15 Years of Rolland

Thomas Röfer[1], Christian Mandel[2], Axel Lankenau[3],
Bernd Gersdorf[1], and Udo Frese[2]

[1] Deutsches Forschungszentrum für Künstliche Intelligenz GmbH,
Sichere Kognitive Systeme, Enrique-Schmidt-Str. 5, 28359 Bremen, Germany
E-Mail: {Thomas.Roefer,Bernd.Gersdorf}@dfki.de
[2] Fachbereich 3 – Mathematik und Informatik, Universität Bremen,
Postfach 330 440, 28334 Bremen, Germany
E-Mail: {cman,ufrese}@informatik.uni-bremen.de
[3] Daimler AG, Research and Advanced Engineering, 71059 Sindelfingen, Germany
E-Mail: Axel.Lankenau@daimler.com

Abstract. The paper presents 15 years of research conducted on the Bremen Autonomous Wheelchair "Rolland". Rolland is a mobility assistant for the handicapped and the elderly. The paper presents the different versions of Rolland that were built over the years, as well as the special input devices that are used with Rolland. Contributions were made to the state of the art in the areas of self-localization, mapping, navigation, safety, and shared control. A number of assistants are the practical results of this research conducted.

1 Introduction

The name "Rolland" was coined by Bernd Krieg-Brückner. It is a combination of the German word "Rollstuhl" for "wheelchair" and the name of the symbol of the independence and liberty of the Freie Hansestadt Bremen, the "Roland" monument. The term is now well-established in the area of research on intelligent mobility assistants.

This paper is structured as follows: first, the different versions of the Rolland wheelchairs will be presented, followed by the special input devices that were used in combination with Rolland. Afterwards the research topics that have driven the development of Rolland are discussed. This work has resulted in a number of applications that are presented before the paper closes with the conclusions.

2 The Different Rolland Models

Over the years, different versions of Rolland were set-up on different commercial wheelchairs. The different versions also reflect the development of sensor technology and computing technology. [1] describes the state of the art in smart wheelchairs in the year 2000, while [2] presents the state of the art seven years later. A clear trend is that the design of Rolland deviates less and less from the

(a) *Rolland I* (b) *Rolland II* (c) *Rolland III* (d) *Rolland IV*

Fig. 1. The different Rolland models constructed from 1993 until 2008.

wheelchair used as base, i. e., the additional equipment has become smaller, and it has been hidden better. Thereby, the additional hardware does impede the normal usage of a power wheelchair lesser and lesser.

In addition, our 3-D simulator SimRobot [3] has been employed during the development, i. e., each version of Rolland also has a simulated counterpart in SimRobot. Thereby, the software development can be significantly simplified, because algorithms can be tested in simulation before they are applied to the real system.

2.1 Rolland I

"Rolland I" is based on an old wheelchair of the company Meyra. It was originally acquired as a mobile platform that was powerful enough to carry a set of analog artificial neurons that, in the mid-nineties, were quite big and heavy. The front axle drives the wheelchair while the back axle is used for steering. Therefore, the wheelchair moves like a car driving backwards. By the student project SAUS [4] it was equipped with a Pentium 100 computer, twelve bumpers, six infrared sensors, 16 ultrasonic sensors, and a camera. The infrared sensors can only detect whether there is an obstacle within a radius of approximately 15 cm; however, they cannot measure the distance. Two different kinds of ultrasonic sensors are fitted to the wheelchair: half of the sensors have an opening-angle of 80° while the other half only measure in a range of 7°. In addition, the wheelchair can measure the rotations of its front wheels.

