Online Control of a Mobility Assistance Smart Walker

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Abstract—This work presents the ASBGo Smart Walker, developed at Minho University with the Adaptive System Behavior Group. It includes the conceptual design, implementation and validation of a Smart Walker with a new interface approach integrated. It was addressed the assembly of the ASBGo with the required electronics, as well as the implementation of the interface based on a joystick. This sensor is intended to read the user's movement intentions to command the walker. Thus, preliminary sets of experiments were performed with 10 healthy volunteers walking with the device. This was followed by the signal processing and extensive analysis of the joystick signals, which showed the capability of the joystick to extract navigation commands from the user. Based on this real-time identification of user's commands, an approach to the control architecture of the ASBGo was developed and it is based on a fuzzy logic algorithm that allowed the control of the walker’s motors. A set of validation experiments were then performed. In addition, it was addressed the security of the user by adding a set of sensors to detect if the user falls.

Index Terms—Smart walker; interface; rehabilitation, fuzzy control

I. CONTEXT

The number of people with reduced mobility capacities increases every year. The reduction on mobility is a factor that influences both people quality of life and their dependence of others in daily life.

This demands the development of devices that can support and aid these people. Among the existing mobility assisting devices, walkers play an important role on giving lateral stability, balance, partial weight support, among others, to its large number of potential users [1]. These potentials arise due to the use of the user’s residual capacities, trying to maintain and enhance them through functional compensation. Thus, they produce an opposite effect comparatively to the wheelchairs, that have an incapacitate effect on users due to the decrease in the use of the lower limbs.

Smart walkers have emerged to promote a better assistance to gait, especially considering navigation [2], gait monitoring [3], and partial body weight support [2]. However, some of these devices are still too complex to use. They have to be built considering that many users present not only mobility problems, but also may face cognitive impairments. For instance, elderly people usually present slower behaviour and are not familiar with mechatronic devices. In order to overcome these cognitive and sensory deficiencies, studies regarding the development of interfaces that establish a direct control of the user are increasing in the literature [2][3]. These interfaces have to be user-friendly, natural and transparent to the users, not being demanding at their cognitive level.

This work aims to build a walker with a system capable of controlling its movement through the extraction of the users’ movement intentions obtained by the integrated sensory system. It seeks to develop a tool that provides for a clear benefit to a large number of people with limited ability to walk by improving the safety and reliability of walkers. Therefore, the users will avoid to inadequately resort to wheelchairs, that have disabling effects, thus contributing to the maintenance/improvement of the physical and cognitive capabilities of the user, through functional compensation.

II. GOALS

This work aims to develop a Smart Walker, considering its design, implementation and validation.

The developed device is based on a conventional four-wheeled walker. It is also proposed a novel, simple interface based on a joystick to extract the user’s movement intentions. This interface was designed to be user-friendly and efficient, meeting usability aspects and focused on a commercial implementation [4]. The joystick converts the user’s intentions into direction and velocity to then inform the walker and as such endows the capability of reading the user’s commands to guide the walker. Then it is required to process and analyse the joystick signals. As the joystick has noisy signals, it were developed tracking filters that can estimate the user’s command intentions in real time, eliminating the higher frequencies related to noisy components.

It are also addressed additional safety measures for the proposed walker, where a set of sensors and their localization were studied and applied to improve the detection of dangerous situations such as as the detection of fall.

Then a control strategy was implemented. This control strategy was based on fuzzy logic and it interprets and classifies the signals sent by the joystick and transforms them...
into motor inputs, such that the walker follows the user’s commands. Finally, it was made the validation of the control strategy of the guidance of the walker. Necessary improvements were made during the validation.

