

# Robots as Interfaces to Haptic and Locomotor Spaces

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## ABSTRACT

Research on spatial cognition and navigation of the visually impaired suggests that vision may be a primary sensory modality that enables humans to align the egocentric (self to object) and allocentric (object to object) frames of reference in space. In the absence of vision, the frames align best in the haptic space. In the locomotor space, as the haptic space translates with the body, lack of vision causes the frames to misalign, which negatively affects action reliability. In this paper, we argue that robots can function as interfaces to the haptic and locomotor spaces in supermarkets. In the locomotor space, the robot eliminates the necessity of frame alignment and, in or near the haptic space, it cues the shopper to the salient features of the environment sufficient for product retrieval. We present a trichotomous ontology of spaces in a supermarket induced by the presence of a robotic shopping assistant and analyze the results of robot-assisted shopping experiments with ten visually impaired participants conducted in a real supermarket.

## Categories and Subject Descriptors

H.1.2 [Models and Principles]: User/Machine systems

## General Terms

Performance, Design, Experimentation.

## Keywords

assistive robotics, haptic and locomotor interfaces, spatial cognition.

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## 1. INTRODUCTION

Research on spatial cognition and navigation of the visually impaired distinguishes two spatial categories: locomotor and haptic [5, 15, 16, 17]. The haptic space is defined as the immediate space around the individual that can be sensed by touch or limb motion without any bodily translation. The locomotor space is defined as a space whose exploration requires locomotion. In the absence of vision, the frames align best in the

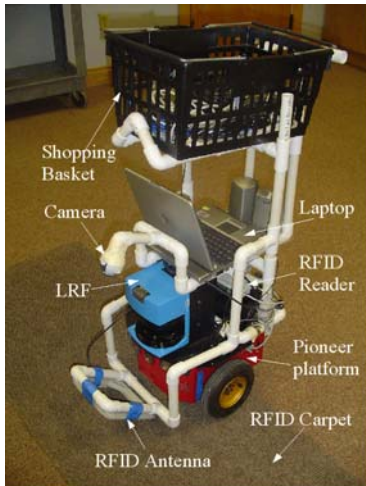
haptic space. In the locomotor space, as the haptic space translates with the body, lack of vision causes the frames to misalign, which negatively affects action reliability. Giving the visually impaired equal access to environments that the sighted take for granted entails designing interfaces to the haptic and locomotor spaces in those environments that either eliminate the necessity of alignment or enable the visually impaired to align the frames when necessary.

What environments should be targeted first? In cataloguing the most functionally difficult environments for the visually impaired, Passini and Proulx [20] top their list with shopping complexes. Grocery shopping is an activity that presents a barrier to independence for many visually impaired people who either do not go grocery shopping at all or depend on sighted guides, e.g., store staffers, spouses, and friends [12]. As a task, grocery shopping can be decomposed into two main subtasks: navigation and product retrieval. A visually impaired shopper (the shopper henceforth) can accomplish the first subtask when the shopper has 1) a means to accurately access the pose (location and orientation) and obtain adequate topological knowledge or 2) a means to reliably maneuver the haptic space in the locomotor space. The first choice ensures accurate frame alignment and leaves to the shopper the maneuvering of the haptic space in the locomotor space. The second choice guarantees reliable maneuvering but takes no position on frame alignment. Either solution requires an effective interface to the locomotor space. The shopper can accomplish the second subtask if the shopper has a means to maneuver the haptic space in the vicinity of a target product until the product is within the haptic space. To guarantee independence, any assistive shopping device for the visually impaired must necessarily address both subtasks and, consequently, provide the shopper with effective interfaces to the haptic and locomotor spaces in supermarkets.

Can robots function as effective interfaces to the haptic and locomotor spaces in the supermarket? We believe that this question can be answered in the affirmative. Several reasons justify our belief. Traditional navigation aids, such as guide dogs and white canes, can act as interfaces to the haptic space in the environment by enhancing the blind individual's perception around the body. However, neither guide dogs nor white canes can effectively interface to locomotor spaces, because they cannot help their users with macro-navigation, which requires topological knowledge of the environment. It is true that sighted guides ensure the reliable maneuvering of the haptic space, but only at the expense of independence. Loss of independence translates into loss of privacy. Our experience with visually impaired individuals in our previous robot-assisted shopping experiments convinced us that quite a few of them are not willing to use store staffers when

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**Figure 1: RoboCart as locomotor interface**

shopping for personal hygiene items, medicine, and other products that require discretion [11, 12].

