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Easing Wheelchair Control by Gaze-based Estimation of Intended Motion

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Abstract: An assistive system easing wheelchair control for severely disabled users is presented. To compensate for the restricted information that can be provided using speciality controls, the person's gaze is used to estimate the intended motion direction. The novelty of the presented method is that motion-relevant portions of natural gaze behavior can be distinguished from non-relevant. Producing wheelchair movement only from relevant gaze information leads to an increased acceptance of powered wheelchairs in the user group and to improved safety.

1. INTRODUCTION

For disabled or elderly persons with heavily reduced physical and/or mental abilities steering powered wheelchairs by means of a conventional joystick is hardly possible. For these persons special control devices (e.g. button pads or sip-puff devices) have been developed. Due to the reduced command set such input devices provide, their use is time-consuming and tiring, leading to significantly reduced acceptance among the user group.

Many approaches of increasing wheelchairs' usability by introducing assistive and autonomous functionalities exist (see e.g. Lankenau *et al.*, 2000 or Demeester *et al.*, 2003). Though, most of these are not suited for severely disabled persons due to the reduced information provided via special input devices. Furthermore, many approaches require knowledge about the environment to be able to provide support.

To enable convenient and dependable support, an approach is needed, that retrieves additional information about the wheelchair driver, without raising the workload imposed on the user. For this purpose, the presented assistive system estimates the currently intended direction of movement of the user by evaluating his/her gaze behavior. Based on this information in a next step appropriate wheelchair locomotion is generated. The user remains in direct control, as his/her input given via speciality device is used to enable and disable wheelchair motion.

2. EXISTING APPROACHES

Using gaze to compensate for the limited bandwidth provided by special input devices is not a completely new idea within the wheelchair domain. Eye movements measured via EOG (electrooculographic potential) are used to interpret wheelchair movement commands. This can be done either directly (e.g. looking up means increase of speed) (Barea *et al.*, 2003) or by selecting icons on a display (Yanco, 2000). One major drawback of such explicit eye control methods is that the user has to learn special commands and control is unintuitive in many cases. This led to the idea of implicitly using the person's natural gaze behavior.

Adachi *et al.* (2004) use a camera and image processing methods to detect gaze direction. Knowing where the user currently looks at, the point of attention is estimated in a known environment to change the route of an autonomously driving wheelchair. Thereto, an attention histogram representing the spatial distribution of recent fixations is built. In Kuno *et al.* (2003) face direction along with environmental information is used to generate the wheelchair's driving direction and averaging is applied to prevent quick head rotations from having an effect. Nodding of the driver detected via face tracking is used to start and stop wheelchair motion.

The basic assumption of these approaches is that the user wants to go where he/she is looking at "for a while". No profound physiological or psychological knowledge about the link between gaze and humans' locomotion has been considered. However, such a direct coupling of gaze or head orientation and intended driving direction neglects the existence of unintentional eye and head movements (e.g. looking around while searching) and therefore will produce inappropriate or even safety-critical output in many cases. Furthermore, by only relying on gaze and omitting input methods severely disabled are used to, the operator's feeling of being in control is substantially decreased, which also can lead to potentially dangerous situations.

Summarizing, it can be assumed that interpretation of natural gaze behavior in general seems to be an adequate method for easing wheelchair control. Preconditions are that the user is given means of direct control and that relevant gaze behavior can be distinguished from irrelevant. Combining the gaze-based estimation of the preferred motion direction with the user's restricted manual input should enable meaningful assistive functionality.

3. GAZE BEHAVIOR DURING LOCOMOTION

Physiological trials document strong correlations between humans' gaze and locomotion. Prior to changing movement direction anticipatory eye and head movements occur, indicating where the person intends to go (see e.g. Hollands *et al.*, 2002 or Imai *et al.*, 2001). Though, not every change in gaze direction during motion is induced by an intended directional change. This is for instance the case, when being distracted by environmental cues or while searching in the environment.

