Modeling and Simulation of Humanoid Stair Climbing

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Abstract

In this paper, a dynamic humanoid with a stair case model is designed to achieve a dynamically stable stair climbing gait pattern, and sequences of stair climbing locomotion analysis (weight acceptance, pull up, forward continuance, foot clearance and foot placement) are presented. A suitable trajectory control strategy is developed for the lower limb's joints (hips, knees, ankles) during stair climbing, and the strategy is tested successfully in simulation. Climbing speed of 0.5m/s has been achieved.

Keywords: Control, humanoid, modelling and simulation, stair climbing.

1 Introduction

Stair climbing (ascending and descending) is a common functional activity of daily life. A recent review of literature has revealed that only a limited number of scientific studies on the biomechanics of normal stair climbing is available [2-5]. It has been reported that stair climbing places a higher demand on the knee when compared to level walking as demonstrated by increased knee extensor moments and greater ranges of knee motion [3],[6]. In 1969 Morrison [7] presented the joint contact force at the knee for level walking, walking up and down a ramp, and walking up and down stairs. The flexor moments for stair ascent and descent were much higher than those during level walking [8].

Basically, there are three main tasks involved in this research: (i) develop a humanoid model with standard human height, weight and density within the Visual-Nastran (VN) software; (ii) gait cycle analysis in stair climbing locomotion, which separates the locomotion into several phases and demonstrates the inter-relation between them so as to produce stair climbing movement; (iii) to build a Simulink model in order to control the humanoid.

2 Model development

A humanoid model of 175 cm height and 65 kg weight was developed according to the standard measurement data from Winter et al [1]. Table 1 shows the corresponding lengths and weights obtained for the segments involved.

Table 1. Body segment lengths and weights

	Head	Upper	Fore-arm	Torso	Foot	Shank	*Thigh*
Weight (kg)	5.265	1.82	1.82	32.305	0.943	3.023	*6.5*
Length (m)	*0.228*	*0.316*	*0.248*	*0.5661*	*0.039*	*0.418*	*0.417*

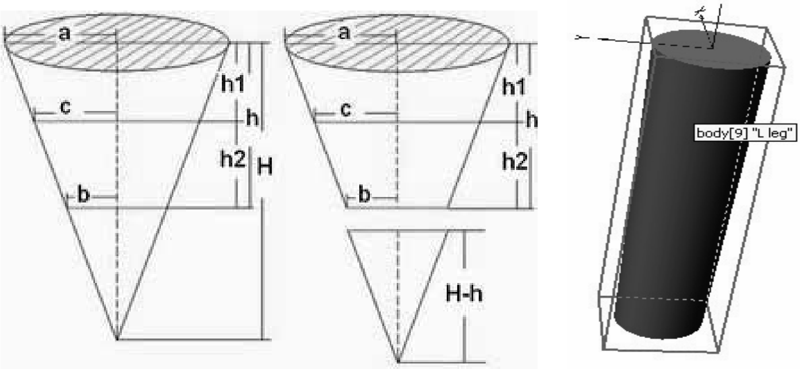

Fig. 1. Segment developed in Auto CAD

Most of the segments, such as arms and legs were developed using cylinder shapes, as shown in Figure 1, using Auto CAD, where

$$H = \frac{3\left(h^2 - 2h_1^2\right) + \sqrt{\left(24hh_1\left(h^2 + h_1^2 - hh_1\right) - 3\left(h^2 + 2h_1^2\right)\right)}}{6\left(h - 2h_1\right)},$$

$$a = \sqrt{\frac{3VH^2}{\pi\left[H^3 - \left(H - h\right)^2 * h\right]}}, \quad b = \frac{a\left(H - h\right)}{H}, \quad c = \frac{a\left(H - h_1\right)}{H}$$

The parameters h, V, h_1 in the above are known from which the unknown parameters H, a, b, c can be obtained and used to develop segments in Auto CAD and import to VN.

