MODELLING USER BEHAVIOUR WHILE DRIVING AN INTELLIGENT WHEELCHAIR

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Abstract: This paper reports on our user modelling work based on an empirical study of users' behaviour while driving a power wheelchair with a safety assistant. The focus was on persons with visual perceptional deficits, who show deficits to control a power wheelchair safely if no additional assistance system is available. Our major concern is to identify users' behavioural patterns which lead to the intervention of the safety assistant, although the empirical study itself covers many different research aspects. The goal of the current work is twofold: to adapt the safety assistance for users with hemianopsia who lost one half of their visual field and to improve their navigation skill in narrow space via suitable interaction.

1 MOTIVATION

The major goal of intelligent living assistance systems is to extend an independent and self-consistent life of persons with physical or cognitive deficits, or of elderly people, thus enhancing their life quality and reducing their dependency on personal health care (Nehmer et al., 2006). An intelligent living assistant should meet several requirements, for example, to be *personalized* to the user's needs, *adaptive* to the user's actions and environment, *anticipating* the user's desires. In addition, new forms of interaction are indispensable for an intelligent living assistant to compensate for users' deficits and to extend their activities (Riva, 2005; Morganti and Riva, 2005). Therefore, the focus of technology research should be on supporting people to cope with their requirements in an effective and transparent way, along with the development of specific new technologies. This requires the identification of users' characteristics (Morganti and Riva, 2005), especially, modelling users' behaviour plays an important role in developing intelligent living assistance systems like therapy robots (Lee et al., 2004; Burgar et al., 2000).

Empirical studies of intelligent living assistance robots with real users have rarely been reported in the literature. To date several empirical studies on human-robot interaction have been published (Kanda et al., 2006). However, to carry out an user based study with a living assistant, additional conditions should be taken into consideration. For example, it is necessary to identify potential user groups based on medical, cognitive, sensory-motor and epidemiological criteria. The definition of application scenarios may provide us with exemplary views of their applications (Hansen et al., 2006), but empirical studies can help us to identify users' behaviour while carrying out pre-defined activities, and can thus be used to improve important features of intelligent assistance systems such as personalization, adaptivity, acceptance and feasibility.

Our main concern in the current work is on the evaluation of a power wheelchair with a safety assistant, which has been developed in our institute (Lankenau and Röfer, 2001; Krieg-Brückner et al., pear), and on the identification of users' behavioural patterns directly before the interventions of the safety assistant. The goal is to find out whether patients with hemianopsia, neglect and with motor deficits, are able to drive a power wheelchair equipped with a safety as-

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sistant in their daily living condition, who would otherwise not be able to drive a wheelchair at all. The aim is also to adapt the safety assistant for supporting such users more intelligently.

This paper is structured as follows: We begin in Section 2 with an introduction to the wheelchair and the empirical study. The data analysis consists of two major steps: pre-processing and qualification, and is discussed in Section 3. Based on the analysis, we develop several user behaviour patterns focused on obstacle avoidance in Section 4. Before concluding, we discuss some exceptional situations and possible applications of these behaviour patterns in Section 5.

2 DO WHEELCHAIR USERS NEED SAFETY ASSISTANCE: AN EMPIRICAL STUDY

Rolland (Lankenau and Röfer, 2001) is an intelligent wheelchair that is equipped with two laser range sensors on the front and back side, wheel encoders recording the speed and direction, and an onboard computer as extensions of a commercial power wheelchair. Several assistance functions have been developed for Rolland. Several similar anti-collision and guidance systems implemented on powered wheelchairs and walkers have been reported in the literature (Dutta and Fernie, 2005; Montesano et al., 2006; Cortes et al., 2008; Röfer et al., 2009). Another approach is proposed by Kulyukin et al who set up a guidance assistance system which requires an intelligent environment embedded with inexpensive sensors (Kulyukin et al., 2008).

This work focuses on the safety assistant, which monitors the surrounding environment using sensor data gathered by the equipped laser scanners and brakes in time if an obstacle is dangerously close to the wheelchair. The user commands are passed via joystick to the safety assistant and, if no obstacle is inside a predefined *safety zone* around the wheelchair, the commands are passed unaltered to the actuators as target translational and rotational speeds. If an obstacle is detected inside the safety zone and the wheelchair is exceeding a safety speed limit with respect to the remaining distance to the obstacle, the current driving speed and the intended user commands, the safety assistant reduces the speed of the wheelchair and brings it to a standstill if necessary. Thus the safety assistant prevents the wheelchair driver from collisions causing severe injuries or damages. On the other hand the safety assistant does not affect the user commands in obstacle free areas attaining a smooth driving behaviour.