Based on the aforementioned physiological findings and self-recorded gaze data from several test persons a set of distinctive gaze patterns occurring during wheelchair navigation has been identified (see Table 1).

Table 1. Identified gaze states typically occurring during wheelchair navigation.

Gaze state	**Abbreviation**	**Description of gaze behavior**
straight	st	constant towards front
preparing left/right	pl, pr	rising deviation to left/right with moderate slope
turning left/right	tl, tr	constant deviation to left/right
realigning left/right	rl, rr	realigning towards front direction from left/right
searching left/right	sl, sr	rising deviation to left/right with high slope and immediate return to front
distracted left/right	dl, dr	rising gaze to left/right with high slope and remaining deviation

Motion-relevant patterns comprise looking to the front while driving straight and three phases occurring during directional change (denoted here as "preparing" turn, "turning", and "realigning"). Being distracted by environmental cues, characterized by fast but remaining gaze deviations, and searching the environment, producing fast and short deviations, have been identified as important motion-irrelevant patterns (see Bartolein *et al.*, 2007).

4. SYSTEM SETUP

4.1 Wheelchair prototype

A commercial electrically powered wheelchair of *Otto Bock Healthcare GmbH* serves as basis for the gaze-based assistance system. It has been equipped with a head-mounted eye tracking device of *SensoMotoric Instruments GmbH,* as shown in Fig. 1. Incorporating a magnetic head-tracking, the eye tracking device provides the user's current gaze direction in relation to the wheelchair.

Fig. 1. Wheelchair prototype equipped with head-mounted eye tracking device and collision avoidance sensors.

To prevent collisions with obstacles the prototype is equipped with ultrasonic as well as infrared sensors. A more detailed description of the assistive wheelchair is given in Bartolein *et al.* (2007).

4.2 Motion generation based on user's gaze

The generation of suitable wheelchair motion depending on the disabled user's gaze is conducted in two successive steps (see Fig. 2).

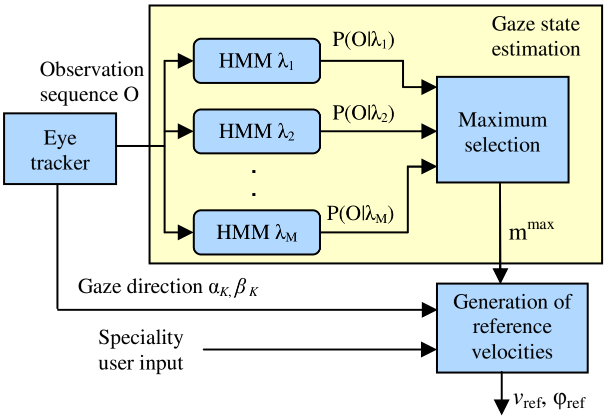


Fig. 2. Generation of suitable wheelchair motion by estimating the user's current gaze state.

First, based on the gaze observation sequence O delivered by the eye tracking device, a setup of Hidden Markov Models (HMM) is used to estimate the user's most probable gaze state m^{max}. A detailed description of the estimation procedure is given in Section 5.

Subsequently, now knowing if the user is currently in a motion-relevant or motion-irrelevant gaze state, indicating, if he/she really wants to move into the accordant direction, adequate wheelchair motion can be initiated. The generation of the translational and rotational reference velocities v_{ref} and φ_{ref} and the resulting behavior of the wheelchair are specified in Section 6.

5. ESTIMATION OF USER'S GAZE STATE

5.1 Modeling of gaze states

To determine the currently active gaze state, all identified gaze patterns (see Section 3) have been modeled using sequential HMMs (see Rabiner, 1989) for looking to the left and right. The observation sequence $O=O_1O_2 \ldots O_K$ serves as input to the set of HMMs and is provided by the eye tracker at a frequency of $10\,Hz$. It consists of elements $O_k=(\alpha_k, \Delta\alpha_k)$, where the angle $\alpha \in (-\pi, \pi]$ represents the horizontal gaze deviation, and

$$\Delta\alpha_k = \alpha_k - \alpha_{k-1}, \qquad 1 \le k \le K \qquad (1)$$

describes the horizontal gaze deviation change. The observation sequence length K has been set to ten, to observe the gaze behavior during the last second.

