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Human-Walker Interaction on Slopes Based on LRF and IMU Sensors

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***Abstract*— Smart Walkers should be able to safely deal with inclinations in order to become a device effectively useful in the daily life of the elderly population. This paper presents a novel model of human-walker interaction on slopes. The interaction parameters are obtained from a Laser Range Finder (LRF) and an Inertial Measurement Unit (IMU). This model is integrated into the conventional closed control loop as a supervisor block. This block modifies, based on inclinations, the control set points to provide an adaptable human-walker desired position to improve comfort and safety and enhance user's confidence in the walker. The practical evaluation shows that the parameters extracted from the natural behavior of the user and the estimated set points determined with the model proposal are highly correlated, presenting a similar trend. This correlation allows performing a more natural control.**

I. Introduction

Considering that the number of Brazilians over 60 years old will reach 58 million in 2050 [1] and that human mobility decreases gradually with age as a consequence of neurological, muscular and/or osteoarticular deterioration [2], there is a significant need to develop safe and efficient ambulation devices. This may help to reduce the incident of fall and fractures [3].

In general, most of the assistive devices found in literature are not prepared to securely deal with slopes. Nevertheless it represents a necessity as slopes are big obstacles for people in need of mobility assistance. Usually, inclinations are found to overcome an architectural barrier, which is a structure or a design feature of a home or a public building that limits the access and mobility of disabled persons. The construction of ramps and inclined surfaces is ruled by strict regulation [4]. Urban environments have a great quantity of them, making the development of slope assistance a priority when projecting assistive devices.

II. Related Works

The vast majority of papers found in literature about assistive robots on slope regard the research area of medical and rehabilitation robotics. Other fields of research could also benefit from a control strategy for slopes.

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The supermarket Walker [5] [6] could be helpful to the user also in presence of the ramps placed to reach the car in a shopping mall. The Adept SPH-2200 [7] could take advantage to move the transported material in an outdoor warehouse passing through a ramp. The versatile mobile robot PeopleBot [8] would expand its operation areas if it could run on slopes, e.g. while helping a blind to navigate.

In the research field of rehabilitation robotics, some active devices include a control strategy for the presence of slopes in their control scheme. The wheelchairs implemented in [9] and in [10] detect inclination and compensate the gravity effect adjusting the dc motor torques. Torque is incremented when the wheelchair moves longitudinally uphill, the motors are shut down and the breaking system is activated when moving downhill. Moreover, in [10], torque is added just to the wheel in the leaning side when the ground is laterally inclined.

The active smart walker developed in [11] is equipped with force sensors on the forearm supports. A gravity compensation technique, that corrects the direction of the impressed forces, is applied to the walker with the goal of making the user feel no additional load while running on longitudinal slopes.

Another trend of research approached the control on slope from a different point of view. They have developed robots that can modify their physical features in order to keep the support area globally in the horizontal position. In [12] it has been developed a smart walker with four actuated legs, which can independently regulate their length in order to keep the top plate supporting platform horizontal.

An innovative solution reported determined that if the control strategy is based on an admittance model and as long as the user and the walker run on the same plane (horizontal or inclined), any modification to the control strategy due to the presence of gravity is unnecessary [13]. This happens because the velocity of the walker is determined only through the forces and torques applied by the user and, on inclined ground, the gravity component of the walker is countervailed by the extra output of the driving wheels, necessary to keep the desired velocity, received as input through the force sensors. The desired velocity has to be modified just in the transitory conditions of passing from an inclination to another, multiplying it for a coefficient that depends on walker inclination.

Smart walkers are devices that widely benefit from solutions for slopes because of two main factors. Firstly, their weight is significant, making a hard task for the user to push and pull the uncontrolled device. Secondly, the user-walker interaction is very complex, because of the large freedom of movement that the person has and the very limited points of contact between user and walker. This makes solutions that treat the human-walker compound as a single entity (as if it was a vehicle) very ineffective.

