NAVIGATION SYSTEMS FOR INCREASING THE AUTONOMY AND SECURITY OF MOBILE BASES FOR DISABLED PEOPLE

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Abstract A navigation module for technological aids for disabled user is presented. Usability and acceptability criteria are considered in the design of this module. Different levels of autonomy for the navigation module are considered for allowing an active interaction of the user with the technological aids. A standardized protocol for the integration of input-output devices for robotic assistive systems is also used. The navigation module is tested on an powered wheelchair and an autonomous mobile base. The sonar sensors are used for on-line detection of possible obstacle collisions. The reliability of sonar readings is increased by the use of a probabilistic map of the environment to support the decisions on obstacle detection.

1. Introduction

Progress, in its general sense, has contributed to reduce the effect of disabling accidents thanks to a better medical prevention, to better general living conditions, and better security conditions in workplaces; this notwithstanding, progress has created new causes of disability because of an increasing number of risk conditions in transportation and in the leisure activities and because of the increase of the average life expectation of the population. This latter factor, associated with the reduced natality present in many “1 World” Countries are producing an increasing incidence of the elderly population with respect to the total population. It is well known that elderly contribute significantly to the number of disabled persons. In Europe for example 70% of disabled is over 60 years.

The problem of the integration of disabled people in the social life is rather complicated and involves the proper interactions among the disabled, their families, the social operators, the technological aids. This problem is being faced in different ways:

- a better social consciousness; for example there are laws protecting disabled people or spontaneous organisations for assisting and helping them;
- the diffusion of specialist centres where disabled are cared;
- a specific sensitivity in planning of buildings and of social services;
- the development of technological aids (Assistive Technology) aimed at reinforcing the residual abilities of the disabled or to substitute their missing function thus helping them in gaining a certain level of independence at least in the activities of daily living.

In this latter context Robotics puts at disposal of the disabled a large number of aids. New terms have been introduced like Assistive Robotics and Rehabilitation Robotics [1], [2]. Many activities in this sector have been focused on telemanipulators controlled by disabled and on manipulators on board of powered wheelchairs to help the disabled in working and in domestic activities [3].

In the European Union the research activities in this sector have been mainly co-ordinated within the TIDE initiative [4]. In this framework, the development of intelligent navigation systems based on sensors easily portable on various powered vehicles for disabled has been developed in the TIDE project SENARIO [3]. Another TIDE project, MOVAID [5], was mainly concerned with the development of a modular mobile robot interacting with the user by means of a friendly interface for the accomplishment of domestic tasks. The TIDE project M3S (Multi Master Multi Slave) [6] was aimed at facilitating the integration of input-output devices for robotic assistive systems. This allows a flexible and reliable communication among aids for disabled made by different manufacturers.

In this paper we focus on a system for the navigation and guidance of a mobile base that can be used for semi/automatic powered wheelchairs or for mobile wheeled platform travelling in non-structured environments. It is mainly devoted to reduce motor disability.

The design of the system has taken into consideration criteria of usability, acceptability, efficacy, and cost, trying to obtain a reasonable tradeoff among specifications that are mutually contradictory. It is well known that, for example, a better efficacy usually claims for higher costs. The design of the system profits of the experience the authors [8], [9] had in the MOVAID project and in particular of the insight they gained on the attitude of disabled people towards high-tech robotic aids used as assistive devices.

Usability and acceptability refer to the interaction with the user. There is not a large technical literature concerning
these aspects for high-tech devices because of their still limited use. Interviews with potential users, i.e. with disabled suffering motor disability such as spastic paraplegics, spastic tetraparetics, hemiparetic subjects due to congenital cerebral tumour and progressive dystrophic subjects, put into evidence the willingness of the user to interact with high-tech systems actively controlling their functions. In this manner the device is felt positively by the disabled that regain his/her self-confidence in controlling appropriately the system while performing an appropriate task.