Every HMM $\lambda = (A, B, \pi)$ possesses N internal states and is defined by its state transition probabilities A, the observation probabilities B, and the initial state probabilities π. As the observations α and $\Delta\alpha$ are of continuous nature, the observation probability for model state n is calculated via the two-dimensional Gaussian probability density function

$$b_n(O_k) = \frac{1}{\sqrt{(2\pi)^2 \det(\Sigma_n)}} e^{-\frac{1}{2}(O_k-\mu_n)^T \Sigma_n^{-1}(O_k-\mu_n)}, \qquad (2)$$

where Σ_n is the covariance matrix and μ_n the mean vector.

In every time step the likelihood $P(O \mid \lambda_m)$ for producing the sequence of the last K gaze observations is calculated for all M HMMs via the forward algorithm (Rabiner, 1989). The most probable gaze state of the user is given by

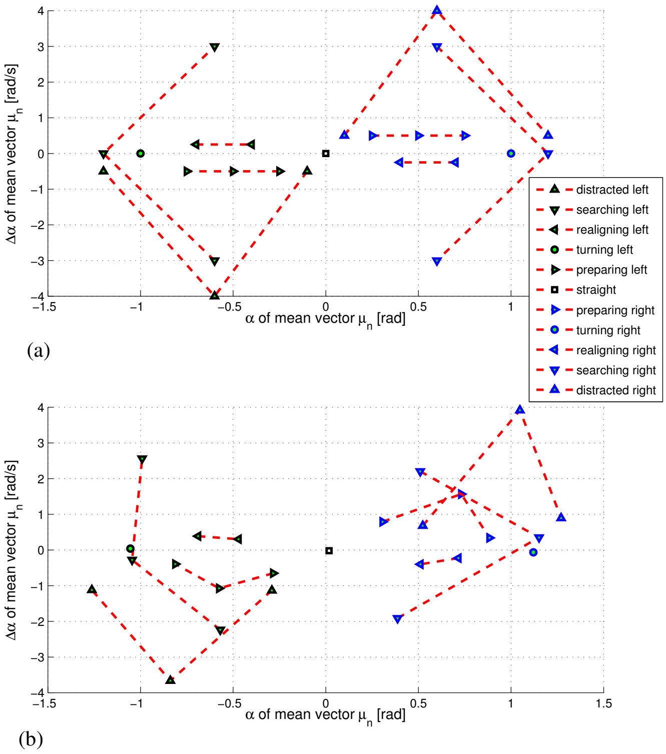
$$m^{\max} = \underset{1 \le m \le M}{\arg\max}\left[P(O \mid \lambda_m)\right], \qquad (3)$$

the HMM providing the highest likelihood for generating the given observation sequence O.

The number N of states used within each model, depends on the complexity of the pattern to be modeled. The constant gaze to the front for the model "driving straight" can be modeled by a single-state HMM. For "searching" or "preparing turn" at least three phases must be taken into account, resulting in models with three states.

5.2 Adaptation of model parameters

The parameters for the state transition probabilities A and the observation probabilities B have initially been set by investigating gaze behavior recordings from several persons during all described gaze states. These chosen general model parameters show satisfactory estimation results for people with normal gaze behavior. People with severe disabilities often show high inter-individual differences in gaze behavior (e.g. asymmetries for looking left and right). For them, using general parameters is not sufficient. The parameters need to be trained to their individual gaze. This is done by recording gaze data (training sets) for all gaze states and adapting the parameters using the Baum-Welch algorithm, which maximizes the likelihood of the training set observations.