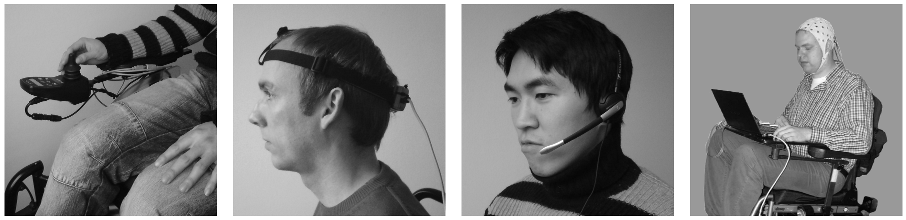
2.2 Rolland II – Meyra *Genius*

"Rolland II" is based on the commercial power wheelchair Genius 1.522 manufactured by the German company Meyra. As Rolland I, the wheelchair is a non-holonomic vehicle driven by its front axle and steered by its rear axle. The human operator controls the system with a joystick. The wheelchair has been extended by a standard PC (Pentium III 600MHz, 128 MB RAM) for control and user-wheelchair interaction tasks, 27 sonar sensors, and a laser range sensor behind the seat. The sonars are arranged around the wheelchair such that they cover the whole surroundings. The electronics is able to simultaneously fire two sensors, one on the left side and one on the right side of the wheelchair. An intelligent adaptive firing strategy has been introduced by Röfer and Lankenau [5–7]. The sonars are mainly used for obstacle detection. The laser range finder has an opening angle of 180° towards the backside of the wheelchair and is able to provide 361 distance measurements every 30 ms. It is used for mapping and localization purposes. The original Meyra wheelchair already provides two serial ports to set target values for the speed and the steering angle as well as determining their actual values. Data acquired via this interface is used for dead reckoning. The odometry system based on these measurements is not very precise, i. e., it performs relatively well in reckoning distances but it is weak in tracking angular changes. The overall software architecture is described in [8].

2.3 Rolland III – Meyra *Champ*

Based on the battery-powered wheelchair Meyra Champ 1.594, the third version of Rolland for the first time featured two laser range finder mounted at ground level, which allowed for scanning beneath the feet of a human operator. As an additional sensor device, the system provides two incremental encoders which measure the rotational velocity of the two independently actuated rear-wheels. The differential drive kinematics comes along with two passive front castor-wheels, giving it the freedom to turn on the spot. The castor-wheels require a significant amount of force to let them turn, which requires a complex controlling behavior when changing the driving direction. Three wheelchairs of type *Rolland III* have been constructed:

1. The first instance is used as a development platform within the Transregional Collaborative Research Center SFB/TR 8 "Spatial Cognition". Since it has no dedicated control PC, a laptop has to be connected (via USB), and sensors, wheelchair and software must be started in the correct order and time.
2. The second instance was built up for a demonstration of the Safety Assistant (cf. section 5.1) in the Heinz Nixdorf Museumsforum as a diploma thesis (see [9]). The software runs on a PC104 embedded computer installed inside the battery box. The system can be started using a single switch in about 80 seconds. The wheelchair was used by thousands of visitors of the exhibition *Computer.Medizin* in a small demonstration area.
3. The last instance of Rolland III was built up as mobility platform for the *SHARE-it* project (http://www.ist-shareit.eu) that is engaged in the field of Ambient Assisted Living. It uses a more powerful embedded PC of type EPIA-NX12000EG with a variety of software assistance. An additional microcontroller board observes PC and wheelchair and stops the wheelchair if the communication is disturbed.



(a) *Joystick* (b) *Head-Joystick* (c) *Speech Control* (d) *Brain-Computer Interface*

Fig. 2. Different input devices developed for a variety of scenarios and target groups.

2.4 Rolland IV[1] – Otto Bock *Xeno*

In September 2008, the Rolland software has been adapted to a prototype wheelchair of type Xeno from Otto Bock Healthcare. Its sensor equipment is very similar to Rolland III (cf. section 2.3), but instead of passive castor-wheels, it uses a *Single Servo Steering* (S^3) for active steering of the two wheels. In contrast to a classical Ackermann steering, this steering method allows turning on the spot (as with the *Champ*), but without additional force from the differential drive, which results in a very smooth and precise path following. Another advantage is the extended wheelbase that allows the front laser scanner to scan between front and rear axles on the left and right side of the wheelchair. The control PC is a netbook installed under the seat and connected to the CAN bus of the wheelchair. An emergency stop can be initiated by the CAN based power control unit if communication problems with the control PC appear.

3 Special Input Devices

Usually electrical wheelchairs are operated by joystick (cf. Fig. 2(a)). From that perspective they handle the handicapped's inability to walk by a control loop that embeds the operator's remaining sensory-motor capabilities into the vehicle's actuating body. In the 15 years of Rolland's development, several interface techniques have been investigated that not only serve the walking impaired but also the quadriplegic.

