Human- and Situation-Aware People Following

Hendrik Zender[*], Patric Jensfelt[†], Geert-Jan M. Kruijff[*]
[*] German Research Center for Artificial Intelligence (DFKI GmbH),
Language Technology Lab, Saarbrücken, Germany, e-mail: {zender,gj}@dfki.de
[†] Royal Institute of Technology, Center for Autonomous Systems, Stockholm, Sweden, e-mail: patric@kth.se

Abstract— **The paper presents an approach to intelligent, interactive people following for autonomous robots. The approach combines robust methods for simultaneous localization and mapping and for people tracking in order to yield a socially and environmentally sensitive people following behavior. Unlike current purely reactive approaches ("nearest point following") it enables the robot to follow a human in a socially acceptable way, providing verbal and non-verbal feedback to the user where necessary. At the same time, the robot makes use of information about the spatial and functional organization of its environment, so that it can anticipate likely actions performed by a human, and adjust its motion accordingly. As a result, the robot's behaviors become less reactive and more intuitive when following people around an indoor environment. The approach has been fully implemented and tested.**

I. INTRODUCTION

It is likely that we soon see robotic assistants appear in our households, offices, hospitals, shopping malls, and other human-populated environments. As this means that these robots interact primarily with the general public, it is important that human-robot interaction is intuitive and socially acceptable. Only then can we expect robotic assistants to become accepted and mesh into the human social fabric.

In this paper, we focus on one aspect of human-robot interaction, namely *people following* in an indoor environment. There are various likely scenarios in which a robot needs to move along with a person, e.g. when the human shows the robot around, pointing out objects or places; gives it procedural instructions; or when they need to jointly perform actions, like carrying groceries. For this to work out the robot's behaviors when following the human should meet at least the following three requirements.

First, following behaviors should be *robust*. Typically a service robot operates in a noisy, dynamic, populated, and (probably) non-instrumented environment – imagine an assistant at a shopping mall or in an office building. This implies that people following has to be based on a robust *tracking* method. This method must be able to keep track of where people to be followed are, even when these may be temporarily occluded, and deal with normally dressed humans in environments with changing lighting conditions.

Second, following behaviors should be *comprehensible*. Experimental evidence shows that people unconsciously, or *mindlessly* [1], react on social patterns in machine behavior. Thus the robot should convey its awareness of the user by employing comprehensible verbal and non-verbal cues – e.g. *readable social cues* [2] like *gaze feedback*.

Third, such following behaviors should not only be comprehensible, but also *socially acceptable*. For example, the robot should keep a certain distance between itself and the person being followed, to respect personal space [3].

These requirements have important consequences for the design of people following behaviors for robots. Standard methods for people following are inherently *reactive*: the robot uses the person to calculate the target position and slavishly follows the human irrespective of the situation. Although this may be done robustly, it can easily lead to incomprehensible and socially unacceptable situations. What this points to is that we need to go beyond purely reactive following behaviors. We need to enable the robot to understand what the human is likely to do, so that it can *anticipate* those actions and suitably adjust its behavior.

In this paper, we present an approach to people following that addresses these requirements, and which enables the robot to anticipate actions by using knowledge about the spatial and functional organization of the environment. We combine people tracking with techniques for Simultaneous Localization And Mapping (SLAM) and conceptual mapping, providing the robot with a sense of where people are, and what can be done in different locations. As main sensor for tracking and mapping we use a laser range finder. Our approach handles two common situations that require a situation-aware behavior and which can be dealt with using context information. The first situation is to make room so that the user can open or close a door, and the second situation is to employ a different control strategy when following the user along a corridor. To provide comprehensible, social feedback during following, we use a pan-tilt unit (PTU) bearing a camera as *iconic* head for providing *gaze feedback*, and speech synthesis for different types of *spoken feedback*. We have implemented and tested our approach on multiple robotic platforms in different office environments. Tests show how our approach leads to appropriate behavior in situations where purely reactive following inevitably fails.

The paper is structured as follows. Sec. II discusses related work regarding person detection, tracking, and following for mobile robots and concerning social aspects of human-robot interaction. Sec. III addresses the underlying techniques of our people following approach: tracking, mapping and navigation, and robot control. Sec. IV describes our method of interactive people following and how it applies social and situational awareness. Sec. V presents evaluation results. The paper ends with the lessons learned and conclusions.

