Using Arms for Balance and Locomotion of Humanoid Robots

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1 Introduction

Legged robots have the potential to surpass animal capabilities, but they currently fall short in replicating the dynamic performance and robustness of their biological counterpart. Current and previous work has focused on footstep and ground reaction force planning for locomotion and disturbance recovery [1, 2], but much fewer attention has been devoted to the use of additional limbs such as arms to improve balance and locomotion. In [2], commanding arm swing reduced the total yaw angular momentum and the foot yaw moment in stance for simulated humanoid running. Similar observations were made on passive walkers by Collins *et al.*, who further found lower metabolic cost of walking when human subjects swung their arms normally [3]. In [4], an arm mounted on a quadruped robot acted as a tail to reduce the body roll by about 1° during lateral trot. While these works showed that arms can improve normal locomotion, far less is known about the extent to which arm action can help recover from disturbances. In this work, we use trajectory optimization to show that arms can play a major role in improving balance and locomotion of humanoid robots when undergoing disturbances.

2 Methods

To generate walking trajectories, we use a centroidal dynamics-based trajectory optimization formulation that takes into account the dynamic coupling between the legs, the arms and the torso [5]. We use a model MIT humanoid, which has 22-degrees-of-freedom and weight 21 kg [6]. To promote the natural emergence of arm behavior, we minimize the robot's angular momentum about its center of mass in the vertical and forward directions. Note that the angular momentum in the lateral direction is not minimized in order to allow for leg cycling [2]. In addition, using the approach in [7], the cost function is designed to track a desired forward velocity while minimizing the orientation error, the lateral velocity and the angular velocity of the main body. The footstep locations are optimized under a fixed gait schedule. The optimization problem is formulated in `MATLAB` using a direct transcription method. The open-source sofware package `CasADi` [8] is used to compute the derivatives required by the `Ipopt` solver [9], which computes optimal trajectories in about 2 second.

We generate multiple walking trajectories over a single gait cycle of 0.8 s. The initial state of each trajectory corresponds to a normal walking state, but with the torso undergoing a lateral velocity disturbance $v_{y,d}$ and an angular velocity disturbance $\omega_{x,d}$, as depicted in Fig. 1). The disturances are sampled over a 10×10 mesh, with the lateral velocity disturbance $v_{y,d}$ ranging between $[-0.5, +0.5]$ m/s and the angular velocity disturbance $\omega_{x,d}$ ranging between $[-172, +172]$ °/s.

To assess the effect of the arms, the set of 100 optimizations is ran three times: 1) with the arms disabled (i.e. constrained to a nominal configuration), 2) with the arms enabled to move freely and 3) with the arms enabled to move freely and with an additional mass of 0.3 kg located at each arm's end-effector. In a standard T-pose, the robot's moment of inertia around the vertical axis is 0.23 kg·m^2 and 0.41 kg·m^2 with and without added mass, respectively.

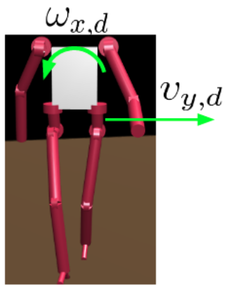


Figure 1: Lateral velocity disturbances applied on the torso. The direction of the arrows indicate positive sign.

3 Results

A single sampled trajectory with $v_{y,d} = +0.5$ m/s and $\omega_{x,d} = +172^\circ$/s, shown in Fig. 2, demonstrates that the roll, pitch and yaw and lateral velocity are reduced by using arms and subtantially more so with added mass. The roll and yaw errors are up to 10° lower with arms and added mass compared to without arms and the pitch error is reduced by up to 23°.

Both arms and legs contribute to disturbance recovery, but the relative contribution of each varies as a function of the disturbances' amplitude and direction, as shown in Fig. 3). For example, the pitch root mean square error (RMSE) without arms is highest with $v_{y,d} = +0.5$ m/s and $\omega_{x,d} = +172^\circ$/s (Fig. 3(a)). For this case, the pitch RMSE is reduced by 27% with arms and by 73% with arms and added mass. Conversely, for trajectories where $v_{y,d} < 0$, the RMSE without arms is already low and the arms do not further re-

