Routemark-based Navigation of a Wheelchair

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Abstract

This paper introduces the concept of a psychologically inspired navigation approach for an autonomous mobile system. It presents the implementation of the architecture's basic modules and discusses the higher levels of the control-system that are still under development. An electric wheelchair is used as robotics platform to evaluate the architecture's capabilities.

1 Motivation

The representation of spatial knowledge is a research topic in many scientific fields, e.g. in biology, psychology and robotics. In Germany, the Deutsche Forschungsgemeinschaft supports the priority program "Spatial Cognition" that facilitates inter-disciplinary collaboration on this subject. The author's research group is in this priority program and is doing research in the detection of landmarks and routemarks and their use for the navigation of an autonomous mobile system.

An architecture with multiple layers has been chosen for the control-system of the autonomous system. In contrast to earlier navigation approaches that have been inspired by biological findings [4, 5] or the reinforcement learning theory [3], our current approach follows certain models that have been discussed with the psychological working groups in the priority program. It consists of the levels "basic behaviors", "route knowledge" and "survey knowledge". Basic behaviors provide a means to robustly move a mobile system through a dynamic world. Route knowledge describes how to navigate along static routes. Survey knowledge is the information about the spatial relationship between the routes.

Figure 1: The wheelchair.

2 The Wheelchair

A wheelchair is used as an experimental robot platform in Bremen. It has four wheels. The front axle drives the wheelchair while the back axle is used for steering. Therefore, the wheelchair moves like a car driving backwards. It is equipped with a Pentium 100 computer, twelve bumpers, six infrared sensors, 12 ultrasonic sensors and a camera. The infrared sensors can only detect if there is an obstacle within a radius of approximately 15 cm; however, they cannot measure the distance to it. Two different kinds of ultrasonic sensors are fitted to the wheelchair: eight sensors have an opening-angle of 80° while the remaining four sensors only measure in a range of 7°. In addition, the wheelchair can measure the rotations of its front wheels. Thus, it is able to perform dead-reckoning.

The sensors are assigned to four control subsystems. Three of these systems are illustrated in figure 2:

Collision detection. The wheelchair uses all bumpers, all infrared sensors and the widely opened ultrasonic sensors to detect collisions with the environment. As long as an obstacle is perceived by the infrared and ultrasonic sensors respectively, the wheelchair is able to stop before physical contact is made.

Steering restriction. As the wheelchair is steering with its back wheels, its rear swings out very heavily. To prevent it from colliding with obstacles at the side during driving maneuvers, the distance to the closest hindrance is measured and the steering angle is reduced as much as it is necessary to avert a collision.

Navigation. The four ultrasonic sensors with the small opening-angle and the six infrared sensors are employed for navigation purposes. They have been chosen because their measurements do not only reflect a certain distance to an obstacle but also determine it in a definite direction. In contrast, the widely opened ultrasonic sensors would not allow a precise localization.

Landmark/routemark detection. The camera is used to scan the surroundings for landmarks and routemarks respectively. It is mounted on a pan-tilt-head. Therefore, it can watch the environment independently from the current orientation of the wheelchair.

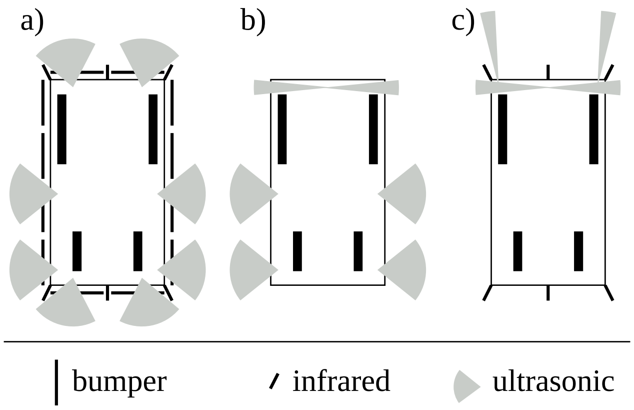

Figure 2: Illustration of the sensor subsystems of the wheelchair. a) Collision detection. b) Steering restriction. c) Navigation.

