Modularity for Maximum Mobility and Manipulation: Biped Balancing Using Series-Elastic Joint Actuators

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1 Introduction

It is estimated that nearly 50% of Earth's landmass is currently inaccessible to wheeled or tracked machines [1]. Humans and animals, however, are readily able to access most of these areas and it is desirable that robots and machines be able to do the same. Biologically inspired robots, specifically legged robots, offer enhanced mobility in these impassable environments. Reconfigurable robots can bypass the complexity of specialized behaviors exhibited in animal locomotion over varying terrain by allowing the robot operator to intelligently choose a task-specific configuration. In this way an entire set of robots with varying configurations, morphologies, and capabilities can be created using a modular approach [2]. We believe this modular approach has many advantages over highly specialized robots that are harder to adapt to a wide range of different environments and tasks. For example, in man-made environments designed for humans, the larger form factor of hexapods and quadrupeds may inhibit the robot's mobility (stairs, narrow corridors, etc.). In these cases a biped configuration may be propitious.

2 Approach

We present a set of modular series-elastic actuators (SEAs) that allow rapid and robust prototyping of mobile legged robots. The SEA modules were originally developed for the a snake robot, *SEA Snake*, and have recently been reconfigured into *Snake Monster*, a multimodal walking robot that can be easily adapted to hexapod, quadruped, and biped configurations [3][4]. The use of SEAs allows the implementation of a compliant hybrid controller using both position and force-based walking [5]. Robust, yet simple, balancing algorithms are implemented on this physical robot to experimentally determine the maximum disturbance forces that *Snake Monster* can undergo and successfully recover from without falling. First, ankle torque strategies are implemented to oppose gravity induced moments. Next, the ankle torques are augmented with an arm strategy which adaptively relocates the biped's center of mass (CoM) when losing balance. The ankle and arm strategies are further augmented by a combined position and virtual model force controller which generates force-torque wrenches at the feet for gravity compensation in flight and body support in stance. This balancing controller is shown through experimentation to stabilize *Snake Monster* Biped Robot for external disturbances of 2-3 N.

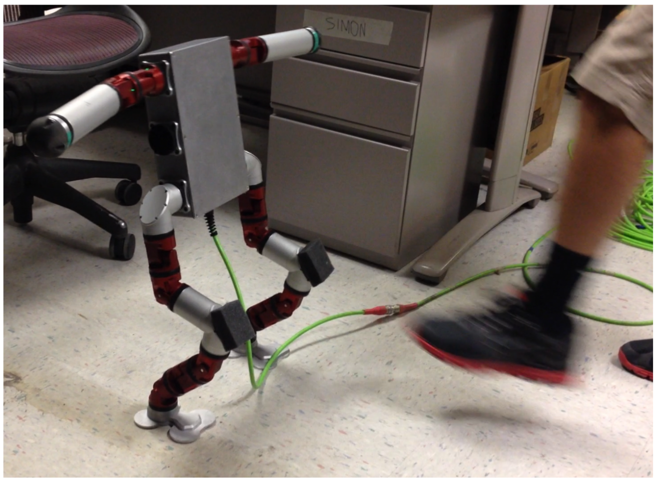

Figure 1: Snake Monster Biped using ankle torque strategy and arm control to recover its balance from a kick.

3 Configuration

The biped is kinematically configured to have 5-DoF legs and 2-DoF arms. The 2-DoF arms allow the biped to shift its center of mass (CoM) and induce inertial forces for balancing laterally and longitudinally. The legs are identical in configuration and each consist of 2 hip joints, 1 knee joint, and 2 ankle joints. The hip and ankle joints provide adduction/abduction and flexion/extension motions while the knee only provides flexion/extension. A passive 90^o leg segment is configured in series between the hip joint and the knee joint to improve the workspace of the limb for walking and balancing. The biped is fit with specialized foot modules containing a 2 x 2 array of custom single-axis force sensitive resistors. The foot has a 0.25" durable rubber sole used to protect the sensors and conform to small perturbations in the ground. The foot sensor, shown in Fig. **??** was designed to provide ground reaction force and center of pressure (CoP) measurements.

4 Experimental Results

After implementing each incremental strategy of the balancing controller a series of experiments were conducted to test the ability of the biped to recover from externally applied disturbances. The experiments focused primarily on longitudinal stability and ignored active lateral stabilization because the support polygon is inherently larger in the lateral direction than the longitudinal direction.

The ankle torque strategy alone was capable of stabilizing itself under an applied 1 to 1.25 N-m of torque about the foot (approximately a 2N force at the upper body). A larger disturbance torque was able to be applied if the impulse of the applied force was reduced. This may be due to the fact that the state-estimator is not exact and susceptible to impact noise. Additionally, the controller gains are most certainly not tuned to respond optimally at this point but are sufficient for minor disturbances. When the ankle torque gains are increased the biped can react faster and thus stabilize under disturbances on the order of 1.5 times larger. However, the controller will often overshoot creating too much momentum in the initial correcting direction causing the biped to fall over in the opposite direction of the initial disturbance force. Sometimes in the intermediate range between a 2-3N disturbance the biped will oscillate a few times around the equilibrium (balanced) position before settling.

After adding the arm control to the ankle torque strategy significantly larger disturbances (order of 1.5 to 2) times the can be reacted to. Similarly however, the controller tended to overshoot so much that the biped would again fall in the opposite direction of the initial disturbance. Further optimization of gains and the implementation of the dynamic inertial effect arm controller should drastically improve the robustness and consistency of balancing performance over even larger disturbance forces.

A dimensionless balancing performance ratio ν relates robot's weight to the max disturbance force it's capable of recovering from. The ratio is calculated by the following equation and used to compare the performance of other biped/humanoid robots.

$$\nu = \frac{D_{max}}{m_{robot}} \tag{1}$$

$$\nu_{SM} = \frac{.3}{8} = 0.0375 \tag{2}$$

Additional experiments attempted to stabilize the biped in 1-legged balancing. These experiments were not successful which can be mainly attributed to the configuration of the biped legs which are separated by the width of the entire body making it difficult to position the biped's center of mass directly over one leg. The bipeds left to right hip distance needs to be decreased to improve both 1-legged balancing and walking were the center of mass needs to switch between legs quickly without large leg motions.

A video of the balancing experiments can be seen at the following link [6]: https://www.youtube.com/watch?v=7CciHJ6SP_o

5 Future Work

The next step in balancing control is to implement N-Step Capture Point Algorithms [7]. This balancing algorithm introduces the ability to take steps when the center of pressure leaves the support polygon and reduces the dimensionality of the very high-dimensional walking problem by requiring estimates of only 2 state variables: the center of mass position relative to the stance foot and the center of mass velocity. This algorithm uses CoM position and velocity to estimate the instantaneous capture point (i.e. the next footstep position that will bring the body's orbital energy to zero)[7]. Pratt et. al demonstrate the N-step capturability balancing control on the M2V2 lower body humanoid (44 kg). This robot is capable of recovering from 21 N forward and sideways pushes which results in a performance ratio of 0.047 compared to Snake Monster's 0.0375. Although the performance of Snake Monster can be improved with more gain tuning the performance ratios of the two robots are fairly similar using Snake Monster's current controller.

References

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