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A Multimodal A* Algorithm to Solve the Two-Dimensional Optimization Problem of Accompanying a Person for an Intelligent Wheelchair

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Abstract— **Impaired mobility have far-reaching consequences for handicapped persons and their relatives. Mobile robotic technologies enable intelligent wheelchairs to regain mobility for those affected. Multiple research projects address human aware navigation and the task of following a person for assistive robots. But just a few projects focus on accompanying a person to enable social interaction. Therefore, we present a navigation system for indoor navigation in dynamic and cluttered environments as well as a novel algorithm for accompanying a person.**

First, we developed an autonomous driving wheelchair for indoor navigation based on the robot operating system (ROS). Thereby, a multi sensor setup using cameras and laser scanner enables localization within a map. People are detected by the same sensors and tracked by a Kalman filter. Afterwards we propose a novel algorithm to achieve a dynamic accompanying behaviour. An attractiveness distribution is introduced to evaluate the possible accompanying positions next to the manually selected target person regarding social interaction. The resulting two-dimensional optimization problem is solved by a novel multimodal extension of the A* algorithm.

The proposed intelligent wheelchair is able to navigate in indoor environments and to accompany any person. In addition it allows social interaction while walking to relieve relatives or nursing staff, which otherwise need to push the wheelchair. The aim is to increase participation in everyday life for those affected.

I. INTRODUCTION

Due to the aging population and the improving medical assistance, the number of people with a physical handicap increases. Especially mobility impairments have wide consequences for the daily live and mental health. They decrease the opportunity to socialize and therefore cause psychosocial implications as emotional loss, altered self-image and self esteem [1]. In recent decades, the research field of mobile robotics has shown enormous progress in autonomous navigation and decision making. This motivates the development of intelligent wheelchairs to enable mobility-impaired persons a better participation in everyday life and to support the care in hospitals or nursing homes.

Detecting and following people are active research areas in mobile robotics but not the task of accompanying a person. From a wheelchair point of view, it is more desirable not only to follow a person but to take up a lateral position next to them to enable social interaction. Meanwhile, collisions must be avoided. An intelligent wheelchair needs appropriate sensors and novel algorithms for this task.

In this paper, we present a setup for an electrically actuated wheelchair with the capability of autonomous indoor navigation and a novel map based algorithm for accompanying a person. The goal is to enable autonomous navigation in known environments as well as accompanying a person. At first, a navigation stack based on ROS is developed. Using the same sensors as for navigation, a person detection and tracking module is implemented. Last, a novel extension of the A*-algorithm is introduced to accompany a person.

II. RELATED WORK

The research on intelligent wheelchairs started in the 80s and since then it has become more and more popular, which can be seen by the continuously increasing number of research projects as outlined by Leaman et al. [2]. Technologies for mobile robots are predestined to assist mobility-impaired people. Because of various handicaps, the robotic system needs advanced capabilities to assist as much as necessary and as little as possible.

With regard to autonomous driving, a distinction can be made between semi- and full-autonomy. The semi-autonomous wheelchair presented in [3] intents to assist the user with an obstacle avoidance based on sensors. In order to achieve complete autonomous navigation for intelligent wheelchairs, mobile robots can be used as a reference [2]. A current example is the Care-O-bot presented in [4], a service robot which is capable of autonomous navigation in indoor environments. Another project presented by Seki et al. pursue a fully autonomous navigation for intelligent wheelchairs [5]. However, the environment still has a huge impact on the reliability of such systems [2]. In ordered environments as hospitals Baltazar et al. present an autonomous wheelchair for automation the transportation of patients [6]. It is able to drive autonomously through the hospital and to communicate with elevators and the management system of the hospital. The navigation is based on a static map of the environment.

For mobile robots moving in the same environment as persons, people perception is crucial. Therefore, there has been proper interest in developing of such frameworks either for optimizing social behaviour or assistance. Lu and Smart [7] use a leg detector to align the head of their robot to a passing person to optimize the social behavior in narrow corridors. Leigh et al. [8] implemented a scan based leg detector whose detections are tracked by a Kalman filter. The drawback of scan based detectors are false positive detections in cluttered environments. Therefore, the high information content of cameras is of interest. Jafari et al. [9] present a real-time RGB-D people detection and tracking algorithm.