We believe that, in order to function as an effective interface to the haptic and locomotor spaces in the supermarket, the robot must satisfy a twofold objective: in the locomotor space, the robot must eliminate the necessity of frame alignment and, in or near the haptic space, the robot must cue the shopper to the salient features of the environment sufficient for product retrieval.

The remainder of our paper is organized as follows. In Section 2, we present a trichotomous ontology of spaces in a supermarket induced by the presence of a robotic shopping assistant. In Section 3, we analyze the results of robot-assisted shopping experiments with ten visually impaired participants. The experiments were conducted in a real supermarket to test several aspects of robots functioning as interfaces to the haptic and locomotor spaces in the supermarket. In Section 4, we discuss our findings. In Section 5, we analyze some user comments on the limitations of our system. In Section 6, we offer our conclusions.

## 2. SPACES IN THE SUPERMARKET

### Spaces and interfaces

Spatial ontologies come about when we attempt to categorize space according to the ways we interact with it [21]. Freundschuh and Egenhofer [3] give a comprehensive review of previous work on categorization of space and distinguish six categories based on manipulability, locomotion, and size and use their ontology to describe previous ontologies of space in the geography literature. We contribute to this line of research a trichotomous ontology of space in a supermarket. This trichotomy is an extension of the dichotomous ontology (haptic vs. locomotor) currently used by many researchers on spatial cognition of the visually impaired. Our trichotomy is certainly incomplete. We developed it solely for the purposes of describing the interactions between visually impaired shoppers and RoboCart, our robotic shopping assistant shown in Figure 1.

RoboCart assists the shopper in two stages. It first guides the shopper into the vicinity of the desired product and then instructs



**Figure 2: L-Shopper scanning barcode, R-Modified barcode reader**

the shopper on how to maneuver the haptic space within that vicinity. In the first stage, RoboCart interfaces the shopper to the locomotor space, guiding the shopper to the required aisle section and interacting with other shoppers by asking them to yield the way when a passage is blocked. In the second stage, RoboCart cues the shopper to some salient features of the environment near the haptic interface through voice instructions grounded in the shopper's egocentric frame of reference.

The design of RoboCart reflects this dual interface functionality inasmuch as the device consists of two modules: locomotor and haptic. The locomotor module consists of a Pioneer 2DX mobile robotic base from ActivMedia, Inc. upon which a wayfinding toolkit is fitted in a PVC pipe structure. A shopping basket is mounted upon the PVC structure, as shown in Figure 1. The PVC structure forms a firm handle at the lower abdomen level. A 10-key numeric keypad is attached to the handle for giving instructions to RoboCart. The rigid PVC handle of RoboCart gives the user useful haptic feedback about the maneuvers that RoboCart performs. An RFID antenna is attached close to the floor so that it can detect the RFID mats on the floor. RoboCart uses Monte Carlo Markov Localization (MCL) with the RFID mats recalibration points [6]. Obstacle avoidance and aisle navigation is done using the greedy open space selection algorithm [10]. Using the numeric keypad, the shopper can either browse through a list of products or enter a product number. Once the shopper confirms the selection, RoboCart guides the shopper to the vicinity of the product.

The haptic module consists of a wireless omni-directional barcode reader shown in Figure 2. The reader is ergonomically modified with a plastic structure that helps the blind shopper align the barcode reader with the shelf. The overall design of RoboCart is based on the principles of ergonomics-for-one [11]. After RoboCart brings the shopper in the vicinity of the product, RoboCart uses the shopper's egocentric frame of reference to instruct the shopper through synthetic speech on how to find the product, e.g. *Honey Nut Cheerios is on the top shelf to your right*. The shopper finds the shelf and uses the barcode to scan the barcodes on that shelf. The product name of each scanned barcode is read to the shopper.