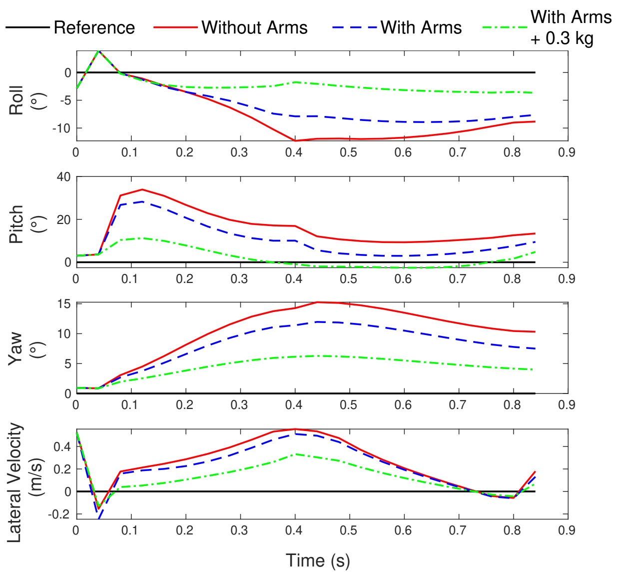
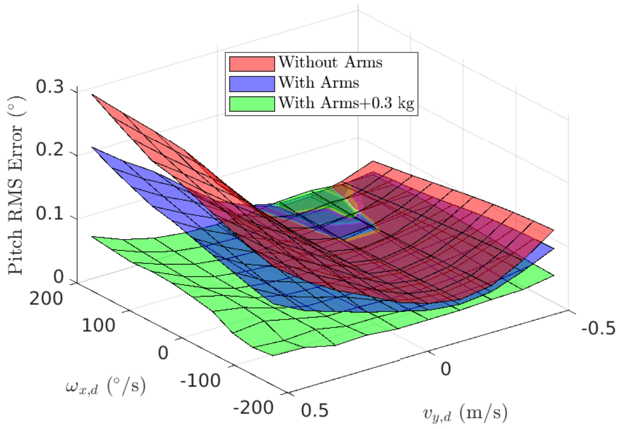
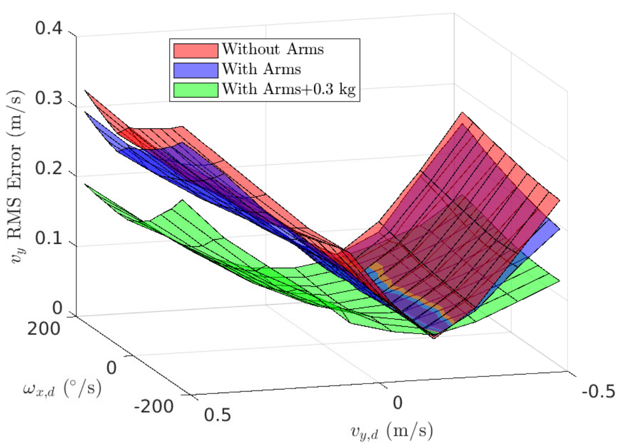


Figure 2: Roll, pitch and yaw trajectories of the robot's torso for $v_{y,d} = 0.5$ m/s and $\omega_{x,d} = +172°$/s.



(a) Pitch



(b) Lateral Velocity

Figure 3: RMS error for each disturbance $v_{y,d}$ and $\omega_{x,d}$.

duce this error significantly.

This variation in arm contribution could be parlty explained by the fact that the supporting right leg is advantageously placed on the ground to produce corrective ground reaction forces when $v_{y,d} < 0$, where the error is already low without arms. On the other hand, in the area where the error is high without arms (e.g. when $v_{y,d} > 0$), the supporting leg alone may be unable to recover from the disturbance and the arms become useful to reduce the error. Similar observations were made for body lateral velocity (Fig. 3(b)), roll, yaw and torso angular velocity.

4 Conclusion

This work motivates the relevance of using the arms to improve balance and locomotion of legged robots. We showed that the arms can substantially reduce the orientation and lateral velocity errors under disturbances, especially when the ground reaction forces not, on their own, sufficient to recover from the applied disturbances.

Future work will focus on the design of an arm controller that generates real-time, feasible motion plans to improve the locomotion capabilities of humanoid robots. Arm collisions with the humanoid's body will need to be properly adressed to ensure safety and reliability of arm motion.

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