In this work, it was developed an innovative technique to make the assisted gait on slope as natural as possible, taking into account the optimization of user's comfort and safety. This work developed and evaluated a model, called Pivot Model, which considers ground inclination in order to adjust the control set points. The model has a focus on the kinematic analysis of human and walker on slope, so to make the control better apply to the actual physics of the problem. This paper is organized as follows. Sections I and II presented the introduction and a brief review of the works that address the problem of robotics on slopes. Section III presents the model developed in this work and the robotic platform used to test the model. Section IV presents the experimental setup description and section V presents the experimental results. Finally, section VI presents the conclusions and future works.

III. Material and Methods

The work was carried out in three phases. First, it was developed a kinematic analysis of the interaction user-walker on slopes, defining the Pivot Model in his two modalities: the pitch model and the roll model. Second, a robotic walker platform was presented. Finally, an experimental study to evaluate the effectiveness of the Pivot model was developed.

A. Pivot Model Proposal

The walker control strategy aims at keeping the user in a comfortable and secure position in order to assure a constant support and body weight unload during the assisted gait. The position of the middle point between user's legs H with respect to the Walker W is described by two parameters: distance d and angle θ both read by the LRF (red mark in Fig. 1) placed on the walker. These two parameters, shown in Fig. 1, are used for the control: keep the distance, d, at a desired value (d_d) and keep the angle θ equal to (θ_d). This is a conventional strategy, in which the set points for parameters θ and d are fixed at a constant value. In this paper this control strategy is referred to as the Normal control method and determines the Normal parameters (Normal d_d and Normal θ_d).

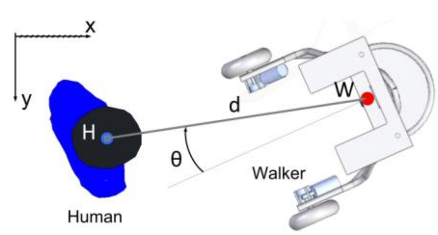

Figure 1. Upper view in the x-y plane of the user and walker model. Control configuration based on distance d and angle θ.

Natural reactions of the user to a certain situation are considered conditions to be achieved in the controlled motion. For this reason the goal is to generate control targets that resemble the natural movement of the user. With the use of video recordings, the targets of the controller in natural uncontrolled situations have been studied, when in presence of inclinations, developing a model that describes the human walker interaction on slope, called the Pivot Model.

In Fig. 2, four schemes of the human-robot interaction Pivot Model, represented by two axes and a pivot, are presented, respectively (a) and (c) in the pitch and (b) and (d) in the roll inclination.

Human-robot interaction on slope can be modeled as two bars, one representing the user, in blue in Fig. 2 and the other one the walker, in red in Fig. 2. The parameter a is the distance between the walker axis and the pivot point P, which is the link between the two bars and is fixed with the walker at handlebar height.

