Combining Haptic and Bang-Bang Braking Actions for Passive Robotic Walker Path Following

Marco Andreetto, Stefano Divan, Francesco Ferrari, Daniele Fontanelli, Luigi Palopoli and Domenico Prattichizzo

Abstract—Robotic walkers are a promising solution for physical and cognitive support to older adults. This paper proposes a low cost path following strategy combining the advantages of a simple mechanical braking guidance, such as safety, passivity and a low cost, and the ones of a vibrotactile haptic guidance, such as comfort and portability. The user is guided by providing indications on the directions of motion using the haptic interface so that he/she can autonomously and comfortably follow the planned path. However, whenever the user significantly departs from the path (for instance s/he gets too close to obstacles), the braking system kicks in to safely steer the user back along the proper direction. The formal correctness of the hybrid strategy ruling the combination of the two guidance systems is proved theoretically. Moreover, a comprehensive experimental study with users aged 64 to 100, including also psychological evaluations, has been performed. The hybrid combination of the braking and the haptic guidance systems is shown to outperform the two individual approaches in isolation. The combination of the two retains the same level of the users’ perceived comfort typical of the haptic-only guidance while ensuring the adequate path following performance typical of the braking-only guidance. In particular, the combined approach produces a mean path following error equal to 41% of the mean path following error ensured by the haptic-only approach. Conversely, thanks to the haptic feedback, the combined approach halves the activation time and the number of interventions needed in the braking-only approach.

Index Terms—Assistive technology, haptics applications, haptic I/O, human performance, perception and psychophysics, dynamic systems and control

I. INTRODUCTION

Service robots are becoming nowadays relevant as supports for seniors to increase their quality of life and help them in their daily duties. Indeed, the interest in inexpensive and easy to use robotic mobility aids is motivated by their supposed efficacy in helping users remain active beyond the walls of their houses [1] and hence reduce physical problems and cognitive decline [2], [3].

The robotic walker FriWalk, which is a standard commercial walking aid endowed with sensing abilities to understand the surroundings [4], with communication abilities to connect to cloud services and with planning abilities to produce safe paths in the environment [5], is an interesting solution developed in the context of the European project ACANTO [6]. The main purpose of the FriWalk is to act as a navigation aid guiding the users without sacrificing their perceived freedom of movement. One standard approach to satisfy this goal and generate “comfortable” manoeuvres is to resort to motors on the back wheels of a standard rollator. Commonly adopted interfaces to control such system are joysticks [7], force sensors [8], [9], laser scanned shin positions [10], depth cameras tracking the lower limb [11].

Unfortunately, the presence of actuation usually generates potential safety problems, which can instead be removed using passive robots [12], [13]. The rationale of a passive robot is to leave the responsibility of the locomotion to the user. The safety comes directly from the absence of thrusting motors in a passive robot (where instead the propulsion is generated by the user): if a system malfunctioning takes place in an active assistive walker, accidental motion may occur and the user may be pushed or pulled (because of the presence of the active motors) and loose his/her balance. Although active walkers have the potentiality to help the users missing the necessary strength to push the device [14], in this work we studied the FriWalk as a passive walker, hence preferring safety to the possibility of supplying additional thrust.

Straightforward ways to build a passive robot is either to use actuated steering wheels [15], to simulate passivity through actuation [16], [14], to resort to modulated electromagnetic brakes for differential drive [17], [18]. As aforementioned, modulating the braking force imply the adoption of an appropriate sensing system to estimate the torques applied by the user.

In order to reduce the system final cost and its complexity, elementary passive solutions should be implemented. To this end, a bang-bang passive walker solution, in which the vehicle is turned on the left by blocking the left rear wheel or on the right by blocking the right rear wheel, has been proposed in [19]. The solution is simple (on/off control action) and inexpensive since additional hardware is not required for braking modulation or human force sensing as in [17], [18], [20]. Moreover, an automated intelligent braking system is a required feature (we could say the bare minimum) to guarantee safety for all robotic walkers. A dual use of the passive braking system (using the brakes also for guidance) clearly contributes to reduce the cost. Despite the inherent safety, the small set of manoeuvres it produces enables a relatively accurate tracking of the path, although with a questionable user comfort [21].
To keep safety features on this inexpensive system and simultaneously increase the user experience, in this paper we selected an additional interface to suggest to the user the correct direction along the path to follow. In real world scenarios, visual and auditory channels may be overloaded with a huge quantity of information, resulting in a rapid error increasing and, in the end, the overall user performance reduction if cues are provided through these channels. A possible solution is to deliver necessary information exploiting an under-utilised sense, i.e. the sense of touch to decrease the overall cognitive load on the user. As the sound, a tactile stimulus is made up of a signal with varying frequency and amplitude, but differently from the auditory feedback, tactile sensation directly engages our motor learning system with extraordinary sensitivity and speed [22], [23]. Moreover, tactile communication can be used in situations where visual or auditory stimuli are distracting, impractical, unavailable or unsafe. The main disadvantage in using haptic guidance is that the stimuli are just indications that are not sufficient to guarantee safety. In fact, an uncooperative user may decide to neglect the haptic stimuli and depart from the safe path, and hence his/her safety is not guaranteed. This issue is solved in the paper by combining the haptic guidance with the mechanical guidance, which may kick in only to ensure safety for uncooperative of distracted users.