III. DESCRIPTION

The ASBGo Smart Walker is presented in Figure 1. This new robotic walker was built during this work, as well as its electronics, through the mechanical modification of a conventional four-wheeled walker. Among the different types of walkers it was selected a four-wheeled to become possible the installation of sensors and motors for the driver of the walker. Among the four-wheeled walker it was given priority to one that allow the installation of the electronics and heavy components in the lower zone of the walker to improve the general stability of the set user-walker. An additional structure was implemented to integrate the motors of the robotic walker and then an additional support base for the upper limbs, in order to find the best way to frame the interface that will be studied on the support. The device was implemented with simple and low cost sensors, as this project has a commercial focus for the prototype. The interface must be user-friendly without requiring a cognitive load or training, based on the fact that many potential users present difficulties related to these factors. The possibility to detect possible falls of the user was also one of the aims integrated in this project.

To program all the implemented strategies on the walker, it was used the Arduino Platform, as it is an economic approach.

A. Specifications of the interface

In order to provide walking support, the ASBGo has to capture the direction that the user intends based on the user manipulation. The directional intent will be identified from physical manipulation because the user’s directional intent and his physical manipulation usually are mutually consistent.

The interface must have the capability to “read” and interpret all the kind of intended motions, to follow the user’s movement, and to provide for a good walking support. Additionally, the novel interface has the advantage of using the forearm supports, improving safety during walking and helping to unload the lower limbs.

The new interface consists on placing, at the center of the upper base support, a joystick associated with a spring that is moved according to user’s manipulation (Figure 2). The joystick is a robust and low cost device that does not require excessive use of electronics, and reduces the risk of failure.

So, when the user applies forces to the handles, a slight movement is transmitted to the upper base support, mechanically coupled to the joystick that reads the user intention. When the user begins his gait, he has to slightly move the handlebar through the handles, moving the joystick to inform the walker which direction and velocity he wants to take.

The joystick outputs three X,Y,Z signals, measured in Volts that specify the imposed movement in the direction of the XYZ-axis attached to the joystick. After some preliminary experiments, it was concluded that Y and Z are sufficient to cover the user’s intention movements, i.e. direction and velocity (as it will be shown in next section).

B. Safety Considerations

Additional safety is envisaged by several sensorial subsystems that complement each other. First, to detect possible forward falls of the user it is monitored the approximation of the user with infrared sensing (GP2Y0A21YK0F) at the height of the chest (Figure 2). If the user is falling forwards, the distance between the user’s chest and the walker will decrease. This decrease will be detected by an infrared sensor (IR), as it is shown in figure 3a). An algorithm was developed to detect abrupt changes on the signal, to then detect if the user is falling forward and stop the walker in time accordingly.

To detect if the user is falling backwards three steps were introduced. First, the walker cannot move backwards. So, if the user pushes the upper structure in his direction, the walker stops. Another subsystem ensures the user is guiding the walker grasping the two handlebars. The proposed safety system is compounded by two Force sensor resistors, one on each handlebar (Figure 2). If the two handlebars are not being held by the user, the walker will immediately stop. A third step is based on two Force sensor resistors, one on each
forearm support, that will verify if the user is with his forearms properly supported on the base supports (Figure 2). When the user is not loading the sensor the output signal is zero (Figure 3b)). When the user relies on the support or grasps it, the sensor immediately responds to the force, and the signal increases. When the user leaves the support, the sensor’s signals immediately decreases. The same algorithm used with IR signals, was used in these two situations.

![Figure 3](image)

Figure 3 a) Typical IR output signal from user that is walking normally and then falls forward; b) Typical signal of the Force sensor resistors when first, the user is not loading the sensor, and then loads.

**C. Interaction Components**

To extract and study the signals from the joystick, it was conducted a study with eleven healthy volunteers, with no history of dysfunctions on either upper or lower limbs. These volunteers had to perform simple tasks like moving forward and then turn left or right (Figure 4). These experiments were performed without any motorized system (no motors).

![Figure 4](image)

Figure 4 a) Walking forward, b) turning right and c) turning left.

On each experiment, forward (Y) and rotation (Z) signals are acquired. The Y-signal, gives an indication of the user intention to move forward and according to the applied force on this axis, the signal will have more or less amplitude, depending on the user’s command intention to go forward with more or less velocity. The Z-signal, gives an indication of the user intention to perform a curve and the signal will present high or low amplitude depending if the performed curve is more or less accentuated. The intention to turn right or left is detected by the sign of the signal, i.e. turn left causes negative signal and turn right causes positive signal.

