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Collaborative Omnidirectional Robot with Remote Eye Tracking System to Optimize Mobility

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Collaborative Omnidirectional Robot with Remote Eye Tracking System to Optimize Mobility

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Abstract. The study proposes optimizing displacements through the implementation of a collaborative omnidirectional system applied to the mobility of individuals using wheelchairs. For the application, an artificial vision system is used with two cameras that obtain an estimation of the movement direction. With eye tracking, the trajectory is defined, and the speed for each Mecanum wheel is calculated. Algorithms were developed in two programming languages: Python, which obtains the images, filters the eye tracking, and estimates the movement direction; and C++, which processes the trajectory and controls the motors using a specific mathematical system algorithm, calculating speeds and emergency stops in case of possible collisions with the help of eight ultrasonic sensors located in each direction of movement. The assistance robot provides users with greater autonomy and freedom of movement, with the ability to navigate in all directions, reducing maneuvering space by at least 30% compared to a conventional wheelchair.

Introduction

Since its creation in 1932 by engineer Harry Jennings, wheelchairs have been used to this day, including certain improvements that allow individuals with mobility difficulties due to injuries or accidents to move around easily. Over time, there have been advancements and enhancements in the design and functionality of wheelchairs, aiming to improve the quality of life and mobility for users. [1]

Currently, wheelchairs have evolved in such a way that the materials, features, and modes of operation are adapted to the users' needs, leading to the emergence of motorized wheelchairs, that provide mobility without external assistance, allowing users to enjoy a certain level of autonomy in their daily activities. [2]

In Barcelona, the CET Special Work Center has designed an omnidirectional wheelchair that enhances the mobility of people with disabilities, proving particularly useful in public spaces such as sidewalks, museums, and exhibitions. [3]

An omnidirectional robots have configurations that allows them to move in any direction with the purpose of navigating towards a point more easily, despite having a complex structure. [4] This type of robot has various applications, such as mobile entertainment carts, robots for archaeological explorations, robots for the transportation of hazardous materials, among other uses. [5]

Scheme of the omnidirectional collaborative robot.

The omnidirectional movement system is designed to obtain displacement parameters in two stages: obtaining the direction of movement through computer vision (CV) and optimizing the movement through sensor-based control to avoid collisions (SO). This way, the machine operates collaboratively with the user. Each of these stages communicates to modify the individual wheel's speed parameters and optimize movement.

