Spatial Context-Aware Person-Following for a Domestic Robot

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***Abstract*— Domestic robots are in the focus of research in terms of service providers in households and even as robotic companion that share the living space with humans. A major capability of mobile domestic robots that is joint exploration of space. One challenge to deal with this task is how could we let the robots move in space in reasonable, socially acceptable ways so that it will support interaction and communication as a part of the joint exploration. As a step towards this challenge, we have developed a context-aware following behavior considering these social aspects and applied these together with a multi-modal person-tracking method to switch between three basic following approaches, namely direction-following, path-following and parallel-following. These are derived from the observation of human-human following schemes and are activated depending on the current spatial context (e.g. free space) and the relative position of the interacting human.**

A combination of the elementary behaviors is performed in real time with our mobile robot in different environments. First experimental results are provided to demonstrate the practicability of the proposed approach.

I. Introduction

Service robots are pervading our daily life gradually. We have more chance to experience and perceive a real robot in the real word. RHINO [1] has been designed as a tour-guide robot at the ”Deutsches Museum” in Bonn at the end of last century. The famous humanoid robot ASIMO [2] from HONDA could perform various tasks with people. So we need to survey the status of robots again. As intending candidates in the human society, service robots that operate around people should behave in ways that are easy-understood and socially acceptable to people.

Following a person is a key competence of a service robot to interact with people and explore the surrounding world in order to learn about it. Rachel Gockley demonstrated that direction-following is the more socially acceptable behavior for the robot to use [3]. But probably humans would change their following behaviors with respect of the real situation now and then. Imagine two people walking in a building passing narrow passages, doors and open spaces. Though one person is the guide, their relative position and orientation is highly effected by their roles and the spatial context. In narrow passages they have to walk in line, while in open spaces they prefer walking side by side to ease communication. Therefore the robot should be aware of the spatial context and take human cognition into account, so as to facilitate interaction during the joint exploration. For the following itself we have designed three elementary approaches, namely direction-following, path-following and parallel-following. However, different partially contradicting goals have to be considered. That is the trade-off between positioning to perceive the human robustly, being engaged in communication, as well as avoiding obstacles and following in appropriate distance.

The remainder of this paper is organized as follows. First we discuss related work on person tracking and following in section II. Our mobile robot is introduced in Section III. Section IV describes the basic following behaviors as well as the proposed context-aware following behavior. The experiments of different behaviors in the real world with the mobile robot are presented in section V. The paper concludes with a summary of the presented work in section VI, and some future work is also shown in this section.

II. Related Work

An important prerequisite of person following is person tracking. Most of the trackers could be categorized into the following two groups: single-sensor-based method, namely uni-modal anchoring and multi-sensor-based method, namely multi-modal anchoring. In the first group many researchers use vision as the main sensor for detecting and tracking people. Skin color detection [3], optical-flow-based person tracking [4] and stereo-vision-based approaches [5] are the most common methods. However the variations of the lighting conditions encountered in the real environment as a robot moves, are prone to result in a instability for any camera-based method. In addition to camera, many approaches using laser data to look for leg hypotheses have been proposed by e.g. Montemerlo et al. [6], who applied a previously mapped environment and particle filter conditioned upon the pose of the robot. Schulz et al. [7] used sample-based joint probabilistic data association filters to track people. But only using laser information makes the robot difficult to confirm the correct followed target at the beginning, when several candidates (people or something with two legs) stand in front of the robot. Besides, active sensors such as RFID [9] or other transmitters are also available for this task. But people must wear extra devices and it might be inconvenient in many applications. Because of the shortages with only single sensor, multi-sensor-based approaches are also proposed. Feyrer and Zell [10] used a potential field for performing sensor-based fusion of vision and laser range data. Darrell et al. [11] defined some combination rules to fuse the results

of individual algorithms from multiple visual modalities. However, the robot may be confused just using face and leg information without an explicit instruction like ”Follow me!” from the real guide-person as what we do in a social manner. Considering the above mentioned disadvantages we use a multi-modal anchoring system from our previous work [8] as the tracking method combining the camera, laser and microphone data.