The humanoid model is equipped with 12 joints: 1 neck, 1 head, 2 shoulder, 2 elbow, 2 hip, 2 knee, and 2 ankle joints. Each leg is driven with 3 joints, namely hip, knee and ankle joints. The upper body has one degree of freedom about the vertical axis of the pelvis. A revolute motor can generate relative force or torque to control the joints to achieve the desired position. In this study the motor is controlled based on orientation, but it can also be controlled on the basis of torque, velocity or acceleration. Six motors and six revolute joints are used to connect the segments, although some motors are inactive at certain times. It is known that the rotation for the ankle joints should be between –25 and 40 degrees, rotation for hip joints should be between –50 and 120 degrees, and for the knee joints should be between –100 and 0 degrees [12]. The stairs are defined as boxes anchored during the simulation with 0.14 m rise and 0.3 m run.

3 Gait analysis

A unique feature of stair climbing locomotion analysis is that unpredictable human behaviour must be taken into account when the control system is designed [10]. The main difficulty lies in balancing the body, reducing the contact force between the feet and steps and avoiding “slipping” of the feet in the support phase. For simplicity, in this paper the analysis of motion is concentrated on the sagital plane. The gait cycle is the period of time between any two identical events in the stair climbing, which can mainly be divided in two phases: the stance phase and the swing phase. A complete gait cycle of stair climbing includes three functional tasks, namely *weight acceptance, single-limb support* and *limb advancement.*

To balance the body, the *weight acceptance* (moving central of mass forward) is essential. To avoid foot “slipping”, two linear actuators are used between each foot with ground by controlling the length of the linear actuator, which might produce large contact force leading to jumping of the model. There are several ways to produce contact force, and these will cause the system to become unstable when the contact force is extremely large.

Table 2 gives details of the phases involved in the gait cycle in each step. During stair climbing the first step and the last one are special.

Table 2. Gait cycle of stair climbing

	First Step	Second Step	Third Step	*Last Step*
Left Leg	FC FP	WA PU FCO	P FC EP	*WA PU S*
Right Leg	*S S*	*P FC FP*	*WA PU FCO*	*P FC FP*

FC = Foot Clearance phase; S = Stance phase; FP = Foot Placement phase; PU = Pull up phase; FCO = Forward Continuous phase; P = Pendulum phase; WA = Weight Acceptance phase

4 Control strategy

The integration of Matlab/Simulink with VN makes it possible for Simulink to send signals to VN and to receive signals from it in real time. In this way, the two software environments work together. In this manner Matlab can be used to develop suitable controllers while VN can be used to give a characterisation of the humanoid behaviour. This makes the simulation less complicated to understand. Hence, a control system in Simulink is essential to enable the joints' angular displacements track desired trajectories and the humanoid to perform stair climbing in VN. As various components of the system are dynamically strongly coupled, slight change in any joint causes variation in the trajectories of all the segments. Hence, it is not easy to construct a precise mathematical model that describes the dynamic behaviour of the humanoid. An open-loop control system is developed to achieve the desired trajectory. This is shown in Figure 2, where the first five inputs are used to control the state of the motors (active '1' or inactive '0') during the simulation, and the remaining six inputs control orientation of the six motors (ankle, knee and hip joint), the 'VN plant' is the block linking Simulink with VN, the output signal is the orientation of each joint during simulation as a function of time, which is exported to the workspace for later use.