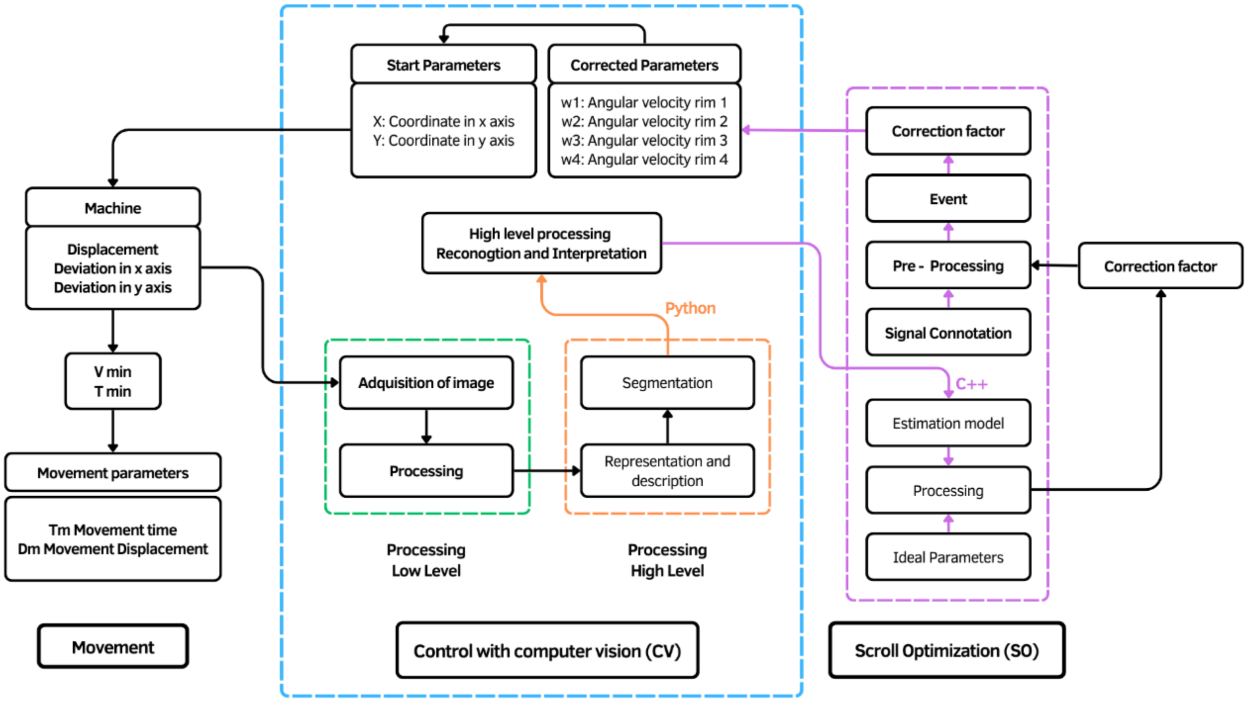

Fig. 1 Configuration of the System.

Mechatronic Design

Taking into consideration the position ergonomics and the composition of the chair, which consists of a base structure and a seat, the design aims to ensure the point load located on the column that supports 81% of the user's total weight. [6]

By calculating the combined stresses present in the structure, considering a load of 90 kg and the reactions from each of the wheels, the structure is fabricated using ASTM 36 steel pipe with a diameter of 2 [in] for the column and ¾ [in] for the structure. As shown in the figure, the maximum deformation obtained in the design is 0.05938 [mm], and a safety factor of 15 is achieved, with 2 being the recommended safety factor [7]. It is determined that the structural design is safe.

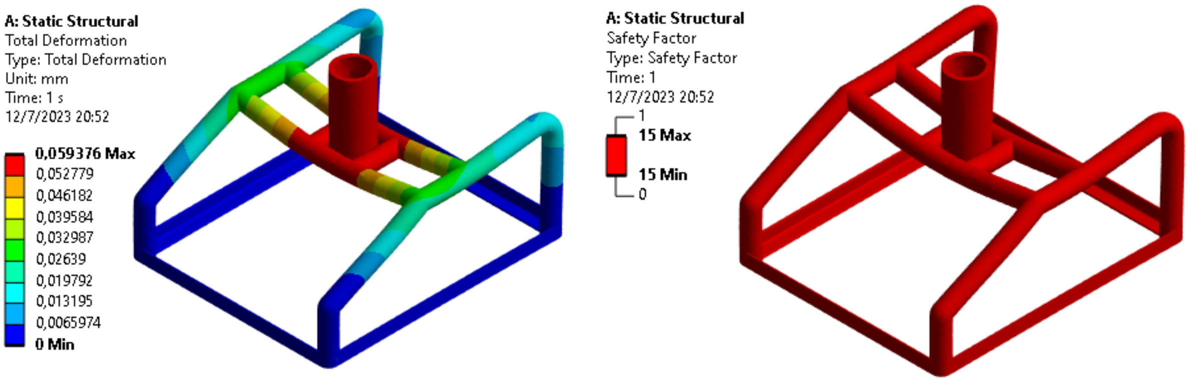

Fig. 2 CAE Results for Static Analysis.

Mathematical Model. Starting from the spatial position of the robot as shown in the figure, we obtain the following equations:

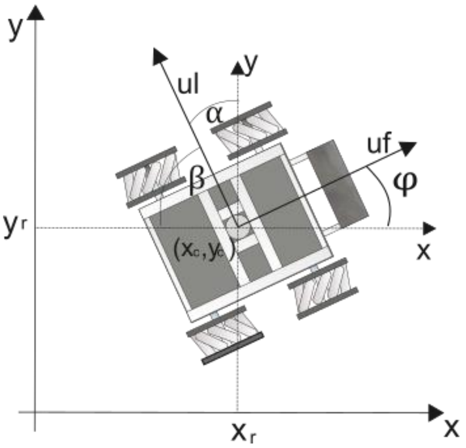

Fig. 3 Omnidirectional robot reference frames.

$$\dot{x_c} = \mathrm{uf}\cos(\varphi) - \mathrm{ul}\sin(\varphi) \tag{1}$$

$$\dot{y_c} = \mathrm{uf}\cos(\varphi) - \mathrm{ul}\sin(\varphi) \tag{2}$$

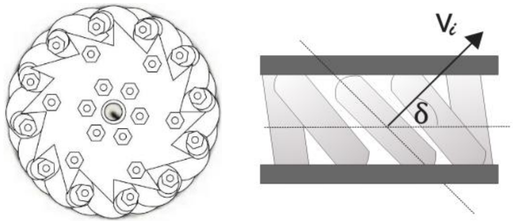

Fig. 4 Mecanum Wheel.