To describe how the visually impaired shopper interacts with the supermarket space using RoboCart, we introduce the category of *target space*. The target space is the shopper-centric subspace of the locomotor space in which the shopper perceives the target product to be. The target space is always defined with respect to a specific target product. Haptic cues in the target space act as external reference points during the shopper's maneuvering of the haptic space in the target space until the haptic space contains the product.

The trichotomy can be illustrated through the following three scenarios. In Scenario 1, the shopper wants to retrieve a product but does not know where the product is in the locomotor space. Thus, the target space and the locomotor space are equivalent. In Scenario 2, the shopper wants to retrieve a product after being given detailed path instructions to the product. The shopper's target space is now a proper subset of the locomotor space. The shopper must operationalize the path instructions to maneuver the haptic space within the target space until the haptic space includes the product. In Scenario 3, the shopper wants to retrieve a product with RoboCart. By guiding the shopper to the vicinity of the product, RoboCart narrows the target space to be easily searchable.

### Inside the target space

RoboCart eliminates the necessity of frame alignment by restricting the target space to the searchable vicinity of the product. In the target space, the shopper is left with the task of retrieving the product from the shelf and placing it into RoboCart's basket. It seems reasonable to conjecture that the shopper's performance in the target space depends on the shopper's knowledge of the target space, the shopper's sensory, cognitive, and physical abilities, and the complexity of the target space.

The knowledge of the target space includes knowledge of distances, product shapes, neighboring products, the spatial arrangement of shelves, and other haptic cues that may be unique to the shopper. If the robot is consistent overtime in how it sets up the target space with respect to a given product and verbally orients the shopper in the target space, then, as the shopper gets more exposure to the target space, the shopper's performance should improve.

The target space instructions given by the robot to the shopper need not be exhaustive. It is unreasonable to expect the robot designer to equip the robot with the knowledge of every possible haptic cue that may assist the shopper with retrieving the product. Instead, our assumption is that with time the shopper learns many haptic cues, such as level differences among shelf levels, bad barcodes, and protruding labels, that may be valid only for that shopper. Thus, the robot ensures the consistency of the target space and orients the shopper inside that target space. These haptic cues are cognitive indexes into the target space used by the shopper in product retrieval. The robot also emits audio beacons to help the shopper with placing the found product into the basket. In the case of RoboCart, the audio beacon is the sonar clicking sound. RoboCart does not use sonars but turns them to further orient the shopper in the target space.

The shopper's performance in the target space may also be conditional on the shopper's sensory and physical abilities. The literature on the haptic space performance of the visually impaired [9, 13, 24] suggests that the degree of vision may affect the efficiency of product retrieval. In addition, the shopper's abilities to bend and scan products on bottom shelves, to hold products, and to find barcodes on the shelves are likely to contribute to the shopper's performance. The shopper's performance may also depend on the intrinsic complexity of the target space. The complexity of the target space can be characterized by the number of products, the product density, the homogeneity of product

types, the number of shelves, package sizes, product layouts, presence of other shoppers, etc.

## 3. EXPERIMENTS

We formulated several research hypotheses to test how well RoboCart functions as haptic and locomotor interface to the supermarket. As is often the case with studies involving visually impaired participants, it is not feasible to test in a statistically significant way all contributing factors in a single study [1]. The main reason is that the visually impaired population in the U.S. is not distributed evenly, with the majority living in just a few urban areas. Therefore, our hypotheses below address only a fraction of the factors outlined in the previous section.

**Hypothesis 1:** *If the robot is consistent overtime in how it sets up the target space with respect to a given product and verbally orients the shopper in the target space, the shopper's efficiency of maneuvering the haptic space in the target space increases with experience in the target space where experience is measured as the number of shopping iterations.*

**Hypothesis 2:** *The shopper's efficiency of maneuvering the haptic space in the target space is inversely related to the area of the target space.*

**Hypothesis 3:** *The shopper's efficiency of maneuvering the haptic space in the target space is inversely related to the complexity of the target space.*

**Hypothesis 4:** *In the absence of any prior knowledge of the target space, minor differences in sensory abilities affect the target space performance.*