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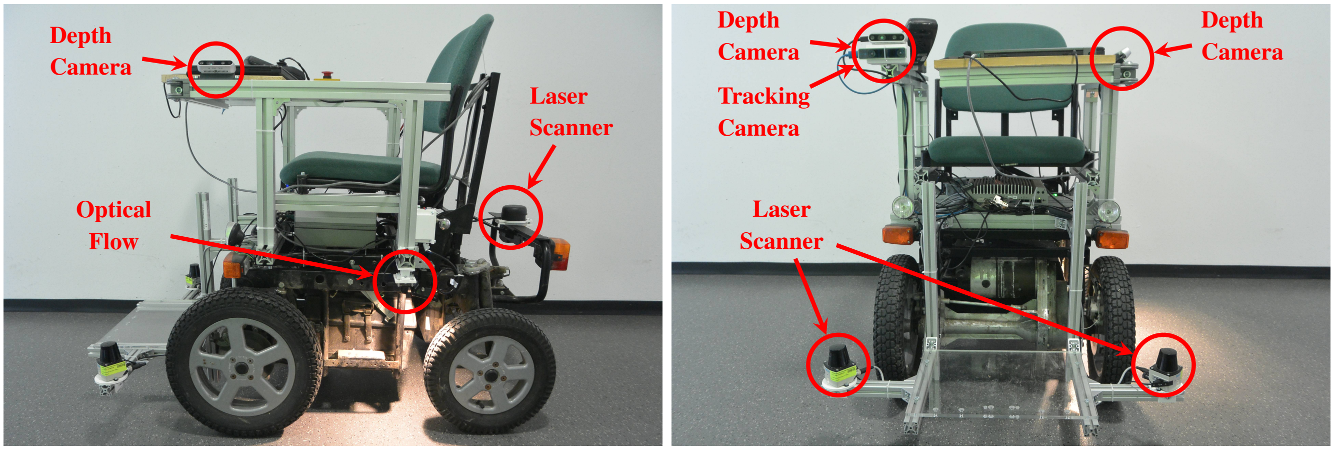

(a) Side view

(b) Frontal view

Fig. 1: Our developed prototype is equipped with three stereo cameras of type Intel Realsense D435, three laser scanners two of the type SICK TIM, one RPLIDAR A2M6 and an optical flow sensor of type PX4FLOW.

They propose specialised algorithms depending on the distance to reduce the computational cost. In close range depth information is used for computing region-of-interests. Where as in far range, geometry extrapolation restricts the search space. Nevertheless, the field of view (FOV) of a camera is restricted and the distance measurements of a stereo camera is inaccurate compared to a laser scanner. As proposed by Linder et al. [10], fusing the two complementary sensor types is advantageous. The combination of a nearest-neighbor data association and a tracking algorithm has proven to be the most efficient and reliable in crowded environments [10].

Following a person is of interest for assistive robots as well as intelligent wheelchairs and is therefore investigated in various projects. Mobile robots for following a person based on laser scanners and cameras are developed. Leigh et al. use their people perception based on laserscans to follow a person with an autonomous wheelchair [8]. A camera based approach is presented in [11] for telepresence robots. However, a generic following algorithm can use any input of a tracking software. In general the following task can be solved by a feedback controller or by moving the goal position for the navigation stack [12]. These approaches do not use any information of a map to react on dynamic obstacles neither are they capable of accompanying a person.

For accompanying a person the wheelchair has to take place next to the target person not behind. Kobayashi et al. present a velocity controller based approach by simply shifting the goal position [13]. In case of to less space they set the goal position behind the target person. Another approach presented in [14] is based on probabilistic trajectory planning. Therefore they sample 300 possible wheelchair trajectories and evaluate them based on cost surface around the target position. The advantage is that they can take the time into account through sampling into the future. Nevertheless, both approaches do not use maps for planning, which could lead into dead ends. Furthermore, a local map is helpful to find efficient paths in highly dynamic environments.

III. METHODOLOGY AND SYSTEM DESIGN

We present a prototypical wheelchair for autonomous indoor navigation and accompanying a person with the intention to realise a setup as modular as possible for further extension. It is based on a commercially available wheelchair with an Ackermann rear-wheel steering (Fig. 1). For our purpose we integrated necessary sensors for navigation and person perception as well as a computer. For processing the sensor data and executing the navigation algorithms the industrial computer Nuvo-7166GC is integrated. It provides an Intel i7-8700 processor with 12 kernels (3.2 GHz) and 16 GB RAM.

