High degree-of-freedom dynamic manipulation

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ABSTRACT

The creation of high degree of freedom dynamic mobile manipulation techniques and behaviors will allow robots to accomplish difficult tasks in the field. We are investigating the use of the body and legs of legged robots to improve the strength, velocity, and workspace of an integrated manipulator to accomplish dynamic manipulation. This is an especially challenging task, as all of the degrees of freedom are active at all times, the dynamic forces generated are high, and the legged system must maintain robust balance throughout the duration of the tasks. To accomplish this goal, we are utilizing trajectory optimization techniques to generate feasible open-loop behaviors for our 28 dof quadruped robot (BigDog) by planning the trajectories in a 13 dimensional space. Covariance Matrix Adaptation techniques are utilized to optimize for several criteria such as payload capability and task completion speed while also obeying constraints such as torque and velocity limits, kinematic limits, and center of pressure location. These open-loop behaviors are then used to generate feed-forward terms, which are subsequently used online to improve tracking and maintain low controller gains. Some initial results on one of our existing balancing quadruped robots with an additional human-arm-like manipulator are demonstrated on robot hardware, including dynamic lifting and throwing of heavy objects 16.5kg cinder blocks, using motions that resemble a human athlete more than typical robotic motions. Increased payload capacity is accomplished through coordinated body motion.

Keywords: Mobile Manipulation, Dynamic Manipulation, Legged Robotics, BigDog, Dynamic Lifting, Dynamic Throwing, Whole Body Manipulation

1. INTRODUCTION

As long as mobile robots have been utilized for mobile manipulation tasks in the field, operators have been pushing them to their extreme limits. The success of robotic manipulation solutions in dangerous arenas, such as the defeat of improvised explosive devices (IEDs), has prompted their widespread use, and led to their use for increasingly challenging tasks. In particular, the limited payload capacity for mobile manipulator platforms limits their applicability for many scenarios. One solution is to build stronger manipulators, however, this results in a heavier platform, and deployability suffers. It often also results in higher system cost and limits mission duration due to battery depletion.

An approach to overcome these limitations that we examine in this paper focuses on utilizing all of the degrees of freedom of a robot to augment the manipulator capabilities, potentially resulting in greater payload capacity, greater reach, and faster end effector speed, all without requiring hardware enhancements. Although this process has some applicability to wheeled and tracked vehicles, we choose to focus on legged systems, as these robots typically have many high-force, large workspace degrees-of-freedom in the robot's legs, which are normally utilized solely for mobility. Therefore, there is a lot of potential increase in manipulation performance by utilizing whole-body behaviors and control strategies by repurposing this existing hardware to amplify manipulation capabilities.

Typically, robotic mobile manipulation has meant a manipulator system mounted to a mobile base, with the two systems operated relatively independently. Recently, researchers have demonstrated a technique for performing fine manipulation from a platform which is not statically stable (segway RMP) [1]. In this example, the techniques developed demonstrate an ability to perform manipulation despite the presence of a mobile platforms rather than enhancing their manipulation performance by utilizing their mobile base. There have been a few exceptions to this approach, most notably [2,3], which take advantage of the additional degrees of freedom provided by the mobility system to improve kinematic conditioning (avoid singularities) and maintain balance while resisting/producing external forces through the manipulation system.

The core difficulty in whole-body manipulation is resolving redundancy – choosing how to position and allocate forces among the entire collection of joints in order to satisfy constraints and ensure robustness to disturbances. In robotics and computer animation, researchers have explored prioritized task space control strategies to turn low-dimensional (i.e.

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abstract) task space commands into high-dimensional joint level controls [4,5]. Later, these approaches were extended to employ unilateral Coulomb friction models [6] with mixed, rather than prioritized, task space control. Another approach to whole-body manipulation is to decouple body and limb control. Rather than explicitly form a Jacobian that includes all of the robot's degrees of freedom [7], we could treat the base of the robot as if it was floating. Wrenches on the base are then converted into desired foot forces in a least-squares fashion [8]. The result is that force-control can be realized using a prioritized version of virtual model control [9].