Vibrotactile haptic guidance has been successfully exploited in the last years presented in [24], [25], and [26]. In [24], a vibrotactile belt is used for waypoint navigation in an outdoor environment. Scheggi et al. in [25] presented a new paradigm for the assisted navigation of mixed human-robot teams using haptic information. Moreover, in [27], the authors proposed a mobile device for human navigation using multimodal communication (audio, visual, vibrotactile and directional skin-stretch stimuli). Finally, Benallegue et al. in [26] presented an innovative head-neck system to balance the human steady gait trajectory. It exploits the tilt estimation within the visuo-vestibular system and contributes to the dynamics of walking due to the head stabilisation.

We tested vibrotactile interfaces, since tactile devices are generally portable, not encumbering and have a wider range of action [28]. Moreover, in this approach, the user has the hands free from the devices, thus holding the handles of the walker is possible.

The capability of the vibro-interface to suggest direction of motion was preliminarily analysed in [29]. Tactile vibratory sensitivity is influenced by the spatial location on the body, the distance between the stimulators, the frequency of stimulation and the age of the user. Studies have demonstrated that vibration is better sensed on hairy skin due to its thickness and nerve depth, and that vibrotactile stimuli are best detected in bony areas [30]. In particular, wrists and spine are generally preferred for detecting vibrations, with arms and ankles next in line [31]. Due to the aforementioned considerations and since our aim is to design an intuitive and non-obtrusive device which could be easily worn, we concentrated on the development of vibrotactile bracelets. Following the results presented by Scheggi et al. in [29], we decided to use the bilateral configuration that required two bracelets, one for each arm.

In this paper we propose an hybrid approach whose application allows a controlled blend of haptic (i.e. two haptic bracelets, equipped with vibrating motors) and mechanical actions (i.e. bang-bang braking action), thus reducing the control authority and guaranteeing the performance. The controller is based on the definition of safety regions around the desired path, where corrective actions simply do not occur. The proposed hybrid controller has been successfully applied to the FriWalk and its effectiveness has been proved through extensive experiments with older adults. We compared the haptic-only strategy and braking-only strategy with the proposed combined approach to exploit advantages of both approaches in terms of user comfort and path following performance, respectively.

The paper is organised as follows. Section II presents the vehicle model and introduces the problem at hand, while Section III discuss the starting point of the presented solution for the mechanical braking system. Section IV describes the haptic guidance system and presents the integration of the proposed heterogeneous guidance systems. Section V summarises the experimental results and the users’ evaluation on the proposed solution, while Section VI reports the conclusions and the possible future research directions.

II. BACKGROUND AND PROBLEM FORMULATION

The FriWalk prototype used for this paper is shown in Fig. 1 and is derived from a commercial walker mounting electro-mechanical brakes on the rear wheels. The braking current is directly controlled by a LitePro®E65C driver communicating with a BeagleBoard black via can interface.

The vibrotactile bracelets are composed by cylindrical vibro-motors, independently controlled via the Bluetooth communication protocol (see Figure 2). The communication

![Figure 1. Picture of the FriWalk prototype with one of the older adults participating in the experimental trials.](image)
is realised with an RN-42 Bluetooth antenna connected to a 3.3V Arduino pro-mini. The wireless connection baud rate is 57600bps. The micro-controller installed on the board is used to independently control the activation of each motor and receiving data from an external platform mounted on the walker. As the user’s maximal sensitivity is achieved around 200-300Hz [32] (the human perceptibility range is between 20Hz and 400Hz), two Precision Microdrives Pico Vibe vibration motors are placed into two fabric pockets inside the bracelet (the width of the wristband is about 60mm), with vertically aligned shafts. The motors have a vibration frequency range of 100-300Hz, lag time of about 20ms, rise and stop time of 35ms. The bracelet guarantees about 4 hours of battery life with one motor always turned on. Each bracelet weights about 90g.

