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A CONTROL SYSTEM APPROACH FOR A TREADMILL WALKING COMPENSATION DESIGN

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Abstract: *Virtual Reality has known exponential development in the recent years, its advantages extending over a large number of other domains, like Medicine and Automation Industry. The common treadmill is taken to another level by simulating locomotion in virtual environments, extending its usage. The purpose of this paper is to present an adapted treadmill capable of compensating the user's walking speed and direction with use in different domains, particularly in Virtual Reality. The system is fully adaptive because of its new concept control system and it allows the user to walk more natural than in the classic treadmill case.*

Key words: *Virtual Reality, Treadmill Locomotion, Control System.*

1. Introduction

Nowadays, treadmills represent systems used mainly for sports and recreational aims, like jogging, running and sprinting. Besides these basic purposes, other different domains may make use of treadmills, to help in regenerative medicine, mobility rehabilitation, human body effort limit tests and even virtual reality.

The treadmill, the main element that pulls all these different domains together, is given a capital condition as in how to adaptively operate to successfully reach the designated goal. For example, in the case of a person that has a locomotion dysfunction, the system must adapt to gradually assist the rehabilitation.

The main difference between a classical treadmill and an adapted version is given by the manner in which the moving band is controlled. The control system must have an appropriate response regarding the user's locomotion in order to assist him in a freely and unrestricted manner.

To this aim the paper presents in the first part, preliminary concepts of natural human walking and applications of adapted treadmills and in the second part, the adapted treadmill integrating the control system, from concept to implementation.

Band motion directions, motion velocity and system accelerations are parameters that must be precisely controlled in order to give the user the feeling of a free, unconstrained natural walking. Thereby the authors intended to develop a system capable to react firm, adaptive, in an undisturbed fashion to any change of the user's locomotion state.

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The rest of this paper is organised as follows. Section 2 describes bio-dynamic elements of the human walking. Section 3 presents related work in different domains of adapted treadmill usage. In Section 4 a description of the proposed walking compensation system is made. Section 5 describes the architecture of the system implemented by the authors. Section 6 is dedicated to presenting the tests conducted by the authors and their results. Section 7 provides the conclusions and future research steps.

2. Bio-Dynamics of Natural Walking

Top-down analysis of natural human walking [15] is based on cause-effect relationships. Joint forces and momentums produce movements of the skeletal rigid links. For simulating natural walking, a structure of rigid links connected by rotary joints with one, two or three degrees of freedom (DOF) is used.

Any break in this sequence of events causes an alteration of walking and may induce locomotion disabilities. Some examples of such causes are signal corruption from the central nervous system to peripheral nervous system, certain abnormalities and disease of skeleton links or joints.

Knoblauch et al. [10] have shown on their study that human walking speed varies by age and sex. They determined that the average speed of a young healthy person is 1.51 m/s (5.436 km/h).

The bio-dynamics [1] of natural locomotion of a healthy young person is presented in Figure. 1.

The walking cycle is defined as the period between two successive toe strikes of the same foot on the ground, being almost symmetrical on both sides. Ordinary gait cycle contains two phases: stance and swing. Stance is considered to be the period between the toe off and the tip down on the ground. Swing phase is the gait sub-cycle or period between tip off and toe down on the ground. Stance represents 62% of total gait cycle and swing 38%.

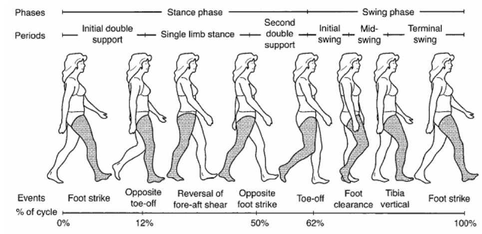


Fig. 1. *Natural human walking* [1]

3. Related Work

In order to investigate the added value of an adapted treadmill with respect to the conventional solutions the main role of these systems must be mentioned. A treadmill is a limited surface system that allows the user to walk in a practically infinite area. Thereby, through a rigorous and adaptive control of travel direction, speed and system acceleration, in relation to the user's locomotion, it is intended to maintain the user in a central area called "dead-zone" [8].