In order to fulfil this kind of requirements, the design of the navigation system has taken into consideration the use of the M3S communication protocol. It manages the interaction among the navigation module and the user interface. It allows the communication of commands generated by means of different types of devices (depending on the user disability) to the vehicle. In this manner it is possible to use the control-device most suitable for the user in terms of easiness of use and of acceptability. Usability and acceptability criteria have also led the design to allow different levels of user control of the mobile base. For users mildly disabled, a low level of autonomy is left to the navigation module. It accepts commands from the user and “filters” these signals by possible “tremor” or noise in order to estimate the real willingness of the user. Collision detection is also done by the navigation module in order to simply stop the mobile base when an obstacle is detected. For users with more enhanced functional limitations, a semi-automatic navigation is allowed. The user has control on the system but this latter corrects the commands received taking into account security constraints. The collision detection and obstacle avoidance modules co-operate to guarantee a minimum safety distance of the mobile base from the obstacles present in the environment (for example the walls). For users heavily disabled a fully automatic navigation is allowed. The user can control the system in a limited way (for example stopping it or indicating to the system the target to be reached). The system acts by its own on the basis of the path planning and obstacle avoidance modules, taking into account the a-priori information on the environment and also information received by the collision detection module.

The modularity of the navigation system and the use of a standardised protocol for data communication among sub-systems also enhance the effectiveness of the system. Note also that, if needed, the self-localization ability of the mobile base can be improved by sensor information fusion (see, e.g., [9]).

For the sake of costs, commercial mobile bases have been considered.

The paper is organised as follows. In Section 2 the general architecture of the navigation system for mobile bases for disabled people is presented. Section 3 presents the navigation module and some details of the exteroceptive sensor systems based on proper sets of sonar sensors. The experimental tests are presented in Section 4.

2. Navigation System Architecture

On the basis of our experience in previous related research projects [7], [8] the navigation system has to allow a proper interaction with the disabled in order to involve the user in the guide of the vehicle without limiting the functionality and security of the system.

Consequently, different levels of autonomy have been defined in order to adapt at the various disability levels of the user. For instance, the low level of autonomy of the navigation module has been developed for a commercial powered wheelchair while the other levels have been designed mainly for a commercial mobile base.

The general architecture of the navigation system is shown in Figure 1.

![Figure 1. Navigation system architecture.](image-url)
architecture has been thought general enough to be applied
for the guidance both of an powered wheelchair and of an
autonomous mobile base. In order to simplify the
integration of the navigation module in the existing
wheelchairs and autonomous mobile a control module has
been introduced which adapt the commands of the
navigation module to the commands of the mobile base
actuators.

To comply such an architecture with the various kinds of
vehicle, the relevant kinematic models have to be employed.
In the navigation system architecture shown in Figure 1, the
user sends commands to the navigation module through the
user interface. The navigation module generates the control
variables according to the specified kinematic model and the
control module translates these control variables in the low
level commands for the actuators of the wheel drivers.

3. Navigation module

The proposed navigation module with its different levels
of autonomy acquires the information of the environment by
a proper exteroceptive system realized by a set of sonar
sensors. In this section some aspects of the sonar system and
of the navigation module are presented. The crosstalk
reduction and the on-line construction of the environment
map are described in the first part, while the navigation
module with different levels of autonomy is described in the
last part of this section.


The navigation module exploits local information on the
environment by a proximity system composed by low cost
sonar Polaroid sensors arranged with a half ring geometry.
The position of the sonar sensors on the wheelchair and on
the autonomous mobile base are shown in Figures 2 and 3,
respectively. The positions and orientations of the sonar
sensors have been deduced by experimental tests performed
on the mobile bases. The solutions proposed represent a
reasonable trade-off between the accuracy of the obstacle
detection and the crosstalk interferences.

The robustness and efficiency of the navigation module
depend on the quantity and on the quality of the sensor
measures. The quantity can be increased by a reduction of the
sonar scanning times. But in this way the number of wrong
readings due to the mutual interference between the sensors
(crosstalk) is greatly increased.