Note that the reference inputs are not know prior to the simulation. Thus, the initial parts of the reference inputs are developed according to common knowledge [9], [11] and the remaining parts are completed gradually along with the simulation. As noted, the swing phase lasts for about 0.5 seconds during the first step, the peak angles of hip and knee flexion are reached almost simultaneously (at about 0.2 second), then the hip keeps the maximum value while the knee extends like a pendulum, until the desired position is achieved, after which the *foot placement* phase commences. The right leg moves like a pendulum while the motors in the left leg are inactive, so the left leg moves forward naturally due to the force of body's weight to accomplish *weight acceptance* and prepare for the next step (at about 0.8 second). After the *weight acceptance*, three joints of the left leg begin to extend, at about 1.4 seconds, the knee and hip joints are fully extended, but there is still some angular displacement in the ankle joints to prepare for the pendulum movement. At the same time, the left leg performs *foot clearance* and *foot placement*. The above analysis of the first two steps describes the procedure of developing the reference input trajectory and how different phases work together to accomplish the climbing task. The three joint trajectories of right side are 0.5 second behind those of the left side. However, ignoring this delay the trajectories for the left and right joints are exactly the same shape, e.g. the left knee (Lknee) and right knee (Rknee) trajectories are basically the same during a whole step. Even though the shapes are alike, a step is not exactly a copy of the previous step due to different circumstances affecting each step, which include the velocity of the body, the vertical position of each segment and the interaction between segments. Table 3 shows the interaction between the inputs for achieving the climbing task.

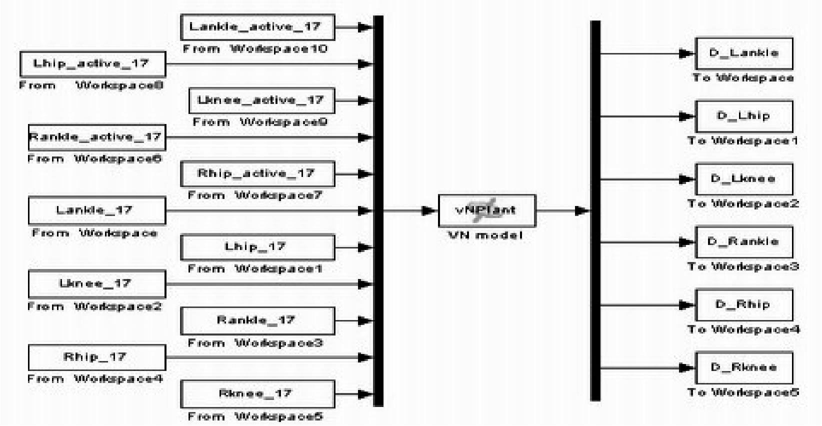

Fig. 2. Simulink representation of the open-loop control system

The input and output for each joint is thus achieved is shown in Figure 3. As noted actual output trajectory is smoother than the reference input signal. However, the output is delayed by about 0.06 seconds and the output cannot reach the desired peak angular value. Accordingly, for the peak output to reach the desired level, the peak value of the reference trajectory has to be increased. The peak error signals indicated by arrows are caused by the inactive relative joints during that time.

Following application of the open-loop control, the humanoid performed basic stair climbing locomotion, which showed some shortcomings. Thus, the left hip (Lhip) joint motor was put into a closed feedback loop with PID controllers. Consequently one more revolute motor was needed for Lhip joint which worked with the previous motor. Another input to control the states of the two motors was used (these were active one at a time). Figure 4 shows the Simulink representation of the control system thus adopted.

Table 3. Open-loop control stratege

	Hip	Ankle	Knee
Foot clearance	Open-loop orientation	Open-loop orientation	Open-loop orientation
Foot placement	Inactive	Inactive	Inactive
Weight acceptance	Inactive	Inactive	Inactive
Pull up	Open-loop orientation	Open-loop orientation	Open-loop orientation
Forward continuous	Orientation=0	Orientation=0	Inactive