In order to solve the localisation problem, the rear wheels host incremental encoders, which are used in combination with an inertial platform measuring the accelerations and angular velocities, and with a camera system. These information are then fused together to ensure that the FriWalk localisation is obtained with a given target uncertainty [33]. The vehicle uses RGB-D technologies to gather information from the surrounding environment by detecting unexpected and moving obstacles. These information are then used to plan the safest path for the user by computing the probability of collisions with other human beings [5]. With the adoption of the described solutions, we assume that 1. a reference path is generated, 2. the vehicle is localised with a good accuracy (i.e. error below 20 cm).

A. Vehicle Model

The assistive walker in Figure 1 is modelled as a unicycle-like robot having equations

$$\begin{cases}
\dot{x} = v \cos \theta, \\
\dot{y} = v \sin \theta, \\
\dot{\theta} = \omega,
\end{cases}$$

(1)

where the coordinates $x$ and $y$ define the position of the mid point of the rear axle (having length $2R$) on the plane of motion and with respect to a fixed reference frame $\langle W \rangle = \{O_w, X_w, Y_w, Z_w\}$ in Figure 3, $\theta$ is the vehicle yaw, i.e. the orientation of the vehicle-fixed reference frame $\langle M \rangle = \{O_m, X_m, Y_m, Z_m\}$ with respect to the fixed frame, $v$ is the forward velocity and $\omega$ is the angular velocity. Since the robot is propelled by the user, the forward velocity $v > 0$ is completely determined by the assisted person, hence it is not a control variable. The angular velocity $\omega$ is, instead, the control input that should be generated by the actuators. The FriWalk is equipped with two front caster wheels, while the rear wheels are equipped with electromagnetic brakes capable of blocking the wheels only, i.e. no modulation of the braking action is possible because of hardware limitations. This way, the vehicle rotates around the blocked wheel with angular velocity $|\omega| = v/R$, while it moves forward if the wheels are free to rotate, i.e. $\omega = 0$. This means that the control input $\omega$ generated by the braking system can assume only three values

$$\omega \in \left\{ -\frac{v}{R}, 0, \frac{v}{R} \right\}.$$  

(2)

Notice that when $\omega = -\frac{v}{R}$ and $\omega = +\frac{v}{R}$ the vehicle turns right and left, respectively, with fixed curvature radius $R$, while when $\omega = 0$ the vehicle can move freely. Notice that the set of control actions (2) describe the vehicle behaviour generated by the braking system. When the brakes are not active the vehicle is totally passive, as a standard rollator. Nevertheless, using the vibrating bracelets, it is possible to adjust the heading by providing haptic stimuli. To limit the use of the tactile channel and the recognition time, the haptic system is used to provide the user with three simple indications, resembling (2):

1) *turn left*: the user is suggested to turn left, i.e. to apply an angular velocity $\omega > 0$, by activating the left bracelet;
2) *turn right*: the user is suggested to turn right, i.e. to apply an angular velocity $\omega < 0$, by activating the right bracelet;
3) *go straight*: no haptic stimuli are provided to the user, who is then suggested to go straight, i.e. to apply and angular velocity $\omega \approx 0$.

To properly represent the path following problem, we adopt a moving Frenet frame $\langle F \rangle = \{O_f, X_f, Y_f, Z_f\}$ (see Figure 3), whose origin $O_f$ is always located on the path and its horizontal axis $X_f$ is always tangent to the path. Let us denote by $\theta_d$ the orientation of $\langle F \rangle$ in $\langle W \rangle$, i.e. the angle
between \( X_w \) and \( X_f \), and by \( s \) a curvilinear abscissa defining the position of the Frenet frame origin \( O_f \) along the path. By rewriting the vehicle equations (1) with respect to the Frenet frame, we have [34]

\[
\begin{align*}
\dot{l}_x &= -\dot{s}(1 - c(s)l_y) + v \cos \theta, \\
\dot{l}_y &= -c(s)\dot{s}l_x + v \sin \theta, \\
\dot{\theta} &= \omega - c(s)\dot{s},
\end{align*}
\]

where the coordinates \( l_x \) and \( l_y \) define the position of the mid point of the rear axle with respect to the Frenet frame, \( \dot{\theta} = \theta - \dot{\theta}_d \) is the attitude error and \( c(s) = \frac{\partial h}{\partial s}(s) \) is the path curvature. The velocity \( \dot{s} \) of the Frenet frame origin \( O_f \) along the path is a control input that can be arbitrarily chosen. The state of the vehicle can be equivalently represented using the coordinates \( \chi = [x, y, \theta]^T \) in (1) or \( \tilde{\chi} = [l_x, l_y, \tilde{\theta}]^T \) in (3).