With the known position of the person, the robot can drive to a goal defined around the person using methods of motion control and path planning. Since 10 years there have been many researchers engaging in the area of person following. Most of them perform a direction-following [3], where the speed of the robot is normally adjusted with a feedback control loop proportional to the distance between the robot and the person (see e.g. [12] and [13]). Calisi et al. [15] integrated appearance models and stereo vision for people tracking based on a fixed stereo camera. They assumed the robot have a priori map of the environment and used laser-based Monte Carlo Localization [16] to localize the robot itself. Thus it will be not proper for an unknown environment. The main drawback of this tracking system is that it is unable to distinguish people wearing clothes similar to the target person or some objects in the background with similar color of the target person. Not like approaches mentioned above, Gockley et al. [17] focused on perceptions of the robot’s person-following behavior and social aspects. They developed two following behaviors: path-following and direction-following. GJM Kruijff et al. [25] focused on a conceptual description of the environment with suited dialogue. However the applied following behavior is only laser-based and the robot directly followed the guider with a socially accepted distance. Considering the discussion in the last section as well, we have developed a so called parallel-following except for path-, and direction-following, in order to let the robot move behind the person on one side. We have also designed a hybrid approach of the three basic following behaviors, with which the robot could automatically switch its behavior considering the environment and the status of the followed person.

III. Robot Hardware

Our approach is integrated with BIRON - The Bielefeld Robot Companion (see Figure 1). It is based on the Pioneer2 PeopleBot from Mobile Robots, Inc. (formerly ActiveMedia). The robot uses one laser range finder mounted at the front at a height of approximately $30cm$ for the perception of the surrounding in front of it. Measurements are taken in a horizontal plan covering a $180°$ field of view. Two color video cameras are mounted for visual perception of the scene and for detailed focusing on persons, areas, and objects. All computation can be done on-board using two 2GHz dual core processors mounted on the back of the robot and one 1.5GHz Pentium Mobile notebook connected via W-LAN.

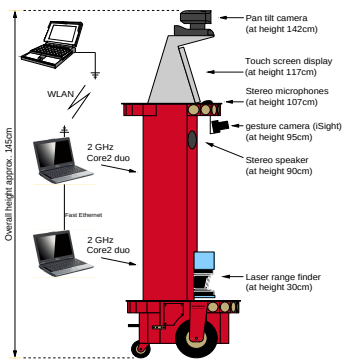


Fig. 1. The mobile robot BIRON

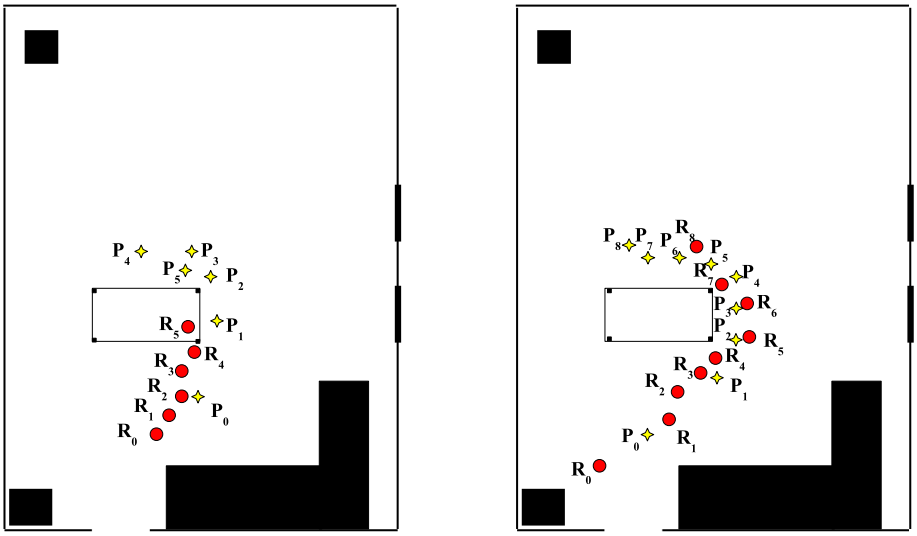
IV. Following Behaviors

To make the robot follow a person in socially acceptable ways, we have developed three basic following-behaviors, namely path-following, direction-following as well as parallel-following and combined these into a context-aware behavior. Following itself is dependent on some perceptual and control capabilities which shall be outlined in the following:

