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Smart Wheelchairs – State of the Art in an Emerging Market

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Due to the shift of the age structure in today's industrial populations, the demands of the handicapped and the elderly are more and more being recognized by politics, industry, and science. The recent development in research areas such as computer science, robotics, Artificial Intelligence, or sensor technology allows to significantly broaden the range of possible applications that support handicapped or elderly people in their daily lives. This article presents the state of the art of the most popular assistive device: the smart wheelchair.

1 Introduction

The increasing mobility of humans will be one of the key issues of the coming century. People do no longer work in the same city they live in, huge shopping malls in the open countryside replace the corner shop, and far distance voyages become more and more popular. This phenomenon is accompanied with a rapid development, especially in the field of information technology. While notions such as *mobile phone*, *e-commerce,* or *GPS-navigation system* are ubiquitous nowadays, a different application field of the new technologies is still in its infancy: *service robotics*.

Common industrial robots usually perform repeating movements with enormous speed and precision in an exactly defined environment. In contrast to them, a service robot's task is to carry out difficult, unpleasant, dangerous, or supporting jobs for humans in their normal environment, e.g. surveillance, inspection, cleaning, or guidance services. In a market analysis from October 1999, the United Nations European Commission for Economy (UN/ECE) predicts that the number of service robots installed world-wide will be quintupled within three years time [22]. Rehabilitation robots, such as smart wheelchairs, will play an important role. By compensating for the specific impairments of each individual, rehabilitation robots enable handicapped people to live more independent and mobile than they could before.

This article focuses on intelligent wheelchair robots in that it summarizes the requirements of a smart wheelchair with regard to the human-machine interface, the technical equipment, functionality, and the safety aspect as well as it presents an overview about current research projects which deal with the development of these vehicles. In the sequel, the projects aware to the authors are referred to by their acronyms or project titles, respectively. The following, geographically ordered list may serve as an introductory overview. From Northern America and Japan, the *NavChair* (University of Michigan, [19]), the *Wheelesley* (MIT, [23]), the *Deictic* Wheelchair (Northeastern University, [6]), the *TinMan* (KISS Institute for Practical Robotics, [13]), and the *TAO* (Applied Artificial Intelligence, Inc., [7]) projects are covered. The European smart wheelchair community is represented by the *SIAMO* (Spain, [1]), the *CALL* Centre (Scotland, [14]), the *SENARIO* (Greece, [9]), the *RobChair* (Portugal, [15]) projects, and the German research groups *MAid* (FAW Ulm, [16]), *OMNI* (Fernuniversität Hagen, [8]), *INRO* (University of Applied Sciences Ravensburg-Weingarten, [18]), *FRIEND* [3], *EASY* [4] and *Rolland* [17] (all from the University of Bremen).

2 General Requirements

Two major concerns have to be taken into account when designing a wheelchair robot for handicapped or elderly people: the adaptability to the individual and the fulfillment of safety requirements.

2.1 Adaptability to the Individual

In order to have a chance of being accepted by its potential users, a smart wheelchair must be adaptable to the needs of each individual person (as an example, cf. the SIAMO project). Especially in the context of supporting handicapped people, the focus should be how the remaining skills of the human operator could adequately be complemented. As a consequence, research and industry do not concentrate on fully autonomous systems but on so-called semi-autonomous wheelchairs. These robots are able to carry out certain tasks on their own, but they have to rely on the human operator and his or her skills and experience when performing other tasks. Thus, a smart wheelchair is a highly interactive system which is jointly controlled by the human operator and the software of the robot. That's why the design of the human-machine interface is a key issue in the development of a smart wheelchair.

2.2 Safety Requirements

As service robots in general and rehabilitation robots in special operate in the direct vicinity of humans, their malfunction could cause severe harm to people. Therefore, such robots have to be considered as *safety-critical systems* [20]. For smart wheelchairs this classification is even more reasonable because they transport persons who often completely depend on the correct behavior of the technical system. If, e.g., the handicapped operator of the wheelchair instructs the vehicle to go to the medicine cabinet, the dependable [12] execution of the command might be life-critical, failure won't be an option.

