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Motion Tracking Hands-free HMI of Electric Wheelchair

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Abstract. The rise in mobility challenges due to aging populations has increased the need for innovative wheelchair technologies. Many users struggle with traditional power wheelchairs, finding them unusable and experiencing difficulties in steering. The solution, proposed by the author, is a novel side-by-side and hands-free Human-Machine Interface (HMI) for an omnidirectional electric wheelchair. It is designed to use a vision-based interface, with cameras capturing the head and torso movements of both the rider and a caregiver. Their motion intentions are interpreted and combined through shared control to produce velocity commands, enabling intuitive and collaborative navigation. This paper focuses on the hands-free HMI working principle. It analyzes how detects and processes the movements of the rider. The inputs are translated into linear and angular velocities relative to the wheelchair base, allowing navigation without using hands. Simulations validate the interface's ability to drive the wheelchair smoothly around obstacles, aligning commands with user intentions. The system offers adjustable sensitivity to accommodate different movement thresholds to generate velocities.

Keywords: SDG 3, motion tracking, Human Machine Interface, Wheelchair, Disability, vision system

1 Introduction

The median age of the population is constantly increasing and this affects the growth of people with walking diseases. In the European zone, the number of people with mobility limitations is over 120 million people by 2020 [1]. According to studies up to 10% of people find it difficult or impossible to use a traditional power wheelchair, another 10% have problems steering without help, and 40% struggle with steering [2]. Moreover, omnidirectional movements perform better in narrow indoor environments [3, 4].

Nowadays the use of new Human-Machine Interfaces (HMI) enables the development of intelligent wheelchairs. The various innovative ways of wheelchair control with a free-hand interface use: EEG [5], eye gaze [6], tactile information [7], IMU and visual information [8], and tongue [9]. Throughout the above and other research and development efforts, the actual challenge is the development of a wheelchair that fits with human life standards like: free to move, inclusion, satisfying social life and happiness. Furthermore, allowing temporary and life-long users to manage their mobility is a goal of the highest interest, capable of restoring quality of life to these people. From this point of view, the implementation of an HMI adapted to the user's disability and capable of assisting the user in navigation is very important.

The authors propose an HMI system to estimate the intentions of both the users of the wheelchair: the driver and the caregiver. The main idea is to develop a sort of shared control of the wheelchair movements, combining the two agents' intentions and defining a set of different rules and various driving solutions in which one of the two agents has priority and the other can make some adjustments. The HMI collects the movements of the face and torso of the rider and caregiver through the vision system and generates the velocity reference for the wheelchair. Thanks to this it is possible to drive the wheelchair with the rider's movements, the caregiver's movements, or with the combination on a hands-free basis. This aim also is addressed in the UN Sustainable Development Goals n. 3, Good Health and Well-Being. This paper mainly discusses the development of a vision system, and some experimental validation to show its feasibility and capability for constructing HMI in the future.

1.1 Explanation of hands-free and side-by-side function

Fig. 1 shows the working principle of the hands-free side-by-side wheelchair. Thanks to the cameras on the left and right armrests, the head and torso movements of the rider and the caregiver are acquired by using specific algorithms of face and torso recognition [10, 11]. These algorithms are calibrated to collect the pose of the head and shoulders