A major goal of this work is to transition robotic manipulation behaviors from the traditional deliberate and precise movements found in industrial robot arms toward a more biological, or athletic regime. It is clear that whole-body strategies are used by humans and animals to increase, efficiency, speed, etc. In short, we are working toward more natural manipulation behaviors.

In this paper, we explore dynamic whole body manipulation techniques for two different tasks. The first is a heavy lift, where the robot moves a mass from the ground to the highest point in the workspace, directly 'overhead.' This task is similar to the Olympic Weightlifting Snatch or Clean and Jerk events where athletes attempt to lift a weighted bar from the floor to a position extended overhead. In this behavior, humans are able to lift significantly heavier loads than their arms are capable of manipulating. This is accomplished by utilizing whole-body motions that inject energy from the legs into inertia of the payload, pulling the mass through areas of kinematic weakness using momentum, and exploiting the increased load carrying capacity of the arms at singular configurations both in tension and compression. We attempt to introduce these characteristics into robotic manipulation in this task, and measure our performance by the largest mass lifted.

The second task that we explore in this work is dynamic throwing. The goal of this task is to throw a mass, in this case a standard 16.5 kg cinder block, as far as possible. Much like the lifting task, there are many athletic analogues, including Olympic Hammer Throw, Discus, Javelin Throw, and Shot putting. All of these sports involve injecting kinetic energy into a heavy object in order to maximize throw distance, and to do so, the athletes twist, spin, run, and extend their bodies to inject energy, manage momentum, and maintain balance. These are the characteristics we plan to apply to our robotic control. We measure the performance in this task by the displacement of the mass when it contacts the ground plane.

2. MECHANICAL DESIGN

2.1 The BigDog platform

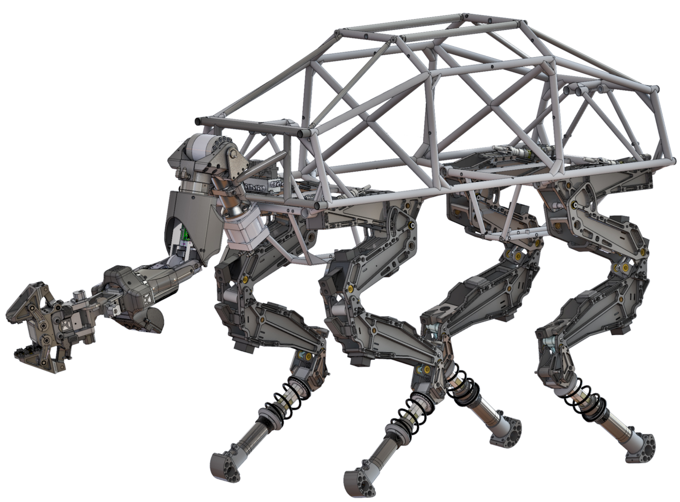


Figure 1. CAD rendering of the BigDog robot (internal components not shown) with an integrated hydraulic manipulator used as the platform for this work.

The base platform for our manipulation efforts in this work is the BigDog robot, a quadrupedal mobile robot capable of carrying up to 250 lb of payload, and highly mobile in outdoor unstructured environments. This robot (shown with manipulator in Figure 1), is an ideal platform for investigating dynamic manipulation due to the high force actuation of its legs (in excess of what is required for simple mobility), relatively large range of motion, and proprioceptive sensors.