**B. Problem Formulation**

This paper solves a path following problem, i.e. ensures that the vehicle approaches and follows a given path by considering the actuator limitations (recall that the brakes are capable of only blocking the wheels). Using the coordinates introduced in (3), the problem can be formalised as follows: find the control law \( \omega(\chi) \) satisfying the actuation constraints (2) and the velocity of the Frenet frame \( \dot{s}(\chi) \) in (3) ensuring

\[
\begin{align*}
\lim_{t \to +\infty} |l_x(t)| &\leq l_{x\infty}, \\
\lim_{t \to +\infty} |l_y(t)| &\leq l_{y\infty}, \\
\lim_{t \to +\infty} |\dot{\theta}(t)| &\leq \dot{\theta}_{\infty},
\end{align*}
\]

where \( t \) denotes the time, and \( l_{x\infty} > 0 \) and \( \dot{\theta}_{\infty} > 0 \) are positive arbitrary constants. Notice that this path following problem is passive and constrained since we are using passive actuators (i.e. brakes) without modulations (i.e. either blocking or non blocking the wheels) and the forward velocity \( v \) is determined by the assisted person. It is worthwhile to note that the haptic bracelets can not be considered as actuators in the control design, since, even when they vibrate, the behaviour of the system is still entirely determined by the user behaviour.

**III. PASSIVE MECHANICAL STEERING CONTROL**

Due to the braking actuation constraints (2), the controlled trajectories are Dubins-like paths [35]. To generate a natural path following behaviour, the introduction of an approaching angle \( \delta \), which varies according to the position of the vehicle with respect to the path and defines the approaching manoeuvre towards the path, is proposed in [36]: for example, if \( \delta = \pi/2 \), the vehicle will approach the path perpendicularly (minimum path length in [35]), while if \( \delta = 0 \) the vehicle moves parallel to the path (see Figure 4 for reference). In [36] it is shown that any possible choice of a limited odd smooth function \( \delta(\cdot) \) works fine, e.g. \( \delta = -\frac{\pi}{2} \tanh(l_y) \).

The aforementioned control algorithms [35], [36] present two main issues, which mine their real implementation: chattering and path following singularity.

The chattering phenomenon comes from the limited set of manoeuvres of the Dubins car. To get rid of it, a hysteresis-based behaviour, which limits the number of braking system interventions along the trajectory, is defined in [19], [21]. This idea is quite close to the user loose path following natural behaviour: when someone is asked to follow a path in an environment, the path is usually followed “approximately”, in accordance with formulation (4).

The singularity issue [35], [36], [19], [21] is generated since the Frenet reference frame is located on the closest point of the path to the vehicle. With reference to Figure 3, this implies that \( l_x(t) = 0, \forall t \geq 0, \) and that \( l_y \) is the minimum distance between the vehicle and the path. The singularity may generate sudden variation of the approaching angle function which may compromise the user’s balance. It takes place whenever the vehicle is in the curvature centre since the closest point is not well-defined. This issue has been firstly solved in [37] for a fully controllable unicycle using a reference frame as in (3), whose advancing velocity \( \dot{s} \) along the path is a control variable that can be chosen. In particular, conditions (4) hold with \( l_{\infty} = \dot{\theta}_{\infty} = 0 \) if \( \dot{\theta} \) converges to \( \delta \), and the advancing velocity of the Frenet frame \( \dot{s} \) is chosen as

\[
\dot{s} = v \cos(\tilde{\theta}) + kl_x,
\]

where \( k > 0 \) is a positive gain. The proof is available in [37].

In the next section we will show how a similar strategy can be applied to the controller in [19] to solve the singular configuration also for the Dubins car.

**A. A simplified hybrid solution**

The hybrid controller presented in [19] has four hysteresis thresholds, i.e. two for each logic variable, to set-up for a proper functioning. Nonetheless, if the approaching angle \( \delta \) has an additional property, i.e. to be strictly monotonic (which is quite natural for a human locomotion), the hybrid system boils down to only two operating modes and one logic variable, hence the tuning of the hysteresis threshold is highly simplified [21]. Moreover, the hysteresis can be defined on the orientation error only \( \tilde{\theta} - \delta(l_y) \). This has a major impact for the integration of the braking and haptic guidance systems in the hybrid controller designed on purpose in this paper. To this end, let us define:
\[ q = \text{desired}\ \theta \mid \epsilon = \omega \]

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2019.2912570, IEEE Transactions on Haptics

- \( q \triangleq \hat{\theta} - \delta(l_y) \), i.e. the angular error of the vehicle. The rationale of the path following controller is that, in order to satisfy conditions (4), this angular error \(|e_q|\) must be kept limited. In fact, if \(|e_q|\) is nonzero but small, the vehicle is moving in the correct direction;