![Figure 5](image)

Figure 5 Typical raw Y and Z joystick data in the ASBGo walker when the user is performing the following trajectory: S1 - The user is stopped; S2- User starts walking forward; S3- User turns right; S4- User walks forward; S5 – User stops.

After this discussion, one can conclude that the joystick system read correctly the user’s command intentions. However, by observing the characteristics of the signals Z and Y, it can be identified two main components of the signals. One component (i) represents the highest frequency noise caused by the vibrations of the structure caused by the irregularities of the ground, electromagnetic noise and wheel eccentricities. This component must be eliminated in real-time, not causing a considerable delay on the signal. For that, it will be used a tracking filter which choice will be presented in detail on the next section. The other component (ii) is the component that contains the information of the walking movement intentions of the user to guide the walker.

**IV. SIGNAL PROCESSING METHODOLOGY**

The signal processing methodology consists in the elimination of the noise (higher-frequencies) present in the Y and Z acquired signals. The data that was collected yields that the user’s commands intentions occur in a frequency range between 0 and 2 Hz in both Y and Z-sIGNALS, and the higher-frequency components are related to noise. The Z-signal has more accentuated higher-frequencies than the Y-signal, since Z-signal has 2.37 of signal-to-noise ratio (SNR) and Y-signal has 48.98. As the SNR of the Z-signal is much lower than the one of the Y-signal, Z-signal has to be further filtered.

The higher frequency components present in the signals can be eliminated with forth and back recursive digital filters, such as Butterworth filters, without causing phase distortion. Its implementation showed that the SNR of the signals after being
filtered increase. However, this approach is not real-time implementable. Still, this filter is a good reference for an ideal signal to be achieved with the filtering strategy to be implemented. Thus, this filter is set as a basis to evaluate the performance of the chosen filter strategy.

Besides being real-time implementable, the required filter has to have low computational cost to avoid the use of expensive hardware, and it cannot introduce larger temporal delay on the filtered signal. Since this signal will be used to control the walker, the user should not perceive the delay between his commands and the movement of the walker. The human perception threshold in applications like this is known to be around the 200 ms.

In the literature [5], two types of filters were identified to be used as potential candidate algorithms to eliminate components of higher-frequency in real-time. These filters are the g-h filter and the Kalman filter.

**g-h filter** In this filter measurements are used to correct the predictions that are made for the signal, minimizing the estimation error. Formulation is presented in [5]. This filter presents two parameters (g, h) that need to be offline tuned. To this, the Benedict-Bordner Filter (BBF), equation (1), and the Critically Damped Filter (CDF), equation (2) will be applied to select the filter parameters.

\[
h = \frac{g^2}{2 - g} \tag{1}
\]

\[
g = 1 - \theta^2 \quad h = (1 - \theta)^2 \tag{2}
\]

**Kalman Filter** provides an efficient computational tool to estimate the state of a process, in a way that minimizes the mean of the squared error [6]. The Kalman version here depicted is the conventional Kalman filter. It was implemented a kalman filter that tracks the user’s intentions modeled as a first order process. Formulation is presented in [6].

The filter parameters are the measurement noise covariance \( R \) and the process noise covariance \( Q \), and they will be measured offline.

The measurement noise covariance \( R \) is determined by the average variance of the measurement noise: \( R = \sigma^2 \). Its value is 8.82x10\(^{-5}\) rad\(^2\).s\(^{-2}\) for the Y-signal noise and 1.3x10\(^{-5}\) rad\(^2\).s\(^{-2}\) for the Z-signal noise.

The selection of the process noise covariance \( Q \) is generally more difficult as it is difficult to have the ability to directly observe the process that is being estimated [6]. In this application the process noise covariance \( Q \) is formulated based on the first derivative noise, which affects the estimation of the user’s command intentions.

**A. Evaluation of user’s movement intentions tracker filters**

In this section is presented the selection of the parameter \( g \) (BBF), parameter \( \theta \) (CDF) and parameter \( Q \) (Kalman).

