Fuzzy Optimization of Foot-Trajectory Profiles in Walking Machines

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Abstract

Leg dynamics obstructs the trajectory following at high speed, thus being responsible of tracking errors and system instability. The election of trapezoidal or parabolic foot velocity profiles can deal with leg dynamic effects. However, the effects of leg dynamics are different for each foot trajectory. Therefore, to optimize foot speed, the foot velocity profile should adjust to leg dynamics for each trajectory in the whole leg workspace. The herein proposed method for trajectory generation is suitable for achieving accurate, smooth and fast foot movements, increasing leg speed as much as leg dynamics allows for each trajectory.

Keywords: Walking Machines, Legged Locomotion, Fuzzy-Logic Based Systems, Trajectory Generation.

1 Introduction

Detractors of legged robots usually point out the machine speed as one of the major shortcomings of these vehicles. Optimization of speed in robot manipulators has been extensively studied in the last two decades [1,9,10]. Similar methods have been developed to find the minimum-time control of serial manipulators along specified paths with actuator torque limitations. The minimum-time control theory assumes that a perfectly accurate manipulator model is available and that there are no external disturbances. In practice, however, it is not possible to obtain such an ideal model.

In this article the authors propose a method to find optimal speed of trajectory tracking for the legs of a walking machine. The proposed approach is an improvement of previous work on this subject [5], where trapezoidal foot-velocity profiles were adjusted to leg dynamics using a fuzzy acceleration tuning approach. However, trapezoidal velocity profiles are not smooth enough, due to the discontinuity in acceleration. Therefore, in this work trapezoidal foot profiles with parabolic blends are used instead [2] (see Figure 1), improving the fuzzy acceleration tuning algorithm proposed in [5]. The SILO4 walking robot is used as a testbed for testing the developed algorithms [3]. The method proposed is computationally efficient and its real time implementation for on-line path generation is proved. The proposed algorithm does not include a mathematical model of the robot leg to avoid errors due to mathematical simplification. It includes the experimental observation of real dynamic effects existing during the leg motion instead.

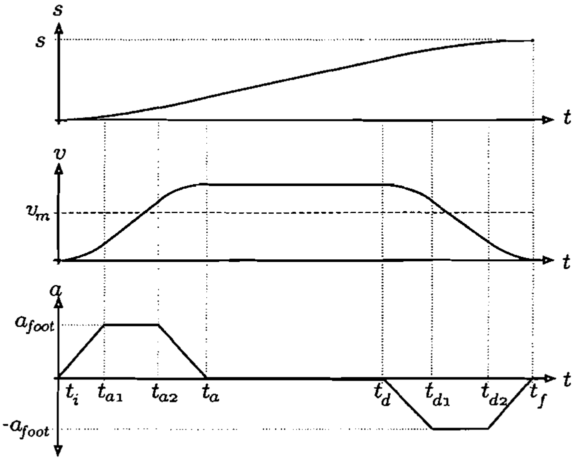


Figure 1: Foot trajectory profiles

For a better understanding of this work, Section 2 states the problem, which is solved by fuzzy rules.

Experimental results are reported in Section 3, and finally conclusions are reported in section 4.

2 Automatic Foot Acceleration Tuning

Leg dynamics critically limits foot performance. An earlier work analyzing the SILO4 leg dynamics showed that the relevant dynamics affecting the motion of such a 3-dof articulated leg are inertial effects over the first joint motion and gravitational effects over the second and third joints respectively [4]. The perturbation of gravity added to non-linear frictional and backlash effects could produce oscillations at the beginning of the upward movement of the leg if the requested speed is high.

Finding an accurate mathematical model of such dynamic effects over the leg motion is unavoidable. Fuzzy theory is an adequate tool for solving nonlinear system problems where a mathematical model is absent [11]. Thus, this soft computing technique is used here to introduce the dynamics affecting the leg motion into a foot-acceleration tuning algorithm, which provided the best acceleration value of the foot for each trajectory. Figure 1 shows position, velocity and acceleration profiles used for on-line trajectory generation. Foot acceleration will be tuned considering the following experimental requirements:

1. Foot acceleration should be increased for short trajectories to obtain higher foot speeds.
2. Foot acceleration could be moderate when trajectories are large enough.
3. Foot acceleration should be decreased for vertical movements of the foot to avoid undesired dynamic effects.