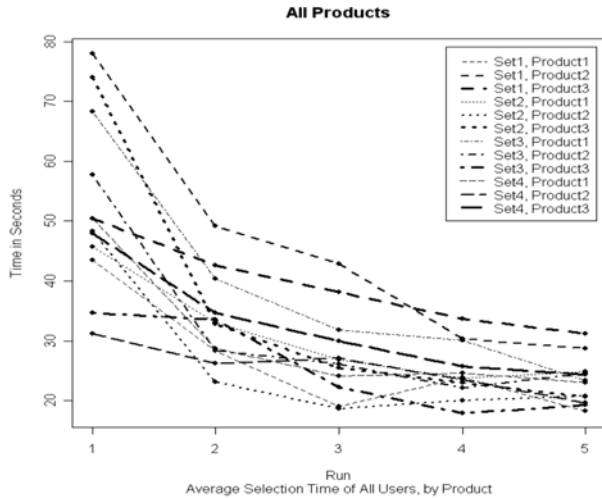
**Hypothesis 5:** *The location of the product on the shelf (top, middle, bottom levels) affects the performance.*

### Participants

Ten visually impaired participants from various locations in Utah were recruited for the experiments through the Utah Chapter of the National Federation of the Blind (NFB) in Salt Lake City, Utah. The Utah NFB Chapter provided us with a list of visually impaired Utah residents. Each individual on the list was first contacted by e-mail. The e-mail briefly described RoboCart and the experiments and asked the addressee if he or she would be interested in participating in the experiments. A brief phone interview was conducted with all those who responded positively. The inclusion criteria were: 1) the participant must be ambulatory; 2) the participant may not have any hearing or cognitive impairments; 3) the participant must understand English; and 4) the participant must be willing to travel to Logan, Utah, for a period of two days. Ten participants were thus selected. Each of the selected participants was transported to Logan, Utah, by vehicle for a period of two days and was paid a \$90 honorarium.

### Procedure

The procedure consisted of three stages. First, the individual was given a 30 minute introduction to RoboCart in our laboratory (USU CSATL). The participant was trained in using RoboCart's keypad and used RoboCart to navigate a short route in the office space around the laboratory. The participant was then asked to



**Figure 3: Performance Vs. Iteration: Learning in target space**

take a technology readiness survey [4, 19] which was used to calculate the participant's Technology Readiness Index (TRI).

Second, the participant was driven to Lee's MarketPlace, a supermarket in Logan, Utah, and asked to use RoboCart to shop for several products. Twelve products were chosen from two aisles: 4 products from bottom shelves, 4 products from middle shelves, and 4 from top shelves. In Lee's MarketPlace, each aisle consists of several shelf sections. A shelf section spans 4 to 5 meters in length and consists of 5 to 8 shelves. The selected products were divided into 4 sets. Set 1 included 3 products on top shelves; Set 2 included 3 products on middle shelves; Set 3 included 3 products on bottom shelves; Set 4 included one product on a top shelf, one product on a middle shelf, and one product on a bottom shelf. A single shopping trial consisted of the shopper picking up RoboCart from the docking area near the supermarket's entrance, navigating to each of the three products from a randomly chosen set, retrieving the products from the shelves, navigating to a designated cash register, unloading the product on the belt, picking them up on the other side of the belt, and navigating back to the docking area near the entrance. Five shopping iterations were conducted for each product set. The following measurements were taken during each run: 1) navigation time from location to location; 2) product retrieval time (time interval that starts when RoboCart stops and instructs the shopper on where the product is in the target space and ends when the shopper puts the product into RoboCart's basket); 3) the distance between the robot and the product; and 4) the number of other shoppers encountered on route. We also recorded observations regarding specific haptic cues used by the participants to find products. Two observers accompanied the participants on every run: the first observer was monitoring RoboCart; the second observer was making and recording measurements and observations.

Third, each participant was given an exit questionnaire to assess the subjective impression of the shopping experience with RoboCart. The questionnaire consisted of five questions whose answers were points on 10 point Likert scales (See Appendix A). If

the participant's response was below 5, the participant was asked to comment on why he or she gave a low mark.