(a)

(b)

Fig. 3. Elements α and Δα of mean vectors μ_n for all eleven HMMs before (a) and after training to specific person (b).

Adapting model parameters also improves recognition quality for persons with normal gaze behavior. Fig. 3 shows the adaptation of the mean vectors μ_n for all gaze states for such a person.

5.3 Estimation performance

To test the described gaze state estimation and to judge about the improvements of individual parameter adaptation, gaze data was recorded while driving the wheelchair.

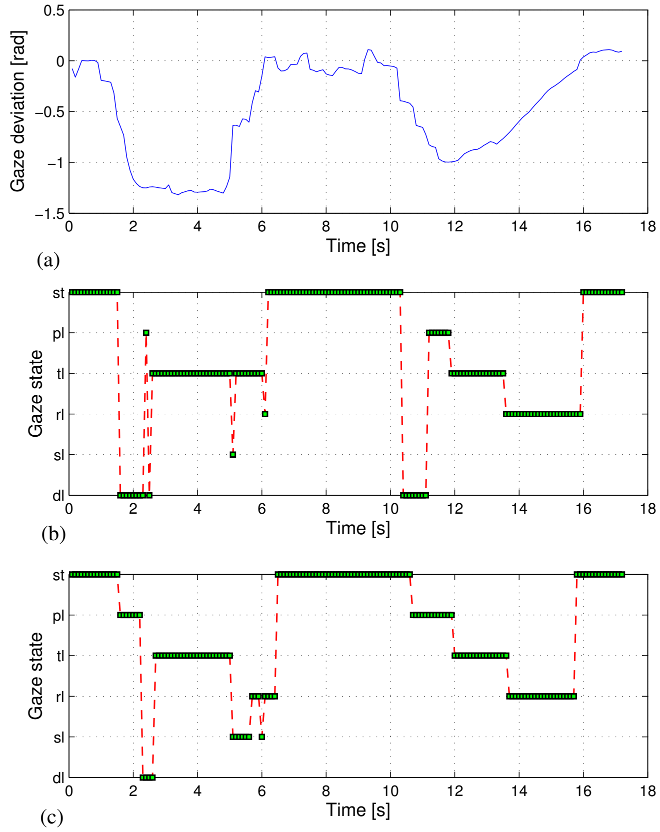


Fig. 4. Exemplary gaze recording (a) interpreted with standard HMM parameters (b) and parameters trained to test person (c).

Fig. 4(a) shows the horizontal gaze deviation of the test person. After initially driving straight for one second the person is being distracted to the left (second two till five), then drives straight again for four seconds and finally conducts a 90° left turn until second 16.

The estimated gaze states for all time steps of the given gaze recording are depicted in Fig. 4(b) for the general HMM parameters and in Fig. 4(c) for the trained parameters presented in Fig. 3(b). In both cases the distraction at second two is recognized correctly. Due to the observation period of one second the following constant deviation is detected as "turning" state. The start of the 90° turn at second ten is interpreted falsely as another distraction by the untrained setup due to the, for a normal gaze behavior, atypically high slope at its beginning. In contrast, the trained setup correctly identifies the directional change with all its phases ("preparing", "turning", and "realigning").

6. GENERATION OF WHEELCHAIR MOTION

After knowing about the motion relevance of the user's current gaze, appropriate translational and rotational reference velocities v_{ref} and φ_{ref} for moving the wheelchair can be generated. For this purpose, in addition to the gaze state information, the user input given via speciality control (e.g. sip-puff device) and the current horizontal and vertical gaze deviations α_K and β_K are considered (see Figure 2).