Presently, a large group of users with specific physical and cognitive disabilities, such as hemianopsia patients suffering from the loss of one side of their visual field, are often not allowed to drive power wheelchairs for safety reasons. In this section we report an empirical study aimed at answering the question: “How does the safety assistant support persons suffering from hemianopsia to drive a power wheelchair?”.

The empirical study took about 4 weeks, in close cooperation with the Department of Medical Psychology at the University of Göttingen and the St. Mauritius Therapy Clinic Meerbusch. Twelve participants with different physical and cognitive deficits took part in the study. One participant in this group suffered from dementia, three from cerebral palsy; another three participants suffered from a visual neglect. Five participants suffered from hemianopsia, but it turned out that one of them had severe comorbidities. Therefore we only included test data from four participants with hemianopsia. Prior to the test runs every participant had up to five training sessions of 30 to 45 minutes each to get accustomed to a power wheelchair with or without additional safety assistant.

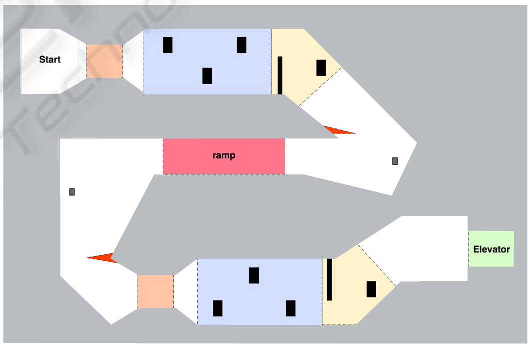

Figure 1: Plan of the test course.

The test course (see Fig. 1) was 8m wide, 14m long, and had a stretch of about 35m. The whole course was delimited by flexible partitions of 80cm height simulating a long corridor. In the test course different types of obstacles were arranged. There were left-right combinations with alternating obstacles of different height, separate low obstacles with a height of 20cm, and higher obstacles to block the drivers view onto the following obstacles. In addition, a wheelchair ramp was placed in the middle of the course. Thus the obstacle configurations contained several critical situations for a wheelchair user with a restricted visual field. Furthermore, the course was constructed symmetrically, such that it provided the same conditions for the subjects with hemianopsia on the left or on the right side. The participants were asked to drive through the test course up to a dead end representing a narrow elevator. After they had reached this dead end they had to turn the wheelchair and return to the starting point.

3 DATA ANALYSIS

3.1 Pre-processing

During the test runs we recorded several wheelchair data such as the wheelchair translational speeds (denoted as OdoSpeedTranslX) and rotational speeds (i.e. the speed of directional changes, denoted as OdoSpeedRotation), as well as the joystick commands, including the intended speed and direction denoted as JoystickSpeed and JoystickDirection. Furthermore, we recorded the safety speed limit (MaxSafeSpeed) described in Section 2. Every test run was also documented with six video cameras recording the test process from different points of view, to support the analysis of the driving behaviour of the participants.

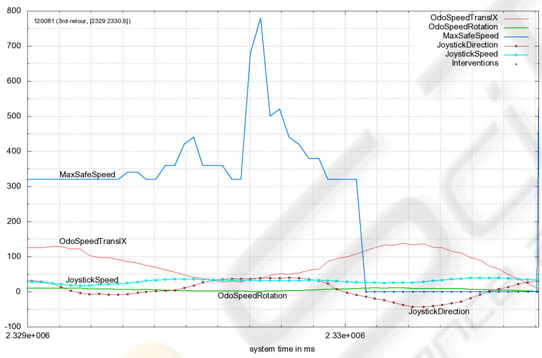

Figure 2: A sample of safety relevant situations.