An optical flow sensor and a tracking camera are integrated to estimate the pose and velocity of the wheelchair. We use the PX4FLOW sensor which is an open hard- and software project presented by Honegger et al. [15]. In addition, a spot light is attached to the wheelchair to illuminate the FOV of the optical flow sensor to provide constant light conditions. The T265 tracking camera from Intel is used to compute a visual odometry. Furthermore, we compute an odometry based on the laser scanners using the iterative closest point (ICP) algorithm.

Laser scanners and depth cameras are provided for environmental perception. Their data is intended for collision avoidance as well as people detection. Therefore, the setup shown in Figure 1 is designed to realize the widest possible FOV for both sensor types. Two SICK Tim scanner are mounted to the foot rest and a RPLIDAR A2M6 behind the seat to enable a 360° two-dimensional scan. We integrate three D435 stereo-cameras for depth images; one in travel direction and one to each side of the wheelchair. The sideways cameras are tilted by 30° to capture higher sections of walls and parts of the ceiling which provide more immutable features than movable objects like tables or chairs. Moreover, the tilted cameras provide a larger area of perception of higher regions in short distances, which allows a better localization of persons walking close to the wheelchair.

Because of the wide range of open source interfaces and available algorithms ROS is used to acquire and process the sensor data. Due to the architectural design of ROS and the usage of standalone nodes the application can be easily extended. To execute velocity commands a micro-controller is integrated into the handheld unit of the wheelchair which imitates the signals of the original joystick. By doing so, we prove that our proposed system is generally integrable into all electric powered wheelchairs if velocity commands are used as interface.

IV. IMPLEMENTATION

As introduced the implementation is divided into three units. First, an autonomous navigation stack is implemented, which is crucial to achieve a precise accompanying. Afterwards, the people detectors which are used to detect and locate persons in the surroundings of the wheelchair are presented. Based on the located persons, velocity commands are derived using an algorithm for accompanying a person.

A. Autonomous Indoor Navigation

For autonomous navigation a system has to solve the problems of localization, path planning and execution. ROS provides multiple algorithms for this task.

To achieve a robust and precise localization within previously unknown environments we use a combined localization approach of relative and global localization. The relative change of position is determined using the optical flow sensor and the visual odometry of the tracking camera. In addition, an odometry is estimated based on the laser scanner using the ICP algorithm of the *rtabmap_ros* package presented by Labbé et al. [16]. The implementation of an unscented Kalman filter of the *robot_localization* package is used to fuse the sensor data [17].

For global localization of the wheelchair within an environment we use a simultaneous localization and mapping (SLAM) algorithm. The concept of a SLAM algorithm is to create a map based on features of cameras or laser scanners in unknown environments. Afterwards, a system is able to locate itself by comparing features of current sensor data with this map. Several implementations are available in ROS such as GMapping, TinySLAM, HectorSLAM or RTAB-Map. Because of its possibilities to integrate sensor data from an external odometry, laser scanners and multiple depth cameras RTAB-Map was chosen for this prototype. Furthermore RTAB-Map provides algorithms for visual odometry as well as scan matching to evaluate different approaches [16]. The use of multiple cameras aims for better localization results if one or more cameras are covered.

Based on the localization a collision-free trajectory has to be calculated and executed. We use the navigation architecture of the *move_base* package provided by ROS. The package features are divided into global planning within a global static map and local planning based on current sensor data. By default, graph based search algorithms for global path planning such as the Dijkstra's and A* algorithm are provided. The A* algorithm is an extension of the Dijkstra algorithm using an heuristic function $h(n)$ to optimise the exploration behaviour. Therefore, it is used for global planning in real-time. For local planning the *teb_local_planner* is used. It is an implementation of the Timed Elastic Band approach and is optimized for car-like robots as presented by Rosmann et al. [18]. The local planner provides velocity commands which are executed by the driving unit.

