INTEGRATION OF SMART USER INTERFACES IN THE NAVIGATION SYSTEM OF POWERED WHEELCHAIRS

Cristina Carletti and Sauro Longhi
Dipartimento di Ingegneria Informatica, Gestionale e dell'Automazione
Universitá Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy

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Abstract: This paper presents a navigation system that extends the use of Electric Powered Wheelchairs (EPWs) to people with upper limbs impairments that prevent them the control of a traditional joystick-driven EPW. To achieve this aim, an Automatic Speech Recognition (ASR) system and a Brain Computer Interface (BCI) have been introduced to enable the user to asynchronously perform and send the control commands to the navigation module, according to her/his limited residual capabilities. Moreover, a shared-control algorithm has been developed to translate the user's guidance wishes into directions of motion that maximize the security and minimize the physical and cognitive effort for the user. A preliminary analysis of the proposed navigation system showed satisfactory results in terms of security and fulfillment of the user wishes.

1 INTRODUCTION

The loss of mobility for an individual represents one of the most severe obstacles for an independent life. The Electric Powered Wheelchair (EPW) is an effective tool to augment the autonomy of people with lower limbs impairments. Nevertheless, these devices are useless for subjects who do not have a sufficient control of the upper limbs. In the last decade a large number of research teams focused on how to extend the use of EPWs to these users.
Two aspects of the problem can be considered. The first one regards the integration of commercial wheelchairs with certain levels of intelligence and autonomy to allow an easy, comfortable and safe navigation, at least in an indoor environment. The ”intelligence” of the wheelchair is based on its capacity to perceive its surroundings thanks to various sensors such as ultrasonic or vision sensors. With these information the wheelchair can generate autonomous or semi-autonomous motions (i.e. obstacle avoidance, wall following) (G.Bourhis and Sahnoun, 2007).
The second aspect concerns the availability of Human Machine Interfaces (HMIs) to enable the guidance of an EPW in an asynchronous way without the use of the upper limbs.
Regarding the first aim, significant research activities have been developed, see, e.g. the VAHM project (Bourhis and Pino, 1996), the NavChair assistive wheelchair navigation system (Levine et al., 1999), (Simpson and Levine, 1999), the Hephaestus smart wheelchair (Simpson et al., 1999). These works provided commercially available EPWs with different levels of autonomy to perform a safe navigation keeping the user in the control loop. In all the above smart wheelchairs autonomy and security aspects are guaranteed by a set of sonar sensors. Different sensor devices, such as vision systems, are also used in the Wheelesley (Yanco, 1998), (Yanco and Gips, 1997) and TAO (T.Gomi and Griffith, 1998) intelligent wheelchairs.
Regarding the HMIs, many research activities in the field of Rehabilitation Engineering are involved to the development of new augmentative communication and control technology for people with severe disabilities. Several solutions to replace a joystick-based control of an EPW have been proposed. These involve eye tracking systems (C.S.Lin et al., 2006), head gesture analyzers (Hu et al., 2007), Automatic Speech Recognition systems (ASRs)(Simpson and Levine, 2002), Brain Computer Interfaces (BCIs) (Millán, 2008). An ASR interface translates vocal words into commands for the control of the device. Therefore, it can be used even by quadriplegic subjects with a

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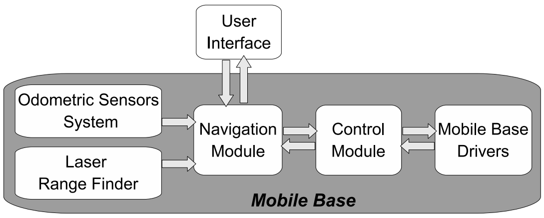

Figure 1: The architecture of the Navigation System.

residual capability of pronouncing a limited set of words. Unfortunately, voice control has proven difficult to implement within a standard EPW. The main difficulties are the wrong recognition of the user's voice, the limited rate by which information can be transmitted by voice, the reduced vocabulary and so the reduced set of available guidance commands.