- **Multi-modal person tracking:** To fulfill a following-behavior, the robot must be able to perceive all potential persons around it and distinguish between different interaction partners. In laser data pairs of legs result in a characteristic pattern that can be easily detected [18]. In order to avoid including some other objects with pattern similar to human legs, a pan-tilt camera is used to recognize faces. In addition, stereo microphones are applied to locate sound sources [19]. The robot prepares to respond to a person with a dialog system [20], only if the legs, the face as well as the sound source of the person are detected at the same time by the three sensors respectively. The output signal of this tracking system is the position of the person expressing with polar coordinate system relative to the robot and some attributes of the status of the person. During a following behavior the robot might not get the face and/or voice information, since the person normally does not often face and talk to the robot. At this time the system only use the laser sensor to track the person, whom has been recognized before. When the tracking system loses the person because of a large relative movement between person and robot in a short time or the person has been out of the range of laser, the robot will utter a hint like ”I can not see you any more!” with dialog system and begin to respond to a person as aforementioned.
- **Path planning and motion control:** We use the Sunflower library [21] to obtain optimal speeds of the robot using dynamic window [14] and make sure of obstacles avoidance to get to goals. Thus the robot could get to goals calculated during following-behaviors through doors, around corners and in other places without collisions.

A. Consideration in social aspects

Since our robot behaves together with humans, it must move in acceptable ways supporting interaction. With the dialog system, people could interact with the robot in a natural way and get useful response regularly. In order to analyze following-behaviors, we divide the complete following into three sub-processes, namely departure, following and arrival. We argue that the robot should comply with the same



(a) (b)

Fig. 2. Comparing the direction-following (a) and the path-following (b) with BIRON in the same environment. The start points of the robot and the person are depicted with R_0 and P_0 respectively and the corresponding positions of the robot and the person during the following are labeled with the same number.

rule at departure and arrival in the three basic following behaviors. However the difference appears just during the pure following phase described in next section.

1) Departure: The robot starts to follow a person, only if it recognizes the person with legs, face and sound from the laser, camera and microphones respectively and at the same time the person gives the robot a instruction like ”follow me”. With respect of safety and comfortability to people, the robot will just turn to the person and without translation until the distance to people greater than a threshold. Considering studies of distance in human-human interaction [22] and the three basic behaviors, we define the threshold for path- and direction-following 1.2m, and for parallel-following 1.0m.

2) Arrival: Arrival deals with what the robot should do at the end of the following or a pause in between, when the guide-person stops and the distance between the robot and the person is less than the threshold defined for departure. A ”stop” function in the Sunflower library will be called, so that the robot could brake in time and would not startle the person, and the robot turn to the person at the same time.

B. Elementary following-behaviors

We designed three elementary methods for person following obeying the departure and arrival mentioned before. In all of the three basic behaviors, goals of the robot will be firstly translated in a global coordinate system from odometry. Because of the frequently updated goals in the three behaviors, the robot use the odometry just for a short distance. Therefor the errors from odometry have only a small effect on the robot. Integrated with the Sunflower library introduced previously, the robot could move in an environment without collisions.

