REDUCED-SCALE CABLE-DRIVEN LOCOMOTION INTERFACE FOR REHABILITATION AND TRAINING

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SUMMARY

This paper presents the final design of a reduced-scale locomotion interface for which the mechanical transmission is achieved with 18 cables. Two six degree-of-freedom parallel mechanisms are used as haptic interfaces for the feet. A one-degree-of-freedom counter-weight is used to maintain the equilibrium of the user. Software integration for rendering the locomotion, visual effects and haptic cues is also covered.

INTRODUCTION

Designing an ecological virtual environment where a user can interact with great level of realism is complex. Walking is a fundamental function for navigating in 3D space. This paper aims to present the software integration for multimodal rendering of simulated material properties in a virtual environment into which a user is walking. Indeed, locomotion inside a virtual environment has great interest in many areas such as training, entertainment and rehabilitation. The design of a system which allows rendering different sensing modalities (auditory, haptics and visual feedback) needs to be performed while taking human factors into account (i.e. consider with human perception thresholds) [1].

This research proposes to develop a control manager for a parallel mechanism that allows not only natural gait in a virtual environment, but also facilitates the simulation of a ground surface with different mechanical properties while being omnidirectional. This multi-sensory visual-haptic system performs bilateral control of the interaction between the human and the physical mechanism inside the virtual environment. Such a Cable Driven-Locomotion Interface (CDLI), shown in Fig. 1, could simulate different coefficients of friction (COF), staircases, slope, compliant or stiff ground. Also, specific algorithms could be implemented for training and rehabilitation purposes.

An application of this device could be understanding of how ground surface properties affect slips and balance in different populations. This involves a combination of controlled clinical experiments with reproducible ground surface properties with the specific acquisition system for analyzing gait. This motivates the design of complex mechanical system with the control software integrated for rendering multimodal (haptic, visual and auditory) simulation.

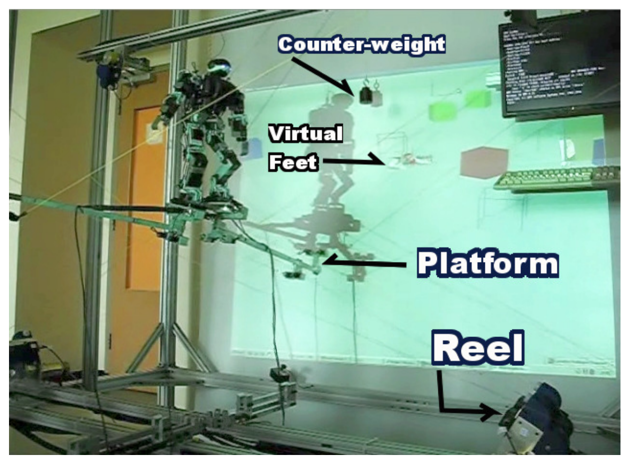

Figure 1: Reduced-scale locomotion interface prototype with a Kondo KHR-1HV

Several concepts of locomotion interfaces have been developed in order to provide a better feeling of immersion in a virtual environment and for automated walking rehabilitation. For instance, the Rehabilitation Robot LOKOMAT [2] uses a hybrid force-position control method for which the force component adjusts the movement of an actuated leg orthosis so as to influence the LOKOMAT's motion and to automate user gait-pattern therapy. Such a control method is implemented in the context of the Patient-Driven Motion Reinforcement paradigm. HapticWalker is a programmable robotic