In Fig. 4, the arrangement of the Mecanum wheels is evident, with the rollers positioned at 45 degrees, as shown in the figure. To achieve the desired displacements, the Mecanum wheels have the following relationship: [8]

$$v_i = \frac{r\,w_i}{\cos(\delta)} \tag{3}$$

Control of the robot will be performed by varying the angular velocities of the wheels. Constant inputs for this control are front, lateral, and angular velocities. All the vectorial velocities involved within the robot are shown in Fig. 5.

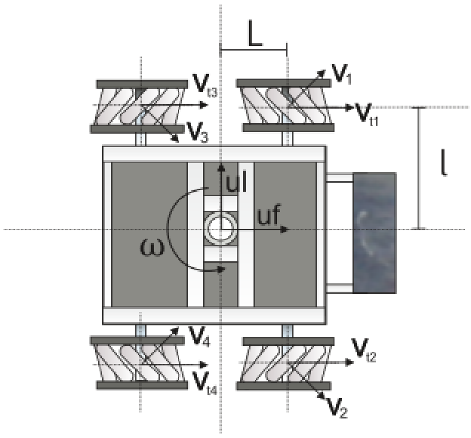

Fig. 5 Omnidirectional robot free body diagram.

Analyzing Wheel 1 in x-axis

$$u_{wheel_x} = uf - lw \tag{4}$$

$$u_{wheel_x} = v_1 \cos(\partial) + v_{t1} \tag{5}$$

$$uf = 2r\, w_1 + lw \tag{6}$$

Analyzing Wheel 1 in y-axis

$$u_{wheely} = ul + Lw \tag{7}$$

$$u_{wheel_y} = v_1 \sin(\partial) \tag{8}$$

$$ul = r\, w_1 - Lw \tag{9}$$

Forming a system of equations with Eq. 6 and Eq. 9 to find the angular velocity of the wheel

$$r\, w_1 = uf - ul - w(l + L) \tag{10}$$

Applying the same process to each of the remaining wheels, we can arrive at the matrix used for the control of the robot.

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & -1 & -(l+L) \\ 1 & 1 & (l+L) \\ 1 & 1 & -(l+L) \\ 1 & -1 & (l+L) \end{bmatrix} \begin{bmatrix} uf \\ ul \\ w \end{bmatrix} \tag{11}$$

Eye-tracking. To accurately obtain eye tracking using the MediaPipe Face Mesh resource, the 468 landmark points of the face were acquired. From these points, the six corresponding (x, y) coordinates for each eye are extracted. This allows for filtering the area of interest and reduces the probability of erroneous results. This resource is independent of changes in lighting, wearing glasses, variations in background, and so on.

Fig. 6 Eye detection.

By employing area segmentation, image dilation and erosion, converting from RGB to grayscale, and applying thresholds to binarize the image, the pupil is effectively filtered, assigning it a pixel value. In real-time, the location of the pupil is compared to the starting point of the reading in order to ascertain the direction of movement for the robot.

Fig. 7 Eye location.

To determine directions, a margin of error of 5 pixels was assigned to account for the difference in position between the pupils. This is necessary because the processed area is small, and eye movements can be subtle.

By using the tangent function and calculating from the initial and final pixel differences of the pupils, the displacement angle is obtained. This signal is then configured as a virtual joystick under the parameters described in Fig. 8.

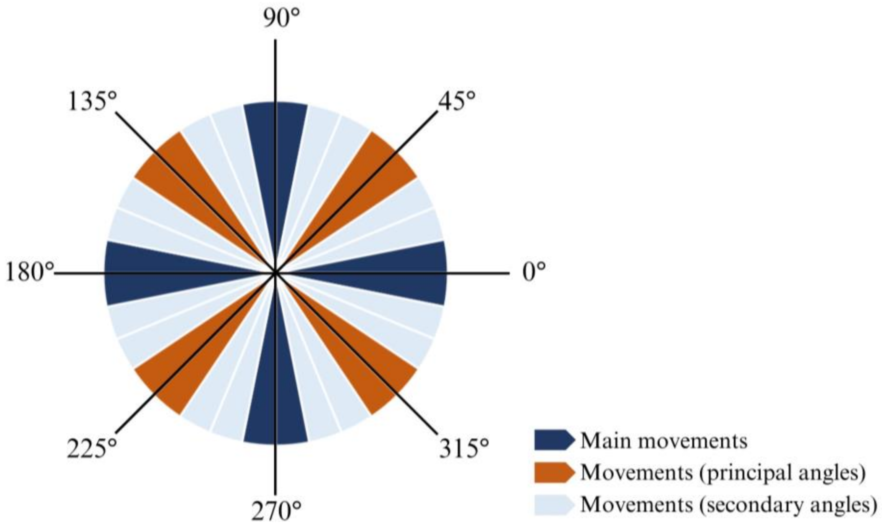

Fig. 8 Direction angles.