II. RELATED WORK

There are several techniques that address detection, tracking, and following of persons in a robot's environment. They differ not only in the sensors used, but also in the degree of mobility of the robot. Kleinhagenbrock *et al.* [4] present a person tracking approach that fuses information from a laser-range based leg detection mechanism and a vision-based face recognition module to keep track of a person. Fritsch *et al.* [5] extend this work by adding a stereo-microphone setup that locates persons through the speech sounds they produce. One reason for combining multiple sensors for tracking a person is the lack of occlusion handling of their laser-range based people tracker. They present an experimental setup in which a static robot has to keep track of a person partially occluded by office furniture while manipulating a typical office object. Although they achieve a fair degree of robustness in the experiments, there is no evaluation of the performance of the approach when used on a moving robot. Moreover, their approach does not have the predictive capabilities to anticipate actions of a tracked person. Topp and Christensen [6] present an evaluation of a laser-based people tracking method that allows for multiple people in the environment and temporary occlusion of tracked persons, similar to the algorithms of Schulz *et al.* [7]. The experiments show that an approach that is only relying on laser data is a good choice for mobile robots that will be operating under different lighting conditions and will have to interact with previously unknown people. However the experiments also reveal the disadvantages of a purely laser-based method: in a typical office environment laser readings of many structures at a height of 30 cm resemble laser readings typical for legs at that height. Arras *et al.* [8] present a machine learning approach to acquire features for person detection from laser scans that could overcome some of these drawbacks.

Various studies have pointed out the importance of taking into account social scripts and conventions that hold in human-human interaction when designing robots. Kanda *et al.* [9] present an integrated robotic system capable of verbal and non-verbal interaction with people. Their experiments show that people apply similar patterns in human-robot interaction as in human-human interaction. Pacchierotti *et al.* [3] observe that such social conventions also apply to more implicit forms of interaction, e.g. robots moving in the presence of people. A robot assistant is thus inherently a *social artifact*, to which people apply the same social behavior schemata as they do to other people [1], [2], [10].

In this paper we present an approach to people following which builds forth on the research cited above. We opted for a laser range finder as the main sensor for our method, as it imposes the least requirements on the clothing of people, their body posture with respect to the robot, and the lighting conditions of the surroundings. Based on sensing input, the robot maintains an awareness of the current situational context. This forms the core, and the novelty, of our approach: a combination of both human awareness and situation awareness to yield a comprehensible, socially acceptable following behavior, which includes keeping an acceptable personal distance (based on Hall's notion of *proxemics* [11], [3]), establishing eye contact, providing verbal feedback, and applying situation-aware interpersonal behaviors.

III. TRACKING AND NAVIGATION

The robot's software architecture, including the navigation system with subsystems for low level perception and control, as well as the dialogue system, is based on the one described in [12]. Thus we will only give some details about those components of the navigation system that are core to the approach presented in this paper.

A. People Tracking

In order to follow its user, the robot must be able to detect and track the positions of people around it. In this paper we focus on the interaction with a single person, the user, which simplifies the tracking problem. To handle the challenges that arise with occlusions and people moving close to each other, a more advanced tracking algorithm such as [7] is needed. Here we apply a method for people tracking that is akin to [13], [14]. The method is essentially based on detecting motion. Something that violates the free space defined by a previously acquired laser scan was either not detected or has moved. Given that the laser scanner detects most objects, it is most likely that the violation was caused by a moving object. In a real world scenario the ego motion of the laser scanner needs to be compensated for when the robot is moving. This is accomplished by using the odometry which has a very low deviation over short distances. The moving objects are tracked using a Kalman filter for each object. When a new moving object is detected, a new hypothesis is created. Before such a hypothesis is considered verified, the object has to move a certain distance d (we use $d = 0.5$m). This is to reduce the effects of spurious detections. These are caused by, e.g., glass windows that sometimes appear transparent and sometimes not, creating the illusion of motion.