The frequency of the crosstalk events depends on the
geometry of the environment and on the position of the
mobile base. Without any a-priori information about the
environment it is impossible to recognize the wrong
readings which are almost identical. Recently Borenstein and
Koren [10] have proposed a method to handle the crosstalk.

It consists in changing the time interval between two
consecutive sonar measures. A short delay time is introduced
before each sonar transmission, which alternatively assumes
two values, satisfying a proper set of constraints. Each sonar
has a different pair of values. In this way, a variation of the
distance measure is detected in the case of a crosstalk
interference. The variation is recognized by comparing the
last measure with the preceding one, and if the difference is
greater than a predefined threshold, the measures are
neglected. Some technical aspects on the adaptation of this
metodology to the commercial sonar system used on our
mobile bases can be found in [14].
In [11] the map construction is obtained with accuracy and with a consequent high computation cost. The simplicity and the computation speed are addressed in the solution proposed in [12], where an on-line computation procedure is developed. The solution implemented in our navigation module finds a tradeoff between the accuracy and the computation cost. The main features of the implemented solution can be found in [14].

An example of a probability map of a domestic environment with a partial a priori knowledge of the environment (walls and some furnitures) is shown in Figure 4. The grey zone (obstacle probability equal to 0.5) denotes the environment area that is not explored by sonar proximity system of the mobile base.

![Obstacle Probability Values](image)

Figure 4. A sonar map of the environment explored by the sonar proximity system installed on the mobile base.

### 3.3 Autonomy levels of the navigation module

The proposed navigation module utilizes the information stored in the environment map built on-line by the sonar system. When an obstacle is detected in front of the mobile base, different actions are performed on the basis of the autonomy level available to the navigation module.

If the lowest autonomy is allowed, the navigation module realizes a simple filtering of the user commands and in front of a detected obstacle the module realizes a **Stop + Wait** action. The navigation module stops the mobile base and waits for the obstacle to disappear, while a warning message is presented on the user interface. After a time-out period, if the obstacle does not disappear, the module stops definitively the wheelchair or the autonomous mobile base, in the absence of an user interaction.

If the medium autonomy level is imposed, the navigation module realizes the same functions of the lower autonomy level and after a time-out period, if the obstacle does not disappear, the system activates the **Stop + Invocation of User Help** action. In this case the navigation module invokes the help of the user who can command to ignore the obstacle (just try to push it away) or to abort the current trajectory and start a new one in the direction free of obstacles. The feasibility of the new motion direction is evaluated by the environment map. At this autonomy level the navigation module is allowed to introduce some local modification of the command generated by the user, in order to guarantee a sufficient distance from obstacles and walls. These local modifications are produced on the basis of the environment map built-up by the sonar proximity system and of a-priori information on the environments (walls, doors, furnitures).

The algorithm used in this autonomy level is a simple adaptation of the on-line obstacle avoidance algorithm proposed in [8] for the navigation of an autonomous mobile robot used for helping disabled people.

The navigation module with the highest autonomy level realizes the same functions of the other autonomy levels and, in addition, when an obstacle is detected and a time-out period is waited, the system finds an obstacle avoidance manoeuvre in an autonomous way. The obstacle avoidance algorithm used at this level is an extension of the algorithm proposed by Lumelsky and Stepanev [13] to the case of sonar measures aggregated in a sonar map of the environment [14]. This algorithm is able to find a trajectory without obstacle collision also in a cluttered environment.

The navigation module with the higher autonomy is able to plan in an automatic way also the path from the start configuration to the goal configuration chosen by the user for the mobile base. The collision-free path planned with this module takes into account the non-holonomic constraints of the mobile base and the known obstacles of the environment [15].

### 4. Experimental tests

The proposed navigation has been implemented in the lower autonomy levels on a commercial wheelchair guided by a joystick [16]. The choice of a commercial powered wheelchair reduces the development costs but requires the introduction of a control module. This module translates the commands generated by the navigation module in the driving commands for the actuators of the wheelchair (see Figure 1).