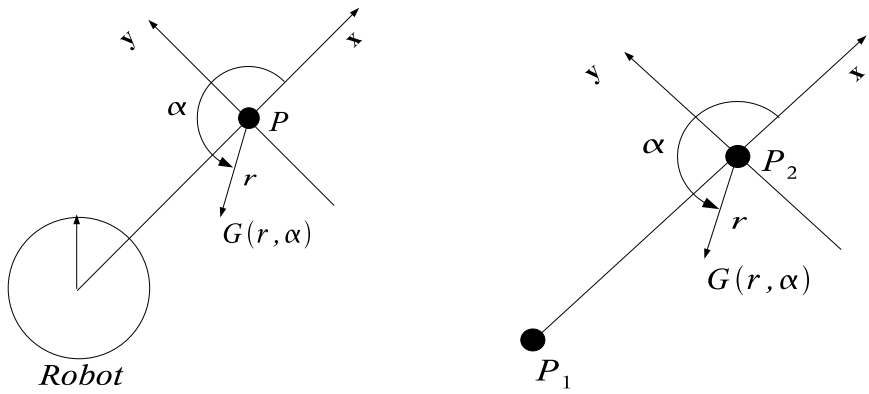
1) Direction-following: The simplest method of following a person is to have the robot always drive in the direction to the guide-person if he or she moves. The goals of the robot defined with (x, y, θ) are the results of the output from the tracking system calculated in the global coordinate system. When the robot moves in the vicinity of the person, the ”arrival” behavior will be applied.

2) Path-following: An alternative is that the robot drives along the path of the guide-person as exactly as possible. The path of the person is actually a set of points he or she passed. Some important parameters and rules applied to optimize the path are outlined as follows:

- A minimal distance between the two adjacent goals on the path is constrained.
- The number of the goals on the path is determined with the curvature of the path. That is the more goals will be taken, when the curvature is greater than a threshold.
- All of the old goals will be deleted, if the person does go back to the robot. Otherwise new goals will be computed. We assume that the person would like to change his current path in this situation. So the robot do not have to get to the goals which are not available any more.
- The direction of the current goal is defined with the vector from the last to the current goal.

Since the robot must arrive at different goals on the path of the guide-person, path-following might not be so effective as direction-following[1]. However the robot benefits from this behavior in some cases, e.g. if there are many scattered obstacles in the surrounding area. In addition the perceived area of the laser is only a half-plane with a certain height. Everything out of this area is unknown to robot. Figure 2 shows two experiments: (a) direction-following and (b) path-following. All of the obstacles which the laser can perceive

[1]See the results in the section V



(a) (b)

Fig. 3. Calculation of the goals defined with $G(r, \alpha)$ for the robot in parallel-following. (a) depicts the initial state, in which only one position of the person is obtained by the robot. (b) presents the goals during the following.

are colored with black area. The outline of the table is presented with a rectangle. But only the four small legs of the table could be "seen" by the robot. The robot could avoid the table using path-following successfully. However a collision to the table happened on direction-following at the end of the experiment as the pair of points R_5 and P_5 in the Figure 2(a) presented.

3) Parallel-following: The last basic following behavior that we have designed is the so-called parallel-following. This idea stems from a normal human-human following. We observed that a more suitable following behavior for two persons who knows each other is not that one does go exactly along the path of the other or just try to move directly to the guide-person, but one would like to find and get in some free space on the side of the guide-person, so that he or she could get a relative good field of vision and the both people could communicate in a natural and comfortable way. The implementation is similar with the direction-follow. However the goals for the robot are substituted with positions around the current positions of the guide-person as Figure 3 shows. As the goals defined with r and α and the positions of the guide-person during the following form approximately pairs of parallel lines piece by piece, we call this behavior parallel-following. All of the goals will be also computed in the global coordinate system. At the beginning of this behavior, the robot takes goals defined with a local coordinate system as Figure 3(a) presented. A local coordinate system will be built with the x axis, which is the direction from the position of the robot to the current position of the person marked with P. If the person moves, the robot observes the moving direction of the person at the same time, so that the robot could "walk" parallel beside the guide-person as possibly. Figure 3(b) shows the corresponding calculation of goals: two adjacent positions of the person will be recorded to calculate the moving direction of the person. The coordinate system is defined with x axis, which is the direction from $P1$ for the last position and $P2$ for the current position. Applying with this behavior, the robot will not follow the person just behind. However this behavior is constrained with the free space in the environment.