3 Basic Behaviors

Several basic behaviors, e.g., wall-following and turn-into-door, form the basis of the presented navigation method. They enable the wheelchair to move in corridors, to enter and exit rooms. They are fairly robust against changes in the environment because they hardly ever assume certain compositions of the surroundings.Their implementation uses the sensors of the navigation subsystem. As often mentioned in the literature, e.g. in [2], ultrasonic sensors have several weaknesses. The signal that has been sent out by a sensor may not return to the same sensor if it hits a smooth surface diagonally (reflection) or is caught by another sensor (cross-talk). As the wheelchair's sensors with the small opening-angle do not seem to produce cross-talks at all but often miss smooth objects instead, it is not possible to implement the basic behaviors by a straight sensor-motor-linkage. Instead, the measured distances are inserted into a grid-map (Figure 3). This map plots the local environment around the wheelchair and represents an area of 4×4 m^2. If the wheelchair drives, the measurements in the map are shifted in the same way as the environment passes by the moving wheelchair. Everything that is scrolled out of the map is forgotten. In addition, measurements that are older than 30 seconds are forgotten, too. This allows the wheelchair to cope with dynamic obstacles.

The information in the grid-map is utilized by placing two *virtual sensors* into the map and by using their measurements for the navigation. The virtual sensors work like ultrasonic sensors: they determine the distance to the closest obstacle in their measuring range. In contrast to the real sensors, the virtual ones only measure distances to objects already represented in the grid-map. Thus, they can exploit the sensory data that has been collected in the last 30 seconds. Therefore, they may even detect an obstacle if the real sensors currently overlook it. The two virtual sensors scan the map from a position that corresponds to a location that is in reality 10 cm in front of the wheelchair. One is oriented towards the left side; the other towards the right side (Figure 3).

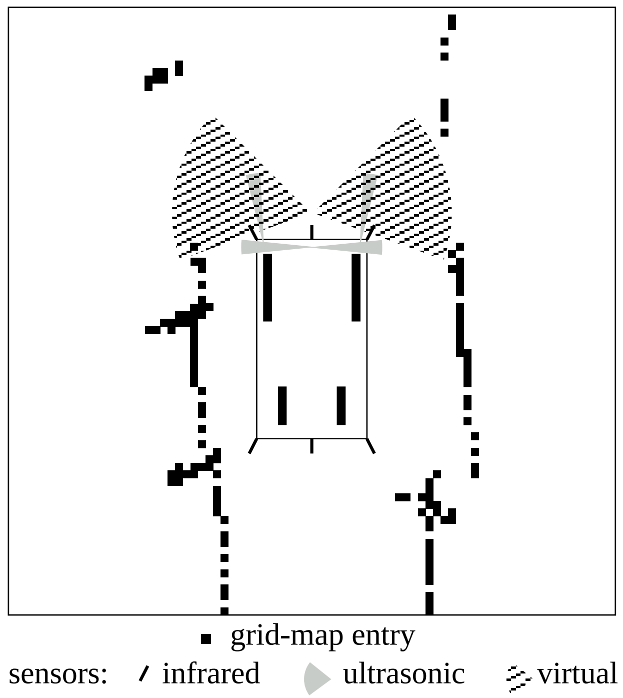

Figure 3: Illustration of the local navigation grid-map.

Six basic behaviors have been implemented:

Center between walls. If this behavior is selected, the wheelchair tries to measure the same distances with both virtual sensors. To achieve this, it always steers in the direction with the larger measurement. First, the difference between both sensor readings has to be calculated:

$$\Delta = v_{left} - v_{right} \tag{1}$$

Then this difference is transformed into a *steering radius*. The steering radius is the radius of the arc that describes the wheelchair's trajectory. A negative radius describes a curve to the left, while a positive radius represents a curve to the right. As a special case, a steering radius of zero stands for a straight ahead movement:

$$r = \begin{cases} 0 & \text{if } \Delta = 0 \\ \operatorname{sgn}(\Delta)\,\frac{w}{\Delta^2} & \text{otherwise} \end{cases} \tag{2}$$

While performing this behavior, the wheelchair is driving in forward direction. As it is possible that an obstacle may have been overlooked, the wheelchair can collide with a hindrance, i.e., the collision detection subsystem perceives the barrier and stops the vehicle. In this case, the wheelchair performs the same behavior in a backward direction for a distance of 50 cm and then it returns to driving forwards. In most cases, the infrared sensors will have detected the missed obstacle during the collision. As their measurements have been entered into the grid-map, the wheelchair is aware of this obstacle during further actions.