Persons with hemianopsia are supposed to have problems identifying obstacles on their blind or not perceiving side while driving a power wheelchair. The analysis of the recorded wheelchair data confirms that participants with hemianopsia had a higher occurrence of safety assistant interventions when passing narrow passages or obstacle configurations with alternately left and right positioned obstacles. Moreover, the interventions are concentrated at locations where participants passed obstacles positioned on the deficit side. For this reason we decide to use such situations for our analysis purpose.

Figure 2 shows a sample situation, in which the odometric data recorded the behaviour of a participant with hemianopsia on the left side continuously. The visualized odometric data exhibits that the wheelchair speed changes from 125 to 30, and from 30 to 120 directly before the intervention. In the whole time there is only a slight rotation speed toward the left. The joystick direction changes slightly to the right, and again to the left. Directly before the intervention the joystick direction is changed to the right again. A global view of the situation is presented in Figure 3, where the wheelchair is stopped by the safety assistant.

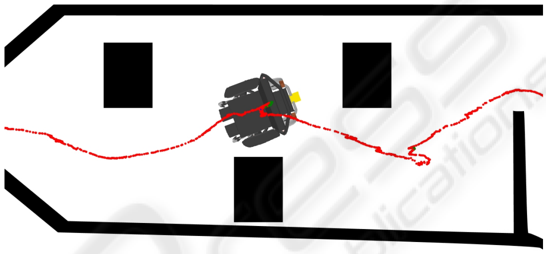

Figure 3: A participant drives the wheelchair through a right-left-right obstacle combination while having problems to pass the second obstacle on the hemianoptic side.

3.2 An Approach to Data Abstraction

Usually, humans explain, perceive and process spatial situations in a qualitative manner, which does not directly mirror the actual measures in real life. In Artificial Intelligence, such mental conceptualizations of space are formalized and modeled in the subfield of qualitative spatial representation and reasoning. This kind of abstraction can make valuable predictions about human spatial behavior (Cohn et al., 1997; Freksa, 1992; Shi and Krieg-Brückner, 2008). The abstraction of the empirical data in the present work has two additional reasons: to enable a qualitative analysis of the safety relevant situations, and to identify and specify users' behaviour patterns.

The recorded wheelchair's rotation speed has values between -30 and 30 in millimeters per second, and the direction given via the joystick between $-180°$ and $179°$, where the positive values represent the left side and negative values the right side. We distinguish them by four qualitative values: *front*/*back* for forward/backward movements or commands, *deficit* or *normal* for any rotation or command toward the subject's deficit or normal side, respectively. If the subject's deficit side is on the left, then the rotation speed -20, for example, is interpreted as *normal*, or the direction 50 as *deficit*. Rotation speed ranging from -5 to 5 or direction from -10 and 10 is interpreted as *front*, and the direction from 170 to 179 or from -180 to -170 as *back*.

Furthermore, four qualitative values have been introduced to interpret speeds, i.e., *standStill*, *slowSpeed*, *midSpeed* and *fastSpeed*. The translational speed ranges from -400 to 400 millimeters per second, the speed given via the joystick from -64 to 63, and the maximal safety speed between -3000 and 3000 millimeters per second.

Table 1 contains the mapping between the ranges of metric speed data and their qualitative correspondings.

Table 1: Abstraction of the metric speeds.

Abstract.	*standStill*	*slowSpeed*	*midSpeed*	*fastSpeed*
Wheel-chair speed	(0, 20)	(20, 100)	(100, 200)	(200, 400)
Joystick speed	(0, 4)	(4, 16)	(16, 32)	(32, 63)
MaxSafe Speed	(0, 50)	(50, 500)	(500, 1000)	(1000, 3000)

We decided on these qualitative representations, because an abstraction with finer granularity, for example, with more qualitative directions or speeds, did not deliver more information about safety relevant behaviour, but increased the complexity of the modelling process. On the other hand, it was impossible to distinguish any meaningful patterns with a coarser abstraction.

4 MODELLING USERS' BEHAVIOUR

4.1 Safety Relevant Situations

A set of situations, which lead to the intervention of the safety assistant, called *safety relevant situation*, has been selected by analyzing the odometric data. As stated in the last subsection, we first interpret these situations qualitatively to enable pattern identification. Each situation contains two safety relevant points: a *critical* one and an *unsafe* one. At the *critical point*, the user still has enough time to pass an obstacle located at his/her deficit side without the intervention of the safety assistant. However, if an unsafe point is reached, the intervention is indispensable to avoid the collision. At a critical or unsafe point the safety speed limit has a value of *midSpeed* or *slowSpeed* respectively.