Given that the goal is to ensure safe assistance, double blinking is determined as confirmation for directed movements. In research work developed by Soukupová and Čech "Real Time Eye Blink Detection using Facial Landmarks" [9] , they utilize an equation that reflects the Eye Aspect Ratio (EAR) with the reference locations of the eyes. [10]

$$\mathrm{EAR} = \frac{\|p_2 - p_6\| + \|p_3 - p_5\|}{2\|p_1 - p_4\|} \qquad (12)$$

The result of Eq. 12 approaches zero when a blink occurs, so by segmenting the area, we can also obtain information about the user's blinking. Additionally, by studying common facial expressions in humans, closing the eyes for 4 frames is identified as an emergency stop condition.

Electronic and control design. Electrical and electronic components that make up the collaborative robot are:

a) Electric actuators: For movement, NPC-2212 DC motors with reduced gears are used to increase torque and smooth out startup loads. They are paired with Sabertooth 2x32 drivers.
b) Sensors: They emit signals that condition the robot's movement based on distances and depending on the direction of travel.
c) Processors: Two controllers were used for data processing and user interaction. A Raspberry Pi 4 was employed for processing user interaction data, and an ATmega328P microcontroller that processes and sends the required speeds to the drivers and handles the sensors.

The control system constitutes the intangible essence of the robot, enabling coordinated operation of the four Mecanum wheels that allow omnidirectional movements. It is divided into two phases. The first phase involves user interaction through an algorithm programmed in Python, which ensures that the required functions are carried out. The communication with the second phase is established through an algorithm programmed in C++, which processes the robot's motion matrix based on the data obtained from the interaction and provides signals to the motor drivers.

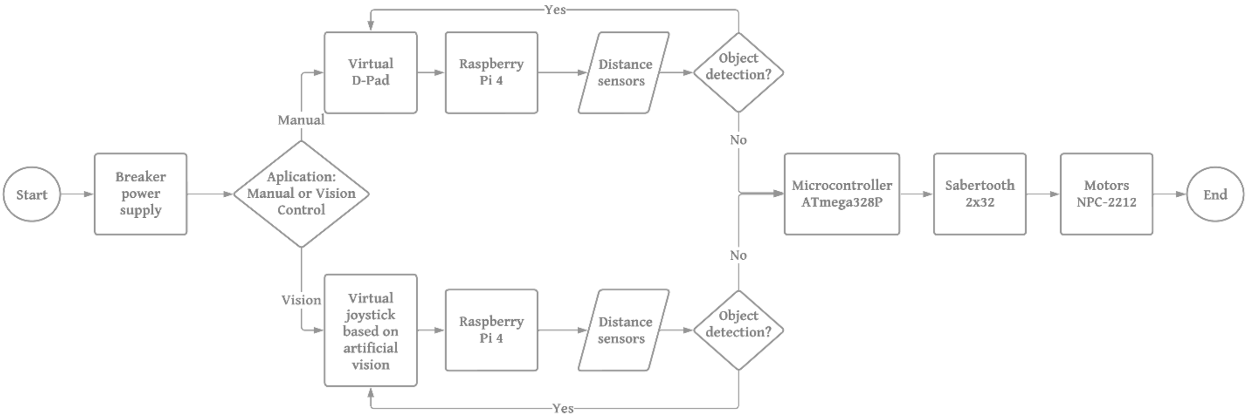

Fig. 9 Control diagram.

The omnidirectional collaborative robot features a system of distributed sensors throughout its entire structure, which allows it to establish a collision-free safety zone, ensuring the integrity of the user and their environment. It stops its movement when an object enters its safety zone, as long as it is in a relevant direction for the motion.