B. Person Perception

A comprehensive person perception requires algorithms for detecting as well as tracking of people. Laser scanner and cameras can be used for person detection. In this work the *spencer_people_tracking* package presented by Jafari et al. [9] is used for person perception. It provides multiple person detection modules for depth cameras and laser scanners. Furthermore, its architecture can be extended by other detectors. The different detections are associated using a Nearest-Neighbour approach. The tracking module predicts the movements of people using a Kalman filter based on a constant velocity model. This enables the tracking of previously seen persons that are currently not in the perception area of the sensors. This is relevant, for example, when a person is temporally covered by other people or already walked around a corner. As the last step of the pipeline filters are integrated to avoid false detections.

We combine three different people detectors because of their complementary properties. As introduced the laser scanner provide a FOV of 360° which is an advantage especially for accompanying a person. For people detection in 2D Range data the re-implementation of the boosted classifier presented in [19] is used. They propose fourteen features for legs in a scan and use an AdaBoost algorithm to classify them. Nevertheless, the information content of range data is low and the classification of legs in a 2D-scan is error-prone, due to similar looking objects like table legs. In contrast, depth cameras have an high information content but a restricted FOV. We therefore use the approach applying different detectors depending on the range as proposed by Jafari et al. [9]. For close range the upper-body detector is implemented. Whereas, for far range the full-body HOG detector based on CUDA is integrated. Both algorithms are implemented in the *spencer_people_tracking* package. To save computational power, the far range detector is just applied on the front camera. Because of the propensity of the lateral cameras, their FOV is restricted to short distances.

Finally, we integrate two filter steps to avoid the false detections of the leg detector by a static map filter and just visual confirmed people are tracked. The navigation map enables to filter false detections for a more robust people tracking. A person is only tracked if they have been visually confirmed by a camera. After that confirmation, the detections of the laser scanners are also fused. In this way, the advantages of the detectors of the laser scanners and camera are combined.

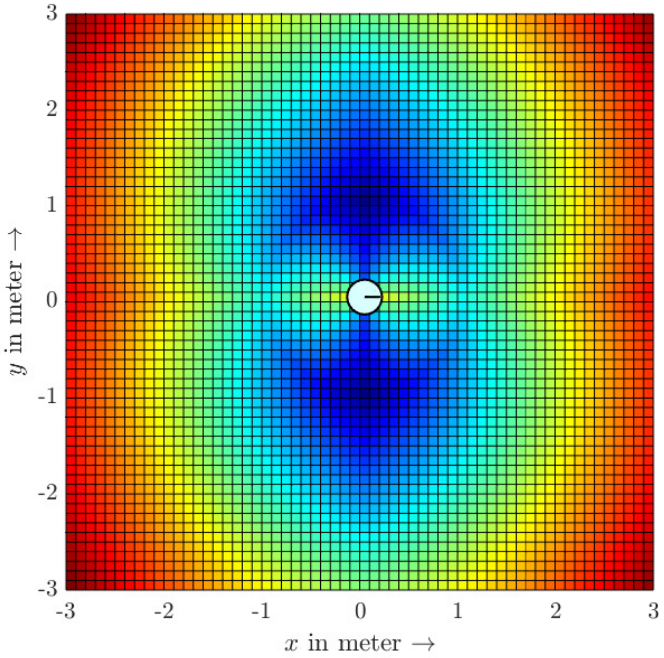

Fig. 2: Attractiveness distribution to evaluate accompanying positions of a person proposed in [14]. Red to blue showing unattractive to attractive for a desired distance $p_d = 1$ meter.