To protect user's walking on the platform, and to restrict locomotion over the physical limits of the surface area it is imperative that the control system react fast enough to limit the movement only in the restricted "dead-zone" area. Any excursion outside the restricted area is corrected by the control system and the user is carried back to the centre of the treadmill. This control is done at a hardware level by controlling the actuation motor(s) that carries the band and at software level by control algorithms.

3.1. Rehabilitation Platforms Using Treadmills

As mentioned in Section 1, there are different domains that may use adapted treadmills for different goals.

A. *Rehabilitation of persons with locomotion disabilities*

According to the study undertaken by Lange et al. [11] treadmills are often used with good results for locomotion system rehabilitation. The main issue of this study is given by the muscular activity quantification at slope displacement. It concludes with the idea that treadmills present utility both for testing and studying persons that suffered walking disorders.

B. *Recuperative rehabilitation following surgery on inferior limbs*

The main objective of this study [6] was to compare patients that suffered hip arthroplasty in two cases: first in walking using a treadmill with partial body support case and second in classic ambulatory therapy case. The study conclusions revealed that recovery using a treadmill was more efficient than classic therapy.

C. *Rehabilitation of persons with disease of neurological disorders*

Studies as [12] and [5] revealed that the second death and disablement risk factor was given by cerebrovascular disease (stroke) as a total of 9.5% of the total number of deaths, represented at a global scale. About 35% of the survivors that suffer partial or total paraplegia will never regain normal functions, and between 20%-25% will never walk again without assistance.

According to [13], [14] using treadmills with partial or total weight body support, is a re-learning method of walking with good results in the case of patience with severe stroke.

D. Physical recuperative exercises for elderly or children

Referring to treadmills, we can consider that these systems are ideal in the case of physical exercises with diverse objectives both in elder and very young children case. It presents importance in improving bones, limb muscle strength as well as increasing stamina and walking speed.

Exercises and effort tests aiming a better illness understanding and a better approach to treatment are often used.

3.2. Locomotion in Virtual Environments

In Virtual Reality the conventional locomotion solution involves a position tracking system. In the simplest scenario a joystick controls displacement [9].

More complex scenarios involve moving a user in a restricted area and tracking its position. There are systems that track the user's position using cameras attached to an HMD. A different approach involves a CAVE system, which uses screens for image projection and magnetic sensors for motion detection.

Other approaches include platforms that move the user in a passive manner. Nevertheless this passive approach does not involve a physical and realistic effort from the user.

Active locomotion devices are interfaces that involve the user in Virtual Environments in a realistic fashion. In this case the user is not the one that moves or pushes the walking surface in the opposite direction as in the passive case type. The platform has the role of cancelling the user's displacement in an active manner.

Three examples of active walking devices will be presented:

1. *Sarcos Treadport*, was designed in two phases. Initially the platform had a 1.2 m by 2.4 m walking surface and a mechanical tracking arm with 6 DOF. Having push and pull capabilities this arm simulates the inertial force [2]. The second generation [7] had an improved walking surface of 1.8 m by 3m, speed of 5.3 m/s and 1 G acceleration. An updated control system with the role of gradually resetting the user's position in the center of the platform was introduced [2].

2. *Omnidirectional treadmill (ODT)*, may be considered the first revolutionary device used for walking in virtual environments because of its characteristics. At the level of 1997, ODT was the first device that allowed the user to walk or run unrestricted. The basic principle [3] included two perpendicular treadmills, one inside another, generating the possibility of walking in any direction (any planar vector). Device characteristics were: maximum user's walking speed of 2 m/s, 1.3 m by 1.3 m active surface area, 0.46 m height, 544 kg mass and was actuated by DC motors of 3.4 kW.