## Results

To test Hypothesis 1, the two populations were product retrieval times for the first and the fifth iteration, respectively. Each participant shopped for 12 products, which gave us 12 items in each sample. The paired t-test at  $p = 0.01$  was used to compute the t-statistics for all participants. The resulting p-values for each of the t-statistics are statistically significant at the  $p = 0.01$  level. There appears to be sufficient evidence to reject the null hypothesis that the shopper's efficiency in the supermarket is not affected by the shopper's exposure to the target space. As Figure 3 indicates, the product retrieval time reduces with every iteration. Thus, the participant's efficiency in maneuvering the haptic space in the target space appears to improve with experience. It is reasonable to expect that the shopper's performance in the target space eventually reaches an asymptote and becomes optimal given the participant's sensory, cognitive, and physical abilities.

To test Hypothesis 2, we measured the distance to the product from where the robot stops. Since the description that RoboCart gives to the shopper after it brings the shopper into the target space contains the direction and shelf number of the product (e.g., product X is on the third shelf on your right), the distance can be considered as an accurate indicator of the area of the target space.

Surprisingly, we found a very low correlation coefficient (Pearson's product moment) of 0.37 between the target space area and the shopper's performance, which suggests that Hypothesis 2 may not hold for our sample. Our notes during the experiments and informal conversations with the participants after the experiments suggest that this outcome may be explained by the presence of various haptic cues in the target space. Certain haptic cues in the target space help the shopper retrieve the target product faster. One participant remembered the shape of the cooking oil spray can (one of the target products) and remembered that it was located near a label protruding from the shelf. Another participant remembered that a target product was located 10 barcodes to the left of a bad barcode which the barcode reader could not read.

To test Hypothesis 3, we used the product density as the measure of the target space complexity. The product density was computed as the number of products per foot between the robot and the target product on the correct shelf. The measurement was motivated by our previous ergonomic studies where it was found that the shoppers easily find the correct shelf from the robot's instructions but may have difficulties scanning the barcodes on the shelf. A general trend of decrease in efficiency with increasing complexity is observed. Product retrieval time and target space complexity have a correlation coefficient of 0.7.

To test Hypothesis 4, we compared how the participants performed with respect to each other. During the first shopping iteration, the shopper does not have any knowledge about the target space. Since the target space complexity is the same for all shoppers for any given product, it is sensible to suggest that the shopper's individual sensory and physical abilities will make the greatest difference in the absence of any knowledge of the target space. Using the data from all participants after the first shopping

iteration, one-way ANOVA was used to test for a statistically significant difference in the target space performance between the participants. To make the test less biased, we removed Participant 10, because she had partial sight sufficient enough to detect product shapes and even read product labels at a close distance. Among the other 9 participants, 4 had some residual vision and could see color blobs. However, none of them could read enlarged text. The other 5 participants were completely blind. No significant difference in performance was found ( $df = 8$ ,  $F = 1.504$ ,  $P = 0.17$ ). One explanation is that RoboCart minimizes minor sensory differences of the shoppers and enables them to retrieve products in the absence of any knowledge of the target space.

One-way ANOVA was computed on the data from 9 participants after the fifth iteration, i.e., after the participants were exposed to the target spaces. It was found that there was significant difference in performance between participants after exposure ( $df = 8$ ,  $F = 5.961$ ,  $P < 0.0001$ ). Thus, minor differences in sensory abilities appear to make a difference given some knowledge of the target space. The shopper may be able to utilize his or her sensory abilities optimally after receiving some exposure to the target space, but not before.

Hypothesis 5 is based upon our conjecture that some parts of the target space are more easily accessible than others. We expected that there might be significant differences in performance of the shoppers between retrieving products from top, middle and bottom shelves. Using the data collected after the first iteration, one-way ANOVA was computed for three samples of runs, each of size 40. It was found that there was significant difference in performance ( $df = 2$ ,  $F = 4.737$ ,  $P = 0.011$ ). We were now interested in finding out if knowledge of the target space was a factor. One-way ANOVA was computed on three samples of runs, each of size 40, obtained after the fifth iteration. No significant difference in performance was found ( $df = 2$ ,  $F = 0.2701$ ,  $P = 0.76$ ). Some knowledge of the target space appears to make different parts of the space equally accessible.

We also tested whether the technology readiness index (TRI) [4, 19] is an indicator of how well the shopper performs with RoboCart. Each participant was given the TRI survey. The survey consists of four groups of questions to be answered on a Likert scale: Optimism, Innovativeness, Discomfort, and Insecurity. All four TRI components have low correlation coefficients with performance: 0.47, 0.29, 0.53 and 0.22, respectively. While the TRI may be a reliable predictor of a user's readiness to use desktop computer technologies, it was not a reliable predictor of how the participants in our sample performed with RoboCart.