B. Representing the Environment

The approach to interactive people following presented here makes use of knowledge of spatial organization to navigate the robot during following, and to anticipate a person's behavior so that the robot can suitably adjust its following behavior – e.g. applying different motion strategies in corridors and cluttered rooms. Our robot is endowed with a *multi-layered conceptual spatial representation* of

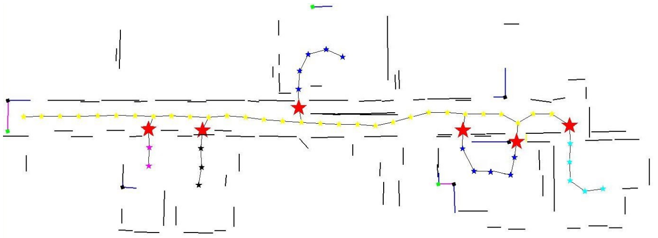


Fig. 1. The map of the robot's environment: line features for SLAM corresponding to walls and the navigation graph (stars and edges). The coloring of the places nodes (small stars) denotes the topological partitioning of the environment. Doorways are represented by large red stars.

its environment which comprises low level metric maps for SLAM, a topological abstraction layer, and a conceptual representation used for situated dialogue with the user. We only mention those aspects necessary for our approach and refer the reader to [12] for a more detailed description.

At the lowest level, we maintain a *metric map*, created using SLAM [15]. The metric map contains a feature map with lines, i.e. walls and other straight surfaces in the environment, extracted from laser scanner data. Its main purpose is to support localization. To establish an adequate description of the free space for navigation, we build a *navigation graph* that encodes free space and how it is connected, based on the notion of a *road-map* of *virtual free-space markers* [16], [17]. As the robot navigates through the environment, such a marker (*navigation node*) is added to the map whenever the robot has traveled a certain distance from the closest existing node (in our case $\sim$1m). There are two types of nodes in the graph: *place nodes* and *gateway nodes*. Each place node in the navigation graph is classified into *Room* or *Corridor* using a laser based classifier [18]. This classification can be used for high level reasoning [12] and in selecting appropriate motion control strategies (cf. Sec. IV-B.2). Abstracting over free space, we create a *topological map* dividing the navigation graph into areas. An area is a set of interconnected nodes. We assume that each area is delimited by gateway nodes. The topological map thus simulates the topological view that humans adopt as its areas typically correspond to what humans perceive as distinct rooms. Currently, we detect doorways simply based on detecting when the robot passes through a narrow opening. The door is then stored as a gateway node in the navigation graph. Fig. 1 shows an integrated view of the metric map and a navigation graph in a typical indoor scenario.

As both the robot and the human user are localized with respect to the map, this allows the people following module to adapt the robot's behavior based on the situation.

C. Robot Control

Depending on the mode of operation, e.g. autonomous exploration or people following, the goal state of the robot is governed by different modules. Common to all modes of operation is that there is an obstacle avoidance layer that takes care of not colliding with objects in the environment. Depending on the situation, a different obstacle avoidance strategy can be used. The obstacle avoidance layer uses a local representation for the environment a few meters from the robot. The modules for people following or exploration provide the target robot pose, and obstacle avoidance ensures it is reached in a safe way. If the goal location is far away, the navigation graph is used to plan a path.

IV. INTERACTIVE PEOPLE FOLLOWING

Here we describe the human- and situation-aware people following algorithm we have implemented. We first present the general algorithm and then explain how social and situational awareness adjust the robot's following behavior.

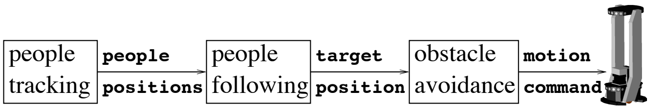


Fig. 2. Information flow for robot control in people following mode

The people tracking module keeps a list of the current dynamic objects. A dynamic object is represented as a tuple $o_i = \langle id, x, y, \theta, v\rangle$ where (x, y) is its position in the metric map, θ the direction of motion, v its speed and id a unique identifier to keep track of objects over time. This information is processed by the people following module, calculating a target robot position $p_t = (x_t, y_t)$ which is at a distance D_p from the person followed. The value of D_p is determined according to the situation (described below). The calculated target location is then passed on to the obstacle avoidance modules to calculate the appropriate motion commands. The basic motion control algorithm used for obstacle avoidance is the Nearness Diagram [19] which is able to handle very cluttered scenes. Fig. 2 illustrates this information flow.