3. *CyberCarpet*, is a more actual virtual walking device that allows the user to move unrestricted in any direction [4].

Two mechanisms, one linear (ball-array belt) and one angular actuate the device. The ball-array belt has the role to generate an opposite movement to the user's feet in a distributed fashion (because of the high number of balls - 4332) thereby limiting angular and linear velocities and accelerations (inertial forces) felt by the user. At the level of 2007 CyberCarpet was the fastest and largest ball-bearing platform having capabilities of 2 m/s linear, 2 rad/s angular and an active surface area of 0.8 m^2.

4. Walking Compensation System

This Section, apart from the approaches described in Section 3.2, presents the author approach for a walking compensation system, including the Energetics Power Run 3000 HRC treadmill.

4.1. Design Stages

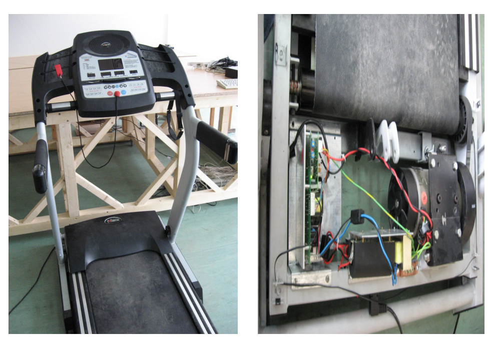
In this section the steps needed for remodelling the Energetics Power Run 3000 HRC treadmill, in order to have the capability of using it in one of the domains presented in Section 3, are included. The authors identified four basic steps necessary for changing a classic jogging treadmill and model it for different types of locomotion (back-forward with different speeds, acceleration and inertial moments):

1. Cancelling the initial control system.
2. Implementing an adaptive control system for direction-sense and speed.
3. Testing and upgrading the control algorithms.
4. Tracking system integration into the control system of the treadmill.

4.2. Energetics Power Run 3000 HRC Treadmill

The implemented design uses a classical treadmill, having the following characteristics: dimensions - 150 cm (L) by 50 cm (W); walking speed of 0-18 km/h; maximum allowed mass - 135 kg; incline capabilities and emergency stop key; a set of predefined programs; actuated by a DC motor, Figure 2, of 180 V, 7.5 A, 2 hp, 3000 rpm.

Initially the system worked with its own predefined programs. For the proposed aim the initial control system, programs and a part of the architecture had to be cancelled. A new control system capable of actuating the moving belt at different speeds had to be designed.



a) b)

Fig. 2. *Energetics Power Run 3000 HRC - structure* (*a*) *DC motor, control module* (*b*)

4.3. Adaptive System Control

Parameters like the treadmill's band displacement and speed, relative to user's locomotion, accelerations and inertial forces, must be controlled in order to allow an unrestricted and natural user movement. All these must be correlated in a system able to react promptly, *adaptive*, to any change or disruption of the user's movement in an un-affective manner.

From the original treadmill, for the new proposed aim, only the underlying platform, the belt, the DC motor, Hall sensor and emergency stop system were used. The new control designed system includes elements that are presented in detail in Section 5.

5. System Architecture

The system's architecture includes both hardware and software components.

5.1. Hardware Architecture

The general hardware architecture is presented in Figure 3. It includes the following sub-systems:

a) Notebook - HP EliteBook 6930p;

b) System power supply - 220 VAC-12 VDC, 1.5 A;

c) Serial data interface - including a driver/receiver MAX232 serial data module with up to 120 kbit/s data transmission capabilities;

d) Data acquisition and processing sub-system - includes an ATMega8 controller used for acquiring, processing and sending data to or from control application and power sub-system;

e) Power transistors driver module - four TLP250 modules with optocouplers integrated having both galvanic isolation (protection) and signal transmission role;

f) Power H bridge sub-system - including four power MOS transistors with current flow capabilities of up to 120 A;

g) Speed and sense of rotation detection sensor - magnetic sensor, optic sensor or a small DC motor can be used in a particular configuration;

h) DC motor of 180 V, 7.5 A, 2 hp, 3000 rpm.