Only few groups put a lot of effort into the question how to design a safe smart wheelchair. For instance, the Rolland project aims at applying formal methods such as hazard analysis techniques [10] and model checking to define safety requirements of the system, to prove the satisfaction of these requirements during operation and to handle the so-called *mode confusion problem* that arises in shared control systems [11].

3 Functionality

The variety of required functionality is as large as the amount of different handicaps. The realization of the necessary skills must be easy to use by persons who do not have a technical education. A smart wheelchair has to work reliably and robustly in the natural environment of its user. It is not acceptable that this environment must be completely rebuild in order to let the wheelchair operate as intended by the developer. Maintenance and configuration have to be as intuitive as possible because they should be carried out by the staff of the reha-provider, and not by the robotic expert.

In the following subsections, a brief overview of the relevant skills figured out so far is given.

3.1 Obstacle Detection

On the one hand, the quality of the detection of obstacles is a question of the sensor equipment used. On the other hand, it is a question of the interpretation, representation, and processing of the data provided by the sensors.

3.1.1 Sensor Equipment

Every project tracks the locomotion of the vehicle by processing the current speed and the direction of movement which are delivered either by externally mounted wheel encoders, or by the internal wheelchair electronics. In contrast to that, the employed proximity sensors vary significantly. *Sonar* sensors are very common. Often, they are mounted in a ring around the wheelchair (e.g. SENARIO, Rolland), but sometimes they only cover the front of the vehicle (e.g. NavChair, INRO). The SIAMO project developed a special setup that avoids sonar cross-talks [21]. *Infrared* sensors are also fairly widespread (e.g. RobChair, Wheelesley, and SIAMO), but only the TAO project uses them as the only active proximity sensors. As they are relatively expensive, *laser range finders* are only sparsely used (e.g. MAid).

Prominent passive proximity sensors are *bumpers* which provide a binary signal whether or not they are in touch with an obstacle (e.g. Deictic, Wheelesley, and TAO). Other passive sensors are *video cameras* which can also be used to estimate distances to objects in the surroundings, e.g. if used in a stereo vision system (TAO, Deictic) or by exploiting optical flow. Cameras are additionally used to detect potholes or descending staircases by determining the deviation of the actual shape of a laser beam from the target shape in the picture (INRO, Senario).

3.1.2 Handling of the Sensor Measurements

As almost every project implemented a basic safety layer to avert collisions, the primary purpose of the proximity sensors is to allow the control software to stop in time if an obstacle is dangerously close to the wheelchair. Only the TAO robots employ a direct sensor-action coupling and do not store the data delivered by their sensor system. The majority of the other projects maintains a local obstacle map (or "certainty grid") to accumulate sensor readings (NavChair, Senario, Rolland).

3.2 Obstacle Avoidance

To ensure safe travelling, a smart wheelchair has to provide a reliable *obstacle avoidance* skill. However, there are various interpretations of the notion "obstacle avoidance" among the projects.

3.2.1 Reactive Obstacle Avoidance

The purely reactive approach is exclusively propagated by the TAO project. As mentioned, they directly map the current sensor readings to motor actions. If the human operator does not accept a decision of the so-called TAO Autonomy Management System, he or she is able to override the command with a contradicting joystick command.

3.2.2 Obstacle Avoidance Based on a Local Map

The most popular obstacle avoidance approach is the use of a local obstacle map. By accumulating the most recent sensor readings, a rather reliable detection of potential obstacles is ensured. The most prominent approach is the so-called Vector Field Histogram [2] used by the NavChair project. This method finds a compromise between the user's goal direction and the best (with respect to the expected collision-free travel distance) possible direction. Other research groups (e.g. Senario) use different extensions to the vector field histogram method.