For this selection the Kinematic Estimation Error (KTE) was used. KTE evaluates the smoothness, response time, and execution time of a tracking algorithm [7] and is expressed by:

\[
KTE = \sqrt{|F|^2 + \sigma^2} \tag{9}
\]

\(|F|^2\) and \(\sigma^2\) are the mean and variance of the absolute estimation error between a desired signal and the measured signal. The desired signal is obtained by filtering offline the signals’ measurements with a Butterworth filter.

To select the filters parameters (\( g \) for BBF, \( \theta \) for CDF, \( Q \) for Kalman), eleven individuals drove the walker without any motorization executing three different trajectories with five repetitions each. During these experiments the signals of the joystick were acquired.

These signals were then introduced off-line in the filters algorithm (BBF, CDF and Kalman) using a broad range of \( g \), \( \theta \), \( Q \) parameters. The result was processed by the KTE. The best solutions for each filter, i.e. the ones with the lowest KTE, were chosen for each user, experiment and repetition. With these results, it was calculated the mean of the best 165 solutions for each parameter, as well as the mean of the delay (between the input and the output) for each case. Table I and II present these results.

As it can be seen in Table II and III, \( g \) of the Z-signal compared with the \( g \) parameter of the Y-signal shows a lower value. Similarly, the average \( \theta \) and \( Q \) parameters of the Z-signal compared with the average \( \theta \) and \( Q \) parameters of the Y-signal shows a higher value. These results were as expected, since the SNR of the Z-signal is much larger than the one of the Y-signal, requiring to be further filtered [5].

All filters are of high quality for a human-machine interaction because the introduced delay is much more inferior to human perception (200 ms), not causing prejudice to the human-machine interaction.

KTE is very low for all filters, being the lowest one, the BBF’s KTE value, as well as its dispersion. Additionally, the BBF detains the lowest signals’ delay.

Since BBF presents the lowest KTE for both signals, one can conclude that it is the best option to choose for this application. This can also be seen in an example of joystick signal in figure 7, where are presented the differences between BBF and CDF; and figure 8 presents the differences between
BBF and Kalman, as well as the reference. The BBF shows a higher attenuation on the oscillations than the CDF and Kalman filters. Thus, a Benedict-Bordner g-h filter was applied to the joystick data. The \( g \) parameter was chosen to be \( 44.29 \times 10^{-3} \) for the \( Y \)-signal and \( 16.87 \times 10^{-3} \) for the \( Z \)-signal.

The chosen filter has a low computational cost algorithm, making it a good option to this application, since it can run in a low cost hardware with enough robustness for a commercial device. This processing is fundamental to develop the control strategy that will control the motors’ movement.

![Figure 7](example.png)

**Figure 7** a) The raw \( Z \) with the results of BBF, CDF and Butterworth; b) The superposition of the raw \( Y \) with the results of BBF, CDF and Butterworth.

V. CONTROL STRATEGY

In this section, it is addressed a control strategy based on fuzzy logic to classify the signals sent by the joystick and transform them into motor inputs, in such way that the walker drives the motors according to the user’s commands.

The premise behind fuzzy logic is that precise outputs can be obtained from imprecise or vague inputs [8]. The two fuzzy logic controllers are proposed for the \( Y \) and \( Z \)-signals.

It was defined a set of membership functions (MF) for each joystick signal and they were constituted by Gaussian and bell functions. The variables, which form the set of MF for the \( Z \)-signal and that will interpret this signal, are divided onto: much left (ME), little left (LE), zero (Zi), little right (LR) and much right (VR). Similarly, the variables, which form the set of MF for the \( Y \)-signal and that will interpret this signal, are divided into: negative (Neg), zero (Ze), little positive (PP) and very positive (MP). For the motors right (MR) and left (ML), the output MF set is divided onto: zero (Z), slow (S) and fast (F). The decision-making rules are presented in Table III.