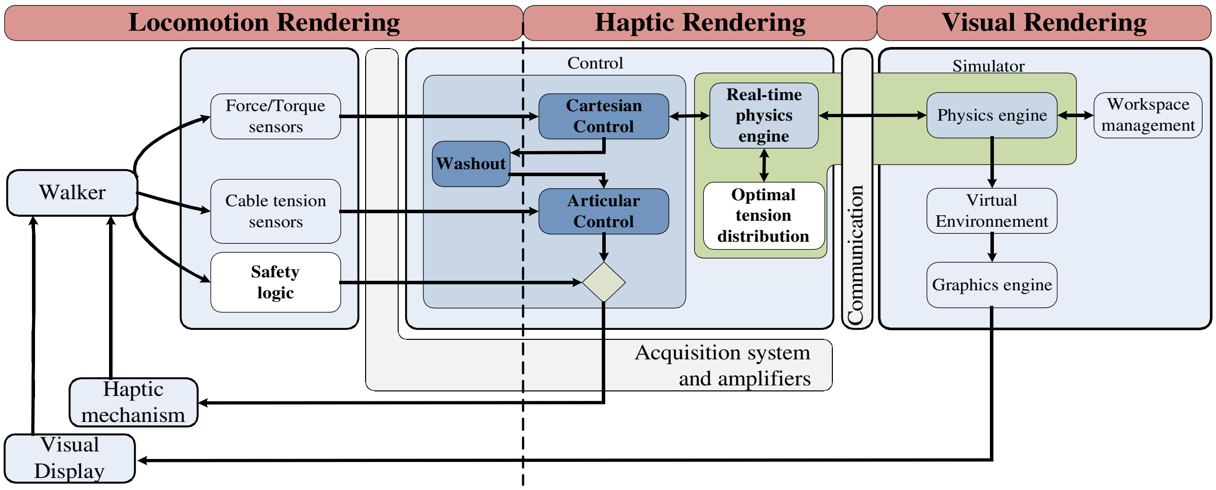

Figure 2: Multimodal rendering for a locomotion interface

footplate device that allows arbitrary foot movements during user gait training via specialized motion generation algorithms [3].

However, with locomotion interfaces currently available, the dynamics attached to a natural gait is rarely preserved. User's movements are usually restricted by the dynamics of actuators and a small workspace in the real world [4]. In most interfaces, the user must learn to walk on the platform to avoid exceeding the mechanism dynamic limits. Therefore, a design requirement for a locomotion interface should be the reduction of the cognitive demand on the user.

Moreover, the control strategies previously presented are not well adapted to a CDLI as well as haptic rendering of contacts with any virtual objects or uneven terrains. In fact, a CDLI shows substantial advantages over conventional locomotion interfaces and has the potential to achieve better performances than other devices. For instance, the haptic foot platform in a CDLI can reach higher accelerations and can move in a larger workspace.

Two main criteria should guide the interface design: the accuracy of control and the reduction of the cognitive demand on the user. The ideal locomotion interface will facilitate rapid movement over long distances without sacrificing accuracy and will be transparent to the user [5]. The next sections explain the design, safety issues and some challenges that need to be solved in the implementation of a CDLI.

HARDWARE DESIGN

As shown in Fig. 1, a CDLI uses two similar platforms, one for each foot. Each platform is attached to eight cables optimally configured for reducing interference (contact between two cables) and for increasing the size of the workspace. Other designs of locomotion interfaces using fully constrained platforms, such as the K-Walker [6], use two similar platforms although the biomechanics of walking generates different foot trajectories and they are different for each user. The control algorithm must be specifically designed for rehabilitation or training [7].

The motorized reel is a very critical component of the the CDLI design. Controlling cable tension is one of the most challenging tasks for reproducing accurate haptic interaction with virtual objects.

Motorized reel

At the articular control level, tensile force sensing (cable tension measurement) is useful for optimal control and for avoiding the need for modeling the friction losses in the mechanism. Among other things, the tensile sensor can linearize a portion of the reel and amplifier. This tensile force measurement is useful in computing the optimal distribution of tension in the cables and in managing interference between cables. Indeed, the accurate measurement of cable tension will increase the transparency and efficiency of the mechanism. The risk of using only current control in the motor of the reel results in a variation between the actual effort applied to the platform and controlled effort. This variation may be felt by the user and may prevent the forces and torques applied by the user to be balanced.

When a haptic interface is controlled by redundant motorized reels, the tensions in all cables are responsible for reproducing a precise pose in the virtual environment and are responsible for generating a precise wrench. Transparency is achieved when all the reels can generate the same response with a minimum settling time as the tension controller approaches a unit gain. Some parameters should be optimized for the design of a motorized reel used in haptic applications:

- increase stiffness of the system (reel and overall structure) for avoiding control instability;
- increase frequency response for simulating rigid contact;
- increase precision in angular velocity measurement for adequately compensating friction and inertia;
- decrease the friction hysteresis for avoiding sticking of cable on reel parts at low velocity;
- optimize the controller for limiting overshoot and for reducing settling time and
- reduce the overall noise level of the acquisition system.