Within the Rolland project, the obstacle avoidance skill is implemented differently. They also use a Cartesian local obstacle map that is the basis for the extensive use of the principle of function tabulation: On the one hand, for each combination of travel direction, steering angle, and orientation of the wheelchair in the map, the grids, the wheelchair would visit if it moved, are calculated in advance and stored as the so-called *virtual sensors*. On the other hand, it is pre-calculated for each cell in the map, how fast the wheelchair must be at most, if it wanted to pass an obstacle located in that cell.

3.2.3 Solutions to the Shared Control Problem

The problem of shared control always arises if a human operator and a technical system are jointly in charge of control. The obstacle avoidance approaches used in the NavChair and in the Rolland project pay attention to the shared control problem in that they consider the human operators intention where to travel as the bias direction. In the Rolland project for instance, the travel direction indicated by the joystick is projected into the local obstacle map in order to decide on which side the obstacle should be passed, if it should at all.

3.3 Behavior-Based Skills

The human-machine interfaces used in the smart wheelchair projects (cf. section 3.5) enable the user to instruct the robot on a significantly more abstract level than an operator of a common power wheelchair could do. Thus, several projects implemented various local navigation skills such as corridor following, object tracking, turning on the spot, doorway passage, and others. More advanced, the Deictic wheelchair allows the human operator to issue rather abstract commands which refer to objects in the surroundings of the robot. The commands are executed by tracking the relevant object in the video picture taken by the stereo vision system.

3.4 Navigation

The basic requirement of navigation is a working self-localization technique. To provide self-localization methods that work in natural environments that are not necessarily known in advance is a key challenge for the research groups in this area.

A popular approach to facilitate the wheelchair to be adapted to various scenarios is the idea of learning by tuition. After service staff trained the wheelchair to operate in a certain environment, it is able to perform navigation tasks in that environment. During the training process the system has to build a map of its environment which is matched with the real world afterwards using a self-localization technique. Among the projects presented here, there are some that employ topological maps (TAO) and others that use a combination of topological and metrical maps (Rolland, Senario).

For outdoor navigation, the satellite based Global Positioning system GPS can be employed. The INRO project makes use of this technique for self-localization by a differential GPS module.

3.5 Human-Machine Interface

Many groups simply use the standard joystick as input devices and provide no special output device apart from simple displays. Some groups (RobChair, SIAMO) employ speech recognition systems to enable the user to issue commands by voice. In the Wheelesley project, the human operator controls the wheelchair by choosing high-level commands via a graphical user interface on a notebook [23]. The SIAMO project provides even more input devices: Apart from joystick control, switches and a voice recognition system they offer a blow control and a facility which enables the user to instruct the wheelchair by head movements, using a CCD micro camera mounted in front of the user in order to track his or her face. In order to control the Deictic wheelchair, the human operator has to use a four component control panel as human-machine interface to choose a motion, a direction, the placement of the most important object close to the wheelchair, and a distance or speed.

The experimental platform of the FRIEND project is equipped with a control-PC and a robotic arm structure, the MANUS manipulator. The main topics of the project are the control of the manipulator and its human-machine interface [3]. The INRO as well as the RobChair project employ a radio link from the wheelchair to a remote station for various tele-operation purposes.

4 Outlook

Despite of the convincing progress the smart wheelchair community made within its ten years of existence, there is still a lot of work to do before such devices can be commercially available. The research wheelchairs are not yet robust enough to operate for a long time in the house or flat of a handicapped person. In order to increase the acceptance in the potential buyers' mind as well as to ease to certification by the administration, the safety issue has to be examined more thoroughly. Nevertheless, the chances to provide a useful tool to significantly improve the quality of life of many people are quite realistic. Maybe that's why the company of Johnson&Johnson invested $50 million to develop IBOT, a smart wheelchair that is able to climb the stairs [5]. IBOT is projected to be commercially available by the end of 2001, at about $25,000.

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