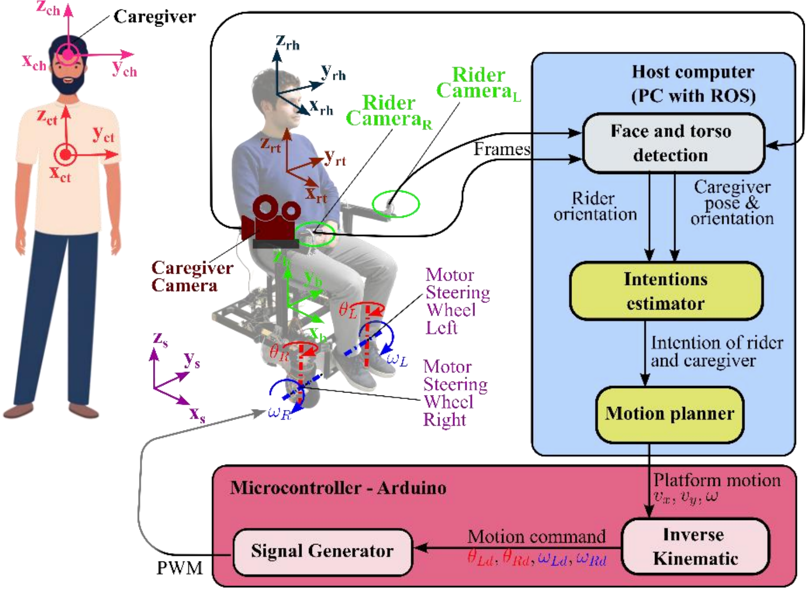

Fig. 1 Working principle of the hands-free side-by-side wheelchair.

with respect to (w.r.t.) wheelchair base reference frame. The pose of the shoulder is detected according to the position of some characteristic points of the shoulder called landmarks. By monitoring the landmarks in the image frame of the cameras and using some algebraic calculations, it can estimate the position and the rotations of the shoulder. The detected pose of the rider head is acquired thanks to an algorithm that has already been validated in our precedent research [8]. The same logic will be applied to detect the caregiver's pose of the head and torso, and both the user and caregiver pose represent the rider and caregiver's intention of motion. These intentions are simultaneously sent to the intention estimator, which analyzes and interprets all the data to provide a unique intention output from the rider and caregiver.

There are several possible approaches to determining a single multidimensional command signal by combining requests from two agents. This paper does not address this aspect but focuses on techniques to produce a command from only one of the two agents. The motion planner is in charge of producing the velocity command, it transforms the intentions into two linear along the x and y axis and one angular around z for the. Finally, the velocity references are transformed into motion commands for the traction motors and the steering motors. The peculiarity of this working principle is the minimal use of physical contact to drive the wheelchair. The signals are mostly acquired without the need for the use of the hand or any other specific contact between a human and a wheelchair.

2 Hands-free HMI working principle

This paper will focus on how the rider's intentions are used to produce a velocity command for an omnidirectional wheelchair, using the so-called hands-free Human Machine Interface (HMI). Fig. 2 shows the relationship between coordinate frames to establish the proposed HMI working principle. The main objects in this drawing are presented with the reference frame: space {s}, wheelchair base {b}, right camera {camR}, left camera {camL}, torso (or shoulder) of rider {rt}, head of rider {rh}. The two

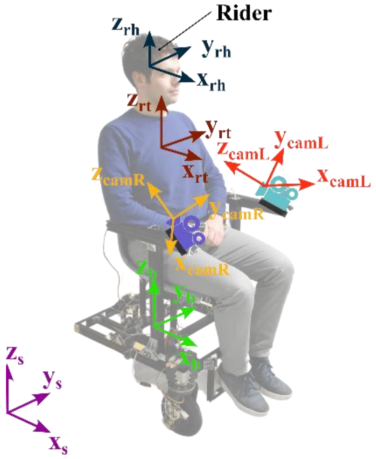

Fig. 2 Reference systems of the components of HMI between wheelchair and rider.

cameras collect head and torso movements through the acquisition of the frames and process them with a torso and face recognition algorithm to obtain movement information. The movements need to be transposed into the wheelchair base reference frame to obtain the rider's movements in a coherent reference for the rider's point of view.

The idea behind this HMI interface is to allow hands-free movement of the wheelchair and to give velocity command to the wheelchair with torso and head movements. Table 1 describes how the relationship between the movement of the torso and head w.r.t. wheelchair base reference frame produces velocity command for the wheelchair base.