2.2 Manipulator design

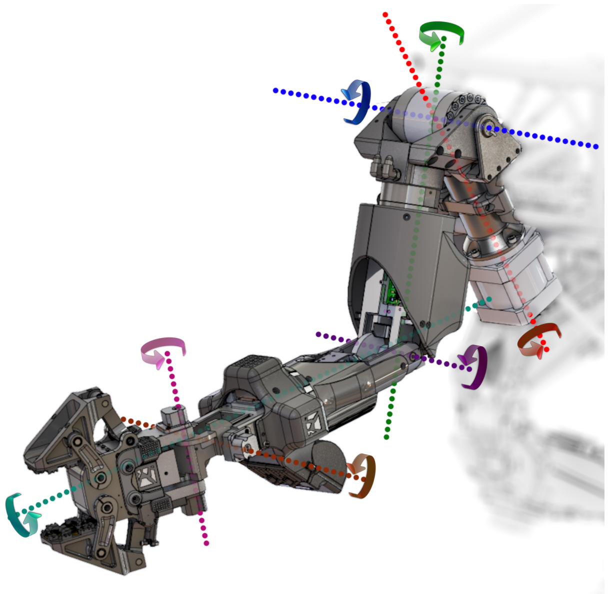


Figure 2. The hydraulic manipulator has seven rotational degrees of freedom (three shoulder, one elbow, three wrist), and a parallel jaw gripper mechanism.

After a comprehensive survey of commercially available manipulators, we opted to design and build a custom manipulator for the BigDog platform. Hydraulic actuation was chosen for its high force density and the availability of hydraulic power from the BigDog's existing power plant. The manipulator was designed with eight degrees of freedom including gripping. This configuration is similar in morphology and scale to a human arm, having a 3-dof shoulder, an elbow, and a 3-dof wrist. The morphology of the manipulator is illustrated in Figure 2. The goal was to enable the robot to appropriately interact with objects in manmade environments, while not providing sufficient strength to manipulate the target object (a 16.5kg cinder block) by static methods, thus requiring the use of whole-body manipulation techniques. The large number of joints also allows for more potential kinematic solutions, which enables the generation of more complex and natural behaviors than a simpler manipulator configuration. The parallel jaw gripping mechanism was designed with enough gripping force (approximately 250 lbf) to hold a cinder block under heavy acceleration to allow for dynamic throwing behaviors.

The manipulator is mounted on the BigDog platform in an orientation which allows for a large workspace below, in front, laterally, and above the robot, but avoids large overlap of the workspace with the body and legs. The manipulator can be assembled in either an 'elbow up' or 'elbow down' configuration, each with its own workspace.

3. BEHAVIOR GENERATION TECHNIQUES

3.1 Simplified Dynamics Model

Our behaviors assume a simplified rigid-body dynamics model of the robot which abstracts the legs to be generalized force sources which act on a finite base of support formed by the convex hull of foot locations. The 6-degree-of-freedom body and the 7-degree-of-freedom arm result in a 13-degree-of-freedom system, shown in Figure 3.

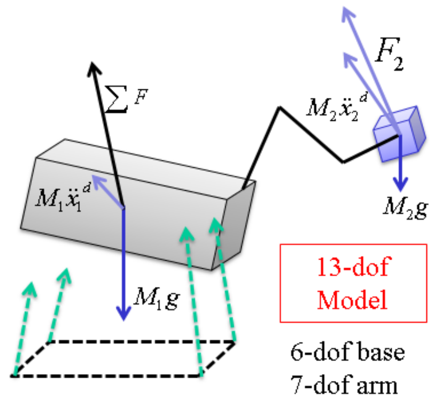


Figure 3: The dynamic behaviors assume a simplified model of the robot.

Given the generalized coordinates, $\vec{q}$, and derivatives, $\dot{\vec{q}}$ and $\ddot{\vec{q}}$, the generalized forces, $\vec{\tau}$, of this fully actuated system can be solved for analytically and take the form,

$$\vec{\tau} = \left(M_1(\vec{q}) + J(\vec{q})^T M_2 J(\vec{q})\right)\ddot{\vec{q}} - C(\vec{q},\dot{\vec{q}}) - G(\vec{q}) - J(\vec{q})^T M_2\left(\vec{g} + \dot{J}(\vec{q},\dot{\vec{q}})\dot{\vec{q}}\right) \qquad (\#)$$

where $M_1(\vec{q})$ and M_2 are the inertia matrices of the robot and the manipulated mass, respectively, $J(\vec{q})$ is the Jacobian relating the velocity of the manipulated mass to the generalized velocities of the robot, $C(\vec{q},\dot{\vec{q}})$ is the centrifugal and Coriolis forces, and $G(\vec{q})$ is the gravitational force.

