Comparing Foot Placement Strategies for Planar Bipedal Walking

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I. Motivation

A number of foot placement strategies for walking have been proposed that make use of widely varying model complexities. Although a number of successful demonstrations have been individually shown in simulation and on physical robots, it is difficult to make a direct performance comparison due to the large differences in hardware, gait generation strategy, control system gains, actuator saturation limits, sensor noise, and many other physical limitations. Here we present a quantitative stability comparison of four foot-placement strategies based on: The Inverted Pendulum Model **(IPM)** [1], Capture Point **(CP)** [3], Foot Placement Estimator **(FPE)** [5], and Foot Placement Indicator **(FPI)** [4]. We implement each of these strategies in simulation and evaluate the Gait Sensitivity Norm (GSN) [2] as a measure of stability during a push disturbance using step duration as a gait indicator. We give a quantitative comparison of these approaches under the same physical simulation. We also discuss our progress in comparative push recovery experiments on our new torque-controlled planar bipedal robot with series-elastic actuators.

TABLE I
QUANTITATIVE COMPARISON OF FOOT PLACEMENT STRATEGIES

	FPE	**FPI**	**IPM**	**CP**
$\alpha\left(1/\Vert\frac{\partial \mathbf{g}}{\partial \mathbf{e}}\Vert_2\right)$	1.0	0.96	0.75	0.72
$\mathbf{e}_{\max}$ (N)	45.1	49.5	34.4	36.6

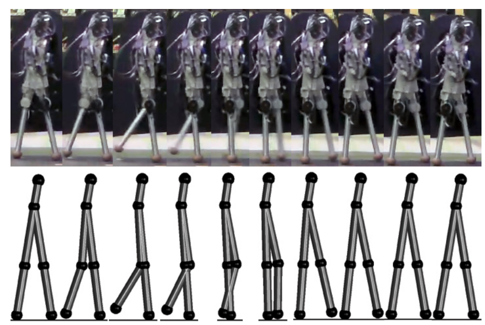

Fig. 1. A snapshot sequence comparing the walking gait of the real robot to that of simulation using the inverted pendulum foot placement strategy.

II. Comparison Baselines

A PID controller was used to track foot placement during walking. The same gains and gait generation strategy was used in all experiments and actuator limits were imposed to match our physical robot. A push disturbance was applied to the hip of the biped with a force equal to approximately 20% of the robots weight for a duration of 0.1s.

III. Current Results

The first row of Table 1 shows the inverse of the GSN for the four foot placement strategies, normalized to the range $[0\ 1]$. The FPE performs marginally better than the FPI, despite the FPI's use of a more detailed model. Note that because the foot placement strategies do not take into account the full dynamics of the gait, a more detailed model doesn't necessarily mean higher performance during gait generation. The second row shows the maximum push disturbance handled by the different approaches. Note that the FPI is able to handle a much larger push disturbance than the FPE. This is likely due to the fact that the predictive power of the simpler models tends to degrade as the system diverges outside of its nominal motion.

IV. Ongoing Work

We have successfully demonstrated the IPM foot placement strategy for walking on our real robot and have produced successful push (by hand) recovery experiments (Figure 1). We are currently in the process of instrumenting a push rod with a force-sensor in order to make the GSN calculations on the physical system. We hope to use these results in developing improved foot placement strategies.

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