A BCI enables the communication between an individual and a computer through a conscious and spontaneous modulation of the brainwaves (Millán et al., 2004). It provides the user with new communication and control ways that do not depend on the brain's normal output channels such as peripheral nerves and muscles (Wolpaw et al., 2002). After a training period, even a completely paralyzed person can write messages using a virtual keyboard on a computer screen, browse the internet, operate simple computer games and move a cursor. However, current ElectroEncephaloGraph(EEG)-based BCIs are not suitable for complex applications, i.e. controlling a neuroprosthesis or driving an EPW, due to low information transfer rates (Millán, 2008). In this context, good results have been obtained using synchronous P300-based BCIs (Iturrate et al., 2009), (Blatt et al., 2008). The problem is harder when an asynchronous motor imagery-based BCI is used because a very small set of guidance commands is allowable. However, it has been shown that online EEG signal analysis is sufficient for humans to continuously control a wheelchair, if combined with advanced robotics and machine learning techniques (Millán et al., 2004).

The proposed navigation module implements a shared-control algorithm which enables a safe guidance with a reduced set of commands and with a low transfer-rate. These features allow the integration in the navigation system of usable HMIs like an ASR and a BCI.

The paper is organized as follows. Section 2 describes the navigation system while the Section 3 introduces the main features of the human-computer interfaces integrated in it. The experimental and simulation tests are discussed in Section 4.

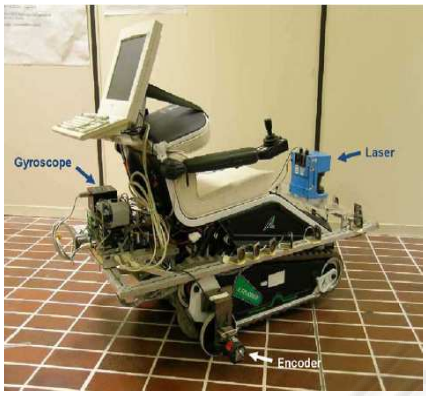

Figure 2: TGR-Explorer with data acquisition system.

2 NAVIGATION SYSTEM

2.1 Architecture

The architecture of the proposed navigation system is represented in Figure 1. The mobile base is the TGR-Explorer (http://www.tgr.it), a joystick-driven wheelchair successively equipped with a 100MHz 486-based computer and a sensor system (Figure 2). Two incremental optical encoders aligned with the axes of the driving wheels and a fiber optic gyroscope, mounted on the back of the vehicle compose the dead-reckoning system. A laser range finder is also present, for detecting obstacles in the surrounding environment. Data acquired by the sensor system and the user command sent by the user interface module are received by the navigation module and elaborated in order to compute an obstacle-free direction of movement. Finally, the control module translates the control variables into low level instructions for the actuators of the driving wheels.

2.2 Map Building

A real time map building algorithm has been developed. It is based on the *Histogramic In-Motion Mapping* (HIMM) and modified to work with the laser sensor instead of the traditional ring of ultrasonic sensors. Following this approach, the environment is represented through a two-dimensional *Histogram Grid*. Each cell of the grid is associated with a *Certainty Value* (CV) which represents the confidence in the existence of an obstacle at that location. The map is continuously updated by new sensor data while the robot is moving. To reduce the computational cost, the map updating involves only a reduced area (*Active Region*) inside the measure range of the laser. This area is a

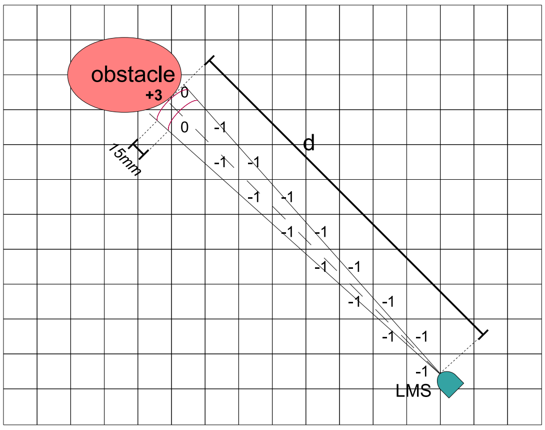

Figure 3: Histogramic Grid Update using a Laser Measurement System (LSM).

semicircle of radius $3m$ centered at the actual position of the laser. Moreover, inside the Active Region, only the CV of the cells lying on the actual reading axis of the sensor are updated. In particular, the CV of the cell corresponding to the measured distance d ($d < 3m$) is incremented, while the CV of the all cells lying between the obstacle and the sensor (along the central axis of the actual measure cone) is decreased. As the measure cone of the laser is continuously and rapidly sampled, a histogramic probability distribution is obtained, in which high CVs are associated with cells close to the actual location of the obstacle. Limiting the CV update to the cells along the central axis of each measure cone, the HIMM procedure allows a fast map-building that can be used for real-time applications, i.e. real-time obstacle-avoidance procedures.