A. Social Awareness

The people following behavior presented here preserves socially acceptable distances from its human user, and gives *readable social cues* (gaze, speech) indicating how the robot tries to maintain engagement during following.

The user can initiate the people following behavior by asking the robot to follow him (e.g. "Come with me!" or "Follow me!"). Following is initialized by selecting and then tracking the closest dynamic object, which is assumed to be the user. The behavior is *interactive* in that the robot actively gives the person feedback about its internal state. Verbal grounding feedback (e.g. "Yes", "Okay!") signals that the robot has understood the command and is ready to follow the user. During the execution of the people following behavior, the PTU is moved to simulate a gaze that follows the user. This signals that the robot is aware of its user's position and provides additional feedback about which person the robot assumes as its guiding person. The pan and tilt angles are adjusted such that the camera that is mounted on the PTU (cf. Fig. 5) points towards the head of the tracked person. We assume the head of the person to be at $\sim$1.7m above ground at the x-y-position of the tracked person.

In accord with Pacchierotti *et al.* [3], the motion control algorithms of our approach employ a control strategy that reflects the notion of proxemics [11]. We only initiate a motion to follow the user if the person is more than 1.2m away from the robot – that is, when the user leaves the *personal distance*. Inside the personal distance, which we assume to be appropriate for interaction with a domestic service robot, the robot will turn its "head" to provide gaze feedback showing its user awareness. As long as he/she stays within the personal distance boundary, the robot will turn in place if the change in angle to the user is larger than an angle α (we use $\alpha = 10°$) in order to keep the user in its field of view. As soon as he/she is further away than 1.2m, we take this as an indication that the robot should continue following its user. For approaching the user, we determine a target point at distance $D_p = 50$cm, thus preserving a personal distance without violating the *intimate distance boundary*. The user can stop the robot at any time (“Halt!”, “Stop!”).

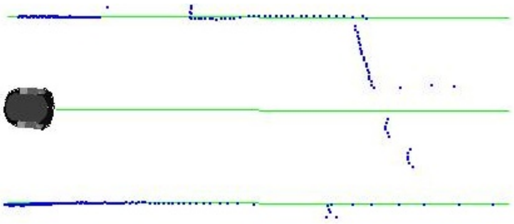
B. *Situation Awareness*

Situation awareness (SA) can be paraphrased as “knowing [the important aspects of] what is going on around you”, where importance is “defined in terms of the goals and decision tasks for [the current] job” [20]. Endsley defines three levels of SA: *perception*, *comprehension*, and *projection*. In the following paragraphs we will explain how our robotic system uses perception and comprehension of the current situation to anticipate projected future states. The two example situations are embedded into the context of following a human user in a known indoor environment.

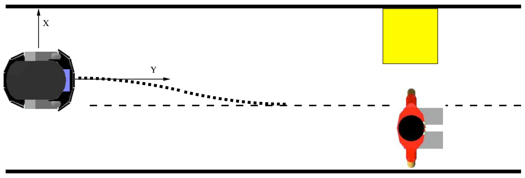
1) Smart handling of doors: When the user approaches a door, the robot can cause problems if it continues in normal following mode. If the user intends to close an open door or open a closed door the robot might end up in a situation where it blocks the user from, for example, swinging open a closed door leaf. A smart robot should be aware of this danger and take appropriate action.

As long as the only sensor used is a laser scanner, it is impossible to detect whether the user intends to open, close, or pass through a door when approaching it. However, a safe assumption is to make room so that the user can perform any such action with the door. The navigation graph contains the position of doors in the environment. Our solution is hence to increase the desired distance between the robot and the user ($D_p = 2$m) when the user is in or close to a door. If the user moves through the door in one motion – i.e. not manipulating the door – the increased distance will not be visible and the robot follows through. If on the other hand the user stops in the door, the robot will also stop and even back off to keep a long distance from the user, thus making room for the user’s actions. As soon as the robot detects that the user passed through the door, continuing his or her way, the robot will decrease the desired distance to the user again ($D_p = 0.5$m) and resume its people following behavior.