Table 1. Description of the variables acquired for driving the wheelchair. Correlation between the recorder variables and the wheelchair movements.

Variable recorded	Type of body movement	Wheelchair velocity command result
x_{rt}	Shoulder movements forward.	Wheelchair forward linear velocity is related to the shoulder front movements (backward is not produced).
y_{rt}	Shoulder movements left/right.	Wheelchair lateral linear velocity is related to the shoulder lateral movements.
$\theta_{z,rh}$	Head rotation clockwise/counterclockwise	Wheelchair angular velocity is related to head rotations.

3 Establishment of the command generation for the rider

Fig. 3 illustrates the inputs from the rider, namely, the rotation of the head around the z-axis of the wheelchair base reference frame, $\theta_{z,rh}$, and the position of the torso, ($x_{\mathrm{b},rt}$, $y_{\mathrm{b},rt}$). By analyzing the image taken by the right- and left cameras, these inputs are acquired in the camera reference frames {camR} and {camL}. Then, they are translated in the wheelchair base reference frame {b}. These three inputs are used to develop a command generation routine for the wheelchair starting from the rider's movements.

The torso or shoulder movements acquired are cleaned from the little involuntary or unrecognized movement applying a threshold of 4 cm in any direction. That means that every movement bigger than 4 cm is registered as an input.

3.1 Command generation process from human motion inputs

To generate the linear velocity of the wheelchair, the shoulder input, ($x_{\mathrm{b},rt}$, $y_{\mathrm{b},rt}$), is transformed from cartesian to polar coordinates so that the parameters become its distance, d_{rt}, from the center of the reference system and the angle, ϕ_{rt}, of the direction w.r.t the x_b axis. The equations used to perform this calculation are below,

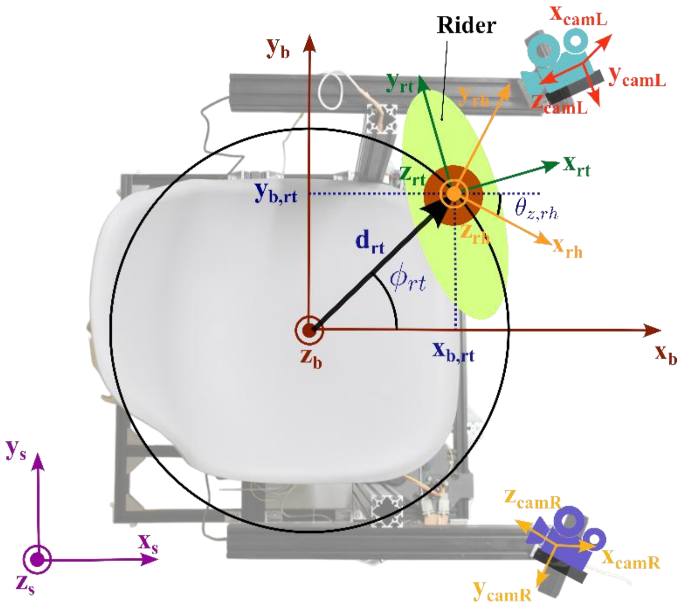

Fig. 3. Rider's shoulders and head moving w.r.t. the wheelchair base reference frame. The coordinates used for describing the rider motion are the HMI input.

$$d_{rt} = \sqrt{x_{b,rt}^2 + y_{b,rt}^2},$$
$$\Phi_{rt} = \arcsin\left({y_{b,rt}^2}/{d_{rt}}\right) \text{ if } d_{rt} \neq 0, \quad \Phi_{rt} = 0 \text{ if } d_{rt} = 0. \tag{1}$$

With this formulation, a maximum and a minimum threshold can be set. All the velocities will have a constant behavior regardless of the direction. Once defined the threshold for the minimum displacement t_{min}, the gain K and the saturation velocity v_{max}, it is possible to write the equation for generating the linear velocity.