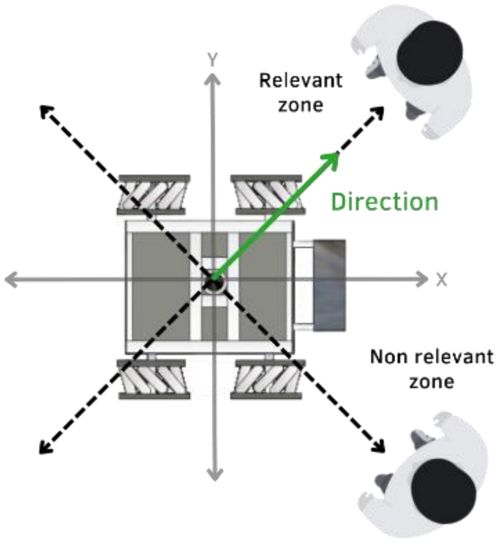

Fig. 10 Collision-free safety zone.

Experiments and Results

For the functionality tests, a comparison has been made between the movement against a conventional wheelchair, manual control of the omnidirectional wheelchair, and control through eye tracking. A predefined route was used for the tests, obtaining the following results:

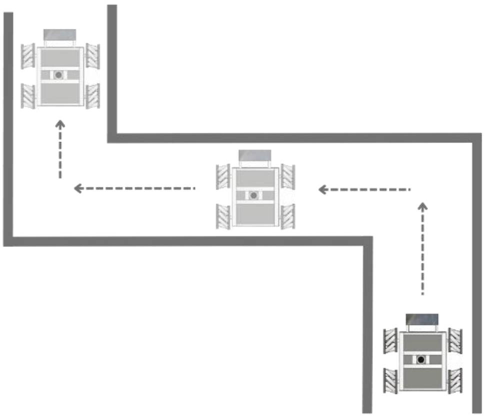

Fig. 11 Predefined route for experiment.

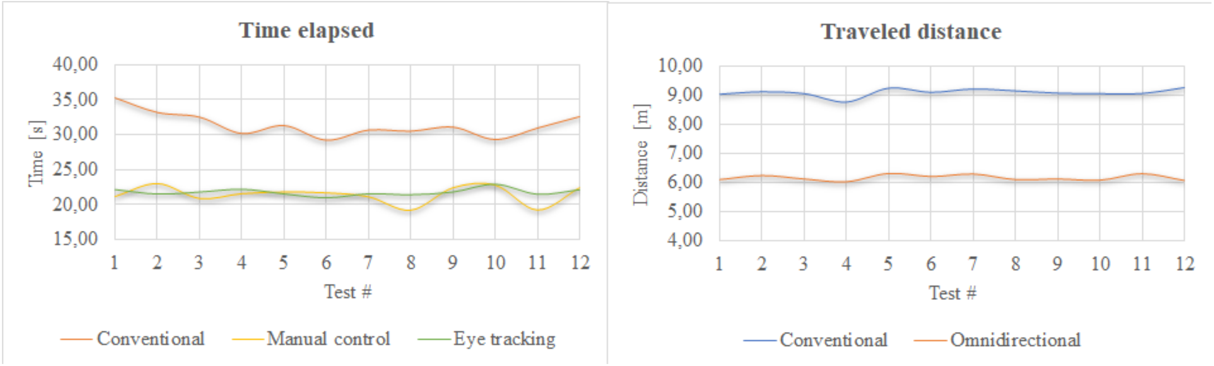

Fig. 12 Results comparation charts.

In Fig. 12, the similarity between manual control of the omnidirectional robot and control through eye tracking can be observed, as well as the significant difference between both forms of control compared to a conventional wheelchair. This demonstrates an improvement in maneuverability, with a 31.68% improvement for manual control and a 30.49% improvement in the case of eye tracking, also we can see that traveled distance by omnidirectional wheelchair is less than conventional in a 32.04%

Conclusions

After analyzing the obtained results, it can be concluded that there is an improvement in displacement when performing the same route for each chair, with a noticeable reduction of 32.04% in the required displacement to complete the trajectory. This reduction also implies a decrease in the required time. On the other hand, it is evident that eye-tracking control is almost on par with manual control, with a time difference of only 1.72%. This demonstrates that the collaborative omnidirectional robot with remote eye-tracking system is capable of optimizing mobility by more than 30% while maintaining response times comparable to a manual control system.

Additionally, work is being done on the development of pupil identification through computer vision using neural networks for its implementation within the omnidirectional collaborative robot, aiming to minimize errors in control through eye tracking caused by external disturbances. Furthermore, efforts are being made to implement an automatic trajectory correction system for obstacle avoidance.

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