2) Following in a corridor: Moving in a corridor is different from general motion in open space or in a more cluttered environment like a room. If the robot is able to take advantage of this situation, a smoother, faster and more intuitive motion can be achieved. The main assumption underlying our approach (cf. Fig. 3) is that the robot can make much better predictions about the motion of the person being followed in the corridor than in a general environment: motion in a corridor is known to be along the corridor. The motion control problem is thus reduced to determining the speed along the corridor and the position across the corridor. For the obstacle avoidance method this means that a standard approach that is governed by the robot’s local surround is not suitable. This would sometimes result in large corrections to the direction of motion when some new structure or person enters into the immediate surrounding of the robot. In a corridor, however, obstacles on the robot’s path can be detected from a fair distance. In our approach, the motion planning method can look ahead in the corridor and make corrections to the path autonomously without relying on detecting that the user adjusts his/her course. The lateral position in the corridor is controlled so that the robot follows a safe *lane* along the corridor. For detecting upcoming obstacles, naturally, the user is not considered.



(a) Detecting the main walls and center line from laser data.



(b) Calculating a smooth trajectory along the corridor.

Fig. 3. (a) The robot automatically detects the center line of the corridor and the position of the main walls (marked with the lines). The small dots denote the laser scan. (b) Following a person in a corridor reduces the motion control problem to adjusting the speed along the corridor and position across the corridor. Predicting how the user will move is also simpler and the robot can initiate an obstacle avoidance maneuver much earlier. The yellow square represents a box close to the corridor wall.

Another observation that can be made is that corridors are transportation roads for people where the speed of travel tends to be a bit higher and where people are used to moving a bit closer to each other when passing each other. The upper bound of the robot’s speed along the corridor, v_{rob}, is controlled according to $v_{rob} = v_p + k(D - D_p)$ where D and D_p are the current and desired distance respectively between person and robot, v_p is the current speed of the user and k is the controller gain (here $k = 0.5$). Experiments show (cf. Sec. V) that increasing the robot’s maximal speed when moving in a corridor yields a better performance.

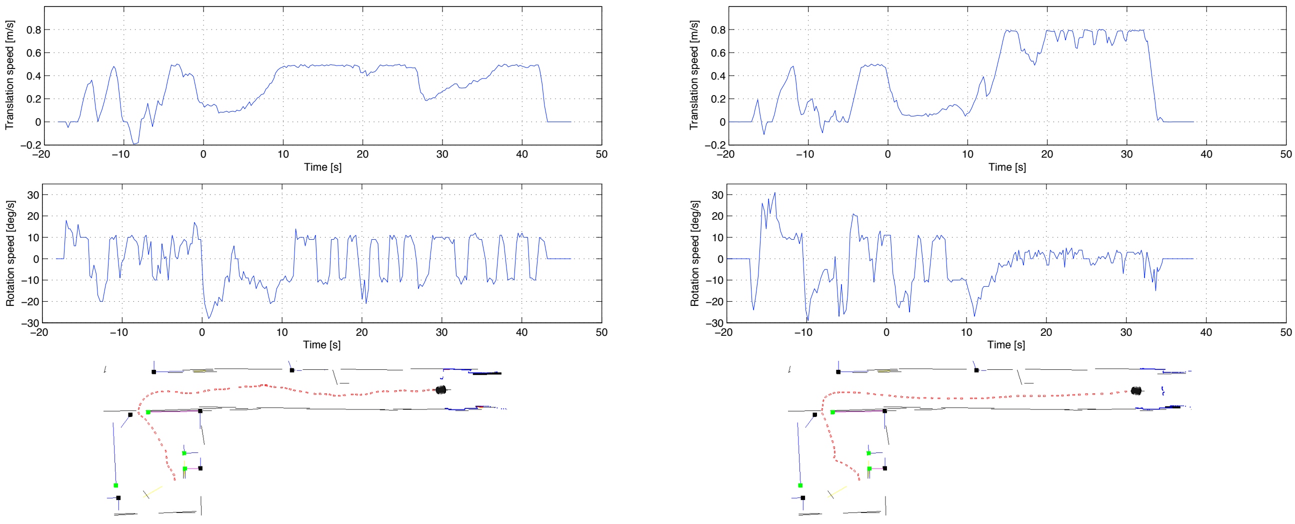
Determining when to switch from normal following mode to corridor following mode can be based on the node classification from the navigation graph. We also require that the parameters defining the corridor, i.e. direction and width, can be found. This is done based on angle histograms similar to [21]. Fig. 3(a) shows an example where the direction and the main walls of the corridor have been found.