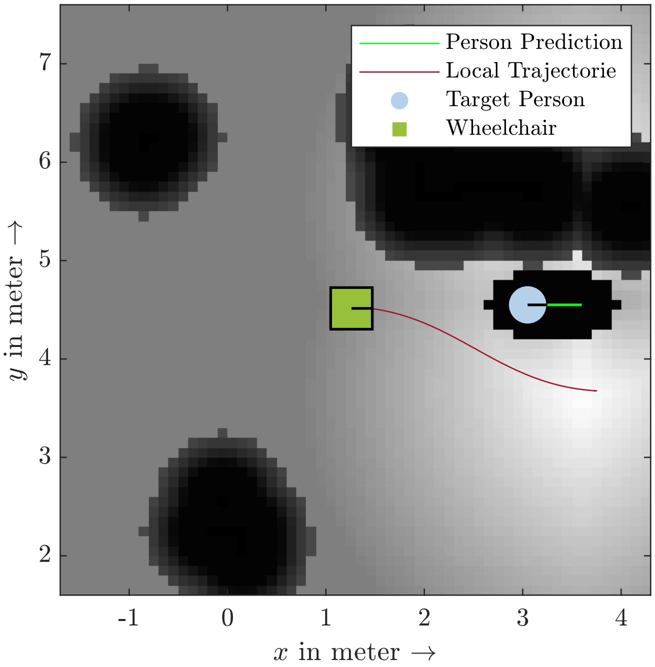

Fig. 3: Local costmap combining the obstacles (black) and attractiveness layer (grey to white) and resulting trajectory.

C. *Autonomous Accompanying of a Person*

As introduced before, the difference in following and accompanying a person is the choice of the lateral position. Normally humans tend to go side-by-side if the environment allows. Therefore an evaluation of the nearby environment of the target person is necessary. The common environmental representation for planning in ROS are costmaps which divide the area into cells $\boldsymbol{c} = [x_c, y_c]$. That's why we implement the metric 1 proposed by Park et al. [14] calling it the attractiveness cost of an accompanying position $a(\boldsymbol{c})$

$$a(\boldsymbol{c}) = |\rho(\boldsymbol{c}) - \rho_d| + c_1\rho_d\,|g(\eta(\boldsymbol{c}) - \eta_d)|\,. \tag{1}$$

Meaning the lower the cost, the more attractive the position. For each cell $\boldsymbol{c}$ of the local costmap, a cost value based on the attractiveness is computed. ρ_d is the desired and $\rho(\boldsymbol{c})$ the actual euclidean distance to the target person which results in a circular distribution. In addition, deviation of the sideways position is evaluated by the angle $|\eta(\boldsymbol{c}) - \eta_d|$ between orientation of the person and the cell. The function $g()$ maps all angles into the interval $(-\pi, \pi]$ and c_1 is representing a factor to scale the weight of the angular deviation. In combination, the result is a leaf-shaped distribution (Fig. 2).

Next, we overlay the attractiveness of an accompanying position with current sensor data. Within a costmap the environment is represented through cost values between 0 (free) and 254 (occupied). A value above 128 means that the robot is in collision depending on its orientation. Therefore, we use 128 as a limit for the level of attractiveness. Current sensor data of the nearby environment is represented in the local costmap of the navigation stack. An examplary local costmap is despicted in Figure 3. Obstacles are marked in black. By overlaying this map with the attractiveness, areas without obstacles are classified in a greyscale from grey not attractive to white attractive. If a target person is located outside of the local map, the position of the detection is taken as goal position for the navigation stack. To catch up with the target person while moving, we interpolate the movement into the future using a constant velocity model.

The intelligent wheelchair has to find one of the global minima next to the target person in the costmap combining the obstacles and the attractiveness of an accompanying position. Whether the minima to the right or the left of the accompanying person is chosen depending on the distance to the wheelchairs position. Because the choice of the closest side comes closest to human behaviour. Furthermore the goal position has to be reachable from the wheelchair's current position. In the case, that no valid minima to eigther side of the person is found, we assume it's always possible to drive behind the person. This is especially relevant in cases of to little space for example in narrow corridors or doors.

We propose to solve this minimization problem by using a graph-based search algorithm with an alternative termination criterion. First, the terminating cell of the search algorithm has to be a local minima, which means that all neighbor cells do have a higher cost. Also, it's important, that the termination criterion distinguishes local from global minima. We can distinguish the minima by defining an upper bound k_{max} for the attractiveness cost of the termination cell $k(\boldsymbol{c}_t)$. As introduced, in a worst case scenario the wheelchair is following behind the person. The cost of this position is the attractiveness of distance p_d and angle $\frac{\pi}{2}$. Therefore, the upper attractiveness bound results in

$$k_{max} = |\rho_d - \rho_d| + c_1\rho_d\left|g(\pi - \frac{\pi}{2})\right| = c_1\rho_d\frac{\pi}{2} \tag{2}$$