$$v = \begin{cases} 0 & \text{if } |d_{rt}| < t_{min} \\ (d_{rt} - t_{min})\,K & \text{if } d_{rt}\,K < v_{max} \text{ and } d_{rt} > t_{min} \\ v_{max} & \text{if } d_{rt}\,K > v_{max} \end{cases} \tag{2}$$

A similar approach is applied also to the head rotation input. According to human physiology and our previous research about head rotation recognition [8], the upper threshold for head rotation is not needed because the recognition algorithm result is reliable and the human head cannot rotate more the 180° starting from one side and ending in the opposite direction. Similarly, the threshold related to the minimum rotation θ_{min} and the gain K_θ are choose for head rotation. Below is presented the equation that transforms the head rotation in angular velocity of the wheelchair.

$$\omega_z = \begin{cases} (\theta_{z,rh} + \theta_{min})\, K_\theta & \text{if } \theta_{z,rh} < -\theta_{min} \\ 0 & \text{if } |\theta_{z,rh}| < \theta_{min} \\ (\theta_{z,rh} - \theta_{min})\, K_\theta & \text{if } \theta_{z,rh} > \theta_{min} \end{cases} \tag{3}$$

3.2 Transformation of the command velocities into the cartesian frame

In the above, command velocities, v and ω_z, have been acquired in the polar coordinate. Then, they should be transformed into the reference velocities in the cartesian frame: two linear velocities v_x and v_y and the angular velocity ω_z. This can simply be done by using the direction Φ_{rt} as

$$v_x = v \cos(\Phi_{rt}),\ \ v_y = v \sin(\Phi_{rt}). \tag{4}$$

The v_x is always positive because, according to the authors' feelings, it is dangerous to give a backward velocity without having the possibility to check where the system is going. A more dangerous situation could happen if the rider turns his head to check the backward direction, the wheelchair will unexpectedly rotate around the z-axis for the rider. It should be implemented an additional safety routine to enable backward movement.

According to preliminary experimental evaluation to test the driving comfortability, ω_z needs to be less sensitive when the wheelchair has a higher linear velocity. This kind of reduction in sensitivity is managed by making a threshold of minimum rotation, θ_{min}, dependence on the velocity as follows.

$$\theta_{min} = \theta_{min,0}\,(1 + k_t\, v), \tag{5}$$

where $\theta_{min,0}$ is the minimum threshold when the velocity amplitude, v, is zero, k_t is the gain that modifies how fast the sensitivity will decrease according to the speed increase. Table 2 summarizes all the variables used, which values were used during the simulation and the meaning of that variable.

Table 2. List of all the variables and constants used during the simulation with their respective value and description

Variable	Value	Description
d_{rt}	Obtained from measured data	Distance of the rider reference frame from the wheelchair reference frame in polar coordinates.
Φ_{rt}	Obtained from measured data	Direction of the rider reference frame from the wheelchair reference frame in polar coordinates.
v_{max}	$1\ m/s$	Saturation for linear velocity.
t_{min}	$4\ cm$	Threshold of minimum displacement in any direction of the shoulder to obtain a linear velocity output.
K	$0.1\ {}^{m}/_{s\ cm}$	Gain that transforms displacement (cm) in linear velocity (m/s).
θ_{min}	Obtained from measured data	Minimum angular rotation of the head to obtain an angular velocity of the wheelchair.

$\theta_{min,0}$	$0.174\ rad$ (10°)	Minimum head rotation threshold when the linear velocity is zero.
k_t	$1\ s/m$	Gain to increase or reduce the linear velocity effect on the threshold.
K_θ	$1.1\ 1/s$	Gain that transforms the head rotation in wheelchair angular speed.