5.2. Software Architecture

The programming language used for creating the control program implemented on ATMega8 controller was C. The embedded algorithm follows the next steps:

1. Device initialization: digital ports, ADCs, serial interface, PWM, timers and interrupts.

2. Testing serial interface for commands received from the control application: setting reset signal, sense of rotation, duty factor changes for increasing/decreasing rotation speed etc.

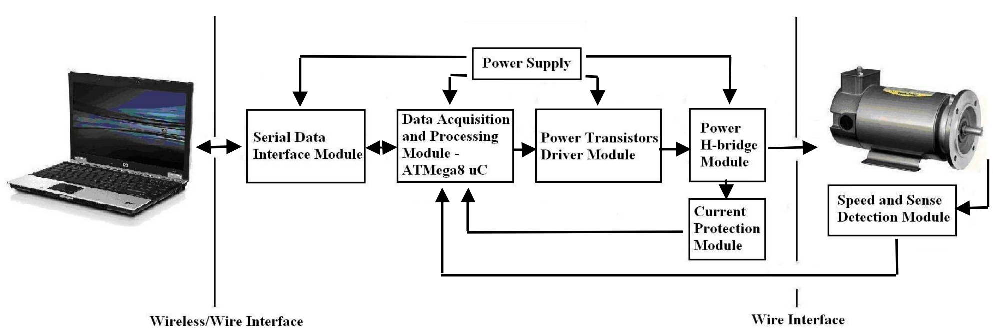


Fig. 3. *General hardware architecture*

3. Testing duty factor value according with superior/inferior set limits.
4. Receiving system parameters digitized information, processing it and sending data to control application.
5. Testing digitized data about current flow through the motor for system shutdown in case limits are exceeded.

The application used for controlling the system's parameters was developed in two stages, each aiming for a certain type of motor control.

In the first stage there was a need of control exclusively by the human operator. A minimal set of commands were defined using buttons for setting the sense of rotation, increasing/decreasing speed granularity (by 0.1%, 1% and 10%), reset system and start/stop system.

In the second version, Figure 4, there were added automatic capabilities to the control system. The need was to set a fixed speed value and the system to follow it accurately. In order to maintain a stable, non-oscillating speed value it was a demanding request that a minimal PID controller to be implemented. PID control was used for its simplicity, good performances and because it is considered to be an industrial standard in dynamic system control. In this second application version only four parameter values can be set: motor speed value and KP, KI and KD PID coefficients.

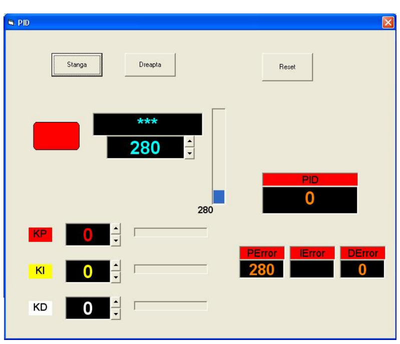


Fig. 4. *Control application - version 2*

The appropriate PID coefficient values needed for a fast and non-oscillating response of the motor to the given value are determined by empirical methods (trial and error). Specific tests used to determine correct functionality of the system at different speed value and PID parameters values are presented in Section 6.

6. Experiments and Results

The implemented control system, using PID algorithm, was tested in a series of trial and error tests, performed in order to determine the proper PID coefficients and observe system response and stability. The main goal was to determine if the control system was working accordingly and if the motor was following the specified digitised rotation values given by the human operator, properly. The tests were performed (under laboratory conditions) using the adapted control system and control application, at different power supply loads ranging from 10 V-60 V and the DC motor in no load condition.