Algorithm 1 Multimodal A* algorithm for person company

```
$open\_list \leftarrow [\boldsymbol{w}]$
$closed\_list \leftarrow []$
while $size(open\_list) > 0$ do
    $\boldsymbol{c} \leftarrow lowestCost(open\_list)$
    $closed\_list \leftarrow [\boldsymbol{c}]$
    if $localMinimum(\boldsymbol{c}) \wedge k(\boldsymbol{c}) < k_{max}$ then
        return $\boldsymbol{c}$
    end if
    for all neighbours $\boldsymbol{n}$ do
        if $\boldsymbol{n} \notin open\_list \wedge \boldsymbol{n} \notin closed\_list$ then
            $open\_list \leftarrow [\boldsymbol{n}]$
        end if
    end for
end while
return $failure$
```

using metric 1. This additional condition ensures that our novel algorithm does not get stuck in local minima.

Because of its graph-based exploration and efficiency a variation of the A* algorithm is developed. Starting from the wheelchair position $\boldsymbol{w}$ the algorithm needs to expand cells in two directions, because of the two possible positions on the left $\boldsymbol{l}$ and right $\boldsymbol{r}$ of the person. Therefore we use the minimization of both euclidean distances as heuristic

$$h(\boldsymbol{c}) = \min\left(||\boldsymbol{c} - \boldsymbol{l}||, ||\boldsymbol{c} - \boldsymbol{r}||\right). \tag{3}$$

Our implemented algorithm as stated in Algorithm 1 starts by adding the wheelchair position $\boldsymbol{w}$ to an open_list. After that, the cell with the lowest cost is chosen from the open_list and moved to the closed_list. If this cell fulfils the termination criterion the most attractive cell is found. Otherwise, all neighbours of the current cell are added to the open_list. This procedure is repeated until an appropriate cell is found. By having all expanded cells in an open_list the algorithm is capable of jumping from one expanded branch into the other in case of a dead end on one side of the person. The computed cell is the goal position for the navigation unit which will prefer more attractive positions for accompanying using the overlaid costmap shown in (Fig. 3).

V. EVALUATION AND RESULTS

To evaluate the presented autonomous wheelchair and our navigation approach to accompany a person, we set up two different scenarios in our lab. In the first one, the wheelchair has to navigate collision free in a previously unknown environment and in the second one the wheelchair has to accompany a person.

An exemplary result of the navigation scenario is depicted in Figure 4 by the global trajectory located within the global map of the navigation stack. The task for the wheelchair is to drive from the hall, to the coffee machine, to the office and back. Thereby, the hall is a very cluttered environment whereas the corridors are poor in features. In addition, the evaluation is executed during working hours with moving people. The results show that the developed setup is capable of navigating in the cluttered and dynamic environment at our laboratory. By using three cameras, the amount of visible features is increased, but it also increases the need of memory and computing power. In addition, the tilted cameras capture parts of the ceiling with more long-term static features. This setup results in more localization points of the SLAM algorithm and leads to a robust navigation in our laboratory.

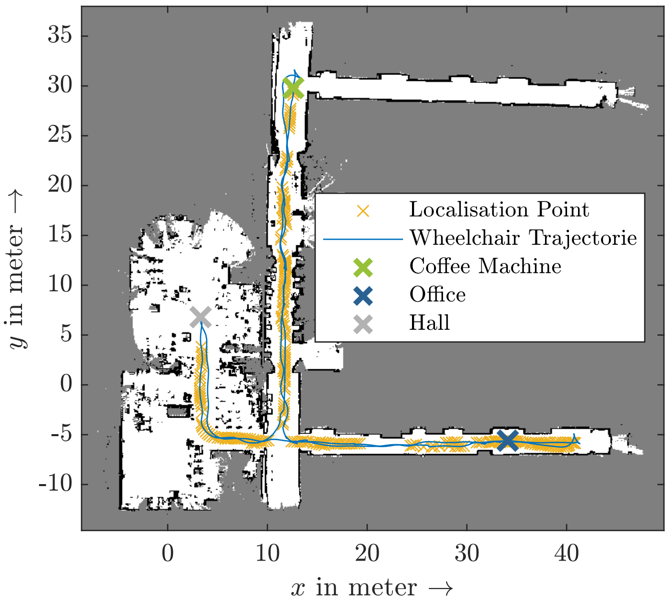

Fig. 4: Global map of our lab with the trajectorie of the autonomous wheelchair between the marked goal positions in dynamic and cluttered environment (hall). In addition localization points of the SLAM algorithm are marked.

