A ROBUST AND FLEXIBLE CONTROL SCHEME TO SYNTHESISE BIPEDAL WALKING

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Introduction

An alternative approach to synthesise bipedal walking is proposed, in which trajectory planning and control are not separated. Generation of cyclic gait for a planar seven linked bipedal model with human dimensions is generated by controlling: (1) the Centre of Mass (CoM) velocity at push off; (2) the configuration of the swing leg at the end of swing; (3) the trunk orientation; and (4) the knee that bears body weight

Regulating the walking velocity is possible by varying the desired velocity of the CoM at the end of the double support phase. Variation of only two end-point objectives generates various types of gait. Although various combinations of walking speeds and step lengths are possible, the energetic costs differ. For a specific speed, the required energy per unit distance depends on the step length. For every speed there is an optimal step length which requires less energy per unit distance than other step lengths. For larger walking velocities, the optimal step length increases.

The proposed control scheme is robust to mechanical perturbations as well to structural changes in the bipedal dynamics. The model is able to walk uphill, asymmetric, and with passive knees and ankles. Exposed to pushing, pulling and stumbling at different phases of the gait cycle, the model maintains walking after making maximal four corrective steps. Maximal tolerable forces are phase and direction dependent.

Methods

The biped model is two-dimensional and contains seven segments: shank, thigh and foot of both the legs, and a trunk. Dimensions and inertial properties of the segments are based on a human subject (body mass 80 kg, length 1.90 m). In contrast with many other control schemes to generate bipedal gait, the movement is not preplanned; i.e. prescribed trajectories (e.g. Lum, Zribi and Soh, 1999; Miura and Shimoyama, 1984; Salatian, Yi and Zheng, 1997) or trajectories defined by the minimization of a general criterion, basically 'open loop' (Yamaguchi, 1989; Pandy and Anderson, 1999). An alternative approach to synthesize bipedal walking was proposed. The backbone of the model is the regulation of a few variables at the end of the swing and double support phase that are related to step length (S), step time (T) and walking velocity (V).

The basic idea of this alternative approach is the observation that during the swing phase the Center of Mass (CoM) moves almost ballistic. When the knee of the stance leg remains relative straight, CoM motion resembles the motion of an inverted pendulum. When the initial velocity (V_{TO}) and position of the CoM at the beginning of the swing phase are known, the position of the CoM at the end of swing phase -defined by the swing time T - can be calculated. Hip position is known from CoM position. This hip position and the configuration of the swing leg (knee and ankle angle) at the end of swing phase determine the thigh angle, since by definition the heel contacts the ground at the end of the swing phase. Initial CoM position and velocity (V_{TO}), swing time (T), and the configuration of the swing leg at the end of swing determine the step length (S). It is straightforward to determine S from V_{TO} and T, or to determine V_{TO} from S and T for a specific initial CoM position. S, T, and V_{TO} are descriptors of normal gait. From these descriptors two can be independently chosen. Control objectives are derived from these gait descriptors and additional assumptions that the trunk remains upright and the weight bearing knees remains straight. Control objectives are: (1) the desired velocity of the CoM at the end of the double support phase; (2) the desired ankle, knee, and thigh angle at the end of swing phase; (3) the desired knee angle of the weight bearing leg; and (4) the desired trunk orientation.

The end-point control objectives (1 and 2) are reconstructed from S and T, from S and V V_{TO}, or from V V_{TO} and T. Control objectives 1 and 2 are determined at the beginning of the double support and swing phase, respectively. The continuous control objectives (3 and 4) are included to ensure that the assumptions made (trunk upright, relative straight weight bearing knees) are not violated.