The problem of finding the best value of foot acceleration for a given foot trajectory is overcome by using a Mamdani fuzzy inference system [6]. Three input linguistic variables define foot trajectory, which are: desired average foot speed (v_m), distance from initial to final position (s), and relative z-increment (Δz_{rel}), which is the ratio between z increment and distance traveled for a given trajectory, that is:

$$\Delta z_{rel} = \frac{\left| z(t_f) - z(t_i) \right|}{s} \leq 1 \qquad (1)$$

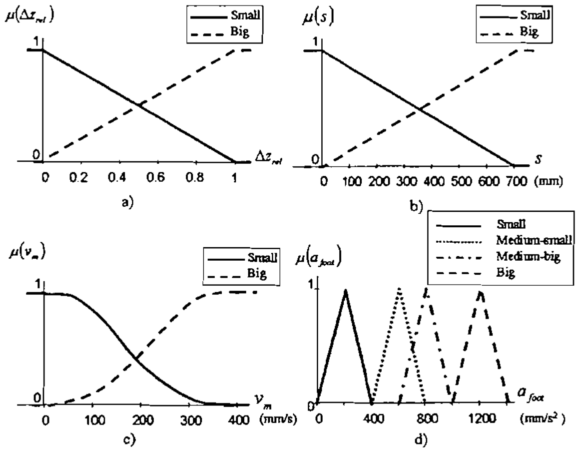


Figure 2: Membership functions of the fuzzy inference system input and output variables. a) Relative z increment; b) Trajectory distance; c) Average foot speed; d) Foot acceleration.

The output variable of the fuzzy inference system is the foot acceleration, which is needed for foot trajectory generation.

In this work guidelines on fuzzy controller design have been followed [7]. Taking this into consideration, the following assumptions have been made in order to design the fuzzy system:

1. The relative z increment in a trajectory, Δz_{rel}, is represented by two fuzzy sets {*SMALL*, *BIG*}. Membership functions of this input variable are trapezoidal and are shown in Figure 2a.
2. Trajectory distance (s) is also represented by two fuzzy sets {*SMALL*, *BIG*}. Two trapezoidal distance membership functions are shown in Figure 2b.
3. Average foot speed (v_m) is represented by two fuzzy sets. However, membership functions are parabolic rather than trapezoidal (see Figure 2c) just to adjust to the relationship between acceleration and velocity in a trajectory profile.
4. The output of this fuzzy inference system is the foot acceleration (a_{foot}), which is represented by four fuzzy sets {*SMALL*, *MEDIUM-SMALL*, *MEDIUM-BIG*, *BIG*}, and triangular membership functions are shown in Figure 2d.

The limit values of all membership functions are obtained experimentally for the SILO4 leg example.

Hence, the inference mechanism is based on the following five rules:

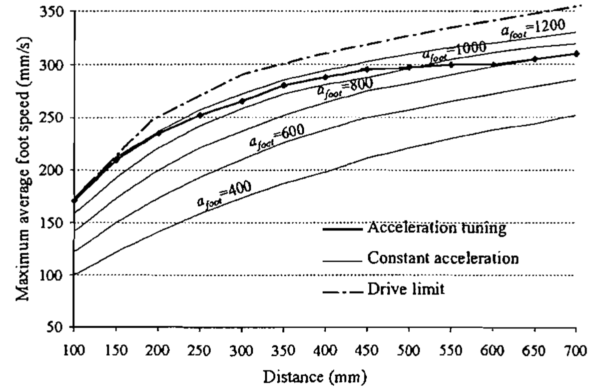


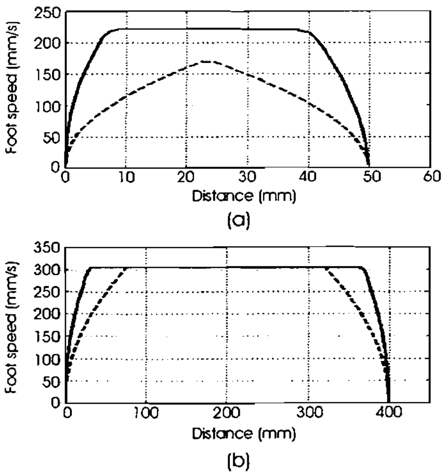
Figure 3: Curves of maximum average foot speed versus trajectory distance with constant foot acceleration profile and with foot acceleration tuning.