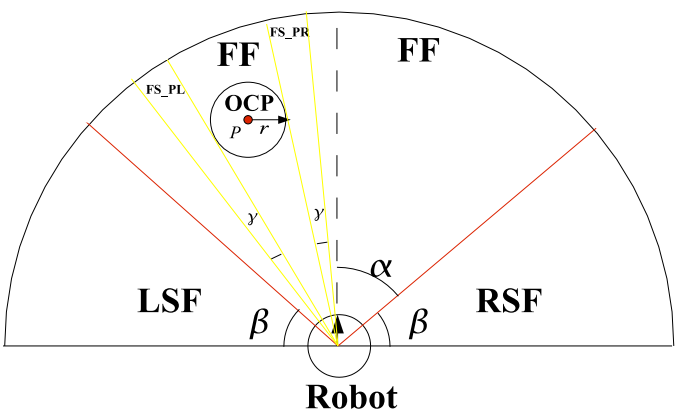


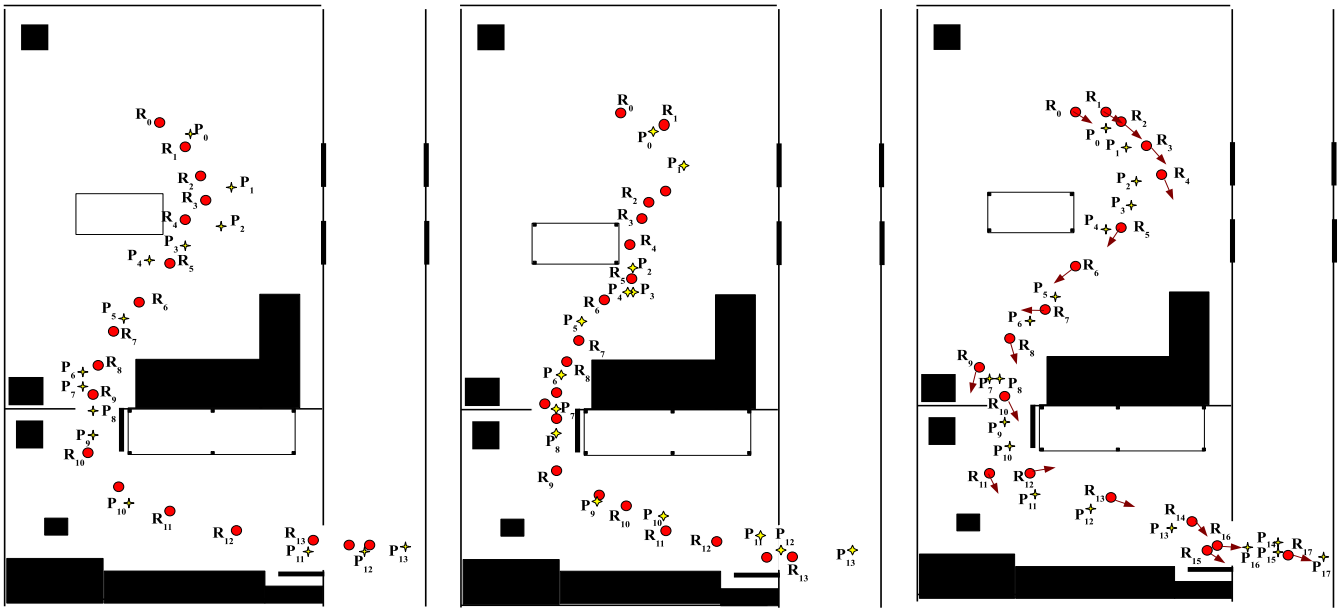
Fig. 4. Description of the criteria, which the robot used for switching its behaviors automatically.