4 Driving simulation result of an electric wheelchair with the proposed hands-free HMI

Several user tryouts have been conducted to demonstrate the feasibility of the above-mentioned command generation logic using hands-free HMI. The proposed logic was carried out in a 3D-physical simulation software running on a desktop PC, receiving real-time user input from a USB camera. During the test, the rider has to drive around a cone (red dot in the image) and avoid going outside a barrier with a 3 m radius from the center cone (red dot around path). In all trials, the velocity generation has no difficulties in producing a velocity twist coherent with the human motion intentions. It was also possible to combine two different velocities (linear and angular). In many tests, like the one displayed, the command was good enough to not require any lateral compensation. As a result, only the trace of the v_x velocity component and ω_z are changing simultaneously in Fig. 4 while v_y remains flat. It is also appreciable, in red, the threshold zone in the input plots.

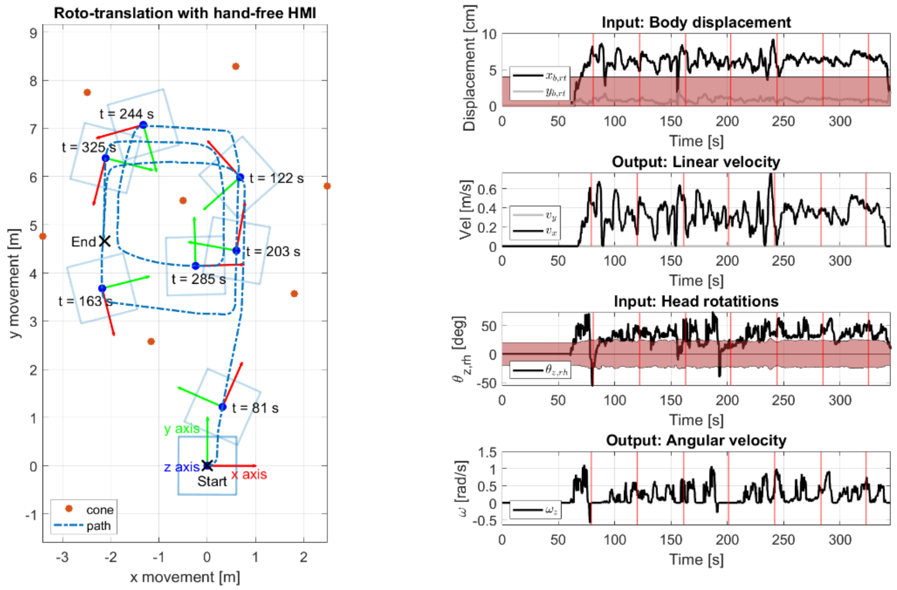

Fig. 4. Simulation of driving an electric wheelchair with the hands-free HMI. On the left is displayed the trajectory, on the right is displayed the torso and hed input and the linear and angular velocities generated

Fig. 4 also shows 7 samples of the wheelchair position and orientation with the relative input and output. This highlights how the thresholds are working and the possibility of giving two simultaneous commands to the system. Another important result, shown in Fig. 4, is the effectiveness of the filter in removing an important part of the noise from the command. All the noise in $y_{b,rt}$ and in $\theta_{z,rt}$ is prevented from becoming an unwanted velocity output.

During the test, the riders feel the necessity to have a more stable velocity signal produced from his / her movements. For this reason, the exponential filter to reduce the noise in all three velocity commands is used as follows:

$$s_t = \alpha x_t + (1-\alpha)s_{t-1}, \quad t > 0, \tag{6}$$

where α is the smoothing factor, and $0 < \alpha < 1$. When s_{t-1} is substituted into s_t continuously, the formula is fully expressed in terms of x_t. In the first iteration $s_0 = x_0$ and in our simulation $\alpha = 0.6$.

5 Conclusion

This paper demonstrates the drivability of an omnidirectional wheelchair using the rider's motion to produce an intention of motion that is transformed into velocity input. Thanks to the simulation it was possible to verify the feasibility of this driving interface. This result should be validated in a real test, with the wheelchair prototype. The next step of our research on this topic should be a real test to compare and validate the simulated results.

6 Acknowledgments

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