V. EVALUATION

We have conducted several case studies to test the performance and appropriateness of our algorithms. The experiments have been carried out at two different locations on two similar robotic platforms (cf. Fig. 5, left). The robots had a map of their environment that had been acquired beforehand. Below we discuss the details of the hardware used and the results obtained from the experimental runs.

A. *Implementation*

The robots used in the experiments and the control systems for mapping, navigation, and spoken dialogue are identical



(a) Speed profiles and trajectory for normal follow mode

(b) Speed profiles and trajectory for corridor follow mode

Fig. 4. Speed profiles and trajectories for two experimental runs with the corridor follow mode deactivated (a) and active (b). In both experiments, the user and the robot started in a room (lower left corner in the map). The user first guided the robot through the door into a hall and then down a corridor extending out from the hall. This first part (episode) of the experiments was used to demonstrate the robot's awareness of the door (Time<0s). The second episode (Time>0s) was used to compare the robot's performance with active corridor awareness against its performance in the non-aware follow mode. In the first episode of both runs, the robot increased its distance or kept a longer distance to the user while the user was close to the door, which can be seen in the translation speed profiles (e.g. at −8s in (a), and at −17s and −9s in (b)). In this phase, the robot also turned a lot in both experiments to keep a posture facing the user, which can be seen in the rotation speed profiles. The behaviors of the robot differed in the second episode. As an additional obstacle, a box had been placed at the side of the corridor. (a) In the normal follow mode the robot's translation speed was limited to 0.5m/s, which was reached rather quickly and maintained until the robot came close to the box, which it only late considered an obstacle (at approx. 28s). The robot corrected its heading very often and in a rather shaky manner, as can be seen by the amplitude of the rotation speed curve. The end position was reached only after 42s. (b) The corridor mode resulted in a shorter trajectory, which took the obstacle much earlier into account. The slow motion between 0s and 10s can be explained by the robot originally facing the wrong direction of the corridor and having to turn around almost in place. From 10s on the robot detected the corridor and started aligning itself in it. After that it accelerated and reached the increased translation speed of 0.8m/s. It only slowed down while passing next to the box. The smooth trajectory planning lead to only small adjustments to the robots rotation speed. The end position was reached after 33s.

to the ones used in our previous studies in [12]. The two ActivMedia PeopleBots are equipped with a SICK laser range finder mounted at a height of 30cm, which covers a field of view of 180° at the robot's front with an angular resolution of 0.5° and a frequency of 5Hz. Both robots feature a pan-tilt unit bearing a camera. On one robot this PTU is mounted upside down below the top platform, on the other one the PTU carries a stereo-vision camera and is mounted on top of the top platform of the robot. In both cases the camera itself is not used in the experiments. The pan-tilt unit however serves to provide *gaze feedback* by moving the camera to "look at" the user. The top velocity for the robots as recommended by the manufacturer is 0.5m/s. Tests have clearly shown that it is not advised to violate this upper bound in normally cluttered space, e.g. an office. In line with Sec. IV-B.2, however, we claim that an increased top speed of 0.8m/s is reasonable when the robot is moving in a corridor employing the proposed control algorithm.

B. Experiments

The experiments were run by people familiar with the system as the main purpose was to validate the usefulness of the proposed algorithms. All the experiments start with the user asking the robot to follow him. The robot acknowledges its understanding ("Okay.") and initiates the people tracking and following mechanisms. The user then guides the robot around the environment, moving inside and between rooms and corridors, to create those situations we are interested in, i.e. passing through doors and moving along corridors.