3.1 Head-Joystick

First proposed in [10] and later evaluated in [2, 11, 12], the basic idea of the head-joystick (cf. Fig. 2(b)) is to let the user of an automated wheelchair control the translational and rotational velocity by continuous pitch and roll movements of

[1] As the system is developed in cooperation with a new partner, it will have a different name. However, since the name has not been decided yet, it is still referred to as "Rolland IV".

his/her head. Still able to observe the environment by turning the head around the free yaw-axis without causing any control commands, the user's head movements around the remaining two axes must exceed a so-called dead-zone in order to evoke a desired movement. The necessary hardware configuration consists out of a small-size 3-DOF orientation tracker (IMU) that is mounted at the back of the operator's head by means of an easy to wear headband. Here, the IMU continually monitors the user's head posture and acceleration w.r.t. the pitch-, yaw-, and roll-axis.

3.2 Speech Control

With the interpretation of natural language route descriptions [13–15], speech control has been tackled as a verbal interface that allows for the execution of utterances such as "Go down the corridor and take the second door to the left" (cf. Fig. 2(c)). One of the basic concepts involved is the decomposition of instructions given by humans into sequences of imprecise route segment descriptions. By applying fuzzy rules for the involved spatial relations and actions, a search tree is constructed that can be searched in a depth-first branch-and-bound manner for the most probable goal configuration w.r.t. the global workspace knowledge of the wheelchair.

3.3 Brain-Computer Interface

Brain-Computer interfaces, or BCIs for short, are tools that facilitate communication with artificial artifacts via direct measures of the human brain's activity. In cooperation with the *Bremen Institute of Automation*[4], classified steady-state visual evoked potentials (SSVEPs) in brain activity have been used to derive qualitative directional navigation commands. The overall system that has been first described in [16] projects the given commands onto a frequently updated route graph representation of the environment. The metrical target locations deduced are subsequently navigated to by the application of the well-established Nearness Diagram Navigation method (cf. section 4.3).

4 Research Topics

During development of Rolland, we have done research in many areas, some of which are traditional topics in mobile robotics such as mapping, self-localization, or navigation. Others are more specific to a wheelchair, i. e., a device that carries a person who is also partially controlling it (*shared control*).

4.1 Mapping and Self-Localization

Self-Localization was investigated along routes, in route graphs, and in metric maps. The latter was done in combination with mapping, i. e. simultaneous localization and mapping (SLAM).

[4] Contact: A. Gräser, and T. Lüth. Institute of Automation, 28359 Bremen, Germany. E-Mail:{ag,thorsten.lueth}@iat.uni-bremen.de.

Localization Along Routes. In [23–26] a simple approach for the acquisition and representation of spatial knowledge needed for controlling a semi-autonomous wheelchair is presented. Simplicity is required in the domain of rehabilitation robotics because typical users of assistive technology are persons with severe impairments who are not technical experts. The approach proposed is a combination of carrying out so-called *basic behaviors* and the analysis of the wheelchair's *track of motion* when performing these behaviors. As a result, autonomous navigation in the user's apartment or place of work can be learned by the wheelchair by teaching single routes between potential target locations. The work focuses on the analysis of the motion tracks recorded by the vehicle's dead reckoning system. As a means for unveiling the structure of the environment while the system is moving, an *incremental generalization* is applied to the motion tracks. In addition, it is discussed how two of such generalized motion tracks are matched to perform a one-dimensional self-localization along the route that is followed.

RouteLoc – Self-Localization in Route Graphs. RouteLoc is a self-localization approach that needs only minimal input (i. e. no expensive proximity sensors are required) to absolutely localize a robot even in large-scale environments [27–30]. RouteLoc works robustly in structured large-scale environments. It can be seen as an extension of the approach discussed above to localize in maps instead of a single route. As input data, RouteLoc requires a topological-metric map and a so-called incremental route generalization. It calculates a position estimate in a human-compatible form, e. g. "The robot is in the corridor leading from A to B, about x meters past A". In [27], RouteLoc solves, among others, the so-called "kidnapped robot problem" in real world experiments with Rolland on the campus of the Universität Bremen.

Scan-Matching-based SLAM. In [32–34, 31] an approach to generate consistent maps in real-time using a laser range sensor is presented. It improves an existing scan-matching algorithm in several aspects. It also introduces a mapping method that is based on the scan matching method. Using a laser scanner mounted on the wheelchair, it generates consistent maps, i. e. maps that do not have discontinuities resulting from the accumulation of errors in the mapping process. As such accumulations cannot be avoided, the resulting errors are corrected whenever the wheelchair returns to areas already mapped. An important property of the approach is its real-time capability. The mapping is performed on the fly and thus, the resulting maps can immediately be employed for self-localization. An example of the mapping process is given in Fig. 3.