3.2 Full Body Control

Solving the inverse dynamics above only gives the arm torques and 6-dof generalized wrench on the body. The remaining 16-dof joint torques on the legs are resolved in order to achieve the 6-dof body wrench. This force allocation scheme involves solving for the desired contact forces, $\vec{F}_i^d$, at each point foot and applying a Jacobian-transpose control, $J_i^T \vec{F}_i^d$, where J_i is the Jacobian associated with each foot end effector. Only standing balance behaviors, which do not move the legs, are considered in this paper.

3.3 Dynamic Lifting

Manipulating heavy objects can be a difficult task for a robot, especially if there are constraints such as torque limits and balance requirements. Given the task of lifting an object overhead, a slow or quasi-static motion is likely to fail as soon as a single joint actuator is saturated. However, such constraints can be overcome by taking advantage of dynamics. This section describes an approach to generate dynamic lifting behaviors that increase the lifting capacity of a mobile manipulator.

The core component of this behavior generation technique is a trajectory optimization that takes into account a simplified dynamics model of the robot and manipulated object. Trajectories are optimized directly using a nonlinear function optimization technique [10]. The behavior is then shaped by constructing a cost function that attempts to minimize effort while enforcing constraints on actuator torque and velocity limits, balance requirements and kinematic workspace ranges. The procedure is summarized in Figure 4.

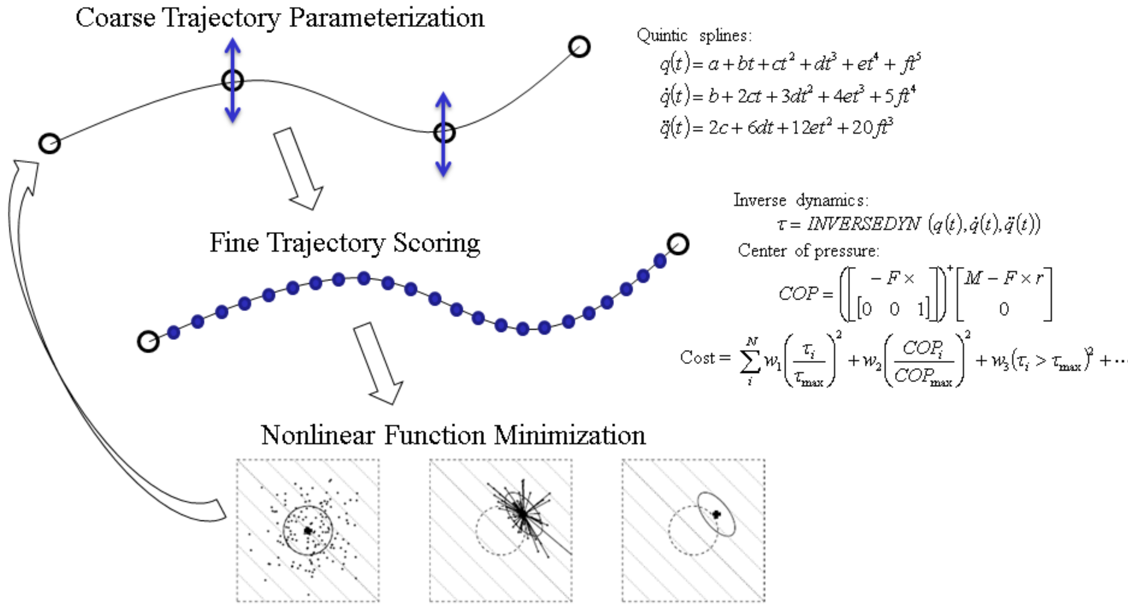


Figure 4. A high-level representation of the trajectory optimization procedure for dynamic lifting. The optimization adjusts the mid-points of a spline with fixed beginning and end points. A cost function is evaluated at evenly-spaced discrete times along the length of this trajectory. The nonlinear function optimization technique uses several samples to approximate an update step that will minimize the total cost.