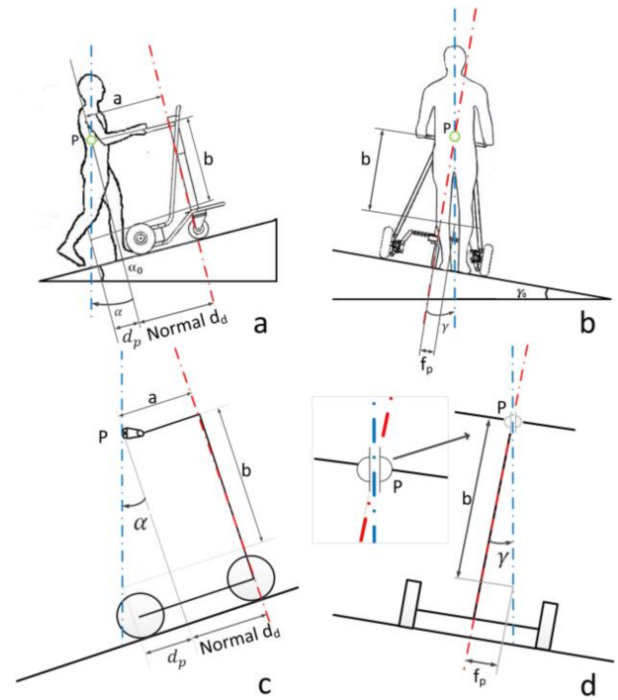

Figure 2. (a) Human walker on longitudinal slope. (b) Kinematic model of human and walker on longitudinal slope. (c) Human walker on lateral slope. (d) Kinematic model of human and walker on lateral slope, with closeup on the kinematic link.

Moreover, parameter b is the distance between the point of measurement of distance d and the handlebar. Angle α and γ are respectively the pitch and roll inclination angles. d_p is the additional component of the desired distance due to the pitch angle and f_p is the lateral displacement of the user's feet due to the roll angle. The same model treats both pitch and roll inclinations.

The introduced Pivot model allows analyzing some very important features of human natural and controlled motion on slopes. First, the human body is considered to remain vertical while running on slope, the compensation of inclination is considered to be done mostly by the ankles. Second, the walker remains perpendicular to the ground, due to the good grip of the wheels and the limited velocity that it develops.

The pivot was chosen to be the link between user and walker because it allows two desired movements: the rotation of the human axis, which remains always vertical even if the walker rotates and the shifting of the human axis in vertical direction, in order to have its lower end always in contact with the ground.

B. *Pitch Model*

When the walker encounters a longitudinal inclination, uphill or downhill, a speed change of the walker occurs: acceleration if the walker encounters a negative variation of pitch angle and deceleration if positive [13].

Moreover, it results in an uncomfortable situation for the user because, if in a positive variation of pitch angle, the handlebar gets closer to user's waist and the user perceives the need to push the walker harder, or lower the gait speed. It is possible to conclude that, when in this condition, an increment in the traveling speed of the walker is desirable. The opposite reasoning can be applied to a negative variation of inclination.

It is important now to define the concept of "load feeling" or "burden" meaning the perception of the user when using a device; it can be defined as the amount of push requested to the user in order to keep its desired speed. Commonly, a good goal for slope compensation is to make the user feel as if he was on flat ground, meaning that even on slopes the burden perceived has to be constant [11].

In order to assure a constant "load feeling" to the user, it is required that the distance between user and walker, at the contact point in between them, the handlebar, remains constant. For this reason the desired distance d_d at legs height varies depending on the pitch angle.

Moreover, it has been defined that the desired speed of the walker has to vary when it encounters a slope. When a positive variation of pitch angle occurs, the speed required to the walker, in order to have a linear velocity at the handlebar equal to the one of the user, is higher than the one it would normally have. For this reason, the desired distance is raised during the evolution of the pitch angle, making the walker increment its speed to reach the desired distance d_d. The new desired distance, called Pivot desired distance ($Pivot\ d_d$), was obtained from Fig. 2a and 2c:

$$Pivot\ d_d = Normal\ d_d + d_p \quad (1),$$

where $d_p = b * \tan(\alpha)$.

C. *Roll Model*

It was observed that the user tends to compensate lateral inclinations mostly with his/her ankles, remaining in a vertical position with his/her trunk. In order to do so and to keep a comfortable position for arms and shoulders, the natural human reaction is to displace his/her feet laterally in direction of the lower side, with respect to the center of the walker. From the kinematics, observable in Fig. 2b and 2d, the f_p distance is obtained as follows:

$$f_p = \mathrm{b} * \tan(\gamma) \quad (2)$$

In the case of no lateral inclination the parameter f_p is null, because $\tan(0) = 0$.

From another perspective the displacement described is extracted with other parameters, Fig. 3 shows an top view over user and walker.