4.2 Behavior-based Navigation

Behavior-based Navigation, in contrast to metric navigation and planning, is a reactive way to navigate. Usually, the representation of the environment is not metric. Instead, features of the environment are associated with necessary

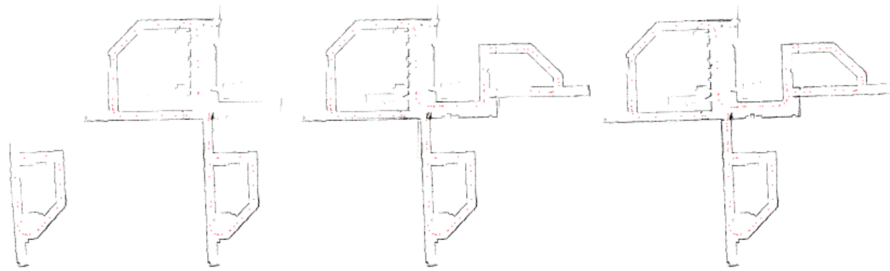


Fig. 3. Four snapshots while mapping an office floor.

changes in the behavior. Two approaches have been investigated: *image-based homing* and navigation using *basic behaviors*.

Image-based Homing. In [17–19, 35–38] an image processing method is presented that enables a robot to orientate in unchanged, existing environments. The approach is based on the use of one-dimensional 360° (panoramic) color images that are taken by a special optical sensor. From two of these images, the Panama algorithm determines the spatial relationship between the positions where the images have been taken. The approach can be compared to methods that determine the optical motion flow but it addresses a different application: it is used to determine the spatial relations between positions that may be located several meters apart. The image processing method is embedded in a navigation technique in which the environment is represented as a network of routes along which the navigating agent can move. These routes are represented as sequences of panoramic images. This route knowledge is acquired by teaching. A teacher only presets the routes that should be learned but not the images that are required for their description. These images are independently selected by the autonomous system during the training, depending on the particular environment and the system's kinematic restrictions.

Basic Behaviors. In [17, 20–22] an approach is presented that describes routes as sequences of basic behaviors, such as wall-centering, wall-following, entering a door, etc. The recognition of routemark constellations triggers the switching between these behaviors. The information when to use which basic behavior and when to switch to the next one is acquired during a teaching phase (cf. Fig. 4). The method detects possible navigational errors and tries to recover from them by backtracking the previous way.

4.3 Metric Navigation

Local navigation approaches that provide the ability to deal with dynamic and unforeseen obstacles typically employ a sensor-based map of the robot's local

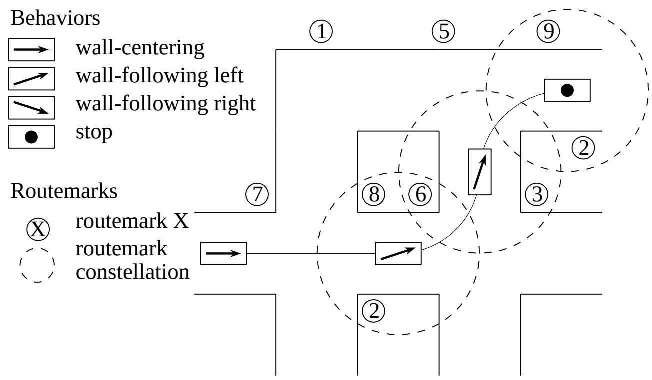
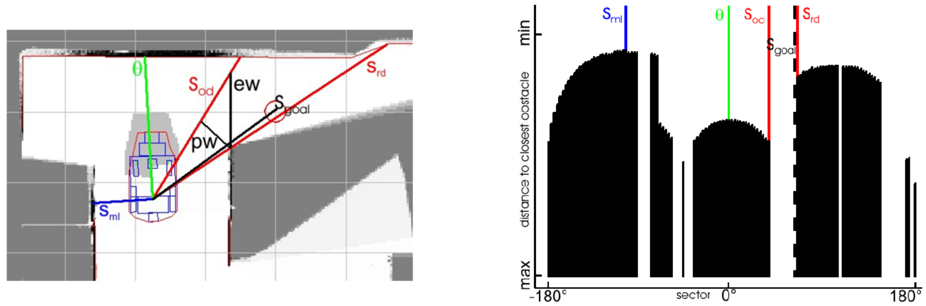


Fig. 4. Teaching of routes as an association of routemark constellations and basic behaviors.

