Robots that Walk: What the Challenge of Locomotion says about Next-generation Manufacturing

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Why study walking and running robots, and bipedal robots in particular? We want robots to go wherever people can, but perhaps isn't safe. This includes malfunctioning nuclear power plants, or the staircases and corridors of burning buildings – places designed to be navigated by bipedal humans. In addition to these disaster-response and exploration applications, the study of bipedal robotics also informs the design and control of assistive devices. Robotic prosthetic legs and exoskeletons hold the potential to enable walking and running for patients who have lost the ability to do so, or perhaps even enable superhuman performance (e.g. carrying immensely heavy loads).

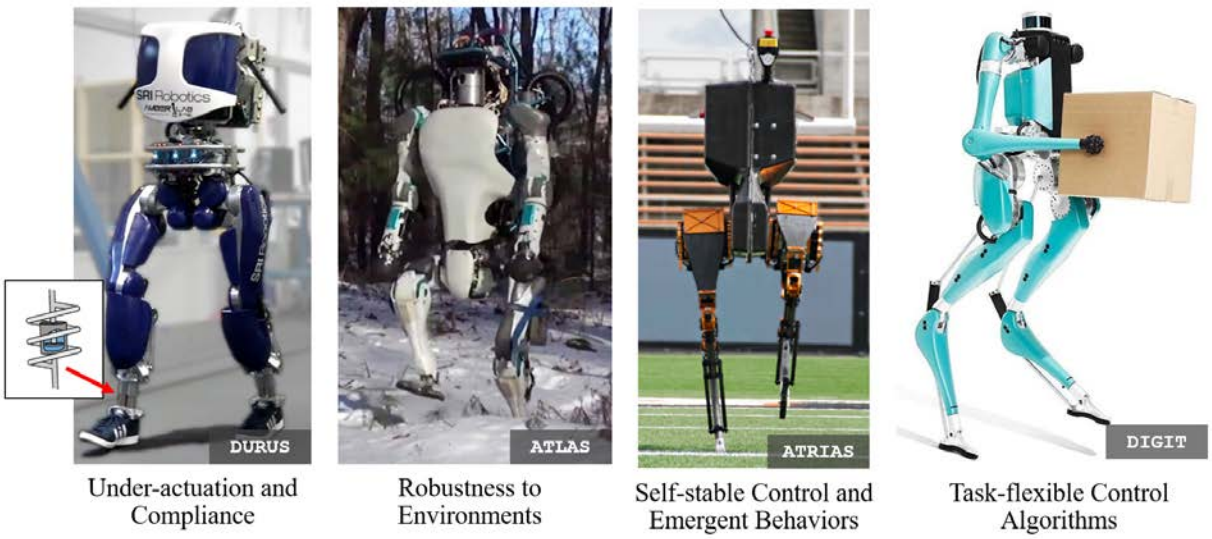

Figure 1. Examples of bipedal robots embodying modern trends in the field which have promising applicability to modern manufacturing. From left to right: the DURUS humanoid from SRI International [XXX] is an example of built-in flexbility (or compliance). The ATLAS humanoid from Boston Dynamics [XXX] demonstrates remarkable robustness to challenging terrain. The ATRIAS bipeds [XXX] demonstrate that stable dynamic behaviors (like running) can emerge that are not explicitly pre-programmed. The DIGIT robot from Agility Robotics [XXX] is capable of a variety of dynamic maneuvers, including expeditiously carrying packages.

More broadly, however, the challenge of engineering bipedal robots yields general lessons across the autonomy-related fields: including manufacturing. While manufacturing has excelled in extreme repeatability of its process in controlled environments (famously measuring quality in "sigmas"), legged robotics is forced to grapple with the uncontrolled outside world. If manufacturing is to push its capabilities or venture into increasingly remote and uncontrolled locations, it may be beneficial to learn some of the lessons from the field of legged robotics.

This essay summarizes four key lessons that were essential to recent advances in walking and running robots and how they can be applied to manufacturing. While bipedal roboticists have designed robots with **underactuation and compliance** for improved agility and efficiency, automated manufacturing facilities can similarly lower capital and energy costs. Additionally, walking and running controllers are designed being designed for **robustness to unknown terrain**, manufacturing can use similar robust control to operate on parts of unknown shape and softness. Locomoting robots that rely on **self-stable and emergent control behaviors** provide an example for lessened reliance on heavy computation and how to find surprising effective behaviors not thought-of by their control engineers. Finally, the need to change locomotion behaviors on-the-fly to change speeds or tasks has driven the development of **task-flexible control algorithms** that can make robots more versatile (e.g. tasks like carrying packages (Figure 1d)).

Underactuation and Compliance

Legged robots have made enormous strides in terms of agility and stability (with Boston Dynamics' ATLAS doing backflips), but energy economy is a long-standing challenge in legged robotics. Humanoid robots typically require an order of magnitude more energy to walk than an equivalently sized person. This drastically limits the range that robots can travel on a limited energy supply, pushing legged roboticists to find ways to do more with less energy. One such efficiency-driven approach involves building bipedal robots with fewer motors, or so-called underactuation. Having fewer motors forces the controller to do the same task while using less power. Additionally, underactuation can reduce the robot weight and robot stiffness induced by highly geared drive transmissions. These combined factors often lead to increased efficiency. A simple underactuated walker called the Cornell Ranger was able to walk 40 miles on a single battery charge.