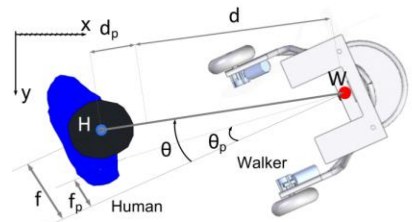

Figure 3. Top view in the x-y plane of the User Walker model in the case of Roll inclination.

f is the lateral displacement of the middle point between user's legs, in direction perpendicular to walker's axis and is extracted from Fig. 3 as follows:

$$f = d * \sin(\theta) \quad (3)$$

f_p is the parameter extracted in Equation. 2 and is the desired value of lateral displacement. This parameter can also be expressed as follow:

$$f_p = d * \sin(\theta_p) \quad (4)$$

θ_p is the angle that produces a lateral displacement equal to the desired value f_p. When no lateral inclination is present this angle is null because the f_p is null, due to γ being null;

Inserting Equation. 2 into Equation. 4 results in Equation. 5. This equation is used to extract the desired θ_p as follows:

$$\theta_p = \arcsin\left(\frac{b}{d} * \tan(\gamma)\right) \quad (5)$$

From this analysis, it was obtained that, in order to keep the walker in a comfortable condition for the user, the target for the control θ_d (desired theta) had to be changed from 0, when no inclination is detected, to θ_p.

D. *Supervisor Model, the Pivot Model*

The kinematic analysis developed in sections *Pitch Model* and *Roll Model* was integrated in the closed control loop, as shown in Fig. 4.

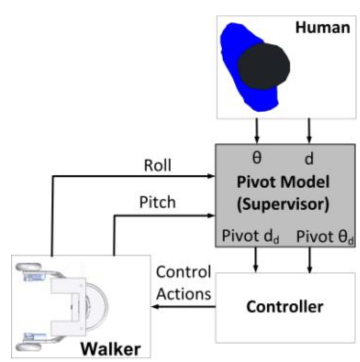

Figure 4. Block diagram of the Pivot Model (Supervisor).

The input defined in this model come from human localization (θ and d) and from walker orientation (Roll- γ and Pitch- α). The outputs are the Pivot d_d and the Pivot θ_d that represent the adjusted set points entering the controller in order to close the control loop. Finally the control actions are fed to the walker.

Next sections are dedicated to the implementation and evaluation of this model.

E. Robotic Walker platform

This section discusses the hardware and software components of the robotic platform named *UFES Smart Walker* shown in Fig. 5a. The developed robotic platform consists in a pair of differential rear wheels driven by DC motors and a front caster wheel.

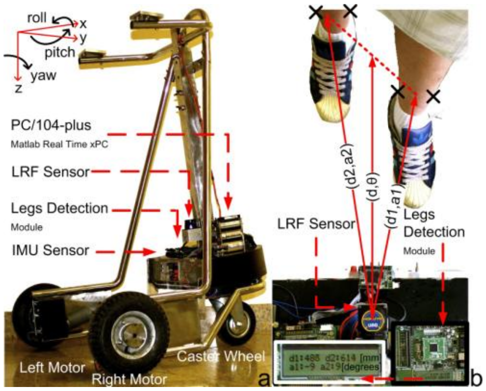

Figure 5. Robotic walker configuration. (a) UFES Smart Walker. (b) Description of the legs' localization detection.

An embedded computer based on the PC/104-Plus performs control and processing tasks. It is based on a 1.67 GHz Atom N450, 2 GB of flash memory (hard disk) and 2 GB of RAM. The application is integrated into a real-time architecture (Matlab Real-Time xPC Target Toolbox). The sensor configuration includes:

- One LRF sensor model URG-04LX [14] from Hokuyo, which is mounted on the walker at legs height. It is used to detect the legs localization through the Legs Detection Module (Fig. 5b), which is implemented on a processing board based on the dsPIC33F microcontroller. It is linked to the embedded computer via serial interface (RS232) and provides the legs localization every 100 ms.
- One IMU sensor, developed in a previous research project [15]. This sensor is installed in the walker structure and it communicates via serial interface with the embedded computer. The IMU information is used to get walker 3D orientation (roll, pitch and yaw, Fig 5a). All data are sampled every 20 ms.