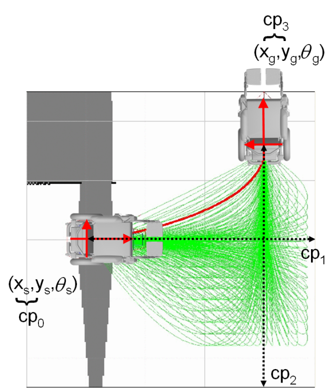
neighborhood for planning purposes. By means of this data-structure, geometric path planning algorithms and reactive steering methods either calculate a complete trajectory that leads the vehicle to the designated target, or just determine a set of velocities to be applied in the next time frame. In the following we present local navigation approaches implemented on *Rolland* during the last 15 years.

The Nearness Diagram Navigation approach (NDN), initially developed by Minguez et al., is a representative of the class of reactive steering methods. NDN describes the sensor measurements of the visible part of the environment along with the desired target position as a unique element of an exclusive and complete set of situations. Each of the five situations originally defined is associated with a specific control law that determines the translational and rotational speed to be applied, as well as the desired direction of movement. Since Rolland is an example for a non-circularly shaped mobile robot that cannot independently control its kinematic degrees of freedom, we have augmented the basic NDN control laws in such a way that they look ahead for upcoming turn maneuvers and initiate a preparatory sheer out movement when necessary (cf. [39] for an in-depth discussion).

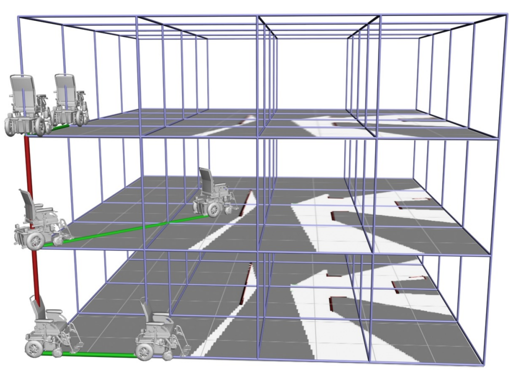
Behavior-Based Local Navigation splits the local navigation problem into two parts. The first one is to approach the goal and the second one is to avoid obstacles on the way. The first part, i. e. the local navigation module, simply determines the actual driving command from the current pose of the wheelchair and a local target pose in each control cycle. A pose consists of the three components (x, y, *rotation*) in global coordinates. The speeds determined are used to control the Driving Assistant that is described in section 5.2. The local navigation generates motion commands as if the wheelchair would drive in free space,



(a) Illustration of the *Nearness Diagram Navigation* approach within a simulated environment. S_{od} and S_{rd} denote the borders of the free walking area, while s_{goal} and θ describe the direction to the local target p_g and the current orientation of the wheelchair respectively (cf. [39]).



(b) The *Bezier-Curve Path Planner* selects an optimal path (red) from a set of possible paths (green) by reducing the time of travel and maximizing the distance to nearby obstacles.



(c) The *A* based Path Planning* approach searches the discretized configuration space (x,y,θ) for an optimal path. Atomic translational moves are illustrated as green lines, while atomic rotational moves are painted as red lines.

Fig. 5. Illustration of three local navigation approaches implemented on Rolland. While the Nearness Diagram Navigation belongs to the class of reactive navigation strategies, the Bezier-Curve Path Planner, and the A* based Path Planning approach are geometric and complete planning algorithms respectively.

i. e., it completely ignores the current obstacle situation. However, since the Driving Assistant avoids obstacles, the wheelchair is robustly able to navigate even in narrow environments, as long as the target poses are selected appropriately. In general, target poses should be located at narrow passages, e.g. between door posts, with the orientation perpendicular to the narrowness. In case the wheelchair gets stuck or, for any reason, misses the target pose, a shunting behavior allows retrying and thereby ensures robustness.