We conducted exit surveys to assess the participants' subjective impression of safety, smoothness, comfort, informativeness, and overall experience with RoboCart. The questions in our survey focused more on safety and comfort and are less generic than the NASA Task Load Index (NASA-TLX) questionnaire [7] that attempts to assess the perceived level of workload using more abstract categories. We obtained the average values for each quality, in the range of 1 to 10, with 1 being the worst and 10 being the best. The averages were as follows: safety = 8.66; smoothness = 7; comfort of navigation = 8.5; informative feedback from the robot = 6.66; overall experience = 8.33. Low value for smoothness was given by one participant who thought that RoboCart made several sharp turns at the ends of aisles. Two

participants gave low scores on robot feedback from the robot and indicated in their comments that they wanted more feedback from the robot during locomotion. We will address their comments in Section 5.

## 4. DISCUSSION

The shopper's efficiency in maneuvering the haptic space in a given target space appears to improve with experience provided that the target space remains the same each time the shopper is exposed to it. By providing an effective interface to the locomotor space of the supermarket, the robot ensures the stability of the target space with respect to each product over time, which gives the shopper an opportunity to learn how to maneuver the haptic space inside the target space.

Ideally, the target space coincides with the target space. In practice, however, the best the robot can do is to bring the size of the target space as close to the size of the haptic space as possible. A low correlation coefficient was found between the target space area and the shopper's performance in our sample, which may indicate that the target space sizes ensured by RoboCart and the egocentric verbal instructions inside the target spaces contribute to faster product retrievals and minimize the effect of minor differences in visual abilities. The shopper's performance in the target space is likely to become optimal with respect to the shopper's sensory, cognitive, and physical abilities. It remains an open question what is the optimal size of the target space for a given shopper and a given product.

Our results suggest that the paucity of verbal instructions in target spaces may be desirable for some shoppers, because it does not raise the shopper's cognitive load and enables the shopper to acquire individually valid haptic cues not explicitly mentioned by the system. Minor differences in sensory abilities appear to make a difference only after some knowledge of the target space has been acquired. In other words, the shopper may be able to put to personally optimal use his or her sensory abilities after receiving some exposure to the target space.

We have argued that, to guarantee independence, an assistive shopping device for the visually impaired must provide the shopper with interfaces to the haptic and locomotor spaces in the supermarket. Robotic mobility aids, such as GuideCane [23], Guido [25], and Harunobu-6 [18] focus on the haptic space and leave the handling of the locomotion space to the user. Recent proposals to address the visually impaired shopping problem with purely wearable means also stay in the haptic space [14]. In our opinion, these solutions are unlikely to lead to the elimination of the barrier to large scale or small scale shopping, because they focus only on one space (haptic) and do not address the loss of independence. We believe that, to remain independent, the visually impaired shopper must be able not only to retrieve products from shelves but to handle the locomotor space in the supermarket.

Are robots necessary to overcome this barrier for the visually impaired? For large scale independent shopping the answer appears to be affirmative inasmuch as the locomotion with a shopping cart in front may not be possible in the absence of vision. Whether or not wearable small scale shopping solutions will be found for the visually impaired may well depend on the

ability of those solutions to provide effective interfaces to the locomotor spaces of supermarkets.

## 5. USER COMMENTS

User comments provide valuable insights into the limitations of our system. In this section, we will analyze several user comments that are relevant to the problem robotic interfaces to the haptic and locomotor spaces in the supermarket.

**Comment 1:** *Instead of just following the robot, doing nothing, I would like to know what products I am passing by.*

The comment suggests that some participant may want to get more out of their shopping experience than just buying the required products. It is an open research question how much information is enough. More broadly, this question is related to the question of understanding and representing the user's context to provide more useful computational services dynamically [2, 8, 22]. In the context of a supermarket, it is not practical to tell the user about each and every product that the robot passes by. Perhaps, informing the shopper about sales and higher product categories, e.g. cereal, canned products, etc, is what some participants would like RoboCart to inform them about.