The legs two-dimensional position is calculated in polar coordinates (Fig. 5b). The general process is based on the differences between two transition events that define a leg pattern (x-marks on Fig. 5b). After that, both distance and angle measurements are calculated in relation to the middle point of each leg. In Fig. 5b, ($d1$, $a1$) and ($d2$, $a2$), respectively, represent the polar coordinates of the left and right legs localization. Thus θ and d control parameters are calculated from the legs position.

IV. Experimental Setup

A healthy subject without any locomotion-related problems of height 175 cm volunteered to perform the experiments. Trials have been done without control, which means that the motors were disconnected from the axes of traction during the experiment. The purpose of these experiments was comparing the natural evolution of parameters d and θ, obtained walking without control, with the Normal control targets and the Pivot control targets.
Two different experiments were conducted to evaluate the Pivot method definition of the control targets for slope navigation.

A. Experiment 1: Linear path

Fig. 6 shows the different sections of the linear path on slope, which in this case is climbed uphill. The path begins with a horizontal section of 2 meters, followed by a +4° longitudinally inclined section of 9 meters and ended by another horizontal section of 4 meters.

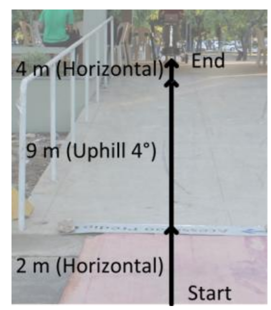

Figure 6. Linear path on longitudinal slope.

The candidate was asked to perform the linear path uphill while guiding the walker.

B. Experiment 2: U-turn path

Fig. 7 shows the different sections of the U-turn path on slope. The path begins with a horizontal section of 3.5 meters (first black solid line in Fig. 7), followed by a -4° longitudinally inclined section of 3.5 meters (first grey solid line in Fig. 7), then comes a U-turn (black dashed line in Fig. 7), composed by two left turns and a short, 1 meter long, section of laterally inclined path, a +4° longitudinally inclined section of 3.5 meters (second grey solid line in Fig. 7), and a horizontal final section of 3.5 meters (second black solid line in Fig. 7).

The candidate was asked to perform the U-turn path while guiding the walker.

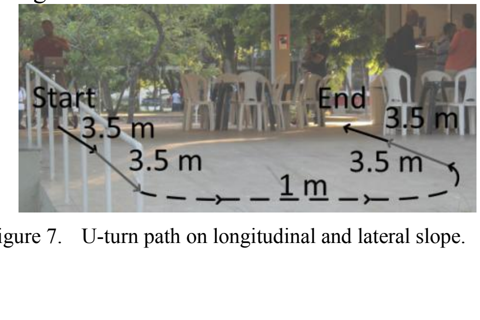

Figure 7. U-turn path on longitudinal and lateral slope.

V. RESULTS

This section discusses the results obtained from the experimental validation of the Pivot Model. The authors acquire the Normal d_d value at the beginning of each experiment. This value is obtained from a static position before the user begins to walk. This posture represents the comfortable position for the user and Normal θ_d is imposed to 0 making the user have a centered position with respect to the walker axis. It would be used as a desired position to be reached in a conventional control strategy.

A. Experiment 1: Linear path

In Fig. 8a are shown the values of distance read by the LRF for right and left leg respectively in black and grey and their average value in red.

In Fig. 8b it is possible to appreciate the variation of the walker pitch signal, confirming that the path was crossed uphill, showing a positive variation up to 4°, a constant section in which the walker is on slope, a negative variation which brings the pitch back to almost 0° and a last section on horizontal ground.

