BigDog, the Rough-Terrain Quaduped Robot

Marc Raibert, Kevin Blankespoor, Gabriel Nelson, Rob Playter
and the BigDog Team

Boston Dynamics, Waltham, MA 02451
USA (Tel: 617-868-5600; e-mail: mxr@BostonDynamics.com).

Abstract: Less than half the Earth's landmass is accessible to existing wheeled and tracked vehicles. But people and animals using their legs can go almost anywhere. Our mission at Boston Dynamics is to develop a new breed of rough-terrain robots that capture the mobility, autonomy and speed of living creatures. Such robots will travel in outdoor terrain that is too steep, rutted, rocky, wet, muddy, and snowy for conventional vehicles. They will travel in cities and in our homes, doing chores and providing care, where steps, stairways and household clutter limit the utility of wheeled vehicles. Robots meeting these goals will have terrain sensors, sophisticated computing and power systems, advanced actuators and dynamic controls. We will give a status report on BigDog, an example of such rough-terrain robots.

1. INTRODUCTION

Less than half the Earth's landmass is accessible to wheeled and tracked vehicles, yet people and animals can go almost anywhere on Earth. This situation motivates the development of robot vehicles that use legs for their locomotion, thereby embracing nature's mobility solution. The goal is to achieve animal-like mobility on rough and rugged terrain, terrain too difficult for any existing vehicle.

2. BACKGROUND

Over the past 40 years, a variety of engineers and scientists have embraced the opportunity of legged locomotion, building a diverse set of ingenious and inspiring legged robots. For example, see Berns, (2006), Kar (2003) and for many examples.

The present authors got started in this area 25 years ago, focusing on legged robots that moved dynamically Raibert (1986). They developed a series of laboratory robots in the 1980's and 1990's that moved dynamically and balance as they went. These robots included one-, two-, and four-legged systems that hopped, ran with trotting, pacing and bounding gaits, climbed simple stairways, jumped over obstacles, set a world land speed record for legged robots 6 m/s (13 mph), and performed simple gymnastic manoeuvers. See Raibert (1986) for more details and Figure 1.

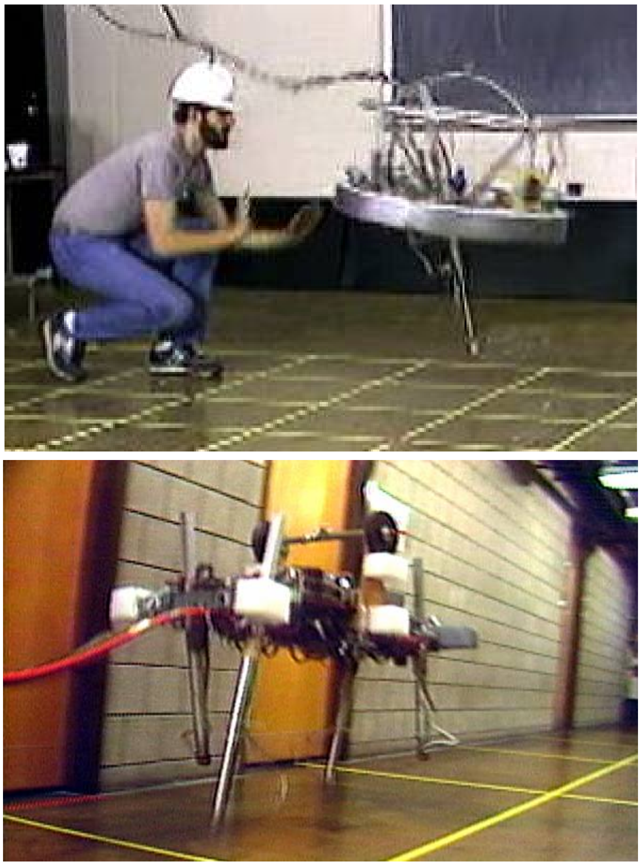

Figure 1. Legged robots developed to study dynamic control and balance. Top: One-legged hopping robot hops in place while responding to a push disturbance delivered by researcher. Bottom: Quadruped robot trots down hallway at about 1.4 m/s (3 mph). Both robotswere powered through hoses by a remote hydraulic pump. These robots were developed in the CMU Leg Laboratory 1981-1986 and the MIT LegLab 1987-1995. To see video of these robots in action, click here: www.BostonDynamics.com/dist/LegLab.wmv

We found that we could control all of these robots with a relatively simple control approach that broke the behavior down into three primary activities: supporting the body with a vertical bouncing motion, controlling the attitude of the body by servoing the body through hip torques during each leg's stance phase, and by placing the feet in key locations on each step using symmetry principles to keep the robots balanced as they moved about. Although the details of the control varied from machine to machine, they all shared these three essential ingredients.

Whereas the Leg Laboratory robots did a good job of demonstrated the feasibility of dynamically balanced legged systems, they had two primary limitations that would need to be addressed to build practical legged vehicles. One is the need for on-board power so the robot could operate in the field without hoses and wires. Another is the need for control algorithms that provide locomotion and stability on rough terrain. We now turn to BigDog, a self-contained quadruped robot that uses many of the ideas and concepts of the Leg Laboratory robots, but also addresses the practical problems of onboard power and rough-terrain controls in order to move toward practical legged vehicles.