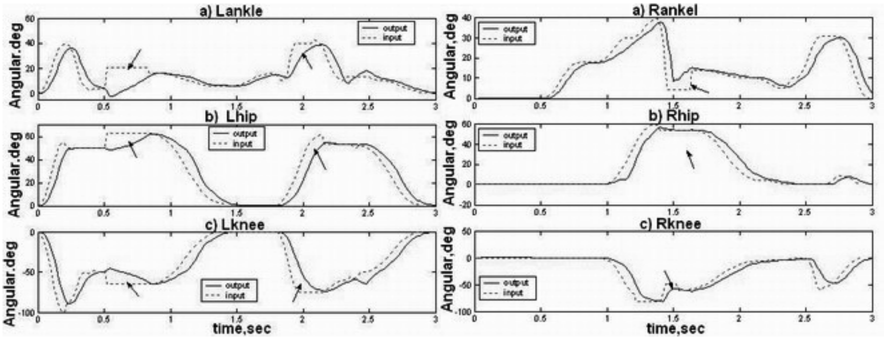

Fig. 3. Reference input and output signal of the open-loop system

Figure 5 shows the closed-loop input and output of Lhip joint, the error signal and the torque produced at this joint during the simulation. Since there is not much offset, the integral component of the PID controller was not used here, and since variation in the error signal was noticeable, the derivative term was used to improve the situation. As noted in Figure 5 the error between the actual and desired trajectory is not significant and the behaviour of the closed-loop system is not much different from the open-loop one. Accordingly, the advantage of the closed-loop control system over open-loop control system is not clearly apparent from this trial. The system is still sensitive to disturbances and parameter variations.

Figure 6 shows the sequence of simulation in VN during one gait cycle. The first step takes 0.56 seconds, whereas the first normal step takes 1 seconds, the second normal step takes 0.8 seconds, and the final step lasts 0.52 seconds.

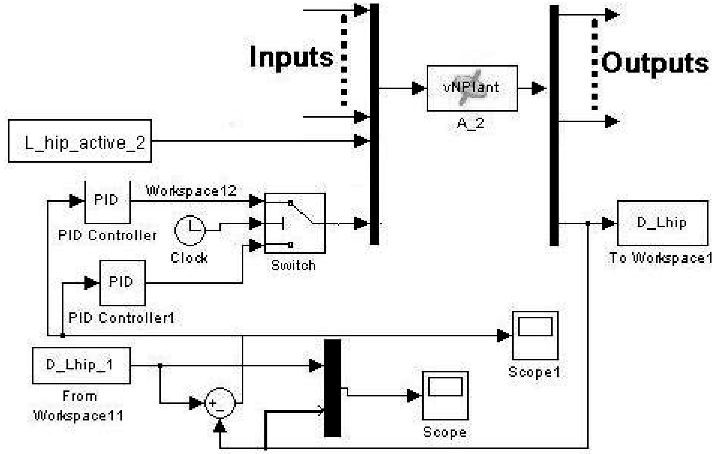

Fig. 4. Closed-loop controls Simulink diagram

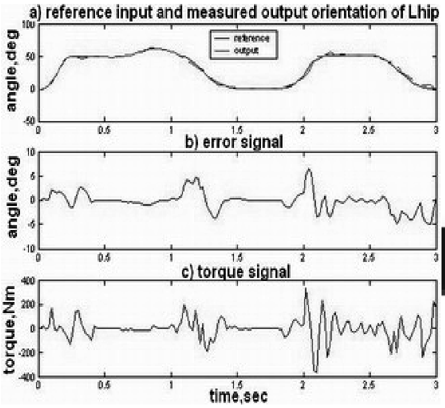

Fig. 5. Input and output signal of closed-loop

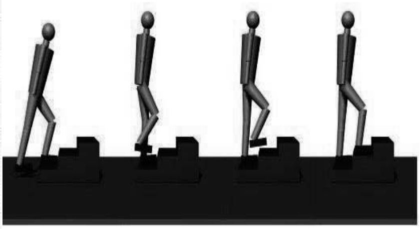

Fig. 6. Sequence of simulation in VN during one gait cycle

5 Conclusion

The development of a humanoid model, gait analysis of stair climbing locomotion and simulation and control with VN and Matlab/Simulink have been presented. Some important results have emerged from this study: Firstly, the most important phase of the locomotion is weight acceptance phase, which transfers the central of gravity forward to balance the body and to prepare for the next step, for which it is simple to apply orientation-based motor control on the joints using intuitive strategies; Secondly, the reference input trajectories vary with the rise and the run of the step, but the basic shape will not change significantly. Finally, there is limitation in using a linear actuator, which fixes an object, but also makes the system sensitive to disturbances, so it has to be used carefully.

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