Table 2 shows two samples of critical points detected in test runs of a subject with hemianopsia on the left side, in which the safety speed limit is reduced in the middle range and the wheelchair is approaching an obstacle on the left hand side. In the first case the wheelchair moved slowly and rotated slightly to the left, and the command given by the subject was to drive straight with a moderate speed. The second case describes a situation, in which the wheelchair moved slowly forward, and the subject commanded the wheelchair to move slowly toward the right front.

Table 2: Sample critical points: the subject has the deficit side on the left.

	OdoSpeed TranslX	OdoSpeed Rotation	Joystick Speed	Joystick Direction
1	*slowSpeed*	*leftSlow*	*midSpeed*	*front*
2	*slowSpeed*	*front*	*slowSpeed*	*rightFront*

A critical point may be changed to an unsafe one by joystick commands given by the user, see the two examples in Table 3, which followed the two cases in Table 2. They were reached by giving the left front as the next direction in the subject's last command.

Table 3: Sample unsafe points resulting from *leftFront* as next direction.

	OdoSpeed TranslX	OdoSpeed Rotation	Joystick Speed	Joystick Direction
1	*slowSpeed*	*leftSlow*	*fastSpeed*	*leftFront*
2	*fastSpeed*	*rightSlow*	*midSpeed*	*leftFront*

4.2 Identification of Behaviour Patterns

After analyzing a total number of 21 safety relevant situations found in the test runs of the four participants with hemianopsia, we identified the following three behaviour patterns, each of which is divided into a *critical* and an *unsafe* part.

4.2.1 Pattern 1

In 12 out of 21 safety relevant situations the following behaviour has been identified: the subject drives toward his or her hemianoptic side – the side with the visual deficit – and away from an obstacle that is well perceived on the non-hemianoptic side. The critical point of this pattern is specified as follows: the wheelchair moves forward or rotates toward the user's hemianoptic side and the user keeps commanding the wheelchair to move in this way. At the same time the qualitative value for the safety speed limit is reduced to a value in the middle speed range because of an approaching obstacle. If the described movement continues and the value for the safety speed limit is reduced to *slowSpeed* at the same time, the unsafe point of this pattern is reached (see Figure 2 for an example). Table 4 contains the qualitative definition of the pattern.

4.2.2 Pattern 2

In four of the 21 situations we have identified a behaviour pattern, in which the subject kept driving toward his/her normal side if possible, in order to avoid obstacles that may occur at his/her deficit side. If the user tries to avoid an obstacle located on the normal side by steering the wheelchair to the other side, but does not notice an obstacle located on the deficit side, an intervention of the safety assistant is necessary to avoid a collision with the obstacle located on the deficit side; see Table 4 for its specification. In this pattern, the change of the critical point to the unsafe one is caused predominantly by the change of the joystick direction from the normal side to the deficit side.

4.2.3 Pattern 3

The third pattern describes situations in which the subject commanded the wheelchair to carry out an obstacle avoidance maneuver by driving backwards, however the safety module intervened to avoid a collision with an obstacle located in the back of the wheelchair; see Table 4 for its definition. In this pattern the rotational direction of the wheelchair is insignificant. This pattern is found in 3 out of 21 situations.

5 DISCUSSION

The three behaviour patterns cover 19 of 21 situations, but the remaining two situations cannot be identified by any reasonable pattern.

The related video material exhibited that the subjects tried to apply several different steering commands to navigate the wheelchair through the narrow obstacle configuration. These changes of driving directions in a short temporal sequence led to unpredictable orientations of the caster front-wheels. Although the intended steering commands are appropriate at that moment, the wheelchair could not follow the subject's commands in time. The subjects were confused by the wheelchair's behaviour, since they were not aware of the position of the caster front-wheels. As a consequence, they behaved unpredictably. This phenomenon implies the existence of a mode confusion, in which the wheelchair is situated in a state different from the one expected by the subject. Mode confusions occur typically in shared-control systems (Thimbleby, 1990), such as the wheelchair.