Thus by calculus methods the authors obtained the digitized reference value equivalent of 280 (for a 1024 bits scale, 10 bits ADC integrated in ATMega8) representing motor speed equals 0. The following motor speed limits (represented in bit - ADC values) were set:

1. counter-clockwise (CCW) motor sense: zero speed - 280, maximum speed - 500;
2. clockwise (CW) motor sense: zero speed - 280, maximum speed - 100.

To determine the motor's response at different PID coefficient values and different speeds the following test algorithm was applied:

- Set motor sense: CCW or CW.
- Set PID coefficient value sets: KP, KI, KD = (0; 0; 0), (0.1; 0.1; 0.02), (0.2; 0.2; 0.02) and (0.1; 0.3; 0.02).
- Increase motor's speed at every 10 s with the following speed sets (ADC values):

350-380-400-430-450-500 for counter-clockwise sense; 250-220-200-170-150-100 for clockwise sense.

The test representing the best motor response is presented in Figure 5 and it was obtained having KP, KI and KD coefficients set at (0.1; 0.3; 0.02).

The motor response is evaluated at every set of PID coefficients and the results are represented in Figure 6. Thus, there are seven speed samples (levels): 280 (1) - 350 (2) - 380 (3) - 400 (4) - 430 (5) - 450 (6) - 500 (7) representing the motor's speed scale,

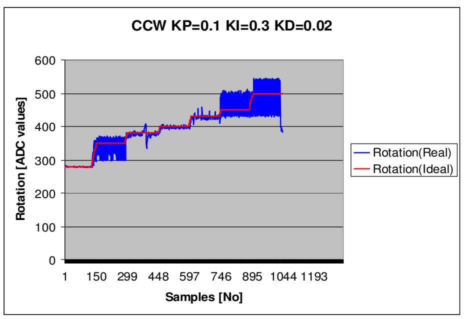


Fig. 5. *CCW motor sense- best response*

from minimum to maximum limit. All tests, at different PID coefficient values, are represented in parallel on the same graph bar as follows: white- reference set speed; orange-speed value at zero PID coefficient values; yellow-speed value at KP, KI, KD: 0.1; 0.1; 0.02; blue-speed value at KP, KI, KD: 0.2; 0.2; 0.02; brown-speed at KP, KI, KD: 0.1; 0.3; 0.02.

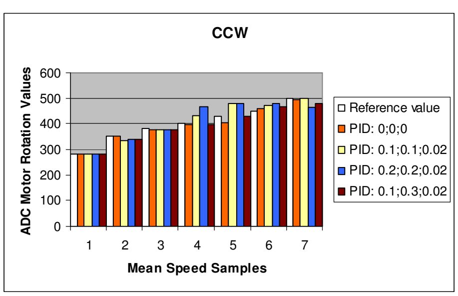


Fig. 6. *Mean motor speed values*

All speed values were obtained using sample mean algorithm after nonsense values were eliminated.

Relative error (%), Figure 7, was obtained for each of the seven samples (1-7) and the total relative error (%) for all the seven samples was calculated. Maximum relative error was 14.027% (PID: 0.2; 0.2; 0.02) and the minimum was 4.083% (PID: 0.1; 0.3; 0.02).

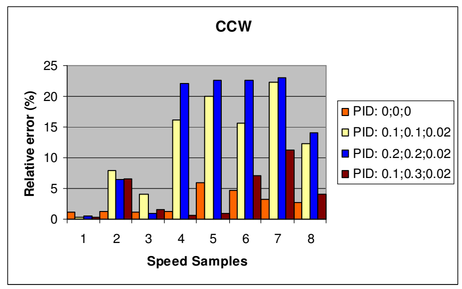


Fig. 7. *Relative error* (%)

The total relative error when the PID coefficients were set to zero was 2.671%. Even though the minimum relative error was under 5% the implemented PID algorithm and PID coefficients must be improved, because system stability is a decisive factor in our case.