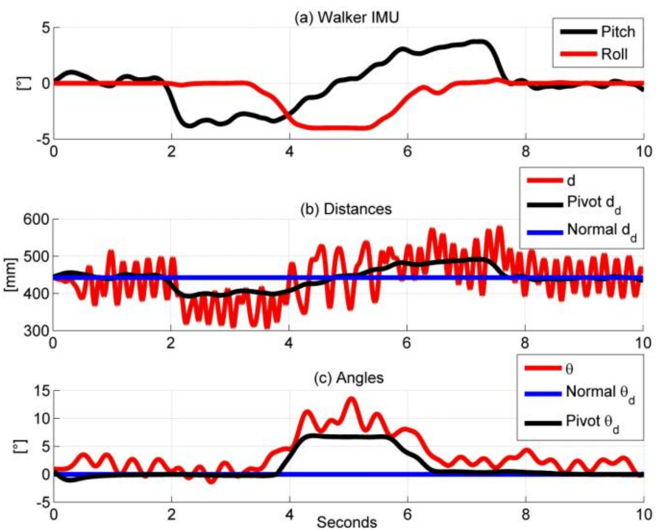

Figure 8. (a) Rigth and left legs distances read by the LRF respectively in black and grey and their average in red. (b) Walker pitch signal. (c) Legs distance in red, desired distance of Normal method in blue and desired distance of Pivot method in black.

In Fig. 8c the real distance d (in red), the Pivot d_d (in black) are represented and the Normal d_d (in blue). The real distance d and the Pivot d_d have a similar trend in their evolution, different from the Normal d_d, which is constant.

The Mean Absolut Errors (MAE) indices for the d - Pivot d_d and d - Normal d_d are respectively 31.98 mm and 55.48 mm, which result in an improvement of the 42.34% in the estimation.

The authors assume that if, in an experiment performed with no controlled motion, the target value and the control set point present a similar trend the controlled system would present a natural behavior.

Additionally, the fact that the Pivot desired distance d_d evolves similarly to the natural distance d, when a variation in the pitch signal occurs, assures a comfortable position of the user with respect to the walker.

The pick of parameter d encountered at approximately second 10 of Fig. 8a is due to the position that the user has when begins to push the walker uphill. In order to generate the necessary pushing force the user inclines his body and brings his feet farther from the walker.

B. Experiment 2: U-turn path

In Fig. 9 it's possible to define 5 different phases in the evolution of the trial.

Approximately every two seconds of the test it is defined a new phase. Phase I is between seconds 0 and 2 and corresponds to the first black solid line in Fig. 7. Phase II is between seconds 2 and 4 and corresponds to the first grey solid line in Fig. 7. Phase III is between seconds 4 and 6 and corresponds to the black dashed line in Fig. 7. Phase IV is between seconds 6 and 8 and corresponds to the second grey solid line in Fig. 7. Finally, phase V is between seconds 8 and 10 and corresponds to the second black solid line in Fig. 7.

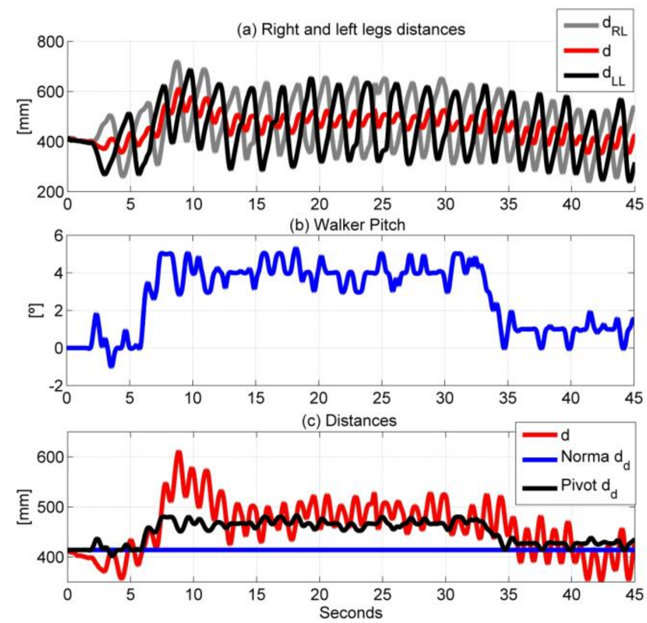

Figure 9. (a) Walker pitch and walker roll signals. (b) Legs distance in red, desired distance of Normal method in blue and desired distance of Pivot method in black. (c) Theta in red, desired theta of Normal method in blue and desired theta of Pivot method in black.