On execution, the 13-degree-of-freedom optimized trajectory is played back on the robot. The inverse dynamics are computed according to the simplified dynamics model. Often several terms are dropped, including the centrifugal, coriolis, gravitational, and off-diagonal inertia terms. The generalized forces on the body are distributed to the four legs to both track the body trajectory and compensate for the mass of the robot. For very heavy weights, the dynamic lifting behavior switches to a recovery motion much like a "jerk" used in weight lifting which quickly lowers the body momentarily easing the load on the arm so that it may finish the lift motion. An example of one lifting motion is illustrated in Figure 5. In the Figure, snapshots of a simulated lift have been composited to illustrate a dynamic swing-up style lift.

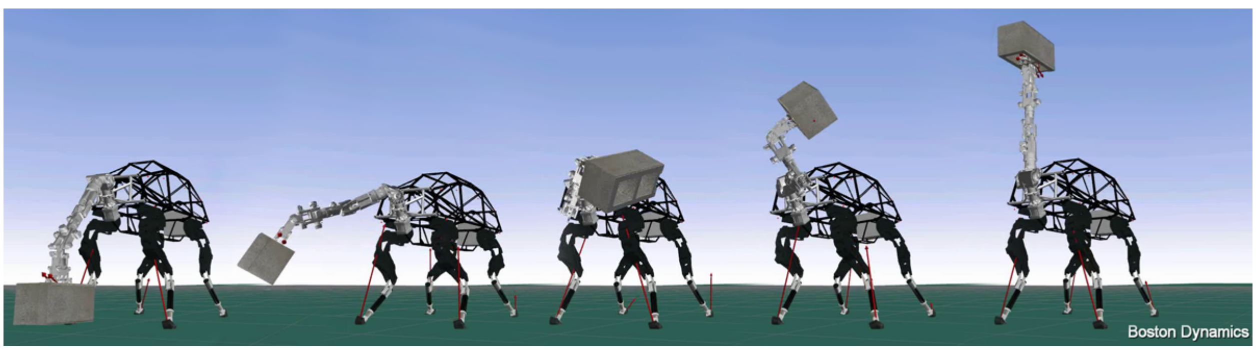


Figure 5. Screenshots from a simulated dynamic swing-up style lift. Foot forces are visible as red arrows.

3.4 Dynamic Throwing

The goal of the dynamic throwing behavior is to toss a 16.5kg cinderblock as far as possible using the manipulator-equipped quadruped. When throwing, it is not sufficient to simply command the manipulator arm to follow a predefined joint trajectory. This is because the heavy weight of the cinder block causes the relatively weak actuators of the arm to saturate. This is especially true of the weaker distal degrees of freedom, but even the stronger shoulder actuators quickly reach their limit when attempting to throw a heavy mass. To maximize throwing distance it becomes necessary to utilize a dynamic, full body motion that imparts force on the cinder block pushing on the legs and pulling along the axis of the arm. The ability to coordinate the motion of the body in this manner is a key advantage of our legged platform. However this coordination is non-trivial since the legs must simultaneously keep the robot (dynamically) balanced during the behavior.

The throwing strategy we implemented was inspired by observation of human attempts to throw a heavy mass. To avoid the use of the weaker joints and to take advantage of body motion, humans keep their arms straight when throwing a large mass. Only the shoulder degrees of freedom are in motion. We use a similar strategy on the robot. Momentum is imparted to the cinder block by swinging it across the body from right to left. At the start of the throw, the x-axis shoulder joint is initialized to its farthest extent on the right. Over the course of the motion, maximum torque is applied to this degree of freedom. The motion of the y-axis shoulder joint is slaved to the motion of the x-axis joint in order to avoid collisions with the legs and the ground. The release of the gripper is triggered when the x-axis joint crosses a specified threshold. After release, the arm motion continues for a brief period of time and the wrist joint is oriented to avoid collision with the free-flying cinder block. Other directions for the swinging motions were considered but ultimately rejected primarily due to workspace limitations of the manipulator.