6.1 Modeling of user input states

Due to the great range of kinds and degrees of disabilities different types of speciality controls used by disabled

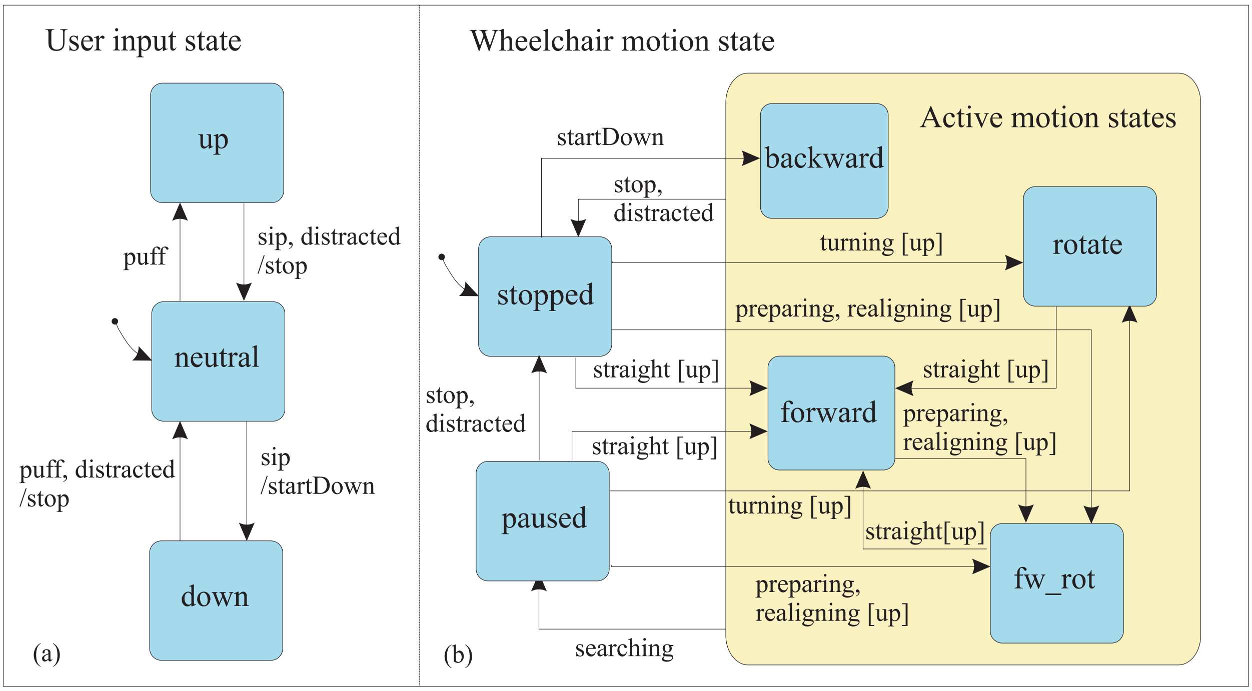


Fig. 5. Statechart setup for processing sip-puff user input (a) and determining wheelchair motion state (b). Both state machines work concurrently and communicate via production and consumption of events (e.g. "stop"). Some state transitions are bound to conditions (e.g. "up").

wheelchair users must be covered. Therefore, a flexible approach based on individually configurable finite state machines (FSM) has been chosen. Figure 5(a) shows the processing of user input on the example of a sip-puff device possessing the two-symbol alphabet “sip” and “puff”. To allow concurrency of several FSMs (in particular with the motion state FSM described in the following section), the so-called Statechart notation, introduced by Harel (1987), is used. Starting in the “neutral” state, the FSM roams through the states “up”, allowing forward motion, and “down”, enabling backward motion, according to the given sip/puff inputs. Additionally, the occurrence of a “distracted” gaze state resets the FSM to “neutral” from any motion-enabling state. Furthermore, some state transitions trigger events, e.g. “stop” when going from state “up” to “neutral”.

