEE RO-MAN. pp. 26–29. Korea (2007)
11. Koay, K.L., Walters, M.L., May, A., Dumitriu, A., Christianson, B., Burke, N., Dautenhahn, K.: Exploring robot etiquette: Refining a hri home companion scenario based on feedback from two artists who lived with robots in the uh robot house. In: Proc. of Social Robotics. pp. 290–300. Bristol (2013)
12. Koay, K.L., Syrdal, D.S., Ashgari-Oskoei, M., Walters, M.L., Dautenhahn, K.: Social roles and baseline proxemic preferences for a domestic service robot. International Journal of Social Robotics 6(4), 469–488 (2014)
13. Lu, D.V., Ferguson, M.: Navigation (2017), `http://wiki.ros.org/navigation`
14. Mostefaoui, S.K., Hirsbrunner, B.: Towards a context-based service composition framework. In: Proc. of the Intl. Conf. on Web Services. pp. 42–45. Nevada (2003)
15. Palmisano, C., Tuzhilin, A., Gorgoglione, M.: Using context to improve predictive modeling of customers in personalization applications. IEEE Transactions on Knowledge and Data Engineering 20(11), 1535–1549 (2008)
16. Quigley, M., Conley, K., Gerkey, B., J.Faust, T.Foote, Leibs, J., R.Wheeler, Ng, A.Y.: ROS: an open-source robot operating system. In: ICRA Workshop on Open Source Software (2009)
17. Reiser, U., Connette, C., Fischer, J., Kubacki, J., Bubeck, A., Weisshardt, F., Jacobs, T., Parlitz, C., Hagele, M., Verl, A.: Care-o-bot® creating a product vision for service robot applications by integrating design and technology. In: Intelligent Robots and Systems. pp. 1992–1998. IEEE (2009)
18. Saunders, J., Burke, N., Koay, K.L., Dautenhahn, K.: A user friendly robot architecture for re-ablement and co-learning in a sensorised homes. In: Proc. 12th European Conf. Advancement Assistive Technology in Europe, (AAATE13) (2013)
19. Sumi, Y., Etani, T., Fels, S., Simonet, N., Kobayashi, K., Mase, K.: C-map: Building a context-aware mobile assistant for exhibition tours. In: Community Computing and Support Systems, Social Interaction in Networked Communities, pp. 137–154. Springer-Verlag, London, UK (1998)
20. Takayama, L., Pantofaru, C.: Influences on proxemic behaviors in human-robot interaction. In: Proc. of Intelligent robots and systems. vol. 15, pp. 5495 – 5502. St. Louis, MO, USA (2009)
21. Walters, M.L., Dautenhahn, K., t. Boekhorst, R., Koay, K.L.: An Empirical Framework for Human Robot Proximity. In: Proc. New Frontiers in Human-Robot Interaction, AISB2009 Convention. pp. 144 – 149. Edinburgh, Scotland (2009)
22. Walters, M.L., Dautenhahn, K., Koay, K.L., Kaouri, C., t. Boekhorst, R., Nehaniv, C.L., Werry, I., Lee, D.: Close encounters: Spatial distances between people and a robot of mechanistic appearance. In: Proc. of Humanoid Robots. pp. 450–455. Tsukuba, Japan (2005)
23. Walters, M.L., Dautenhahn, K., Woods, S.N., Koay, K.L.: Robotic etiquette: Results from user studies involving a fetch and carry task. In: Proc. of Human-robot Interaction. pp. 317–324. ACM, New York, NY, USA (2007)
24. Weiser, M.: The computer for the 21st century. Scientific American pp. 94–104 (1991)