Considering a laser scan angle equal to $180deg$ and a sensor resolution of $1deg$, we can assume to have 181 measure cones, much more than the typical number of sensors composing a sonar system (16 or 24 typically). Moreover, as the amplitude of the light spot is about $0.25deg$, the measure cones are very narrow comparing to the sonar ones, typically of $30deg$. Consequently, every measure cone can be approximate with a line, corresponding to its central axis. The CV range has been chosen varying from 0 to 15 and its initial value has been fixed as 7 for all cells in the grid. It means that until the robot has no information about the external environment, all the cells have the same probability to be empty or occupied. As laser data arrive, the CV of the cell corresponding to the measure is increased by $I^+ = +3$ while the CVs of the cells lying along the reading axis are decreased by $I^- = -1$. Finally, the CV of the cells adjacent to the increased one are not modified. The reason is that the maximum measure error for the laser is smaller than $15mm$ and the cell side is $50mm$. Consequently, the largest measure error could affect only the CV of the neighboring cells. A schematic representation of this procedure is shown in Figure 3. According to the experimental results, occupied cells do not significantly spread out during the robot movements in the presence of obstacles. This can be explained by the large number of measurements available and the accuracy of the laser. Moreover, due to the high angular resolution, the saturation of cells' CV is reached in few steps. The result is a very detailed map, as will be described in the Section 4 and by the Figure 4.

2.3 The Autonomy Levels of the Navigation Module

The definition of the right level of autonomy for a navigation system is a critical aspect when the user is within the control loop. A higher level of autonomy helps to reduce the user guidance effort and requires a lower guidance skill. However, it bounds the user control capability, leading to the feeling of losing the vehicle control. Therefore, the right tradeoff between autonomy and control power is very important for the acceptance of the system by the user and for the adaptation to her/him residual capabilities. For this reason, two levels of intelligence and autonomy are developed.

In the first one, the navigation module performs a simple filtering of the user commands: if an obstacle is detected inside a certain "security area", the module starts the *Stop* procedure decreasing the vehicle's velocity. If the system receives a new user command, the feasibility of the new motion direction is evaluated and, in case of positive result, the new command is executed. Otherwise the vehicle is stopped until a new user command arrives. The "security area" is a cone-shaped portion of the environment in front of the robot with opportunity dimensions to guarantee the stop of the vehicle whatever manoeuvre it is executing .

In the second level of autonomy, a VHF-based obstacle avoidance algorithm (Bell et al., 1994) introduces some local corrections on the user commands. If the obstacle is detected inside the security area, a correction on the velocity and on the steering angle is automatically introduced. This correction is computed considering the relative position of the detected obstacle and the last user command.

3 HUMAN MACHINE INTERFACE

The aim of the navigation system is to extend the use of EPWs to people with severe upper limbs impairments and even to those completely paralyzed. To reach this goal, two human-machine interfaces are considered: an Automatic Speech Recognition (ASP) device and a Brain Computer Interface (BCI).

3.1 Automatic Speech Recognition

An automatic speech recognition (ASR) converts acoustic signals emitted by an individual, into digital signals available for a computer.
ASR can be very helpful for users with disabilities that preserve them for using a keyboard, a mouse or a joystick. Unfortunately, voice control has proven difficult to implement within a standard power wheelchair. The main difficulties concern with the wrong recognition of the user's voice, the limited rate by which information can be transmitted by voice, the reduced vocabulary and so the reduced set of available guidance commands (Simpson and Levine, 2002). Moreover, the pronunciation of the same word can change from user to user and even for the same user in different time instants and/or operative conditions.
In the developed ARS module, that has been integrated with the navigation module, a reduced set of guidance commands has been introduced and a low transfer rate has been used. Specifically, only four commands are available: they are "go forward", "turn right", "turn left" and "stop", associated to the words "forward", "right", "left" and "stop" respectively. The reverse motion is not implemented because no sensors are present in the rear side of the vehicle.
The considered transfer rate is $0.5 bit/sec$. This channel capacity has been chosen according to the previous explanation and to the features of the BCI, as described in the next subsection.