**Comment 2:** *It would really help me if it can tell me in which direction to go after I scan every barcode. That way I can know if I miss a barcode.*

During the experiments it was observed that some participants would often overestimate the distance from the robot to the product. In such cases it was hard for them to realize that they should scan the next barcode in the opposite direction. What is needed is a detailed spatial topology of barcodes in target spaces. Once such a topology is available, RoboCart can give the user step-wise instructions to find the product in the target space: scan left, scan right, move one shelf up, etc.

**Comment 3:** *It would be really helpful if the robot could stop exactly in front of the product.*

RoboCart cannot stop exactly in front of the product. Even if the robot knew the x and y coordinates of every product in the store, it would still be unable to stop exactly in front of each product due to the presence of other shoppers in the store. When this was explained to the participant, the participant gave the following comment.

**Comment 4:** *Okay, I understand that. However, it is easier to stay behind the robot than go around it. So it would be nice if the robot could stop after passing the product.*

This is a fair comment that gives us a valuable insight on how we can improve the robot's interface to the target space in the future.

**Comment 5:** *It would be better if the robot can emit some beeps instead of the sonar clicking. The clicking sound gets irritating real soon and is difficult to trace in presence of background noise.*

This comment suggests that such seemingly minor issues like the sonar clicking can affect the shopper's experience. Since the shopper must return to RoboCart after retrieving the product from the shelf, RoboCart should emit adequate sonification beacons in the target space. What beacons are adequate is a research question that we hope to address in the future.

**Comment 6:** *How will this thing help me with produce?*

It will not. RoboCart can take the shopper to the target space of a given item in the produce section and instruct the shopper on how to find the target item. However, RoboCart cannot help the shopper recognize the freshness of fruits and vegetables. We consider this important problem to be outside of the scope of our project.

## 6. CONCLUSION

An assistive shopping device for the visually impaired that ensures independence must provide the shopper with interfaces to the haptic and locomotor spaces in the supermarket. These interfaces should either eliminate the necessity of frame alignment or enable the visually impaired to reliably align the frames. Robots can function as interfaces to the haptic and locomotor spaces in supermarkets by eliminating the need of frame alignment in the locomotor space and cuing the shopper to the salient features of the target space sufficient for product retrieval.

The paucity of verbal instructions in target spaces may be desirable for some shoppers, because it does not raise the shopper's cognitive load and enables the shopper acquire individually valid haptic cues not explicitly mentioned by the system. Minor differences in sensory abilities appear to make a difference only after some knowledge of the target space has been acquired. In other words, the shopper may be able to put to personally optimal use his or her sensory abilities after receiving some exposure to the target space.

To remain independent, the visually impaired shopper must be able not only to retrieve products from shelves but to handle the locomotor space in the supermarket. Thus, robot assistants may be necessary to for the visually impaired in large scale independent shopping, because locomotion with a shopping cart in front may not be possible in the absence of vision. Whether or not wearable small scale shopping solutions will be found for the visually impaired may well depend on the ability of those solutions to provide effective interfaces to the locomotor spaces of supermarkets.

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## 8. REFERENCES

- [1] Bradley, N. and Dunlop, M. An Experimental investigation into wayfinding directions for visually impaired people. *Ubiquitous Computing*, 9:395-403, 2005.
- [2] Dey, A. and Abowd, G. Towards a better understanding of context and context-awareness. In Proceedings of the CHI

Workshop on the What, Who, Where, and How of Context-Awareness. The Hague, NetherLands, 2000.

[3] Freundschuh, S. and Egenhofer. Human conceptions of spaces: implications for geographic information systems. *Transactions in GIS*, 2(4):361-365, 1997.

*ACM Human Robot Interaction (HRI) Conference*, Salt Lake City, USA, 2006.

[5] Golledge, R., Klatzky, R., and Loomis, J. Cognitive mapping and wayfinding by adults without vision. In *J. Portugali (Ed.) The Construction of Cognitive Maps*, pp. 215-246, Kluwer, the Netherlands, 1998.

[6] Gharpure, C. P., Kulyukin, V., Kutiyawala, A., Jiang M. Passive Radio Frequency Exteroception in Robot Assisted Shopping for the Blind. To appear in *the Proceedings of the Ubiquitous Intelligence and Computing (UIC) Conference*, Wuhan and Three Gorges, China, 2006.