- \( g(q, e_q) : \mathbb{R} \times \mathbb{R}_{\geq 0} \rightarrow \{-1, 0, 1\} \) defined as the function

\[
g(q, e_q) := \begin{cases} \text{sign}(e_q), & \text{if } |e_q| \geq e_q, \\ 0, & \text{if } |e_q| < e_q. \end{cases} \quad (6)
\]

In practice, function \( g(q, e_q) \) is the sign function of \( e_q \) with a dead zone defined by \( e_q > 0 \) (see Figure 5);

- \( q \in \{0, 1\} \) as the hybrid controller logic variable. Condition \( q = 0 \) will be used to state that \( |e_q| \) is negligible and the controller does not need to kick in to ensure that conditions (4) hold. On the other hand, condition \( q = 1 \) will indicate that the attitude error \(|e_q|\) has to be reduced by the controller (e.g. by braking) to properly follow the path;

- \( \Theta \triangleq [\chi^T, q, \omega, s]^T \) the extended state of the hybrid system, introduced for convenience of notation.

The hybrid controller is then defined as follows:

\[
\begin{aligned}
\dot{\chi} &= f(\Theta, v), \\
q &= 0, \\
\dot{\omega} &= 0, \\
\dot{s} &= v \cos(\hat{\theta}) + kl_x, \\
\chi^+ &= \chi, \\
q^+ &= 1 - q, \\
\omega^+ &= -g(q, e_q) \frac{v}{R}, \\
s^+ &= s,
\end{aligned} \quad (7)
\]

where function \( f(\cdot) \) describes the nonlinear dynamics (1), \( k > 0 \) is a tuneable gain, the flow set is \( C = C_0 \cup C_1 \) and the jump set \( D = D_0 \cup D_1 \), where

\[
\begin{aligned}
C_0 &= \{ \Theta \in \mathbb{R}^6, |e_q| \leq \theta_{q2} \land q = 0 \}, \\
C_1 &= \{ \Theta \in \mathbb{R}^6, |e_q| \geq \theta_{q1} \land q = 1 \}, \\
D_0 &= \{ \Theta \in \mathbb{R}^6, |e_q| \geq \theta_{q2} \land q = 0 \}, \\
D_1 &= \{ \Theta \in \mathbb{R}^6, |e_q| \leq \theta_{q1} \land q = 1 \},
\end{aligned} \quad (8)
\]

where \( \theta_{q2} > \theta_{q1} \) are two positive constants defining the hysteresis mechanism. The constant \( e_q \) used in function \( g(q, e_q) \) satisfies \( e_q \in (\theta_{q1}, \theta_{q2}) \). With this choice of \( \theta_{q1}, \theta_{q2} \) and \( e_q \), the hysteresis is well defined and the control system never brakes when the orientation error is smaller than the lower threshold \( \theta_{q1} \). A graphical representation is depicted in Figure 6: the vehicle starts oriented as the dotted line, labelled \( \hat{\theta} \). The above three steps can be considered as a sketch of the proof of the following theorem, while more details are in [21].

**Theorem 1:**

Consider the system (1) subjected to the limitations (2). Suppose that the forward velocity of the vehicle is limited by...
exists a constant $l$ bounded such that the hybrid controller (7) solves the path following problem in the sense of (4).

Notice that the Theorem holds for any $\epsilon_q \in (\theta_{q_1}, \theta_{q_2})$, that can then be chosen arbitrarily in the set.

B. Delay compensation

The experimental results reported in [19] show that the actuation delay worsens the system performances. We propose a method to compensate this delay using predictions on the control inputs $v$ and $\omega$ computed on a feedforward term. The expression $\omega^+ = -g(\epsilon_q, \epsilon_q) \frac{\partial l}{\partial R}$ is replaced by $\omega^+ = -g(\hat{\theta}_p - \delta(l_{y,p}), \epsilon_q) \frac{\partial l}{\partial R}$, where $\hat{\theta}_p$ and $l_{y,p}$ denote the predicted values of $\theta$ and $l_y$, respectively. The prediction is computed via Euler’s forward integration rule, i.e.

$$\hat{\theta}_p = \hat{\theta} + \hat{\Delta} \tau,$$

$$l_{y,p} = l_y + \tilde{l} \Delta \tau,$$

where $\Delta \tau$ is the estimated actuation delay and where the control inputs $v$ and $\omega$ are supposed constant.