6.2 Modeling of wheelchair motion states

Having knowledge about the user’s current gaze state and the user input state, suitable wheelchair movement can be generated. Thereto, a set of reasonable motion states has been defined, describing potential movements intended by the user. Table 2 shows, how the translational and rotational reference velocities v_{ref} and φ_{ref} are created, according to the active motion state. Rotational motion is calculated depending on $sin\ \alpha_K$, as higher horizontal gaze deviation should lead to faster rotation. A factor of 0.6 is used to obtain convenient turning radii. If the user looks downwards (indicating interest in closer surrounding), locomotion speed is to be decreased. Therefore, the translational speed is generated using $cos\ \beta_K$. For further details see Bartolein *et al.* (2007).

Table 2. Reference velocity outputs of motion states.

Motion state	**Abbr.**	v_{ref}	φ_{ref}
motion stopped	stpd	0	0
motion paused	psd	0	0
forward motion	fw	$V_{max}\ cos\ \beta_K$	0
rotational motion	rot	0	$\varphi_{max}\ sin\ \alpha_K$
combined forward /rotational motion	fw_rot	$V_{max}\ cos\ \beta_K$	$0.6\varphi_{max} sin\ \alpha_K$
backward motion	bw	$-0.5V_{max}$	$\varphi_{max}\ sin\ \alpha_K$

The motion state generation is illustrated by the Statechart given in Figure 5(b). Transitions to new motion states depend on events triggered by motion state changes (e.g. “distracted” when gaze state “distracted left“ or “distracted right” becomes active) and events issued by the user input FSM (e.g. “stop”). Some of the state transitions are conditional. For example, the transition from “stopped” to “straight” only occurs, if “straight” is the current gaze state and the user input FSM is in state “up”. To prevent single gaze state occurrences from having an effect, a new gaze state becomes active after occurring three times in a row.

To avoid wheelchair movement not intended by the user, the states "paused" and "stopped" have been introduced. Short gaze changes in fast succession, as typical for visual search behavior, cause the vehicle to pause motion and, when the user decided about where to go (visual search finished), to automatically resume motion towards the newly intended direction. In case of fast but sustained gaze deviations, indicating lasting distraction of the user's visual attention, locomotion is stopped by setting the input state to "neutral" and must be explicitly re-initiated via speciality control. In contrast, the solution of Kuno (2003), being based on simple averaging, might produce unintended wheelchair motion, at least for longer lasting gaze deviations.

7. EXPERIMENTAL RESULTS

To test if the described gaze-based motion generation approach produces reasonable output to potentially ease wheelchair navigation for severely disabled users, trials in an indoors scenario were conducted. Fig. 6 shows data recorded with the trained gaze state estimation setup presented in Section 5 and the according test person.

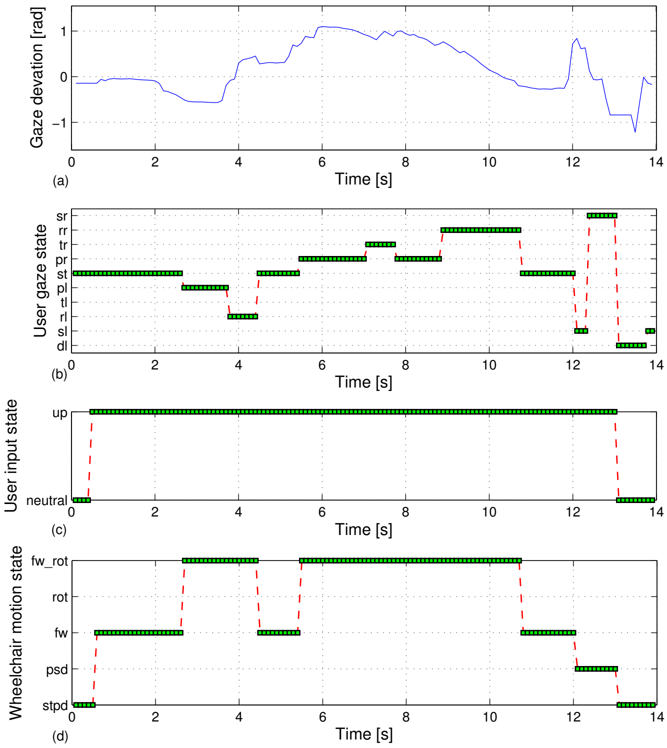


Fig. 6. According to the present gaze behavior of the person (a), the gaze state is detected (b). In combination with the issued user input (c), the gaze state decides about the active motion state of the wheelchair (d).