Another approach to increased efficiency comes in the form of compliance, or elasticity in the robot. Robots traditionally are built with highly rigid bodies, which is in part to make control algorithms simpler. Humans, however, have elastic tendons in their legs which can store and return energy that would otherwise be lost to heat while walking. Following this example, robots like DURUS (Figure 1a) have spring-legged feet which helped reduce the energy cost of locomotion by 70% over previous humanoid robots. For the field of manufacturing, assembly-line manipulators may save on energy cost by intentionally omitting actuators and including flexible linkages.

Robustness to Unknown Terrain

The terrain of the outside world is messy. Not only can it be uneven or rocky, it can also be soft like soil, sand or snow. This means that vision alone cannot always tell you all the necessary properties of oncoming terrain to inform control a priori. This reality of real-world environments obviates the need for robots that are robust to unknown terrain. Figure 1b shows the ATLAS humanoid from Boston Dynamics walking over a snow bank, an effective example of this terrain robustness.

This need for terrain robustness led researchers to develop *force control* techniques for locomotion. For instance, if you control a robot leg to produce a specified *force*, it has a vastly different behavior in response to disturbances than if you tried to control its *position*. If a force-controlled leg were to step in a soft patch of earth, the force controller automatically pushes the leg harder into the ground in order to hold up its weight, instead over stumbling over from the unexpected terrain. This allows legged robots to travel on all kinds of terrain without falling, including the Cassie biped and the MIT Cheetah which can walk up slopes and stairs that they can't even see. In the context of manufacturing instead of locomotion, force control is a useful mode for sensitive manipulation using robotic arms. A force-controlled end effector can grip and move an object of unknown geometry or softness, thereby decreasing the sensitivity to unknowns in manufacturing.

Self-stable and Emergent Control Behaviors

Roboticists have given a lot of thought to one of the key questions about effective control: "what quantities do you control, exactly?" Do you control the position of a robot's legs, the orientation of its torso, the forces at its feet, etc.? All of these options have been useful in different corners of the field of legged robotics. The right choice of control target can lead to self-stable and emergent behaviors that are far more capable than you even predicted. The bipedal robot ATRIAS (figure 1c) was programmed with a self-stabilizing walking controller that would systematically cycle its feet and control its forward speed. For one, this controller was self-stabilizing, in that it did not need elaborate computation to maintain balance. Further, when commanded to speed up using this relatively simple controller, the robot did something unexpected – it started running - going airborne without being explicitly commanded to do so. Imagine how this emergent behavior might manifest in an automated factory. In a task where one robotic arm must transfer a part to another robotic arm, if commanded to transfer faster, might simply toss the part to each other. With emergent control behavior, a factory can be inherently more clever and effective than initially imagined by its engineers.

Task-flexible Control Algorithms

Not only has the locomotive robotics field pushed for more stable, faster, and more-efficient locomotion, but also a need for a variety of walking and running behaviors. How do you jump over an obstacle, run around a corner, or walk with a fragile object? Pre-programming each task with its own human-derived controller quickly becomes impractical. Consequently, achieving a “task-flexible” control framework has become a critical push for practical viability.

The push for task flexibility has led to a proliferation of real-time optimization methods to generate stable controllers on-the-fly for the suited task. Model-Predictive Control (MPC) was developed or this aim, where easy-to-compute optimizations are solved extremely quickly, and the solutions to which form a plan for the controller to complete its task in a specified timeframe. The key benefit of MPC is the ability to thoughtfully react to disturbances, which are myriad when out in the field. If you run into an obstacle or your goal suddenly changes, you simply re-plan using your fast optimization.

This task-flexibility made MPC and similar optimization-based methods popular approaches for the vaunted DARPA Robotics Challenge. Teams at this challenge were tasked build a robot that would respond to a simulated industrial disaster. They needed to control a robot to drive a car to the site, exit the vehicle, open a door, walk over rubble, climb a staircase, shut off a valve, and drill a hole in a wall – all with minimal human supervision on site. They succeeded in formulating optimizations that could handle the complexity of robots with dozens of degrees-of-freedom, and yet were solved hundred of times per second. The emergence of these planning algorithms enabled the next generation of versatile legged robots, including prototypes for package delivery with Agility Robotics’ Digit robot (Figure 1d). Future manufacturing may need such real-time task flexibility as well. If a robot performing one specialized task malfunctions, another robot that was not designed explicitly for the role could then be adapted to replace it.

Conclusions

Legged robots have had to make a number of advances in order move out in the real-world. Many of these approaches have straightforward extensions to the needs of improved manufacturing. At the same time, legged robots would be lucky to have the reliability of our manufacturing processes. So, clearly, there are lessons that legs can take from our factory robots too. Hopefully, we can all look forward to a future where our assembly lines are as robust and adaptable as human walking, and on the converse, the reliability of our walking robots is measured in “sigmas” like our manufactured products.