Also the evaluation of the autonomous accompanying provides promising results. The trajectory of the target person is shown in the global map (Fig. 5). Our evaluation shows that combining people detectors based on the data of the lateral mounted cameras and laser scanners provides the best results. When combining both sensor types, their specific disadvantages are compensated and a robust person perception is achieved.

The developed algorithm solves the two-dimensional optimization problem of finding an accompanying position. The resulting trajectory of the wheelchair is also depicted in Figure 5. Executing the frequently computed goal positions leads to a side-by-side behaviour if there is enough space and otherwise in a following behaviour e.g. while passing doors (cf. Fig. 5, at x = 10, y = -5). The evaluation demonstrates that the developed algorithm dynamically chooses an accompanying position. Nevertheless, some goals are calculated on the wrong side of the person to accompany because the algorithm is dependent on the target persons orientation. The determination of the persons orientation is based on sequences of detections which is error-prone and a weakness of the people perception.

The advantage of our approach compared to the algorithm proposed by Park et al. [14] is a deterministic behaviour which guarantees to never get stuck in dead ends. Furthermore, the graph-based search approach is very efficient

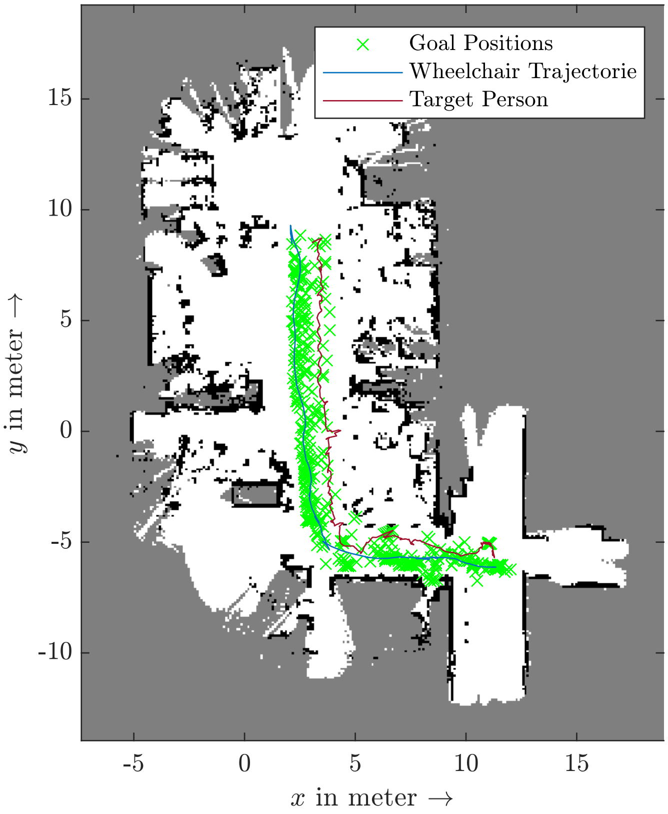

Fig. 5: Resulting trajectories of the wheelchair and the tracked person while accompanying a person at our lab.

because it develops directed to the possible targets. In addition, it just needs to expand the nodes of the local map. By interpolating the movement of the target person, the wheelchair is able to catch up with a person.

VI. CONCLUSION AND OUTLOOK

Within this paper, we present an intelligent wheelchair which is able to navigate in previously unknown, cluttered and dynamic environments as well as accompanying an arbitrary person. A common electric actuated wheelchair is equipped with a suitable sensor setup and the provided data is used for navigation and people perception. For the nearby environment of the manually selected target person an attractiveness distribution is calculated. Finally, we propose a novel algorithm, to determine the most attractive accompanying position based on this distribution.

In future research, we will focus on developing a financially more favourable setup as well as optimized people detectors regarding false detections and orientation estimation of people. Furthermore, the extension of the existing setup for outdoor navigation is of great interest. The opportunities of assistance in road traffic or in public environments offer great potential to increase life quality and safety of handicapped people. Traffic and social rules can be applied to the intelligent wheelchair. In addition, social aware behaviour of the wheelchair has great impact on the social acceptance of its user. Therefore we will improve social accepted navigation algorithms.

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