In the shown extract the person gives a “puff” command during second one, causing the input FSM to go from “neutral” to “up” state (see Fig. 6(c)). Shortly after that, the motion state changes from “stopped” to “forward” (Fig. 6(d)), as the person is looking to the front direction at this time (Fig. 6(a)). In the following the user looks first to the left for around two seconds and then, after a short period of looking straight, gaze deviates to the right with a higher magnitude from second four to ten. As the according motion-relevant gaze states are detected correctly (see Fig. 6(b)) and the user input FSM remains in “up”, the motion state changes to “fw_rot”, “straight” and again “fw_rot”. At second twelve the test person starts searching the environment to both sides in fast succession. The gaze state estimation first detects “searching” behavior and then, due to the gaze remaining to the left, a distraction. This causes the motion state to go into “paused” and shortly after to the “stopped” state. Concurrently, the user input state is reset to “neutral”, when the gaze state changes to “distracted”.

The wheelchair motion produced during the presented trial period is shown in Fig. 7. The trajectory plotted in part (a) shows, that after starting in the origin, the wheelchair performs a slight turn to the left and afterwards a longer turn to the right, according to the detected motion-relevant gaze states for turning to the left respectively to the right. Fig. 7(b) presents the corresponding change in the wheelchair’s orientation. To obtain pure gaze-based motion behavior, collision avoidance functionality was switched off during the trials.

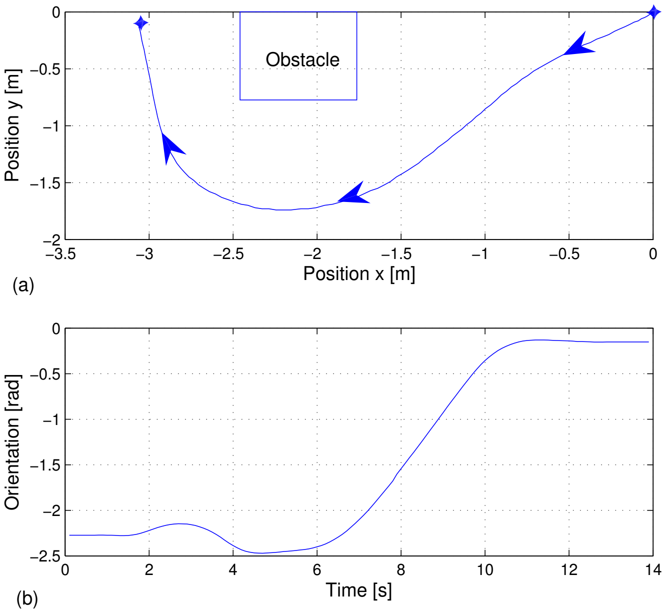


Fig. 7. Trajectory followed by the wheelchair during the trial (a) and corresponding change in orientation (b).

8. CONCLUSION

An approach for generating comfortable wheelchair motion for severely disabled users is presented. The main feature of the developed method is the estimation of the movement direction currently intended by the wheelchair user. For this purpose, the driver’s natural gaze behavior is investigated and motion-relevant gaze portions are identified. These portions are then used, along with the user’s specialty input, to produce suitable wheelchair motion taking the user safely to the intended goal. Furthermore, the proposed approach of estimating the driver’s current gaze state using HMMs provides good adaptability to individual gaze behavior of disabled persons. Due to the considerably reduced handling effort compared to traditional wheelchair control, the presented approach should find high acceptance within the target group of severely disabled.

To quantify the presented method’s benefits compared to the special input devices traditionally for severely disabled a comparative study will be carried out.

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