To perform the same behavior while driving backwards, the difference between the two virtual sensor readings simply has to by inverted:

$$\Delta_{back} = -\Delta \tag{3}$$

Follow left/right wall. The wall-following is realized by a slightly modified wall-centering behavior. The only difference is that the measurements of the virtual sensor that is opposite to the followed wall are limited to a maximum distance of v_{max}. Therefore, the wheelchair assumes that there is a wall within a distance of v_{max} and centers itself between this virtual wall on one side and the followed one on the other side. If the real corridor is narrower than this virtual one, there is no change to the wall-centering behavior.

To follow the left wall, the difference between the virtual sensor readings has to be calculated as

$$\Delta_{left} = v_{left} - \min\left(v_{right}, v_{max}\right) \quad (4)$$

To keep close to the right wall, Δ has to be determined as follows:

$$\Delta_{right} = \min\left(v_{left}, v_{max}\right) - v_{right} \quad (5)$$

Turn into left/right door. These two behaviors enable the wheelchair to turn into a door that is either in the left wall or in the right one. They are quite similar to the wall-following behaviors. The only difference is that on the side of the door, no virtual sensor is used. Instead, the measurements of the real ultrasonic sensor that is oriented toward this side are used. In this way, the hole between the door-jambs can be determined as soon as possible. If the wheelchair has turned more than 60°, it automatically switches to the corresponding wall-following behavior.

Stop. As it is always the goal of the wheelchair to reach a certain position, it has to stop if it has arrived at the target.

4 Landmark Detection

The basic behaviors enable the wheelchair to *move* in an office environment. In order to also allow it to *navigate*, it must be able to localize itself in the environment. Therefore, it has to be capable of recognizing reference points in the surroundings. In the navigation approach that is presented in this paper, these reference points are called routemarks because they are used to locate the wheelchair's position along a certain route. The long-term goal of the author's working group is to use some features of the environment's 3D-structure as routemarks. To achieve this, a camera that is fitted to a pan-tilt-head should take images of the surroundings. These images should be processed by a "structure from motion" image processing method [1] in order to determine the depth information. This 3D-data can be used the extract certain features, e.g. corners or edges. Combinations of such features should be used as routemarks.

At the moment, only artificial 2D-marks are employed that are determined as well by an image processing algorithm. These marks consist of a black circle on a white background (Figure 4). In the circle, there are up to four white, vertical stripes that are interpreted as a scancode. The recognition of the routemarks are performed in four steps:

1. First, the image is scanned for pixels that are darker than a certain threshold φ_{max}. If such a pixel p_i has been found, a continuous region of pixels that are all darker then $\frac{11}{10}p_i$ is determined, starting from the position of the found pixel.

Figure 4: An artificial routemark. The square around the mark indicates that it has been recognized.

2. In a second step, the width w and the height h of the region are calculated. If either the width is smaller than a predefined threshold w_{min} or the height is smaller than h_{min}, the extracted region is not used as a candidate for being a routemark.

3. Based on the values of w and h, 32 prototypical points of an ellipse with these dimensions are calculated. If the distance of at least one of these points to the region's border is larger then a predefined threshold d_{max}, the region is not assumed to be a valid mark.

4. Based on the region's height, the routemark's horizontal center is analysed in vertical direction to extract the embedded scan-code. Again, if there is not at least one white stripe on the mark, it is ignored. If the selected area has got over all these hurdles, it is assumed to be a valid routemark.