Also, a special care should be given to cable vibrations when the platforms are moving.

SOFTWARE IMPLEMENTATION

The locomotion interface control system is shown in Fig. 2. This figure is the final result of the designed software haptic platform which includes three main modalities: locomotion rendering, haptic rendering and visual rendering. Audio feedback is not currently implemented but could be included as a part of the physics engine of the visual rendering module of the system.

Haptic rendering contains the software for articular control of the tensile force in the cables, the Cartesian control of the six degree of freedom platforms for the feet, the embedded real-time physics engine and the safety logic software. This paper suggests that the articular control should be separated from the Cartesian one for allowing integration of different algorithm like washout filters (the method that simulates an infinite environment in a physical limited space) and management of cable interference. Indeed, the Cartesian force sensors under the feet and the resulting poses of the two effectors adjust the direction and speed of the user in the virtual environment.

CDLI Inputs

Two types of inputs have been defined: parameters that define the overall interface with the user and measured inputs that come from intentions or setpoints from the user. Parametric inputs are defined offline. Among others, these parameters are the position of the reels after calibration of the CDLI geometry, the mensuration of the user, the initial lengths of the cables, the sizes of both platforms, the parameters (or coefficients) of the filters used in the feedback loop, the regulator (PID) that ensures the control of the mechanism (both articular and Cartesian control), etc. The workspace is also an important input parameter because it defines the set of poses that the platform can adopt while maintaining static and dynamic balance. Indeed, the platforms must not leave this workspace when there is contact with the virtual environment.

Muiltimodal rendering

Locomotion rendering includes three haptic devices (both platforms and passive harness), virtual environment display and the washout filter which maintains the walker in the center of the workspace as best as possible. Haptic rendering is addressed by the control of these haptic devices while considering the physics that must be rendered to the walker.

Finally, the visual rendering module communicates with the haptic rendering module through a communication interface connecting the two physics engines. This communication interface includes a server with a shared memory that passes information between processes. The intersection of haptic and visual rendering provides a powerful and reliable means of computing physics. Note that bidirectional communication between both physics engines may cause a delay on the refresh rate thereby affecting performance or stability of haptic rendering. This issue explains the reason for the implementation of a second algorithm for computing forces (by the real-time physics engine) in the haptic rendering which are applied between a haptic mechanism and the virtual object. The objective is to simulate the forces (like friction) between the mechanism and the virtual object within the constraints provided without any delay.

Stability and safety

In addition to the delay issue which can be partially solved by the separation of the physics engine, two other sources of instability may be encountered:

- stability of interaction between the human and the haptic interface (without any constraints generated by the virtual environment when the haptic mechanism is free to move in space) and
- stability of interaction with the virtual environment (with a constraint between the haptic mechanism and the virtual object that restricts the movement of at least one degree of freedom of the mechanism).

Moreover, since the mechanism uses cables as mechanical transmission of forces and torques generated by the user and the physics engine, interference between some cables can occur. The management of such interference is a safety level that is part of of Cartesian control. Software and hardware safety logics act on these rendering outputs (locomotion and haptic rendering) and can thus reduce the performance of the simulation. The decision algorithm, which enables a degree of safety in the servo mechanism, is represented by a diamond in Fig. 2.

CONCLUSION AND FUTURE WORKS

In general, multi-sensory interfaces are developed to increase the optimization of decision making in a virtual environment using an interface that defines an ergonomic environment that is adapted for humans. The results of this work is the prototype of a reduced-scale locomotion interface for training and rehabilitation.

Such a mechanism should include both active and passive safety harnesses that are both attached to the center of mass of the user for maintaining his balance and for simulating some other types of constraints in the virtual environment. Moreover, it would have been interesting to add a vibrotactile actuator to simulate different materials properties. Finally, other systems should be implemented such as a virtual reality helmet that measures head position and displays the scene without visual interference from the CDLI.

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