Geometric Path Planning. The basic principle of geometric path planning approaches is to continuously check sets of mathematical curves for a solution path in order to move the robot from its current pose to a given goal-pose. Therefore the algorithms evaluate a cost function that minimizes the length of the path to execute, while maximizing the distance to the obstacles along the selected path. For Rolland several such algorithms have been developed, applying circular arc segments, clothoids, and cubic Bezier splines [40, 41, 14].

A* Path Planning. Recent developments have led to a prototypical implementation of a real-time-capable planner based on A*-search in Rolland's configuration space (x, y, θ). Conceptional drawbacks of NDN and the geometric path planning approaches such as the non-consideration of target orientations, or the sparse covering of the configuration space by means of mathematical curves are avoided. For this reason a typical A*-based planning scenario involves the discretisation of the configuration space into $6 * 10^6$ cells, yielding a spatial resolution of $3 * 3cm^2$, and an orientational resolution of $3.75°$. The algorithmic search itself is guided by two heuristics taking the current obstacle situation and the non-holonomic nature of Rolland into account. Hereby it is possible to maintain planning-cycles of approximately $20ms$.

4.4 Shared Control

The shared-control aspect of manned service robots is to be considered in all applications of *Rolland* that share control between the human driver and an intelligent assistance module. So-called "mode confusion" situations have to be avoided [42, 43]. In the aviation psychology community, the problem of mode confusion has already been discussed for about a good decade. However, the notion as such has never been rigorously defined. In addition, the pertinent publications so far cover almost exclusively the pilot-autopilot interaction. In [27, 44], a rigorous view of mode confusion is presented. A framework based on existing formal methods is established for separately modeling the technical system, the user's mental representation of it, and their safety-relevant abstractions. As a result, an automated model checking approach can be applied to detect mode confusion potential already in the design phase. In a case study, the obstacle avoidance skill of *Rolland* is checked for mode confusion potential with tool support.

4.5 Qualitative Control

In order to solve high level tasks such as the interpretation of qualitative driving commands or coarse qualitative route descriptions, one needs an appropriate global data structure that represents the navigable space in an adequate way. For Rolland we apply a graph structured representation, i. e. the *Route Graph* [45], because of its extensibility by annotations, given either by humans or automatic feature detectors, and because of its interface that supplies basic spatial queries as a foundation for the evaluation of more elaborated spatial tasks.

The underlying idea of the interpretation of *Coarse Verbal Route Descriptions (CRDs)* is that they can be split into *route segment descriptions* that describe the start, the progression along the route, intermediate reorientation actions, and the goal. This observation has been validated by empirical studies in which subjects had to give in-advance route descriptions to a designated goal. For the evaluation of CRDs, i. e. the calculation of the most likely target pose, we utilize a search tree the nodes of which represent fuzzy rated places that result from the evaluation of single CRD-elements. The corresponding algorithm inputs a formalized CRD representing the current task description, a global route graph which holds the available world knowledge, and the global pose of the system. By evaluating fuzzy functions that model the consecutively appearing spatial relations in the CRD, our algorithm builds up the mentioned search tree and searches it in a depth-first branch-and-bound manner to determine the most probable goal pose. For a more detailed elaboration of this work see [14, 15].

5 Applications

Using the techniques discussed above, several assistants have been developed for Rolland [46]: the *Safety Assistant*, the *Driving Assistant*, the *Route Assistant*, the (*Autonomous*) *Navigation Assistant*, and the *Multi Modal Driving Assistant*.

5.1 Safety Assistant

The Safety Assistant mainly consists of a *safety layer* that ensures that the vehicle will stop in time before a collision can occur [47–50]. 30 or 50 times per second (depending on the wheelchair model), the safety layer makes a binary decision. Either the current driving command is safe, and it can be sent to the wheelchair, or it is not, and the wheelchair has to stop instead. “Safe” means that if a stop command would be initiated in the next processing cycle, the wheelchair would still be able to stop without a collision. Otherwise, it has to be stopped in this cycle, because in the next cycle it would be too late. Whether the wheelchair can stop in time depends on the actual speeds of the two drive wheels and the current drive command, because it will influence the current speeds in the future, the shape of the wheelchair, and its current surroundings. The surroundings are measured using the distance sensors (sonars or laser scanners) and a model of the environment is maintained in a local obstacle map (cf. Fig. 6). Based on the current speeds and the commanded speeds, a *safety area* is searched for obstacles in the map. If the safety area is free of obstacles, the current driving command is safe. Since the shape of such a safety area is rather complex, a large number of safety areas were pre-computed and stored in a lookup table.