Phase I is on horizontal flat ground. This phase is characterized by a null pitch and roll angles, an almost constant distance d around value 450 mm, Normal d_d and Pivot d_d follow this value as well and almost null angles θ, Normal θ_d and Pivot θ_d.

Phase II is on the downhill slope. The pitch angle drops to -4°, and the roll angle keeps being null. The θ, the Normal θ_d and the Pivot θ_d remain in almost 0°. d decreases of approximately 100 mm and keeps a constant value for the rest of the phase. The Pivot d_d also decreases of around 50 mm with the same trend as d, while the Normal d_d keeps its constant value.

Phase III is the phase in which the pitch angle returns to being null while performing the first part of the U-turn, remains in 0° during the laterally inclined section and increases up to 4° completing the second turn of the U-turn. The distance d and the Pivot d_d evolve similarly. The roll angle decreases up to -4° during the first turn, maintains this value for the laterally inclined path and goes back to value 0° after the second turn. The θ and Pivot θ_d both increment with a similar trend, respectively up to almost 10° and 7°, with the first turn, keep this value on the laterally inclined path and go back to 0° with the second turn.

Phase IV is on the uphill slope. The pitch angle increases to 4°, and the roll angle keeps being null. The θ, the Normal θ_d and the Pivot θ_d remain in almost 0°. d oscillates but keeps an average value of approximately 500 mm for the rest of the phase. The Pivot d_d keeps its value of 500 mm with the same trend as d.

Phase V, as phase I, is on horizontal flat ground. This phase is characterized by a null pitch and roll angles, an almost constant distance d around value 450 mm, Normal d_d and Pivot d_d at value 500 mm and an almost null angle θ, Normal θ_d and Pivot θ_d.

In the different phases the parameters d and Pivot d_d evolve with a similar trend. In the same way, parameters θ and Pivot θ_d evolve with a similar trend. This behavior shows the effectiveness of the Pivot model in defining the parameters Pivot d_d and Pivot θ_d, which can be used as set points for a control scheme in order to develop a natural and safe control strategy, as explained in Fig. 4.

The MAE for the d - Pivot d_d and d - Normal d_d are respectively 38.50 mm and 48.95 mm, which result in an improvement of the 21.33%. Moreover, the MAE for the θ - Pivot θ_d and θ – Normal θ_d are respectively 2.07° and 3.46°, which result in an improvement of the 40.17%.

VI. Conclusions

This paper presents a novel model of human-walker interaction on slopes, focused on a kinematic analysis of human posture during walker assisted-gait.

The developed model, called Pivot Model, was integrated, as a supervisor block, into the conventional closed control loop implemented in the Smart Walker embedded hardware. This block modifies the control set points to provide an adaptable human-walker desired position in order to improve comfort and safety and enhance user's confidence in the walker.

The parameters used in the model are the legs position and the 3D orientation of the walker. The practical evaluation shows that the parameters extracted from the natural behavior of the user and the estimated set points determined with the Pivot Model are highly correlated presenting a similar trend in their evolution in time.

The MAE indices obtained show a significant reduction of the tracking error of both θ and d.

Moreover, one of the advantages of the proposed method is the computational efficiency. The estimated parameters don't present a considerable increase in the execution time, For this reason, the Pivot Model is suitable for real time control applications.

As future works, the authors are integrating force sensors, applied to the forearm supports, and wearable sensors in the Pivot Model in order to strengthen the interpretation of human behavior during walker-assisted gait on slopes.