C. Context-aware-following

Using the different basic behaviors aforementioned and switching them according to the observation of human-human following schemes, we designed a more sophisticated approach, namely context-aware-following (see Figure 4), with which the robot could change its behavior with respect of the current environment and position of the person automatically. The robot is presented with a circle and the red arrows point its current direction[2]. The range of the laser is outlined with a half-circle. Some important parameters and criteria we considered in this behavior include:

- The region, in which the laser can perceive are divided into three parts: one front field (FF) and two side fields (LSF and RSF) with the same angle, which are defined with α and β respectively. In order to let the robot keep up with the guide-person, the person should be kept in

[2]The directions of the robot are received from the synchronized video and log files as mentioned in section V and depicted approximately on the real map of the lab and floor.



(a) (b) (c)

Fig. 5. Three experiments, namely (a) direction-following, (b) path-following and (c) context-aware-following are performed with BIRON in the same environment depicted with a map. The positions of the robot and person are presented with red points and yellow stars respectively. The corresponding points of the robot and person at the same time are labeled with the same number. For comparing the switch of behaviors with the criteria defined in IV-C the directions of the robot are additionally marked with red arrows in (c).

FF as possibly, just as what we do in a human-human following.

- The occupied space of the person (OCP) is presented with a circle. The center of circle is defined with the position of the person P from the output of the multi-tracking system, and the radius is r.
- The free space FS_PL and FS_PR on both sides of the person, in which the laser will check for parallel-following is achieved with an angle γ turning to left or right from the both boundaries of OCP. The both boundaries illustrated with yellow lines are tangent to the circle OCP.
- When the person is out of the front field FF, the robot will switch to direction-following to have the person in its front field again as soon as possible, on condition that there are no readings from laser shorter than a predefined threshold. Otherwise path-following will be applied to find a safe way for the robot.
- When the person is in the front field FF, the robot will choice path-following in case that the obstacles in LSF and RSF are too near to it or there is no free space in FS_PL and FS_PR. Otherwise the robot will switch to parallel-following.
- Whether the robot should move in FS_PL or FS_PR is determined by the free space of the both fields. If only one of the both fields has enough free space, the robot will choice the goals in this field. If both of the fields are free, the robot will make a decision according to the angle of the person received from the person tracking system. E.g. the robot will choice the FS_PL when the person is in front-right direction.

Integrated with the factors as mentioned above, the robot can switch to a proper behavior during the following.

V. Experiments

The proposed following behaviors have been studied in comparison using our robot BIRON in a lab environment. The parallel-following is only useful in the context-aware systems because it cannot be applied in narrow spaces. Therefore, it is not analyzed separately. In all of the three experiments one person guided the robot through two rooms and ended at the floor[3]. At the same time the other person following behind or on the side of the robot used a video camera to record the whole process. A software for synchronizing the time of the video and the log files which are used for storing the important information occurring in the experiments is applied to analyze the results afterwards. Compared with the positions of the objects on the video and from a real map of the lab and floor the path of the robot and person during the tests are marked on that map. Every register of a new behavior is labeled in the context-aware-following. Therefor when, where and what has happened in this experiment has been thoroughly recorded.

The results of direction-, path- and context-aware-following are shown in Figure 5(a), 5(b) and 5(c) respectively. The position of the robot are depicted with red points. In the context-aware-following the direction of the robot is also marked with a red arrow, because whether the person is in the front field of the robot determines the switch of the behaviors. The yellow stars present the positions of person.

[3]The results reported here are initial ones from a technical analysis of the prototype.

TABLE I

INFORMATION ABOUT BEHAVIOR-SWITCH AND THE CORRESPONDING EVENTS DURING CONTEXT-AWARE-FOLLOWING.