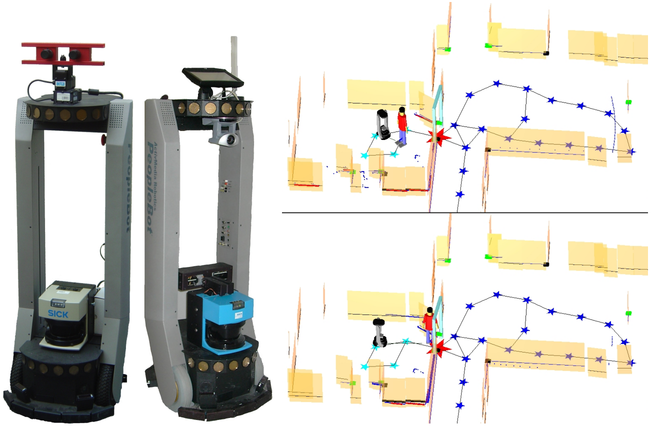


Fig. 5. Left: the two robots used in the experiments. Right: screen-shots taken during the experiments showing the robot and the user in a room that has a doorway which leads into a hall. Note how the robot increases its distance while the user is close to the door (bottom).

The experiments described in Fig. 4 consist of two separate episodes, demonstrating the smart handling of doors and the corridor follow mode. The zero point of the time axis is set to the point when the robot is in the center of the door in order to facilitate the comparison of the two episodes of the individual experiments. In the first episode the robot follows its user through an office, keeping a longer distance while the user is close to the known door. Fig. 5(right) shows two screen-shots that illustrate how the robot keeps a longer distance to its user in order to allow the user to open the door. In the second episode, the robot has to follow its user down a corridor. Our tests clearly show that the proposed motion planning algorithm for following in a corridor outperforms the standard people following mode which the robot has to rely on when moving in unknown or cluttered areas.

VI. LESSONS LEARNED

The case studies show that our approach to a human- and situation-aware people following mode significantly improves the performance of a mobile robot when following a person in a typical indoor environment. Keeping a socially appropriate distance and making use of context knowledge, e.g. from mapping, is however not only applicable and useful in situations where there is only one person, namely the user, in the robot's vicinity. The people tracker proposed in [7] is capable of keeping track of multiple persons. A starting point for future work is thus to make use of the knowledge about the states of various people in the robot's environment. Regarding the corridor drive mode, this would mean that the robot not only has to adapt its driving speed and position to its user and potential obstacles along the corridor. Based on the information about the heading and speed of other people, the robot would be able to decide where and when to overtake them, also taking into account social conventions.

There are some approaches that combine laser and vision sensors for people tracking. Leaving aside that these often require a dedicated training phase for acquisition of visual features for persons [22] or a model of the static background [23], it remains an issue of future research to apply vision-based methods for tracking people on a mobile robot that uses its pan-tilt camera unit to provide gaze feedback.

VII. CONCLUSIONS

People following is one of the core behaviors for interaction between humans and mobile robots. In this paper, we presented an implemented and tested approach to people following that enables a robot to follow a person in a socially appropriate way, producing comprehensible feedback to indicate its internal state. Novel about our approach is the combination of *people tracking* with *simultaneous localization and mapping* and *conceptual maps*, so that the robot can adjust its following behavior on the basis of an understanding of where it is in the environment, and what user actions to expect.

VIII. ACKNOWLEDGMENTS

This work was supported by the EU FP6 IST Cognitive Systems Integrated Project "CoSy" FP6-004250-IP.

REFERENCES

[1] C. Nass and Y. Moon, "Machines and mindlessness: Social responses to computers," *Journal of Social Issues*, vol. 56, no. 1, pp. 81–103, 2000.

[2] C. L. Breazeal, *Designing Sociable Robots*. Cambridge, MA, USA: The MIT Press, 2002.

[3] E. Pacchierotti, H. I. Christensen, and P. Jensfelt, "Embodied social interaction for service robots in hallway environments," in *Proceedings of the International Conference on Field and Service Robotics (FSR 2005)*. Brisbane, QLD, Australia: IEEE, July 2005, pp. 476–487.