Additionally, the authors are integrating the model into the control strategies developed for the *UFES Smart Walker* in order to actively assist human gait.

References

[1] United Nations. (2014, Feb.) World Population Ageing: 1950-2050. [Online]. Available http://www.un.org/esa/population/publications/worldageing1950205/

[2] P. K. Canavan, L. P. Cahalin, S. Lowe, D. Fitzpatrick, M. Harris, and P. Plummer-D'Amato, "Managing Gait Disorders in Older Persons Residing in Nursing Homes: A Review of Literature," *Journal of the American Medical Directors Association*, vol. 10, no. 4, pp. 230-237, 2009.

[3] P. G. MacRae, L. A. Asplund and J. F. Schnelle, "A walking program for nursing home residents: Effects of walk endurance, physical activity, mobility and quality of life," *J Am Geriatr Soc*, vol. 44, no. 1, pp. 175–180, 1996.

[4] Associação Brasileira de Normas Técnicas. (2004, May) Acessibility to buildings, equipment and the urban environment. [Online]. Available http://www.pessoacomdeficiencia.gov.br/app/sites/default/files/arquivos/%5Bfield_generico_imagens-filefield-description%5D_24.pdf

[5] C. P. Gharpure and V. A. Kulyukin, "Robot-assisted shopping for the blind: issues in spatial cognition and product selection," *Intel Serv Robotics*, vol. 1, no. 1, pp. 237–251, 2008.

[6] V. Kulyukin, C. Gharpure and J. Nicholson, "RoboCart: toward robot-assisted navigation of grocery stores by the visually impaired," *in Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp. 2845-2850.

[7] Adept Technology, Inc. (2014, Feb) Adept SPH-2200 Dataseheet. [Online] Available www.adept.com/products/mobile-robots/mobile-transporters/sph-2200/general

[8] Adept Technology, Inc. (2014, Feb) Adept PeopleBot Dataseheet. [Online] Available http://www.mobilerobots.com/ResearchRobots/PeopleBot.aspx

[9] S. Hwang, C. Lee and Y. Bang, "Power-assisted wheelchair with gravity compensation," *in Proc. 12th International Conference o Control, Automation and Systems*, 2012, pp. 1874-1877.

[10] R. Hou, X. Shi and M. Krishnamurthy, "Design and implementation of a novel power assisted drivetrain for a wheelchair," *in Proc. IEEE Transportation Electrification Conference and Expo*, 2012, pp. 1-6.

[11] Y. Nemoto, S. Egawa, A. Koseki, S. Hattori, T. Ishii and M. Fujie, "Power-assisted walking support system for elderly," *in Proc. 20th Annual International Conference Engineering in Medicine and Biology Society*, 1998 , pp. 2693-2695.

[12] G. Yuk, H. Park; H. Jun; B. Dan and B. Jo, "Posture balancing control of smart mobile walker for uneven terrain," *in Proc. 9th International Conference on Ubiquitous Robots and Ambient Intelligence*, 2012, pp. 63-64.

[13] T. Suzuki, C. Zhu, M. Yoshioka, S. Shota, Y. Yoshikawa, Y. Okada, Y. Yan, H. Yu and F. Duan, "Power assistance on slope of an omnidirectional hybrid walker and wheelchair," *in Proc.* IEEE International Conference on Robotics and Biomimetics, 2012, pp. 974-979.

[14] Hoyuko Automatic co. (2014, Feb.) Scanning Laser Range Finder URG04LX Specifications. Hoyuko Automatic co. [Online]. Available http://www.hokuyo-aut.jp/02sensor/07scanner/download/products/urg-04lx/data/URG-04LX_spec_en.pdf

[15] C. Cifuentes, A. Braidot, L. Rodriguez, M. Frisoli, A. Santiago and A. Frizera, "Development of a wearable ZigBee sensor system for upper limb rehabilitation robotics," in *4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2012, pp. 1989-1994.