Figure 2. BigDog climbing a snow-covered hill during testing. To see BigDog in action, click this link: www.BostonDynamics.com/dist/BigDog.wmv.

3. BigDog

BigDog is a legged robot under development at Boston Dynamics, with funding from DARPA. The goal is to build unmanned legged vehicles with rough-terrain mobility superior to existing wheeled and tracked vehicles. The ideal system would travel anywhere a person or animal could go using their legs, run for many hours at a time, and carry its own fuel and payload. It would be smart enough to negotiate terrain with a minimum of human guidance and intervention. The BigDog robots we have built have taken steps toward these goals, though there remains a great deal of work to be done.

BigDog has onboard systems that provide power, actuation, sensing, controls and communications. The power supply is a water-cooled two-stroke internal combustion engine that delivers about 15 hp. The engine drives a hydraulic pump which delivers high-pressure hydraulic oil through a system of filters, manifolds, accumulators and other plumbing to the robot's leg actuators. The actuators are low-friction hydraulic cylinders regulated by two-stage aerospace-quality servovalves. Each actuator has sensors for joint position and force. Each leg has 4 hydraulic actuators that power the joints, as well as a 5th passive degree of freedom. See Figure 3. A heat-exchanger mounted on BigDog's body cools the hydraulic oil and a radiator cools the engine for sustained operation.

An onboard computer controls BigDog's behavior, manages the sensors, and handles communications with a remote human operator. The control computer also records large amounts of engineering data for performance analysis, failure analysis and operational support.

BigDog has about 50 sensors. Inertial sensors measure the attitude and acceleration of the body, while joint sensors measure motion and force of the actuators working at the joints. The onboard computer integrates information from these sensors to provide estimates of how BigDog is moving in space. Other sensors monitor BigDog's homeostasis: hydraulic pressure, flow and temperature, engine speed and temperature, and the like.

The onboard computer performs both low-level and high-level control functions. The low-level control system servos positions and forces at the joints. The high-level control system coordinates behavior of the legs to regulate the velocity, attitude and altitude of the body during locomotion. The control system also regulates ground interaction forces to maintain support, propulsion and traction.

BigDog has a variety of locomotion behaviors. It can stand up, squat down, walk with a crawling gait that lifts just one leg at a time, walk with a trotting gait that lifts diagonal legs in pairs, trot with a running gait that includes a flight phase, and bound in a special gallop gait. Travel speed for the crawl is about 0.2 m/s, for the trot is about 1.6 m/s (3.5 mph), for the running trot is about 2 m/s (4.4 mph) and BigDog briefly exceeded 3.1 m/s (7 mph) while bounding in the laboratory.

BigDog weighs about 109 kg (240 lbs), is about 1 meter tall, 1.1 meters long, and 0.3 m wide.

BigDog is usually driven by a human operator who works through an operator control unit (OCU) that communicates with the robot via IP radios. The operator uses the OCU to provide high-level steering and speed input to guide the robot along its path and to control the speed of travel. The operator can also tell the robot to start or stop its engine, stand up, squat down, walk, trot, or jog. A visual display provides the operator operational and engineering data. The operator only provides high-level input, leaving BigDog's onboard control system to operate the legs, provide stability on rough terrain, and reflex responses to external disturbances.

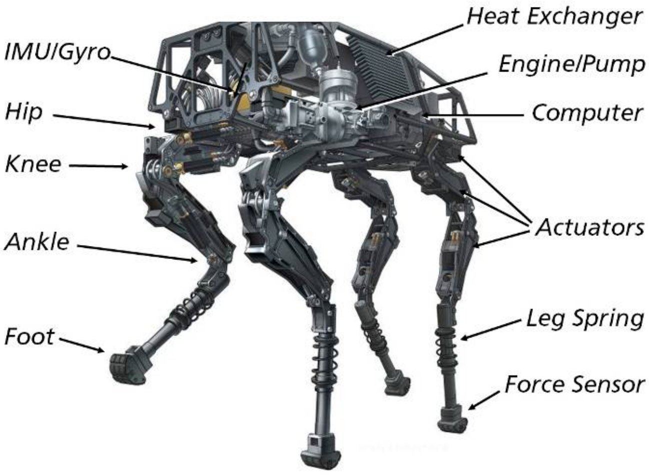

Figure 3. Illustration showing BigDog's major components.

We have tested BigDog travelling in mud and snow and on inclines with a variety of surfaces, including rutted trials, rocky, and loose scree. BigDog has also jumped about 1.1 meters. and carried various loads. On flat terrain BigDog has carried 340 lbs (154 kg), although loads of 50 kg are more typical. We are working on a redesign of BigDog to climb with larger loads.

BigDog's longest continuous operation was a 10 km hike (6.2 miles) that lasted 2.5 hours. We are continually developing BigDog's reliability, with an initial goal of 20 hours mean time to failure.