[4] M. Kleinehagenbrock, S. Lang, J. Fritsch, F. Lömker, G. A. Fink, and G. Sagerer, "Person tracking with a mobile robot based on multi-modal anchoring," in *Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication (ROMAN 2002)*, Berlin, Germany, September 2002.

[5] J. Fritsch, M. Kleinehagenbrock, S. Lang, G. A. Fink, and G. Sagerer, "Audiovisual person tracking with a mobile robot," in *Proceedings of the International Conference on Intelligent Autonomous Systems*, Amsterdam, The Netherlands, March 2004, pp. 898–906.

[6] E. Topp and H. Christensen, "Tracking for following and passing persons," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'05)*, 2005, pp. 70–76.

[7] D. Schulz, W. Burgard, and D. Fox, "People tracking with a mobile robot using joint probabilistic data association filters," *International Journal of Robotics Research (IJRR)*, 2003.

[8] K. O. Arras, O. M. Mozos, and W. Burgard, "Using boosted features for the detection of people in 2d range data," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2007)*, Rome, Italy, April 2007.

[9] T. Kanda, H. Ishiguro, T. Ono, M. Imai, and R. Nakatsu, "Development and evaluation of an interactive humanoid robot "robovie"," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2002)*, 2002.

[10] K. Severinson-Eklundh, A. Green, and H. Hüttenrauch, "Social and collaborative aspects of interaction with a service robot," *Robotics and Autonomous Systems*, vol. 42, pp. 223–234, 2003.

[11] E. T. Hall, *The Hidden Dimension*. Garden City, NY, USA: Doubleday, 1966.

[12] G.-J. M. Kruijff, H. Zender, P. Jensfelt, and H. I. Christensen, "Situated dialogue and spatial organization: What, where. . . and why?" *International Journal of Advanced Robotic Systems, special section on Human and Robot Interactive Communication*, vol. 4, no. 2, March 2007.

[13] M. Lindström and J.-O. Eklundh, "Detecting and tracking moving objects from a mobile platform using a laser range scanner," in *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'01)*, vol. 3, Wailea Maui HI, USA, 2001, pp. 1364–1369.

[14] C.-C. Wang and C. Thorpe, "Simultaneous localization and mapping with detection and tracking of moving objects," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA'02)*, vol. 3, May 2002, pp. 2918–2924.

[15] J. Folkesson, P. Jensfelt, and H. Christensen, "Vision SLAM in the measurement subspace," in *Proc. of the IEEE International Conference on Robotics and Automation (ICRA'05)*, 2005.

[16] J. C. Latombe, *Robot Motion Planning*. Boston, MA: Academic Publishers, 1991.

[17] P. Newman, J. Leonard, J. Tardós, and J. Neira, "Explore and return: Experimental validation of real-time concurrent mapping and localization," in *Proc. of the IEEE International Conference on Robotics and Automation (ICRA'02)*, Washington D.C., USA, 2002, pp. 1802–1809.

[18] O. Martínez Mozos, C. Stachniss, and W. Burgard, "Supervised learning of places from range data using adaboost," in *Proc. of the IEEE International Conference on Robotics and Automation (ICRA'05)*, Barcelona, Spain, 2005, pp. 1742–1747.

[19] J. Minguez and L. Montano, "Nearness diagram navigation (nd): A new real time collision avoidance approach," in *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'00)*, Takamatsu, Japan, 2000, pp. 2094–2100.

[20] M. R. Endsley and D. J. Garland, Eds., *Situation Awareness Analysis and Measurement*. Mahwah, NJ: Laurence Erlbaum Associates, 2000.

[21] R. Hinkel and T. Knieriemen, "Environment perception with a laser radar in a fast moving robot," in *Symposium on Robot Control*, Oct. 1988, pp. 68.1–68.7.

[22] D. Schulz, "A probabilistic exemplar approach to combine laser and vision for person tracking," in *Proceedings of Robotics: Science and Systems II (RSS 2006)*, Philadelphia, PA, USA, August 2006.

[23] R. Munoz-Salinas, E. Aguirre, M. Garcia-Silvente, and A. Gonzalez, "People detection and tracking through stereo vision for human-robot interaction," in *Lecture Notes on Artificial Intelligence*. Springer Verlag, 2005, vol. 3789, pp. 337–346.