Swinging the heavy mass of the cinder block generates considerable bias forces on the robot (both gravitational and centrifugal) that are estimated and counteracted using the legs. Additionally, a virtual "shoulder pull force" is applied to the arm, which uses the legs and the body to pull on the cinder block in the direction of the shoulder joint. Finally, a coordinated yaw and roll motion of the body is synchronized with the arm motion. This increases the height of the initial end-effector position and lengthens the arc of the swing, ultimately imparting more energy into the block.

4. EXPERIMENT AND RESULTS

4.1 Dynamic lifting results

To test the dynamic lifting behaviors, two experiments were performed. First, a "baseline" experiment was used to quantify the lifting capacity of the arm using a quasi-static motion. This motion only used the arm joints and was hand-tuned to keep the mass close to the body to minimize joint torques. The second experiment quantified the lifting capacity of the dynamic lifting behavior. During the two experiments, the robot lifted a mock cinder block overhead. A lift was considered successful if the arm was able to hold the block overhead while fully extended. The mass of the block was incrementally increased by attaching metal plates until failure. The results of this experiment are summarized in Table 1.

Table 1 Summary of dynamic lifting results

Lifting Style	"Baseline"	"Dynamic"
Duration (s)	9	3
Uses Body Motion	NO	YES
Uses "Jerk" Motion	NO	YES
Maximum Mass (kg)	**6.8**	**16.4**

The two experiments are qualitatively compared in Figure 6 and Figure 7. Figure 6 compares the relative power between the arm and lower body joints for the two strategies at a variety of lifting weights. The power was determined by multiplying the joint torques by the joint velocities and summing over the collection of joints at each instant in time. The "energy" was calculated by integrating the power starting at the beginning of the lift. For the 6.8kg mass, both motions are successful. At 10.1kg, the baseline is not successful. A successful 16.4kg trial using the dynamic lifting behavior is also shown for comparison. The "jerk" recovery motion is employed for the 16.4kg mass and occurs around 2.3s into the lift. This motion employs negative work in the legs to boost the positive work in the arm and help it lift the heavy mass.

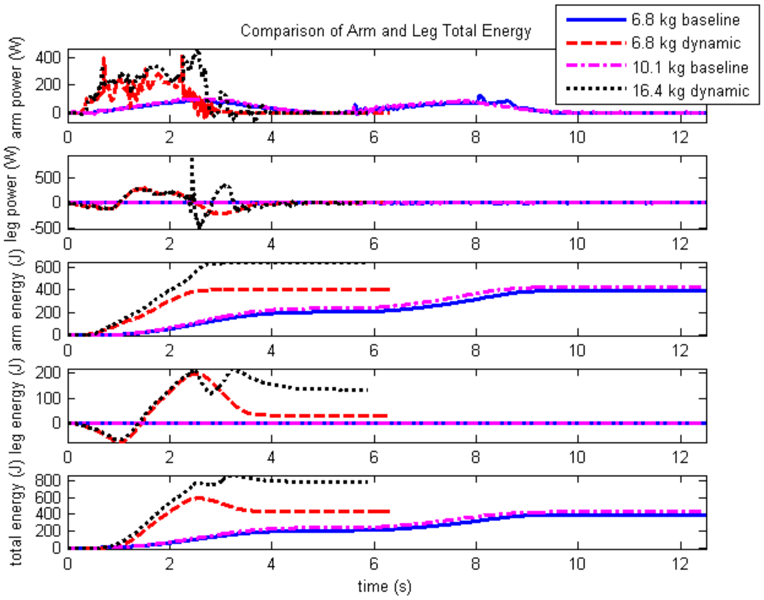


Figure 6 Comparison of relative power and integral of power ("energy") between the legs and arm for various lifting masses. The dynamic lifts inject more energy into the system, making significant use of the legs. Notice also that for the maximum mass (16.4kg), the jerk recovery motion is visible.

Figure 7 compares the joint angle trajectories of the two experiments for the same set of masses. For the 10.1kg mass, the baseline fails because the wrist_ry joint saturates. Likewise, for the 16.4kg mass, the wrist_ry joint also struggles. However, the "jerk" motion is employed to recover and complete the lift.