3.2 Brain Computer Interface

The Brain Computer Interface (BCI) provides user with communication and control channels that do not depend on the brains normal output channels such as peripheral nerves and muscles (Wolpaw et al., 2002). The device analyzes brain waves in order to determine the subjects' mental task. The recognized mental task is then mapped into actions such as commands to move a mobile base. Different BCI implementations exist and they are differentiated with respect to: the technique by which the brain waves are acquired (invasive or non-invasive BCIs), the variety of brainwave phenomena considered (synchronous or asynchronous protocols) and the classification algorithms developed (Lotte et al., 2007)
An EEG-based BCI is here considered. In an EEG-based BCI, the brain electrophysiological signals are recorded by electrodes on the user skin by a classical EEG. These raw signals are first processed in order to extract some relevant features and then sent to a classification algorithm. This component allows to discriminate which mental task the subject is performing and associate it to a command for the external device. Finally, a visual or acoustic or haptic feedback informs the user about the mobile base's state or the task that it is about to be execute. The design of the present navigation system takes into account a MAIA-like BCI (MAIA: Mental Augmentation through Determination of Intended Action). In the following the principal features are recalled (Millán et al., 2004).

- It is an asynchronous BCI based on the motor imagery. This means that the subject can issue commands for the guidance of the vehicle at any moment and without waiting for the synchronization with external cues.
- It is portable (only 8 electrodes are required for the brain signals acquisition) and so it can be carried on the mobile base.
- The statistical classifier is able to discriminate three mental tasks. The tasks are getting relaxed, imaging repetitive self-paced movements of a limb, visualizing a spinning cube, performing successive elementary subtractions by a fixed number (e.g., $64-3=61$, $61-3=58$, etc.), and concatenating related words. Among these tasks, after an initial training period, the subject chooses to work with the three mental tasks that s/he can execute more easily.
- The bit rate is about $0.5 bit/sec$. By assuming to digitalize each of the three commands with two bits, only one command every $4 sec$ is possible. The navigation system provide the wheelchair with the intelligence necessary to make up for the lack of control due to the low channel capacity.

3.3 User Feedback

A video display is used to provide the user a visual feedback. It is made of three different arrows corresponding to the three possible directions of motion for the mobile base. When the navigation system receives the user command, the corresponding arrow is lighted on the screen. This procedure gives a visual feedback to the user about the command computation. More-

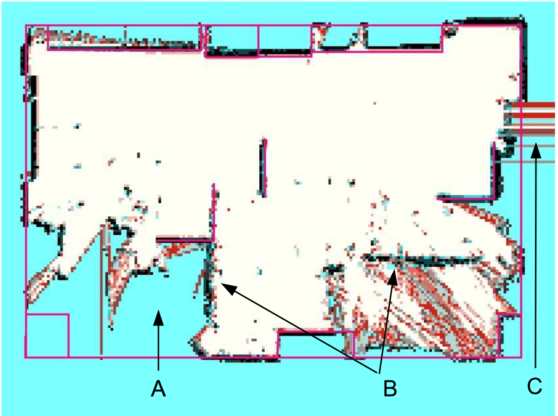

Figure 4: Map built by laser range finder readings at the end of the experimental test in an indoor environment. The black lines represent real obstacles.

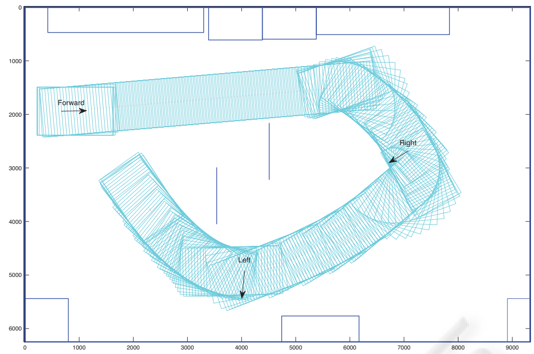

Figure 5: Simulation test in an environment crowded with obstacles. The path performed by the wheelchair with the second level of autonomy is depicted (clockwise direction of motion). The arrows represent the directions chosen by the user in the corresponding instant. The (blue) straight lines reproduce the obstacles. The values are in millimeters.

over, a flashing arrow represents the movement that the mobile base is executing. If an obstacle goes into the security area and the previous movement sent by the user becomes unsafe, the navigation system automatically changes the vehicle direction to a safer one. In this case the flashing arrow and the lighted one will be different. This feedback allows the user to distinguish between an error in the computation of the command or to a safer manoeuvre performed by the security module.