5 Route Knowledge

In the second layer of the control hierarchy, the basic behaviors and the routemark recognition are combined. On this level, the environment is represented as a set of routes. A route is a static way from a starting position to a target place. The wheelchair can drive along such a route by a concatenation of different basic behaviors. Routemarks are used to trigger the starting and changing of basic behaviors. They are the reference marks along the route. Therefore, a route is represented as a sequence of basic behaviors and the routemarks that trigger these behaviors. This sequence can be learned by the wheelchair, e.g. if a teacher controls the vehicle along the route by switching between the available behaviors. Meanwhile, the camera scans the surroundings for routemarks. If the teacher alters the wheelchair's behavior, it stores the routemark that has been detected last as the trigger for the new operation. To improve the representation's robustness, multiple trigger-marks can be stored for a single change of behavior so that the performance of the wheelchair is not affected, e.g., if a routemark would be covered later.

As soon as the recognition of routemarks is not only seen as a binary decision but instead as a process with a particular uncertainty, the representation of knowledge becomes more complex. To develop a solution for this problem, several psychological findings can be employed, e.g. expected routemarks can be detected with a higher probability than unexpected ones. Marks that have been recorded in sequence can support each other in the recognition process. To compensate for the case in which all trigger-marks for a certain behavior have been overlooked, the length or the duration of the route-segments can be captured during the knowledge acquisition. This enables the wheelchair to recognize the missing routemarks. As a result, it can backtrack its way and search for the missing set of routemarks.

6 Survey Knowledge

The autonomous generation of survey knowledge can be considered as the third layer of the architecture. This is the knowledge about the spatial relationship between the routes. On the basis of the survey knowledge, new routes can be generated from multiple learned ones and therefore shortcuts can be detected. The wheelchair can recognize that a particular segment of one route is also part of another route if the same sequence of routemarks exists in both of them. Thus, routes can be combined into a graph that can be utilized to plan shortcuts as well as bypasses around obstacles. If it is necessary to find shortcuts or bypasses by exploration, i.e., without the corresponding route knowledge, dead-reckoning must also be integrated into the navigation strategy.

7 Results

The wheelchair is 72 cm wide and 134 cm long. The basic behaviors have enabled it to drive through 94 cm wide door-frames and to turn into doors in a 176 cm wide corridor. Figure 5 shows a trajectory that has been obtained from a combination of four different basic behaviors. It has been recorded by the wheelchair's onboard odometry. As the odometers are not precise enough to dead-reckon over 30 m, the recorded trajectory has been corrected manually to allow the visualization in the ground-plan. There are some obstacles in the office that are not shown in the plan, e.g. there is a coat-rack in the right corridor that the wheelchair has gone round.

In this early experiment, the basic behaviors have only been switched manually, instead of detecting routemarks as triggers. Further experiments will combine the routemark recognition with the behavior execution.

8 Conclusion

This paper has presented the concept of a psychologically inspired navigation approach. It consists of the levels "basic behaviors", "route knowledge" and "survey knowledge". While the basic modules of the approach have been already implemented and tested, their integration is still under development. The early results show that the basic behaviors are robust in their performance, even if there are dynamic obstacles. The recognition of the artificial routemarks is stable, too—as long as there is no back-lighting.

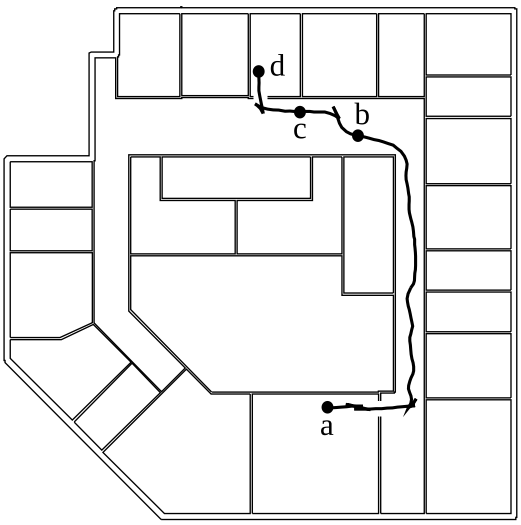

Figure 5: A measured trajectory that has been generated by the combination of four basic behaviors. a) Follow left wall. b) Follow right wall. c) Turn into right door. d) Stop.

Acknowledgements

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