The control objectives are regulated with Quadratic Dynamic Matrix Control (Garcia and Morshedi, 1986). This technique uses an output prediction in the form of:

$$y(\bar{k}+m) = \underline{y}^*(\bar{k}+m) + \sum_{i=1}^{m} A_{i,k}\Delta\underline{u}(\bar{k}+m-i) \qquad \text{(m=1,2,...P)} \tag{1}$$

where $\bar{k}$ is the current discrete time step, $\underline{u}$ are the control inputs (joint moments of force), $\underline{y}^*$ is the predicted output if future controls would be kept constant and equal to $\underline{u}(k)$. $A_{i,k}$ are the step response coefficients obtained by linearizing the model around its current state, and P is the prediction horizon, in our case the difference between the current and final time (defined by the duration of the swing or double support phase). The output vector is defined by the control objectives 1-4. Control inputs are obtained by minimizing a weighed sum of the controls and differences between predicted and desired output ($\Delta\hat{\underline{y}}$).

$$\min_{\Delta\underline{u}(\bar{k}),\ldots,\Delta\underline{u}(\bar{k}+P-1)} \left\{ \sum_{m=1}^{P} \Delta\hat{\underline{y}}(k+m)^T \Gamma \Delta\hat{\underline{y}}(k+m) + \sum_{m=1}^{P} \Delta\underline{u}(k+m-1)^T \Lambda\Delta\underline{u}(k+m-1) \right\} \tag{2}$$

This is a linear optimization problem, which may include constraints and can be solved using standard quadratic programming techniques. Cyclic gait is generated by solving this optimization problem at each discrete time step and feeding the calculated control inputs ($\underline{u}$) into the non-linear equations of motion

Results

Flexibility proposed control scheme

Controlling the walking velocity is possible by varying the desired velocity of the Center of Mass (CoM) at the end of double support. Controlling the step length is possible by varying the desired step length. Variation of only two end-point objectives generates various types of gait. Except for the trunk orientation and knee angle, the joint trajectories are not defined between the beginning and the end of the double support or swing phase. Most joints are relatively 'free' during these phases. By varying only two variables directly related with speed and step length, the proposed control scheme is very flexible.

Although various combinations of walking speeds and step lengths are possible (Fig 1,left), the energetic costs differ. For a specific speed, the required energy per unit distance depends on the step length. For every speed there is an optimal step length, which requires less energy per unit distance than other step lengths (Fig 1, middle). For larger walking velocities the optimal step length increases. This relation between step length and walking speed is also seen in human walking (Koopman, 1989). The minimal energy per unit distance -energy for the optimal step length- depends on the walking velocity (Fig 1, right).

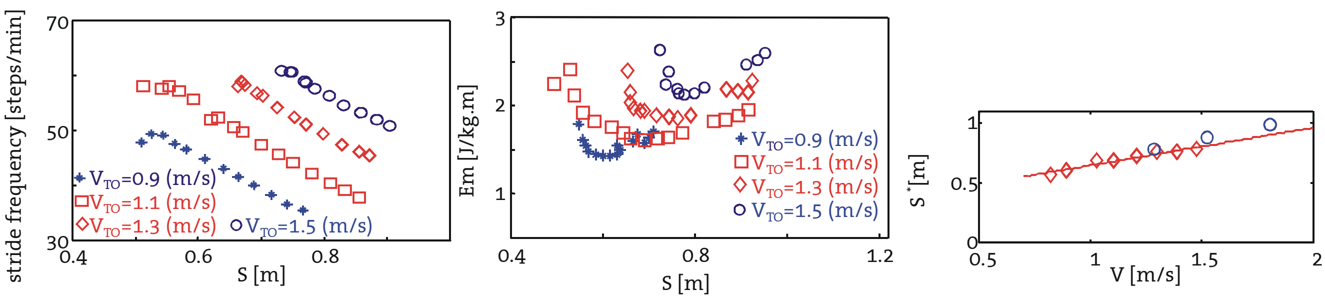

Fig. 1. ***Left****: Relation between step length (S) and stride frequency at different velocities at push off (VTO).* ***Middle****: Model predicted sums of positive joint powers per walking distance (Em) for different CoM velocity at push off (VTO) and step lengths (S). Sums of joint powers are normalized to body weight.* ***Right****: Model predicted optimal step length S* at different walking speeds, V (diamonds). The relation between S and V is approximated by the least square fit of S*=aV+b. (solid line; a=0.31; b=0.33). The step length of a human subject (80 kg, 1.90 m) at three different walking speeds are also shown (circles, experimental data).*