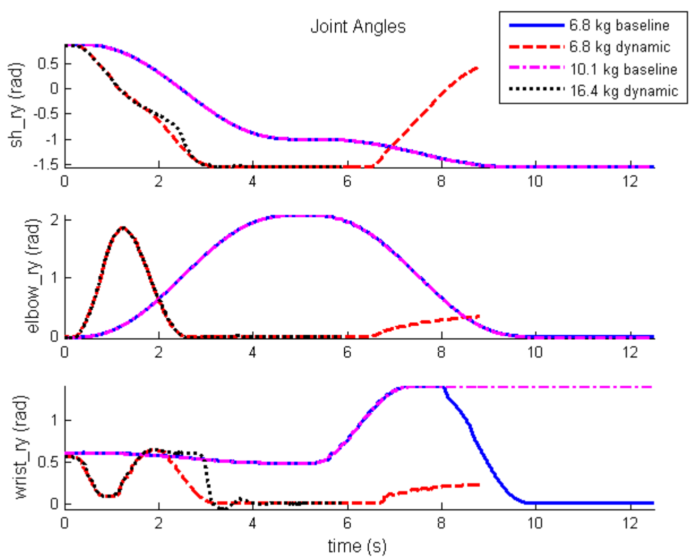
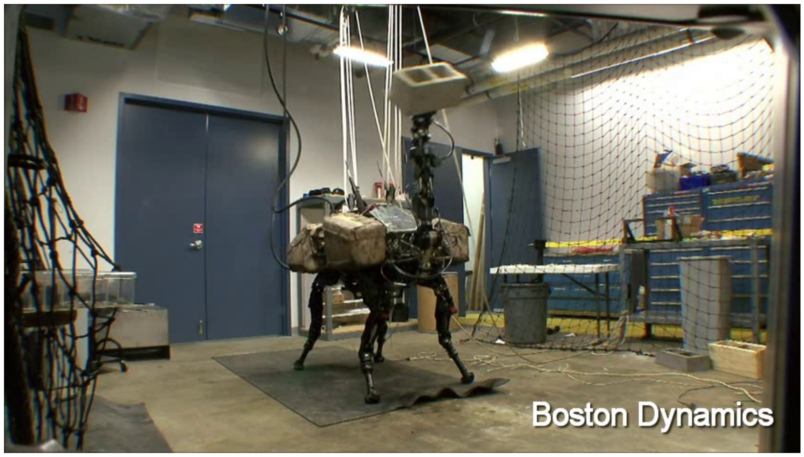


Figure 7. Comparison of joint angles for various lifted masses. Notice that the baseline motion cannot lift the 10.1kg mass due to a saturation in the wrist_ry actuator.

In the video of a successful heavy lift of a 16.5 kg cinder block (Video 1), the motion of the body and contribution of the legs are clearly evident.



Video 1. Video of dynamic lifting of a 16.5 kg cinder block. **http://dx.doi.org/10.1117/12.919939.1**

4.2 Throwing results

In order to evaluate the advantage of using a dynamic body motion for throwing, we compared our throwing behavior to a baseline behavior without body motion. The baseline behavior used the same strategy to control the motion of the arm, but kept the body still by keep the legs stiff. We performed 10 trials for each throwing behavior. Table 2 lists the recorded distance from a common point in front of the robot to a landing location for each trial.

Table 2. This table reports the recorded distance of a thrown cinder block (16.5kg) for 10 trials of both the baseline and dynamic throw behavior. The data suggests that the dynamic throwing behavior is consistently better performing than the baseline behavior, while both behaviors show only small variance in performance.

Trial #	1	2	3	4	5	6	7	8	9	10	Avg.	St. Dev.
Baseline Throw Distance (m)	2.7	2.9	2.9	3.0	2.9	2.6	2.8	3.0	3.0	3.0	**2.9**	**0.1**
Dynamic Throw Distance (m)	4.1	4.1	4.3	4.2	4.1	4.2	4.2	4.2	4.3	4.3	**4.2**	**0.1**

The graph in Figure 8 depicts the estimated distance of the throw using the velocity of the end-effector from the best trial of each behavior. The results clearly show that the dynamic body motion contributes to throwing potential. In this figure, the data after the release are not valid, as the estimation assumes the mass of the block is moving at the velocity of the end effector which is no longer a valid assumption.