The wheelchair has been equipped with a half ring of sonar sensors placed in front of the wheelchair and with two incremental encoders placed on the axes of the rear wheels as shown in Figure 5.

The implementation of the lower autonomy levels has been realized on a PC 486DX2 with PC-104 bus installed on the rear side of the wheelchair. The PC installed on the
wheelchair manages also the sonar and the encoder readings and the connection with the M3S bus. The user interface is connected to the navigation module by the M3S bus (see Figure 1).

Figure 6. The grey area denotes the security area tested by the navigation module.

Figure 5. The TGR wheelchair equipped with the Polaroid sonar sensors and the incremental encoders.

At the lower level of autonomy the possible obstacle in front to the wheelchair is detected by the analysis of a proper area, called security area, on the sonar map of the environment which is up-dated at each sampling instant. The shape of the security area is shown in Figure 6. When the probability of a cell of the environment map contained in the security area is higher than a predefined threshold value, the navigation module activates the Stop + Wait action. The security area of the sonar map is determined by the position of the wheelchair and by the angle of the steering wheel, as shown in Figure 7. In this way, the security of an avoidance manoeuvre imposed by the user is also verified and, as shown in Figure 7, if the imposed manoeuvre is correct the navigation module does not active the Stop + Wait action. The same security area has been considered at the medium autonomy level, in order to guarantee a sufficient distance from the walls. At this autonomy level, the navigation module introduces some corrections on the user commands by a simple adaptation of the obstacle avoidance algorithm proposed in [8]. For example, if an obstacle is detected on the right side of the security area, a correction on the steering angle is introduced until the security area is free of obstacle. This procedure guarantees a sufficient distance from the walls and obstacles.

The approach of the security area on the sonar map of the environment has been followed for increasing the robustness and affidability of the obstacle detection. With this approach satisfactory results have been obtained in domestic environments with different kinds of obstacles.

The highest autonomy level of the navigation module has been tested on the autonomous mobile base LabMate [17]. In fact the highest vehicle autonomy corresponds to the lowest user autonomy. This mobile base can enhance the autonomy of a severely disabled person either by bringing to him/her some things or by displacing the person itself. The highest autonomy level is composed by an off-line path planner and an on-line collision avoidance algorithm. The former consists in an off-line path-planning procedure for calculating collision-free paths, using a-priori information about the environment, while collision avoidance deals with
the modification of the planned motion of the mobile base, on the basis of information about the changes occurring in the environment. The path planner is based on the classical configuration space approach with the introduction of the non-holonomic constrains [15]. The obstacle avoidance algorithm is an extension of the algorithm proposed by Lumelsky and Stepanov [13] to the case of sonar measures aggregated in a sonar map of the environment [14]. In Figure 8 an experimental test is shown. The collision avoidance algorithm is able to drive with a smooth trajectory the mobile base to the goal position.

Figure 8. The solid line is the vehicle path, the dotted line is the planned trajectory and the dots are the sonar measures.

At this autonomy level the efficacy on the estimation of the mobile base position can be improved by the fusion of data coming from exteroceptive sensors as sonar sensors and proprioceptive sensors as incremental encoders, as shown in [9].

5. Conclusions

The analysis of the user needs and of their propension in interacting with high-tech assistive devices, lead us to developed a navigation module for wheelchair and autonomous mobile base able to show different levels of autonomy, though guaranteeing security. This navigation module has been developed by an integration, with proper modifications, of subsystems devoted to specific functions. The choice of the M3S interface has been considered for tailoring to various kind of disabilities.

The preliminary technical tests of the developed navigation procedure have shown that it is reliable and satisfactory in terms of security and of response time. A validation phase of the navigation system is foreseen on a limited number of disabled users living in non structured environments. The results of this activity will be used for improving the usability, the efficiency and the security of the system. Moreover, technical and methodological improvements will be developed in further research activities in order to improve the estimation of the mobile base position by the introduction of fusion of data from different sensors characterized by different accuracy.

References

[16] TGR Explorer, TGR, Bologna, Italy.