Corresponding points (robot and person)	Event	Notation (with respect of criteria)
R_0P_0	Parallel-following	Person was in FF, FS_PL and/or FS_PR was free
R_4P_4	Direction-following	Person was not in FF, LSF+FF+RSF was free
R_6P_6	Person lost	Sent out speech hints from the robot with dialogue system and repeated the following behavior as at the beginning
R_9P_9	Direction-following	Person was not in FF, LSF+FF+RSF were free
$R_{10}P_{10}$	Path-following	The robot tried to go through the door. Person was in FF, but LSF+FF+RSF were not free
$R_{13}P_{13}$	Parallel-following	Person was in FF, FS_PL and/or FS_PR was free
$R_{14}P_{14}$	Direction-following	Person was not in FF, LSF+FF+RSF were free
$R_{17}P_{17}$	Path-following	At the end of the experiment person was in FF, but LSF+FF+RSF were not free because of the wall behind the person

TABLE II

GENERAL INFORMATION FOR THE THREE EXPERIMENTS.

Experiment	Times of person-lost	Total consuming time for person-lost	Total consuming time for an experiment	Consuming time for an experiment without person-lost
Path-following	Twice	32s	2m 23s	1m 51s
Direction-following	Null	0s	49s	49s
context-aware-following	Once	41s	2m 32s	1m 43s

P_0 and R_0 are the start position of the person and robot. Everything that the robot could use laser to perceive are depicted with black area. The border of tables which the robot could just "see" partially are presented with black lines, that means a potential obstacle to the robot. The corresponding points of the robot and person recorded at the same time during the experiments are labeled with the same number. Because of the environment which presented in Figure 5 not all points of the robot have corresponding points of person. Such as the person was far away from the robot, the camera could not obtain both of the robot and person. Or the person has stopped but the robot continued moving. In this case the remaining positions of the robot have the same corresponding points from person. All of the parameters defined in IV-C are obtained from an intuitive hypothesis and optimized interactively in studies.

In the path-following the robot tried to get to all of the goals using the method introduced in IV-B.2. Therefor both paths are consistent to each other on the whole. In contrast with the path-following, the robot changed its direction frequently in the direction-following. As the three basic following behaviors appeared in the context-aware-following, the imprints of them could be easily found from 5(c). Table I describes some important events happened during the context-aware-following. In general the robot switched its behaviors according to the current environment and the position of the person at correct places and all of the behaviors applied during the following could be well explained with criteria designed in IV-C.

The general information of the three experiments is given in Table II. The length of the path in all tests is nearly $16m$. The most effective behavior is direction-following according to the time consumed during the experiment and the person has not been lost in this behavior. However in the other two tests the person has been lost at least once depending on the current relative position of person and robot and our person-tracking system, because the robot must either get to every goal on the path in path-following, or switch the behaviors during the context-aware-following. Another interesting result is that context-aware-following worked more effective and stable than path-following despite of the behavior-switch on the way. The person has been lost only once and the consuming time excluding person-lost is a little less than path-following.

VI. CONCLUSION AND FUTURE WORK

We have designed three different basic following behaviors: path-following, direction-following and parallel-following. A hybrid approach named context-aware-following which integrated all of the basic behaviors has also been developed. In order to study the adaptability of path-following and direction-following, we tested both behaviors in the same environment with a table which the robot could perceive only partially. The results presented in Figure 2(a) and 2(b) confirmed our previous hypothesis. Besides the both basic behaviors are tested and compared with context-aware-following. In context-aware-following the robot tried to find some free space around the guide-person, so that it could accompany the person in a more human-like way. And at the same time it took care of the position of the person in its front field. Thus the feasibility and robustness of a multi-modal following behavior are demonstrated with our initial experiments.

In the near future we will study the basic following behaviors and their applicabilities at large, so as to find some more accurate description about a human-like behavior. In addition a 3D camera could compensate the constrains of laser and perceive obstacles out of the range of laser and help the robot to choice its behavior appropriately. With respect of person-lost during the following person re-recognition will be also integrated to make sure that the robot is following the correct person. A Rao-Blackwellised[23] particle filter based SLAM[4] from the MRPT library[24]

[4]Abbreviation of Simultaneous Localization And Mapping

has been integrated in our system and it makes a global autonomous navigation possible, after the robot has been guided with a person. Besides a high level map based on SLAM will be created to enrich the context perception of the robot about its environment in a human-like way.

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