1. If v_m is *SMALL* and s is *SMALL* and Δz_{rel} is *SMALL* then a_{foot} is *MEDIUM-BIG*
2. If v_m is *SMALL* and s is *BIG* and Δz_{rel} is *SMALL* then a_{foot} is *SMALL*
3. If v_m is *BIG* and s is *SMALL* and Δz_{rel} is *SMALL* then a_{foot} is *BIG*
4. If v_m is *BIG* and s is *BIG* and Δz_{rel} is *SMALL* then a_{foot} is *MEDIUM-BIG*
5. If Δz_{rel} is *BIG* then a_{foot} is *MEDIUM-SMALL*

Once the foot acceleration function has been obtained, optimization methods for real-time implementation of the fuzzy reasoning process can be used [8].

3 Experimental Results

Different experiments using the SILO4 leg have been conducted to show the improvement on straight-line trajectory execution by foot acceleration tuning. One experiment shows the effect of foot acceleration tuning when executing straight-line trajectories of several lengths. Figure 3 illustrates this experiment, depicting the maximum achievable average foot speed for different trajectory distances. Each thin curve in this graph represents the maximum average foot speed that could be reached with a foot velocity profile without acceleration tuning, provided that no dynamics perturbs the motion. If leg dynamics are considered, some high acceleration trajectories will not be possible to perform because oscillations and non-desired effects will appear as shown in Figure 5. A foot acceleration of 600 mm/s^2 should be used for every trajectory as a conservative value that avoids dynamic effects. The thick curve in Figure 3 represents the maximum achievable foot speed during the same trajectories using foot acceleration tuning, which takes leg dynamics into account. Thus, foot acceleration tuning finds the acceleration values that provide higher foot speeds, avoiding the use of very high acceleration values that could impose oscillatory behavior. Average foot speed values as well as distance traveled are listed in Table 1 for each trajectory of the experiment in Figure 3.



(a)

(b)

Figure 4: Comparison between achievable foot velocity profiles with acceleration tuning (solid line) and with constant acceleration of 600 mm/s^2 (dashed line).

Figure 4 illustrates velocity profiles of two trajectories of different length, $s(t)$, executed by the leg with and without acceleration tuning at its maximum achievable foot speed (solid and dashed lines respectively). Figure 4a represents a short trajectory, where average speed is clearly improved when using acceleration tuning. Figure 4b shows the same effect for a larger trajectory. As can be observed from this figure, higher average foot speeds can be achieved using the acceleration tuning approach.

Table 1 reveals that the acceleration tuning method increases the average foot speed by 10 to 100 % over the maximum achievable speed when acceleration tuning is not used.

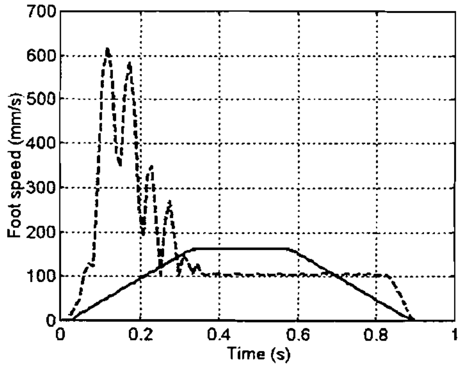


Figure 5: Oscillations in the foot velocity profile during lifting experiments with foot acceleration = 1000 mm/s^2 (dashed line). The smooth behavior of the velocity profile with acceleration tuning approach is represented with solid line.

4 Conclusions

The work presented in this article focuses on optimizing the average leg speed of a walking robot. Acceleration of the velocity profile has been targeted as the proper magnitude to be optimized.

To avoid problems stemming from the robot's parameter uncertainties, fuzzy techniques have been used. For this purpose, fuzzy rules are defined based on experiments, and the optimal acceleration for every given trajectory is found.

Experiments have been carried out to validate the algorithmwhich concluded that the foot acceleration tuning method finds the acceleration values that provide fast and smooth foot trajectories, avoiding perturbing effects due to leg dynamics. The acceleration tuning method increases average foot speed by 10 to 100 percent over the maximum achievable speed when acceleration tuning is not used.

Table 1: Comparison of maximum achievable average foot speeds. (*) means actuator limit reached.

s (*mm*)	V_m^{max} (*mm/s*)		Improvement (%)
	Acceleration Tuning	Acceleration = 600 mm/s^2	
20	108 (*)	54	100.0
50	160 (*)	86	86.0
100	180 (*)	120	50.0
150	215	150	43.3
200	235	180	30.5
400	280	230	21.7
600	300	272	10.2

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