7. Conclusion and Future Work

The treadmill's utility has proved to be not only in recreational or sport domains but in apparently totally different ones also [2], [3], [4-7], [11], [13]. Domains such as Virtual Reality, Walking Rehabilitation, Regenerative Medicine, may take the advantage of using special adapted treadmills for known or future benefits.

This paper describes a practical application that tries to control the sense, speed and acceleration of a DC motor which has the role to actuate an adapted treadmill.

The authors present a novel concept of an *adaptive* treadmill control based on the user's undisturbed locomotion intention.

Hardware architecture and software application of the obtained system are also represented. The test algorithms are detailed and the obtained results are expressed graphically. Although, the value of the minimum relative error of the motor's response is 4.083% the authors consider that the implemented PID controller and algorithm needs future improvement.

Also, as a future development intention, is to test the control system integrated on the treadmill (load conditions) and to obtain relevant parameters about the human-platform system dynamics.

Integration with motion tracking systems either magnetic or optical is another important future step.

The authors' intention is to research and develop a complete virtual locomotion system with applications in actual and future areas of interest.

References

1. Abernethy, B., et al.: *Biophysical Foundations of Human Movement.* (2nd Edition). Human Kinetics, USA, 2005, p. 93-94.
2. Christensen, R., et al.: *Inertial Force Feedback for the Treadport Locomotion Interface*. In: Presence: Teleoperators and Virtual Environments **9** (2000), p. 1-14.
3. Darken, R.P., Cockayne, W.R.: *The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds*. In: Proc. UIST'97, 1997, p. 213-221.
4. De Luca, A. et al.: *The Motion Control Problem for the CyberCarpet.* In: Proceeding of the 2006 IEEE International Conference on Robotics and Automation, 2006, p. 3532-3535.
5. Dobkin, B.H.: *Rehabilitation after Stroke.* In: The New England Journal of Medicine **352** (2005) No. 16, p. 1677-1684.
6. Hesse, S., et al.: *Treadmill Training with Partial Body-Weight Support after Total Hip Arthroplasty: A Randomized Controlled Trial.* In: Archives of Physical Medicine and Rehabilitation **84** (2003) No. 12, p. 1767-1773.
7. Hollerbach, J.M., et al.: *Design Specifications for the Second Generation Sarcos Treadport Locomotion Interface.* In: Proc. ASME Dynamic Systems and Control Division, Orlando, Nov. 5-10, 2000.
8. Iwata, H., et al.: *CirculaFloor: A Locomotion Interface Using Circulation of Movable Tiles.* In: IEEE Virtual Reality Conference, 2005, p. 223-230.
9. Kim, G.J.: *Designing Virtual Reality Systems.* In: The Structured Approach, Springer (2005), p. 3-5.
10. Knoblauch, R.L., et al.: *Field Studies of Pedestrian Walking Speed and Start-Up Time.* In: Transportation Research Record **1538** (1996), p. 27-38.
11. Lange, G.W., et al.: *Electromyographic and Kinematic Analysis of Graded Treadmill Walking and the Implications for Knee Rehanbilitation.* In: The Journal of Orthopaedic and Sports Physical Therapy **23** (1996) No. 5, p. 294-301.
12. Lopez, A.D., et al.: *Global and Regional Burden of Disease and Risk Factors, 2001: Systematic Analysis of People Health Data.* In: Lancet **367** (2006), p. 1747-1757.
13. Moseley, A.M., et al.: *Treadmill Training and Body Weight Support for Walking After Stroke.* In: Stroke, published by AHA, 2003.
14. Roy, M.A.: *Body Weight Supported Treadmill Training for Stroke-Family/ Patient Information.* Available at: http://www.strokengine.ca.
15. Vaughan, C.L, et al.: *Dynamics of Human Gate* (2nd Edition). Cape Town, South Africa. Kiboho Publishers, 1999, p. 481-486.