IV. INTEGRATION OF THE HAPTIC GUIDANCE

The haptic guidance is used to suggest the user to steer the vehicle towards the path. In principle, if the user is cooperative, i.e. he/she properly steers the vehicle when the haptic system is active, the path following requirements (4) may be satisfied without using the brakes, then improving the user’s comfort.

To design the activation policy of the bracelets, recall that we have shown that controller (7) solves the path following problem by maintaining the angular error $|\epsilon_\theta|$ small via a hysteresis mechanism. The same logic is also used to activate the haptic system. To improve the user comfort, we require that:

- If the user is leaving the path, the bracelets vibrate before the vehicle brakes. This way, the user is allowed to follow the path without braking interventions;
- The bracelets are deactivated at a smaller angular error $\epsilon_\theta$, i.e. the lower threshold of the bracelets hysteresis is smaller than the lower threshold of the brakes hysteresis. This way, the undesired situation where the haptic system does not provide suggestions to the user and the vehicle brakes is avoided.

Therefore, if we denote with $\theta^h_{q_2} > \theta^h_{q_1}$ the hysteresis thresholds of the haptic system (the superscript $h$ stands for “haptic”), we impose $\theta_{q_2} > \theta^h_{q_2}$, $\theta_{q_1} \geq \theta^h_{q_1}$, and $\theta^h_{q_2} > \theta_{q_1}$. Moreover, we pick $\epsilon_q \in (\theta_{q_1}, \theta^h_{q_2})$, as depicted in Figure 8.

\[ \begin{align*}
\psi & = 0, \quad \Xi \in C^h, \\
\hat{p} & = 0, \quad \psi^+ = -g(\epsilon_q, \epsilon_q), \quad \Xi \in D^h, \quad (11)
\end{align*} \]

where $\Xi = [\psi, \epsilon_\theta, p]^T$, the flow set is $C^h = C^h_0 \cup C^h_1$ and the jump set $D^h = D^h_0 \cup D^h_1$, where

\[ \begin{align*}
C^h_0 & = \{ \Xi \in \mathbb{R}^3, |\epsilon_\theta| \leq \theta^h_{q_2} \wedge p = 0 \}, \\
C^h_1 & = \{ \Xi \in \mathbb{R}^3, |\epsilon_\theta| \geq \theta^h_{q_1} \wedge p = 1 \}, \\
D^h_0 & = \{ \Xi \in \mathbb{R}^3, |\epsilon_\theta| \geq \theta^h_{q_2} \wedge p = 0 \}, \\
D^h_1 & = \{ \Xi \in \mathbb{R}^3, |\epsilon_\theta| \leq \theta^h_{q_1} \wedge p = 1 \}. \quad (12)
\]

Notice that the correctness of the haptic controller (11) is proved once $\epsilon_q \in (\theta_{q_1}, \theta^h_{q_2})$ as for the mechanical system in Section III, hence it is chosen for simplicity as $\epsilon_q = (\theta^h_{q_2} + \theta_{q_1})/2$.

V. EXPERIMENTAL RESULTS

The experimental results are separately collected into two different subsections. The first refers to the quantitative analysis about the path following performances, while the second is related to the user evaluation. We conduct two studies with older adult participants (details can be found in Table I) in which the testers completed different paths using the FriWalk in one of the laboratory of the University of Trento. In the first study (with 4 males, 10 females, age between 65 and 75 years old), the participants were asked just to travel along a couple of paths using the

<table>
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<th>Males</th>
<th>Females</th>
<th>Older</th>
<th>Younger</th>
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- **Figure 8.** Graphical representation of the hysteresis thresholds.
passive braking system controller only, while in the second study (with 6 males, 9 females, ageing between 64 and 100 years old) a more extensive study, with more than eight paths for each participants were considered, relying on more guidance strategies. In particular, in this second study, the three combinations of guidance were considered. Participants were contacted through the Municipality of Pergine Valsugana and the senior centre “Sempreverde” of Mattarello (both in the Trento province) and invited to participate. Of this group, some of the participants usually use walking aids, such as crutches and/or a walker (28.6% of Study 1 and 43.8% of Study 2 reported under “Walking Problems” in Table I). Overall, the data presented in the paper comprises 29 users: notice that the size of the sample is definitely comparable with other studies performing user evaluation with seniors (e.g. 30 users in [38], 6 in [39], and 31 in [40]). All the participants were informed that data collection and the information provided are covered by the ethical rules conceived for the ACANTO project [6] and that they could quit the experiment at anytime. Once consent was obtained they were invited to perform the tasks with the FriWalk. Before starting, an experimenter showed to the participant the path to follow and explained the features of the robotic walker and its guidance modalities. All participants completed a first trial (which was common for everybody) to take confidence with the robotic walker and its movements. More than ten different paths, starting and ending in the same home position, were randomly chosen for each participant, that completed at least one of them. In the laboratory arena, three tables were placed to emulate an actual indoor environment (see the rectangular obstacles in Figure 9).