Figure 4. Top: BigDog climbing 35 degree slope with loose scree-like surface. The front legs were reversed for this experiment. Bottom:.BigDog climbing a simulated rubble pile using a crawl gait in the laboratory. For this experiment, all terrain sensing is done with the legs, feeling its way along.

We have integrated a stereo vision system and a LIDAR onto BigDog. The stereo vision system was developed by the Jet Propulsion Laboratory. It consists of a pair of stereo cameras, a computer and vision software. The stereo system can be used to acquire the shape of the 3D terrain just in front of the robot, and also to find a clear path forward. The LIDAR is being used to allow BigDog to follow a human leader, without requiring the operator to drive continuously.

4. CONTROL

To move at human-walking speeds, BigDog walks with a dynamically balanced trot gait. It balances using an estimate its lateral velocity and acceleration, determined from the sensed behavior the legs during stance combined with the inertial sensors.

BigDog's control system coordinates the kinematics and ground reaction forces of the robot while responding to basic postural commands. The control distributes load amongst the legs to optimize their load carrying ability. The vertical loading across the limbs is kept as equal as possible while individual legs are encouraged to generate ground reactions directed toward the hips, thus lowering required joint torques and actuator efforts.

Basic walking control uses the control system diagrammed below. A gait coordination algorithm, responsible for inter-leg communication, initiates leg state transitions to produce a stable gait. A virtual leg model coordinates the legs.

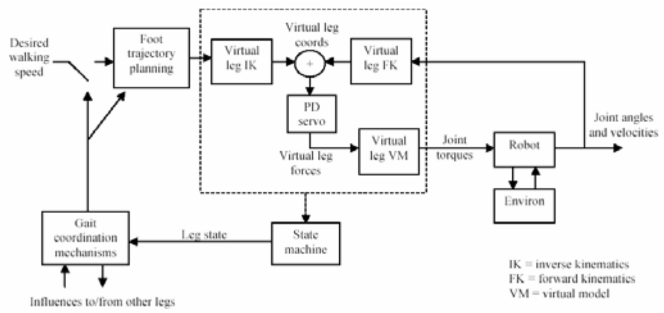

Figure 5: Control Diagram

We developed quadrupedal walking algorithms for inclined and rough terrain and tested it in physics-based simulation before testing on the physical robot. See Figure 6. The simulated robot walks on inclines and declines with rocky slopes up to 60 degrees. It makes transitions from walking on the level to walking on the incline or decline, and it accommodates unexpected changes in terrain height caused by irregularities in the terrain, such as are caused by rocks.

The control system adapts to terrain changes through terrain sensing and posture control. The control system uses joint sensor information to determine when feet are in contact with the ground and to determine the desired load on each leg and actuator. A posture algorithm controls body position by coordinating the kinematics of the legs with the reaction forces of legs in contact with the ground. The posture algorithm implements computed leg compliance on uneven terrain. This approach allows control of body roll, pitch, and height relative to the ground, thereby allowing BigDog to adapt to local terrain variations without higher-level terrain sensing.

BigDog adapts to the terrain in two ways. It adjusts body height and attitude to conform to the local terrain, and it adjusts footfall placement to compensate for orientation of the robot body and ground plane relative to gravity. The control system leans the quadruped forward while climbing slopes, leans the body backwards while descending slopes, and leans it sideways while walking along the contour line. The control system accommodates shallow to moderate inclines by making slight adjustments to body posture, while it accommodates inclines steeper than 45 degrees by also adjusting the walking gait pattern and using smaller steps. Many of these simulated results have been replicated on the physical BigDog robot, except for very steep climbs where traction in the physical world limits performance

Figure 6: Image from physics-based simulation used to develop walking algorithms.

5. FUTURE PLANS

That is a snapshot of where BigDog stands today. While we are happy with the progress BigDog has made so far, much higher performance is possible and many practical problems remain to be solved. Our immediate goals are to focus on four areas:

Rougher Terrain: Although BigDog is doing well on rough terrain, it should be possible to traverse rougher and steeper terrain with more load. It will require a mechanical design that is stronger and has larger ranges of limb motion. Advanced terrain sensing and locomotion planning will also be needed to enable travel on rougher terrain.

Self Righting: BigDog has a significant ability to keep its balance when travelling on rough and irregular terrain, and when disturbed by outside forces. But we expect BigDog to fall over in the field, and it will need the ability to right itself. We plan to add this ability to the next version of BigDog.

Quieter Operation: BigDog is a noisy robot, sounding like a motorcycle. There are several steps we plan to take to quiet BigDog: build a custom muffler, switch to four-stroke engine, enclose the engine and hydraulic pump, and possibly introduce optional hybrid power.

More Autonomy: BigDog currently relies on a human operator to guide it through the terrain. But future versions will use computer vision, LIDAR and GPS to provide more autonomy. See Figure 7. We have already done limited experiments in which BigDog uses LIDAR to follow a human leader in open terrain and another in which BigDog travels to a sequence of pre-defined GPS locations, without human intervention.

Figure 7. Concept for autonomous cross-country operation guided by computer vision and/or LIDAR, without human intervention. BigDog's rough-terrain control and reflexes will combine with terrain sensing to provide a high level of autonomy.

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