![Table III](example.png)

**Table III**

<table>
<thead>
<tr>
<th>Membership Functions</th>
<th>Output MF</th>
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<tbody>
<tr>
<td>Neg</td>
<td>Z</td>
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<tr>
<td>Ze</td>
<td>Z</td>
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<td>PP</td>
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<td>MP</td>
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<td>MR</td>
<td>S</td>
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<td>ML</td>
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VI. VALIDATION OF THE PURPOSED ARCHITECTURE WITH HEALTHY USERS

A series of experiments with 11 healthy users were conducted to assess the functioning of the fuzzy system and allow the tuning of the parameters of the implemented system. In fig. 9, an example of result is shown. The signals were acquired while a user was performing the following trajectory: Start to walk, walk forward, turn left, walk forward and stop.

These validation tests were performed with motorization. Looking at figure 9a) it can be seen that despite the addition of the motors and the control strategy in the movement of the walker, these signals present the same behaviour as the ones acquired with no motorization and control (figure 5). The only difference is that the \( Y \) and \( Z \)-signals present with the validation a more accentuated noise. This is caused by the vibrations and electromagnetic noise due to the motors. However, as it is shown in these same figures, the results from the filter BBF are very satisfactory, proving the good performance of the filter in attenuating the noise components.

In figure 9b) it is shown the result obtained before the BBF filter, as well as an adjustment on the gains of the signals. The \( Y \)-signal was inverted, amplified and is in the range of [-1,1].
The Z-signal is also in the range of [-1,1], and it was amplified.

In figure 9c) one can see the output of the fuzzy control system as well as the result from the smoothing process. It is also seen that the signal was converted to the range of [2.5,5] in order to be sent to the low-level control hardware to command the DC motors.

User transmits to the walker at t=2s the intention to start walking. This can be seen in figure 9b), where the Y-signal increases their amplitude, informing the walker the intentions of the user to go forward. Consequently, both motors start to increase their velocity, as it can be seen in figure 9c) at t=2s. At t=4s, the user decided to accelerate more. This was concluded by the observation of figure 9b), where the Y-signal amplitude increases even more, as well as the motors signals (figure 9c)).

At t=7s, the user wants to turn left, as it is shown in b), where the Z-signal turns negative. This intention is reflected in the motors movement where the left motor decreases its velocity, and the right one maintains its. This way, the walker starts to turn left, as the user commanded. Then, the user transmits to the walker that he wants to increase the velocity of the execution of the curve, passing of a translation curve to a rotational curve. This happens at t=10s, where the amplitude of Y-signal is increased. Thus, the right motor increases its velocity, as it can be seen in figure 9c). The intention to turn left ends at t=12s. At t=16s, the user’s intention is to stop, so he pushes the handles to himself, decreasing the amplitude of the Y-signal. This is shown in figure 9c) where at t=16s the motors’ signals are zero, which means that the motors stopped.

Thus, it was successfully generated a control strategy which has low computational cost, allowing a smooth and enjoyable driving, fast response of the walker and no sense of delay. The user feels that has the control of the device and that it follows his intentions to move.

VII. CONCLUSIONS

In this thesis it was presented a method of user-walker interaction to extract the users’ command intentions. The proposed interface has been mounted onto the the ASBGo walker. A series of experiments using with healthy users were performed which showed the sensibility of the joystick to extract navigation commands from the user. The proposed control strategy based in a fuzzy inference system, classified the signals sent by the joystick, transforming them successfully into motors outputs. It showed very good results, allowing a smooth and enjoyable driving, fast response of the walker and no sense of delay.

In future work a necessary step is to validate this device with disability persons, in terms of easy-to-use and intuitive interface. It must be also promoted contacts with both medical staff and clinics for medical evaluation and quantitative assessment of the walker’s potential as a rehabilitation and functional compensation too.

The advances in the walkers’ field have been enormous and have shown a great potential on helping people with mobility disabilities, however, this work allowed to identify fundamental concepts and challenges that still need to be addressed in the smart walkers’ area, in terms of user-walker interaction and safety that need to be more explored and validate with the target users.

Figure 9 Results from the experiments with the ASBGo walker. a) Raw joystick signals and signals filtered with the BBF filter. b) Signals before the amplification; c) Output of the fuzzy system and its integration.

REFERENCES