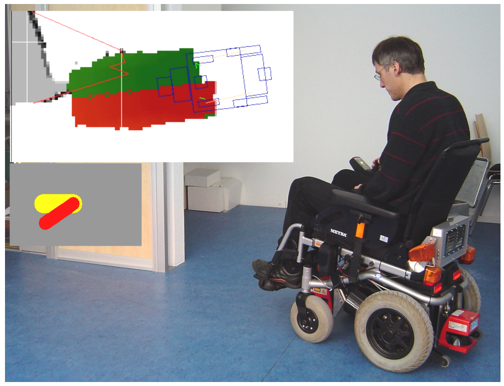


Fig. 6. Intervention of the Driving Assistant. The driver presses the joystick straight ahead (indicated by the thick line); the Driving Assistant detects an obstacle on the right side (cf. safety area in the local obstacle map above), and avoids it to the left (thin line).

5.2 Driving Assistant

The Driving Assistant is a software component that provides obstacle avoidance for Rolland [51, 5, 47, 48, 52]. The Driving Assistant avoids obstacles while the wheelchair is still controlled by the user. The user remains in complete control of the system as long as there are no obstacles on the path driven. Whenever obstacles block the way and would result in the wheelchair being stopped by the Safety Layer (the main part of Safety Assistant), the Driving Assistant takes control and avoids the obstacle with as small deviations from the commands given by the user as possible (cf. Fig. 6). The Driving Assistant on Rolland II also provides a basic behavior for turning on the spot, because this can be quite difficult with an Ackermann steering in a narrow environment. Since Rolland III and IV are equipped with a differential drive, there is no need for such a behavior.

5.3 Route Assistant

The Route Assistant of the Bremen Autonomous Wheelchair [53] has been developed in cooperation with the neurological clinic of a Bremen hospital. It provides the following functionality: During a teaching phase, the system explores the routes and places pertinent for the future user(s). If, e. g., the wheelchair is used in a rehabilitation center for amnesic patients, the routes to all relevant places in the building could be learned and stored for later replay with the help of the route generalization algorithm already mentioned. In the replay mode, a nurse chooses a certain target for the patient in the wheelchair. Similar to a GPS-based navigation system, the large-scale navigation is done by the Route Assistant by giving instructions where to go at decision points, enabling the

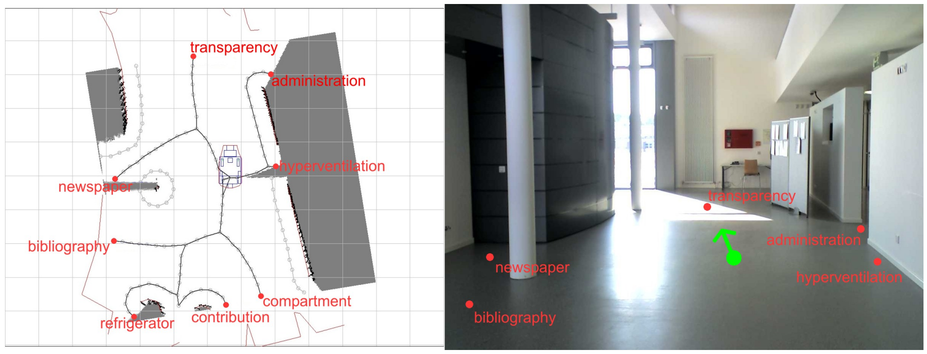


Fig. 7. Multi Modal Driving Assistant: Illustration of navigable paths along with their labelled target nodes (left), and a photograph of the corresponding environment (right). While the left figure presents the current pose of the wheelchair by a detailed shape that is heading to the top, the picture to the right depicts the position and orientation of the wheelchair by a green dot and arrow.

patient to travel around on his or her own. The patient is independently responsible for controlling the vehicle with respect to local maneuvers such as obstacle avoidance.