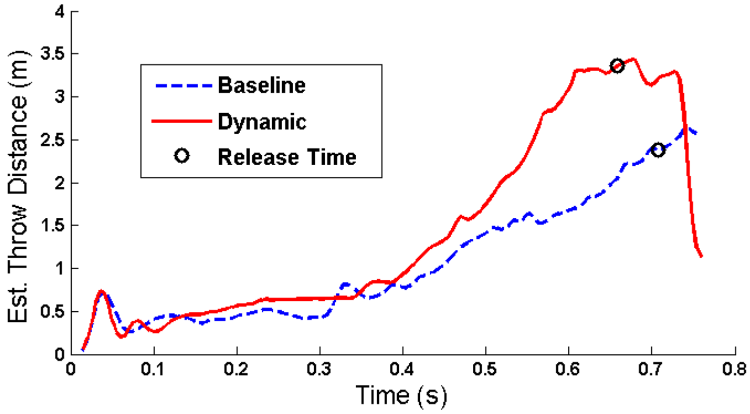
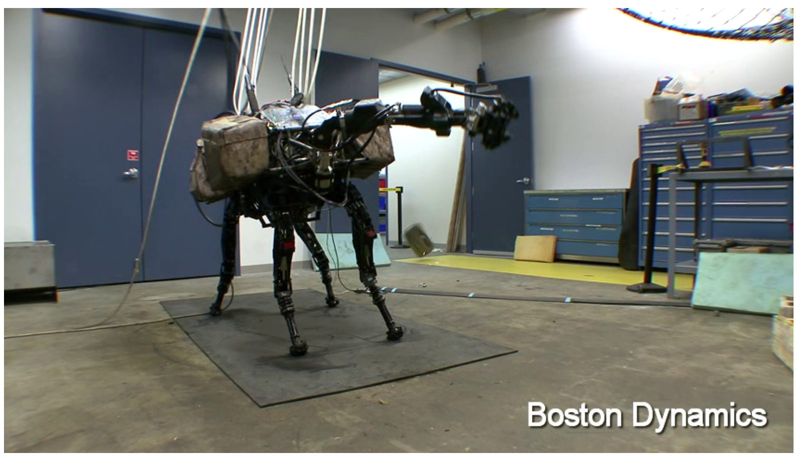


Figure 8. This graph plots the predicted horizontal landing position of a body in free-flight starting from the reconstructed position and velocity of the end-effector at each moment during the throwing behavior. The data is shown for the best instance of each trial for both the baseline (blue-dotted line) and dynamic (red-solid line) behavior. The black circled point is the actual release time.

The video in Video 2 shows the baseline throwing behavior, followed by the dynamic whole-body throwing behavior. Along with the increased throw distance, the body motion is more evident in the dynamic throw.



Video 2. Video of dynamic throwing of a 16.5 kg mock cinder block. **http://dx.doi.org/10.1117/12.919939.2**

5. CONCLUSIONS

We have implemented both trajectory optimized behavior generation and model-based policies to incorporate whole-body motion into robotic behavior development. We demonstrated these behaviors in lifting and throwing tasks on robotic hardware. The preliminary results from our assessments indicate that whole body motions can significantly increase the performance of a mobile manipulation robot, increasing the lifting capacity by a factor of 2.4x, and the throw distance of a massive object by 1.45x compared to manipulator-only strategies. Using whole body motion for dynamic manipulation should allow greater payload capacity and enable new capabilities for mobile robots, or allow for manipulation hardware to be miniaturized and made more cost effective while still matching the performance of existing systems that use traditional manipulation techniques.

We plan to continue to extend these results by starting to use coordinated locomotion along with dynamic manipulation. For example, stepping into a throw, or allowing the robot to take recovery steps after release may allow the system to throw heavy objects significantly further. Significant challenges also remain in generalizing the behavior generation techniques such that a robot system can plan manipulation behaviors online in the field.

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