Robustness proposed control scheme

Controlling progression speed, step length, trunk attitude, and weight bearing is sufficient to generate cyclic gait, even in case of disturbances or structural changes in the skeletal system. Exposed to forces applied at the trunk and heel, the model maintains balance after making maximal four corrective steps. Corrective steps are either shorter or longer, and smaller or larger than normal steps. Humans also make several corrective steps to maintain their balance (Hill and Patla, 1998). The effects of perturbations and their maximal tolerable amplitudes depend on the timing and direction of the disturbances. This is also seen in humans (Dietz et al., 1986; Waterloo, 1999; Schillings, Wezel and Duysens, 1996) and is the result of the non-linear dynamics of bipedal gait.

The robustness to mechanical perturbations of the proposed alternative approach and other approaches to synthesize bipedal gait are compared (Table 1). Compared with Taga's approach the maximal tolerable forces obtained in this paper are about two to three times larger. The maximal tolerable forces obtained by Seo and Yoon are more difficult to compare with the maximal forces obtained in this paper, since they applied the forces during the whole cycle and for various walking velocities. For v=0.4 m/s, the results of Seo and Yoon are better for pushing and less good for pulling, compared to the results obtained in this paper. For v=0.4 m/s, the results of Seo and Yoon are less good, compared to the results obtained in this paper except for perturbations applied in the beginning of the swing phase (BSw). For v=0.4 m/s, the results of Seo and Yoon are less good, compared to the results obtained in this paper, except for pulling in the BSw.

	our approach	Taga	Seo v=0.4 m/s	Seo v=0.56 m/s	Seo v=0.72 m/s
Push DS	2.6e-1		3.4e-1 (+)	2.1e-1 (-)	7.9e-2 (-)
Push BSw	2.1e-1		3.4e-1 (+)	2.1e-1 (+)	7.9e-2 (-)
Push ESw	2.6e-1		3.4e-1 (+)	2.1e-1 (-)	7.9e-2 (-)
Pull DS	5.6e-1	3.57e-1 (-)	1.1e-1(-)	2.1e-1 (-)	3.4e-1 (-)
Pull BSw	1.9e-1		1.1e-1(-)	2.1e-1 (+)	3.4e-1 (+)
Pull ESw	4.3e-1		1.1e-1(-)	2.1e-1 (-)	3.4e-1 (-)
Stumble BSw	9.4e-2	2.9e-2 (-)			
Stumble ESw	9.4e-2	4.3e-2 (-)			

Table 1. Comparison of robustness to mechanical perturbation of proposed alternative approach to generate cyclic gait with other approaches. Shown are the maximal tolerable impulses divided by body weight (N s/kg). Maximal impulse forces obtained in this paper are compared with those of Taga (1995) and Seo and Yoon (1995). . When Taga's and Seo and Yoon's approach sustain larger or smaller perturbations than our approach this is indicated by plusses (+) or minuses (-).

The proposed control scheme was not only robust to mechanical perturbations but also to structural changes in the skeletal system. Cyclic gait with one passive ankle and/or knee is generated without adjusting the structure of the control scheme. To be of use in the design process of new and prosthetic systems, the model should be able to generate a cyclic gait without active controls at the ankle and/or knee. The preliminary results presented in this paper are promising. Further research has to explore the possibilities and benefits of the proposed control scheme in the design process. Whether the assumptions underlying the proposed control scheme are valid for normal and pathological human walking is still an open question. To bridge the gap between the available and needed experimental data of perturbed human walking, devices to perturb human gait are being build at our laboratory (Forner Cordero, Kurstjens and Koopman , 1999).

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