5.4 (Autonomous) Navigation Assistant

The Navigation Assistant goes further. It is based on a SLAM-based metric representation of the environment with an embedded route graph. The aim of the system is to have a robust navigation component for an autonomous wheelchair within a global frame of reference. The user is enabled to choose a specific destination – e. g. “Refrigerator”, “Entrance”, or “Wardrobe” – from a predefined list. Given the destination, the system provides two different use cases: autonomous navigation of the robot without any need for interventions by the user, or a guidance mode which lets the user drive manually but provides information about where to navigate next. The latter assistant is similar to the route assistant, but here the spatial representation is a map, not a route. The key idea behind this assistant is to specify all possible destinations together with all possible routes between these destinations, i. e. the route graph, in advance. This approach shifts parts of the intelligence needed from the robot to an external human expert. Thereby, it can be assured that necessary routes always exist and lead along paths that are actually usable by a wheelchair, i. e., they do not contain any undetectable obstacles. Especially the latter cannot be assured for autonomous route generation given the current sensorial equipment of the wheelchair Rolland.

5.5 Multi Modal Driving Assistant

The essential idea behind the *Multi Modal Driving Assistant* [12] (cf. Fig. 7) is a simple speech interface with which the operator of the wheelchair selects a desired movement from a set of graphically presented navigable paths. Derived from the route graph representation of the environment, the proposed paths are selected by verbally calling their name. In order to improve the recognition process of the applied speech recognizer *VoCon*, each proposed path is labelled by a token coming from an alphabet with multisyllabic words that provide mutually different sounds. Once established the connection between the commanded token and the corresponding path, its endpoint is forwarded to the obstacle avoiding navigation module, i.e. a specialized implementation of the Nearness Diagram Navigation approach (cf. section 4.3).

6 Conclusion

It was a long way from Rolland I, the construction of which is so complex that even healthy people have problems sitting down in it, to Rolland IV that only stands out because of its functionality, but not because of its appearance. Hence, the commercialization of the results is the next logical step. In cooperation with our new partner Otto Bock Mobility Solutions, we will develop some of the assistants presented in this paper to industrial prototypes. However, there are still interesting areas for further wheelchair research, e. g., driving outdoors. In addition, we are investigating another device meant for supporting the elderly: the intelligent walker, i. e. the iWalker.

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Authors' Vitae

Thomas Röfer received his diploma in computer science and his Dr.ing. degree from Universität Bremen, Germany, in 1993 and 1998, respectively. He is in the Executive Committee of the RoboCup Federation, and he is member of the Transregional Collaborative Research Center SFB/TR 8 "Spatial Cognition" at Bremen. He is currently with the German Research Center for Artificial Intelligence at the research group for Safe and Secure Cognitive Systems, Bremen, Germany. His research interests include rehabilitation robotics, robot soccer, real-time computer vision, world modeling, and humanoid robots.

Christian Mandel received the Dipl.Inf. and Dr.Ing. degrees in computer science from Universität Bremen, Germany, in 2002 and 2008, respectively. In 2008 he worked for the German Research Center for Artificial Intelligence at the research group for Safe and Secure Cognitive Systems, Bremen, Germany. He is currently with the University of Bremen at the Collaborative Research Center *Spatial Cognition*, doing research and development on navigation techniques and advanced interface devices for assistive devices, such as electrical wheelchairs.

Axel Lankenau received the Dipl.Inf. and Dr.Ing. degrees in computer science from Universität Bremen, Germany, in 1997 and 2002, respectively. He was member of the *Rolland* project from 1994 until 2002. Currently, he is a manager for documentation process design in the Research and Advanced Engineering department of the Daimler AG in Sindelfingen, Germany.

Bernd Gersdorf received the Dipl.Inf. and Dr.Ing. degrees in computer science from Universität Bremen, Germany, in 1986 and 1992, respectively. In 1995, he started to work in the industrie in the software development for Process Automation, and later for flight safety systems. He joined the *Rolland* project early 2007 with the German Research Center for Artificial Intelligence at the research group for Safe and Secure Cognitive Systems, Bremen, Germany.

Udo Frese received his Ph.D. from University of Erlangen-Nürnberg in 2004. From 2004 until 2008 he has been a post-doc researcher in Bernd Krieg-Brückner's lab at Universität Bremen and in the German Research Center for Artificial Intelligence (DFKI). He is now assistant professor for real-time computer vision at University of Bremen and further on affiliated with the DFKI. His research topics are real time computer vision, in particular simultaneous localization and mapping (SLAM), and computer vision for sport robotics.