A. Quantitative analysis

The controller hysteresis threshold are set to $\theta_{q_2} = 40^\circ$, $\theta_{q_2}^h = 30^\circ$ and $\theta_{q_1} = 20^\circ$. Four sample trajectories along a randomly selected path are reported in Figure 9, Figure 11 and Figure 13 for the bang-bang, haptic and combined strategies respectively. The localisation is provided with an EKF fusing the encoder data and the QR codes and read by the available front camera pointing downwards. Figure 10, Figure 12 and Figure 14 reports the time evolution of the error $e_\theta$ for the Exp1 in Figure 9, Figure 11 and Figure 13, respectively.

1) Bang–bang braking system: In this experiment, we asked the user to follow a desired path (blue solid line in Figure 9) while the FriWalk is controlled by the bang-bang braking strategy reported in Section III. It is important to recall that the user is always in control when the attitude error $e_\theta$ is below the inner threshold (see Figure 10), while the robot is always in control when $e_\theta$ is greater than the outer threshold. Within the two values, the control authority depends on the history of $e_\theta$ due to the hysteresis nature of the controller. Moreover, from Figure 10 it is worthwhile to note that as soon as $e_\theta > \theta_{q_2}$, the controller kicks in and $e_\theta$ does not increase anymore, thus showing that the controller is able to steer the user towards the desired path.

2) Haptic guidance: When the haptic guidance described in Section IV is used, the results look like Figure 11. For this approach, the user is always in control, independently from the value of $e_\theta$, while steering suggestions are given with the haptic interfaces. The user can follow the suggestion of the bracelets and then be steered to the desired path, or ignore the stimuli. It could happen, also, that the user interprets wrongly the information coming from the bracelets, as in Exp2 of Figure 11, where it is possible to appreciate how the user steers right, since he receive a stimulus from the right bracelets, but not enough to follow the desired path. As consequence the user follows a wrong path, leaving the middle table on his right instead of his left. Similarly, in the bottom part of the plot Figure 11, another wrong path is followed in the Exp3. This misbehaving users are not so uncommon in the target class of this work. The time evolution of $e_\theta$ for the haptic guidance is reported in Figure 12. From this graph, once compared with Figure 10, the higher deviation can be easily appreciated, even for Exp1. Furthermore, whenever $e_\theta$ exits
from the outer threshold, it takes some time before the user follows the control signal, with the unavoidable consequence that the error increases largely before decreasing.

3) Integrated controller: The trajectories obtained with the integrated controller detailed in Section IV are reported in Figure 13. Figure 14 reports $e_\theta$ versus time. In this plot it is possible to appreciate how the two strategies can be either both activated or only the haptic strategy kicks in. In particular, at the beginning of the plot in Figure 14, the nature of the integrated strategy is easily recognisable: as soon as $e_\theta > \theta_{q1}$, the bracelets actuation is activated. At this point, if the user is cooperative and follows the suggestion, the error $e_\theta$ remains below $\theta_{q2}$, with the consequence that the braking system is never actuated. Whereas if $e_\theta > \theta_{q2}$, the brakes intervene to steer the user towards the correct orientation, with the positive effect that the error never reaches the high values observed in Figure 12.

B. Performance analysis

The overall controller performance are reported in Table II, where we report the average path-following error $|l_y|$ of the user for the different strategies and its standard deviation, the number of interventions of the controller and the percentage of time that the controller is active during the guidance. For what concerns the path-following error $|l_y|$, the haptic guidance poorly perform due to the high level of freedom given to the user. Using the braking system, either in isolation or combined, the overall mean error $|l_y|$ is reduced significantly.

On the other hand, regarding the number of interventions in Table II (also reported in Figure 15-(a)) we can see how the number of times that the controller is activate is maximum in the bang-bang strategy, meaning that the guidance solution
Table II

<table>
<thead>
<tr>
<th>Feature</th>
<th>Bang-Bang</th>
<th>Haptic</th>
<th>Integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>m</td>
<td>0.24</td>
<td>0.39</td>
</tr>
<tr>
<td>std</td>
<td>m</td>
<td>0.10</td>
<td>0.27</td>
</tr>
<tr>
<td>n° of interventions</td>
<td>20.30</td>
<td>7.00</td>
<td>10.67</td>
</tr>
<tr>
<td>std n° of interventions</td>
<td>12.50</td>
<td>2.00</td>
<td>3.24</td>
</tr>
<tr>
<td>time perc. active controller</td>
<td>21.22</td>
<td>45.95</td>
<td>12.59</td>
</tr>
<tr>
<td>std perc. active controller</td>
<td>10.40</td>
<td>18.60</td>
<td>10.54</td>
</tr>
</tbody>
</table>