During the experiment we observed another mode confusion phenomenon: almost all subjects acted uncommon after the intervention of the safety assistant: they attempted to regain control over the wheelchair, but the wheelchair did not drive in the way they expected; as a result they tried to give the wheelchair some arbitrary commands via the joystick or pressed the joystick powerfully, which caused an even less expected movement of the wheelchair. Mode confusion situations can be avoided through the improvement of the system's behaviour or providing the user with suitable clarification (Thimbleby, 1990).

An interesting application of the critical patterns developed in Section 4 could be to support the rehabilitation process of neglect and hemianopsia patients with cognitive and motor deficits. These patterns enable the wheelchair to inform the user about a possible collision with an approaching obstacle in advance, which would otherwise be noticed too late or, even worse, ignored due to their spatial perceptional problems. Instead of the current feedback from the wheelchair, i.e., the disregard of the user's commands given via the joystick and the braking process in unsafe situations, some acoustic signal, for example, could be used to inform the user of an approaching obstacle on his/her impaired side. As a consequence the user could be trained to drive the wheelchair more smoothly or even without the safety module in a narrow environment.

On the other hand, the behaviour patterns provide us with helpful information to improve the existing safety assistant. In our data we counted up to 5600 interventions in a single test run by some participants, which is inconvenient in real life in spite of the guaranteed safeness. As a possible solution, the safety assistant can be extended with a module that modifies the joystick commands if a situation matching an unsafe pattern has been detected, to compensate users's visual deficits, and reduce the number of the interventions of the safety assistant.

Finally, the current work makes it clear that user studies with an intelligent living assistant and real users present us with hard challenges. They require close cooperation of engineers, neuropsychologists, and other medical professionals. In addition to the experiment design, test environment construction, realization, data analysis and user modelling, the accreditation of a homogeneous user group turned out to be the most difficult one, at least if the group consists of persons with specific cognitive or physical deficits. In

Table 4: Pattern definitions.

	Pattern 1		Pattern 2		Pattern 3	
	Critical	Unsafe	Critical	Unsafe	Critical	Unsafe
MaxSafeSpeed	*midSpeed*	*slowSpeed*	*midSpeed*	*slowSpeed*	*midSpeed*	*slowSpeed*
OdoSpeedTranslX	$\geq$ *slowSpeed*	$\geq$ *slowSpeed*	$\geq$ *slowSpeed*	$\geq$ *slowSpeed*	$\geq$ *slowSpeed*	$\geq$ *slowSpeed*
OdoSpeedRotation	*deficit*, or *front*	*deficit*	*normal*, or *front*	*deficit*	-	-
JoystickDirection	*deficit*	*deficit*	*normal*	*deficit*	*back*	*back*

fact, we originally planned to carry out the experiment with 12 patients with hemianopsia, however, over the duration of the experiment only four patients in the therapy clinic, who met all the requirements, were available for our experiment.

6 CONCLUSIONS

The research work presented in this paper is an empirical study with a real user group and an intelligent assistance system. Specifically, we analyzed the data collected in the experiment carried out with a group of persons who are affected by hemianopsia, and studied their behaviour while driving an intelligent wheelchair passing obstacles located on their impaired side. The analysis process consists of the selection of relevant data segments, interpreting the relevant odometric data, and abstracting the data qualitatively. As a result three behaviour patterns have been identified and discussed.

The application of these behaviour patterns is twofold. First, it enables the development of an adaptive user interface, such that users can learn how to control an intelligent mobile assistant smoothly, even though he/she has visual/spatial perceptional problems. On the other hand, the improvement of the safety assistant by adding an extra functionality to compensate the user's deficits is work to do. In future experiments, we shall evaluate whether the *driving assistant*, which has been developed to avoid obstacles automatically (Krieg-Brückner et al., pear), will overcome such situations.

As discussed in Section 5, we are going to handle the mode confusion problems by comparing the user's behaviour with that of the wheelchair after the interventions of the safety assistant. This requires the construction of a user model using the relevant data collected in the experiment introduced in Section 2. On the other hand, the abstraction of the wheelchair's behaviour is also necessary, such that they can be compared directly for detecting mode confusions. Furthermore, the qualitative models can even be specified formally, thus an automatic mode confusion detection process is possible by using formal techniques (e.g. model-checking, cf. (Rushby et al., 1999; Heymann and Degani, 2002; Bredereke and Lankenau, 2002)).

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