[7] Hart, S. and Staveland, L. Development of NASA-TLX: results of empirical and theoretical research. In Hancock, P., Meshkati, N. (Eds.) *Human mental overload*, pp. 139-183. North Holland, 1988.

[8] Jacquet, C., Bellik, Y., and Bourda, Y. A Context-aware locomotion assistance device for the blind. In Fincher, S., Markopoulos, P., Moore, D., and Ruddle, R. (Eds.) *People and computers XVIII – design for life*. Springer-Verlag, London, 2004.

[9] Kay, L. A sonar aid to enhance spatial perception of the blind: engineering design and evaluation. *The Radio and Electronic Engineer*, 44: 40-62, 1974.

[10] Kulyukin, V., Gharpure, C., Nicholson, J., Osborne, G. Robot-Assisted Navigation for the Visually Impaired in Structured Indoor Environments. *Autonomous Robots*, 21(1):29-41, 2006.

[11] Kulyukin, V. and Gharpure, C. Ergonomics-for-one in a robotic shopping cart for the blind. In *Proceedings of the ACM Conference on Human-Robot Interaction (HRI)*, pp. 142-149, Salt Lake City, USA, 2006.

[12] Kulyukin, V., Gharpure, C., and Nicholson, J. RoboCart: Toward Robot-Assisted Navigation of Grocery Stores by the Visually Impaired. In *Proceedings of the IEEE/RSJ Conference on Intelligent Robots and Systems (IROS)*, Edmonton, Canada, 2005.

[13] Lahav, O. and Mioduser, D.: A blind persons cognitive mapping of new spaces using a haptic virtual environment. *Journal of Research in Special Educational Needs*, 3:172-177, 2003.

[4] Gockley, R. and Mataric, M. Encouraging physical therapy compliance with a hands-off mobile robot. In *Proceedings of the*

[14] Lanigan, P., Paulos, A., Williams, A., and Narasimhan, P. *Trinetra: Assistive Technologies for the Blind*. Technical Report CMU-CyLab-06-006, CMU, Pittsburg, PA, 2006.

[15] Millar, S. Understanding and representing spatial information. *British Journal of Visual Impairment*, 13: 8–11, 1995.

[16] Millar, S. Theory, experiment and practical application in research on visual impairment. *European Journal of Psychology of Education*, 12:415-430, 1997.

[17] Millar, S. The problem of imagery and spatial development in the blind. In B. de Gelder (Ed.) *Knowledge and Representation*, pp. 111-120. Routledge and Kegan, London, 1982.

[18] Mori, H., Kotani, S.: Robotic travel aid for the blind: Harunobu-6. In *Proceedings of the Second European Conference on Disability, Virtual Reality, and Assistive Technology*, Sovde, Sweden, 1998.

[19] Parasuraman, A. Technology readiness index (tri): A multiple-item scale to measure readiness to embrace new technologies. *Journal of Service Research*, 2(4): 307-320, 2000.

[20] Passini, R. and Proulx, G. Wayfinding without vision: an experiment with congenitally totally blind people. *Environment and Behavior*, 22: 227–252, 1998.

[21] Tversky, B., Morrison, J., Franklin, N., and Bryant, D. Three spaces of spatial cognition. *Professional Geographer*, 51(4): 516-524, 1999.

[22] Tversky, B. and Lee, P. How space structures language. In C. Freksa, C. Habel, and K.F. Wender (Eds.), *Spatial Cognition. An interdisciplinary approach to representing and processing spatial knowledge*, pp. 157-175. Springer-Verlag, Berlin, 1998.

[23] Ulrich, I. and Borenstein, J. The guidecane: applying mobile robot technologies to assist the visually impaired. *IEEE Trans. on Systems, Man, and Cybernetics, Part A: Systems and Humans*, 31: 131-136, 2001.

[24] Ungar, S. Cognitive mapping without visual experience. In Kitchin, R. and Freundschuh, S. (Eds.) *Cognitive mapping: Past, Present, and Future*. Routledge and Kegan, London, 2000.

[25] <http://www.haptica.com>.