Figure 15. Comparison between strategy performance: (a) number of controller interventions, (b) percentage of time for which the controller is active.

is not very clear for the user (due to the abrupt nature of the solution). Nevertheless, from Figure 15-(b), we notice that, even if the number of interventions is high, the controller remains active only for 20% of the time, meaning that the corrections are frequent but very short. The haptic guidance is instead characterised by an opposite behaviour, which means that the controller acts infrequently, but the overall activation time is around 45% of the overall experiment. In other words, the user does not clearly interpret the stimulus coming from the bracelets and it takes some time to properly react. These results justify the proposed approach of fusing these two opposite behaviours in a trade-off. Indeed, combining the two solutions in an integrated controller, the number of interventions of the braking system Figure 15-(a) and the activation time of the bracelets Figure 15-(b) is halved, highly increasing the comfort perceived by the user and simultaneously achieve good performance in terms of the path following error $|\delta_y|$.

C. Users’ evaluation

In both studies, we used a questionnaire to conduct a structured interview in order to collect the impressions and opinions of people who participated in the studies. After the tests with the robotic walker, participants were invited to sit next to an experimenter who conducted the structured interview reading the items of the questionnaire. The aim of the structured interview was to collect the impressions of people on the proposed control approach. To this end, we included different questions (open ended and closed ended).

In the present work, we present the analysis of closed ended questions. Participants were asked to answer using yes or no and a 5 point Likert scale (1 “not at all”, 2 “a little bit”, 3 “moderately”, 4 “very much”, 5 “extremely”). The questions are reported in Table III and concerned different features of the interaction with the robotic walker (i.e. if they felt vibration during the use, if it was clear if and when the FriWalk decided the path and if they felt pushed or blocked), followed by items on the pleasantness of usage, the ease of learning, the control over the robot and the adaptability of the walker. For the sake of compactness, we report in Figure 16 the results of the questionnaire in Table III for Study 2 only.

We observed an overall positive opinion on the FriWalk control modalities. Although the quantitative results presented in Section V-A underline that the combined strategy ensures the same path-following error of the bang–bang strategy, the psychological evaluation summarised in Figure 16 shows that the combined strategy offers superior comfort, especially in terms of easy of learning (item L3), control (items C2 and C3) and adaptability (item A3). Participants stated they were aware that the system was programmed to decide the path to follow but they judged this feature as not disturbing. Moreover, since the suggested route is rendered uniquely with vibrations of wristbands on participants’ arms, no one of them reported the sensation to be pulled, blocked or pushed. Participants evaluated the interaction with the FriWalk as pleasant and not frustrating, indicating that it was easy to learn its use. Furthermore, they perceived the system in good accordance with their usual way of walking or their natural speed.

VI. Conclusions

This paper proposes a path following control strategy for a robotic walker combining a mechanical braking guidance and a vibrotactile haptic guidance. The bang-bang braking guidance in isolation ensures safety and guaranteed path following accuracy, but the user comfort is penalised because of the abrupt actuation due to the simple control strategy. Conversely, vibrotactile haptic guidance in isolation results
much more comfortable, but it cannot ensure an adequate path following performance with uncooperative users, so user’s safety is not guaranteed. The experimental study and the psychological evaluation show that the combined hybrid approach has proven to be effective in preserving the safety and the path following accuracy of the braking guidance while improving the comfort of the haptic guidance, thus outperforming the other two approaches in isolation. In particular, the combined approach produces, similarly to the braking-only approach, a mean path following error equal to 41% of the mean path following error ensured by the haptic-only approach. Conversely, thanks to the haptic cues, the combined approach halves the activation time and the number of interventions needed in the braking-only approach.

Future research on the control strategy will focus on the automatic adaptation to the environment of the thresholds $\theta_q$, $\theta_h$, $\theta_{q1}$, and $\theta_{q2}$ defining the integrated controller. For instance, in an open environment (with no obstacles), a large value of the braking thresholds $\theta_q$ and $\theta_h$ (i.e., more freedom for the user) is desired. Conversely, in cluttered environments, where a better path following accuracy is needed to avoid collisions, a reduced value of the braking thresholds should be automatically set. In terms of user evaluation, future research will focus on longer and more ecological interactions of people with the robotic walker. Observing how individuals relate with the robotic walker in natural environments can provide a different kind of observations which cannot be detected in a controlled laboratory scenario.

**References**


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