4 OPERATION DETAILS AND EXPERIMENTAL RESULTS

Experimental tests with the TGR-Explorer were carried out to evaluate the map building algorithm. Figure 4 represents a 9.33*m* x 6.25*m* room (straight magenta/dark grey lines) and a laser map with squared cells of 50*mm* x 50*mm*. The cyan/light grey regions correspond to unexplored areas (A), holding a CV equal to 7; the white parts correspond to empty cells, which have a CV of 0; the black cells have a CV equal to 15 and so they have a very high probability to be occupied. It can be noticed that all the obstacles reached by the laser beam results modeled with high precision also if they are not present in the a priori map (B). Measure errors due to multiple light reflections into narrow areas can be also noticed (C). The result is a very detailed map.

Preliminary simulation tests have been performed in order to evaluate the proposed navigation system. Different obstacle configurations reproducing typical domestic environments have been considered. In both levels of autonomy, the angular width and the length of the security area are 180*deg* and 3*m*, respectively.

Regarding the first level, the navigation module activates the *Stop* procedure when an obstacle is detected in the security area. If the user imposes a safe avoidance manoeuvre before the *Stop* procedure is finished, the navigation module does not stop the vehicle and continues executing the user command.

At the second level of autonomy, the navigation module introduces some corrections on the user commands. A modified version of the obstacle avoidance algorithm proposed in (Bell et al., 1994) was developed taking into account the limited set of guidance commands and the low channel capacity, as described in section 3. When an obstacle is detected in the security area, a correction on the steering angle is made until the security area is free of obstacles and the wheelchair speed is reduced using a linear function of the imposed correction. In the Figure 5 a significant test is presented. The dotted line represents the trajectory performed by the wheelchair with the second level of autonomy as imposed by the navigation module. The arrows represent the directions chosen by the user. It can be noted that the navigation system executes the user command only if this is safe, i.e. for the *Right* command in the Figure 5. If the user commands result unsafe, the navigation system introduces corrections to them in order to guarantee a better security level for the vehicle, i.e. in the case of *Forward* command at the beginning of the navigation and of *Left* command in the second part of the navigation as showed in the same Figure 5. The navigation module maintains trajectory of the mobile base sufficiently far from the wall and from all the obstacles.

5 CONCLUSIONS AND FUTURE WORK

This paper describes a navigation system to extend the use of commercial powered wheelchairs to people with severe upper limbs disabilities.

Two user interfaces have been integrated into the rehabilitation device, an Automatic Speech Recognition program and a Brain Computer Interface, providing the user with new useful channels for communication and control.

A map building algorithm has been developed to work with a laser range finder sensor. Experimental tests performed in indoor environments have shown that the algorithm is able to build in real-time a very detailed map of the explored environment.

Different levels of autonomy for the navigation module of the wheelchair have been developed taking into account the limited set of commands and the low channel transfer rate of the chosen interfaces. Preliminary simulation tests of the developed navigation procedure have shown that it is reliable and satisfactory in terms of security and fulfillment of the user wishes. The design of the navigation module has been done by a modular architecture so that the adaptation of the navigation system to different commercial powered wheelchairs should not be too expensive. It is necessary to adapt just two modules: the control module of the power electronics of the wheelchair electric drivers, and the guidance module of the obstacle avoidance algorithm.

The analysis of the developed simulation tests has specified the necessity of some technological improvements. Information about the environment close to the lateral sides of the robot, not possible for the frontal laser, could be useful to limit the manoeuvre space and/or to enhance the security.

Moreover, an adaptive module could be introduced to let the navigation closer to the user's wishes.

These technical and methodological improvements will be developed in further research activities in order to improve the performance of the developed navigation module in different indoor environments.

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