Perception, motor learning, and speed adaptation exploiting body dynamics: case studies in a quadruped robot

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Abstract: Animals and humans are constantly faced with a highly dimensional stream of incoming sensory information. At the same time, they have to command their highly complex and multidimensional bodies. Yet, they seamlessly cope with this situation and successfully perform various tasks. For autonomous robots, this poses a challenge: robots performing in the real world are often faced with the curse of dimensionality. In other words, the size of the sensory as well as motor spaces becomes too large for the robot to efficiently cope with them in real time. In this paper, we demonstrate how the curse of dimensionality can be tamed by exploiting the robot's morphology and interaction with the environment, or the robot's embodiment (see e.g., [1]). We present three case studies with underactuated quadrupedal robots. In the first case study, we look at terrain detection. While running on different surfaces, the robot generates structured multimodal sensory information that can be used to detect different terrain types. In the second case study, we shift our attention to the motor space: the robot is learning different gaits. The online learning procedure capitalizes on the fact that the robot is underactuated and on a "soft" control policy. In the third case study, we move one level higher and demonstrate how - given an appropriate gait - a speed adaptation task can be greatly simplified and learned online.

Keywords: legged robot, terrain detection, locomotion learning, speed adaptation, body dynamics

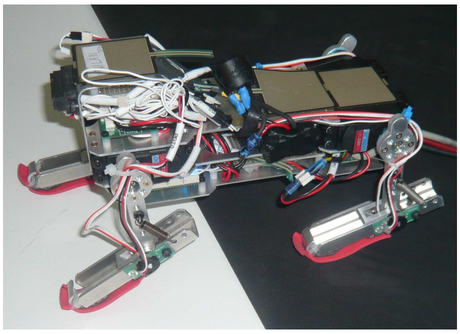

Fig. 1 **Quadruped robot used in case studies 1, 2.** A total of 12 sensors from 4 modalities (4 pressure sensors on feet, 4 angular sensors in passive knee joints, 3 acceleration sensors, and 1 infrared sensor) were used.

1. EXPERIMENTAL SETUP

We have used two underactuated quadrupedal robots in our case studies. They had four identical legs driven by position-controlled servomotors in the hips. The 'knees' were passive and had springs attached. The mechanical design (the weight distribution, proportions, springs used etc.) is a result of our previous research [2]. The robot used in the first two case studies can be seen in Fig. 1.

2. CASE STUDY 1: TERRAIN DETECTION

The first case study dealt with perception, in particular terrain classification. In mobile wheeled robots, this problem is typically solved through fusion of several several distal, i.e. non-contact, sensors (e.g., cameras, laser range finders), followed by supervised classification into traversable vs. non-traversable terrain. Sensing using non-contact sensors has the obvious advantage that information is available ahead of time. On the other hand, such sensors deliver information relevant for traversability in a very indirect manner. Therefore, we have decided to follow an alternative strategy: we want to profit from a full-fledged interaction of the robot with the ground. Following the approach of Lungarella and Sporns [3], who studied how active generation of multimodal sensory stimulation delivers structured sensory information, we have employed information-theoretic methods (mutual information and transfer entropy) that explicitly compare not only sensory but sensory-motor information structure generated by the robot running on different grounds.

3. CASE STUDY 2: LEARNING GAITS

In case study two, we have shifted our attention to the problem of motor learning. The state of the art in robotics can be characterized by two different streams. The first, "traditional", stream employs control laws that prescribe trajectories to the robot's body and the legs and then enforce them using stiff, high-power, actuation. A model of the robot's forward and inverse kinematics and/or dynamics is required. The robot is then capable of precisely executing arbitrary trajectories, picking specific footholds for instance. A good example is the Little Dog [4]. The second "stream" draws inspiration from biology, following the observation by Marc Raibert that the brain does not control the body, but makes suggestions only. The goal is not to override the complex dynamics of the body in the environment but rather exploit it and channel it in particular directions. This strategy results in simplification of central control and greater energy efficiency. Pfeifer et al. [1] provide an overview. We have also conducted studies in a similar vein [2] that gave rise to the quadruped platforms used in this study. Nevertheless, the robots coming out of these studies still lack the versatility of the robots that follow the "strong control" paradigm - they are often restricted to a single gait (an extreme example being the passive dynamic walkers).

In this case study we have conducted preliminary experiments in online learning of different gaits in our underactuated quadruped platform. We use online optimization (simulated annealing - SA) to acquire signals for four active joints of the robot. By taking advantage of the symmetries of the body, we managed to reduce the dimension of the parameter space to mere 7 parameters - to our knowledge, this is extremely low - for instance, Chernova and Veloso [5] faced 54 dimensions in the AIBO robot. We have successfully learned gaits for different speeds and also some turning gaits. Typically, tens of iterations of the SA algorithm (with 30 seconds per iteration, for instance) were required to learn a gait. Videos of the gaits will be shown at the conference.

This case study demonstrates that learning is possible in real time. This follows from the underactuated nature of the robot and the "soft" control policy. It is not only the number of actuated degrees of freedom that is responsible for the shrinking dimensionality; it is also the control "philosophy". Whereas in the AIBO or Little Dog the trajectory of the legs as well as the body is parametrized, in our case, we prescribe signals to the actuators only - everything else (e.g. COM trajectory) is emergent from the interplay of the actuators, the body, and the environment.

4. CASE STUDY 3: SPEED ADAPTATION

In our third case study, we closed the perception-action loop and studied a feedback control scenario. The robot equipped with an ultrasonic distance sensor should keep a fixed distance from the treadmill end and respond to changes of speed of the running belt and to changes of the target distance. The difficulty of the task largely depends on the complexity of speed modulation in the robot. We have developed a bounding gait in which the speed can easily be controlled with a single paramater - frequency of all legs. Moreover, the relationship between the frequency and the resulting speed of the robot was linear and the gait covered a big range of speeds, from 4 to 28 cm/s (or 0.25 to 1.7 of robot's length). The task could then be accomplished with a simple proportional-derivative (PD) control of a single parameter: frequency. The controller was tuned by an online parameter search for the P and D gains using the simulated annealing algorithm. A sample of the performance is depicted in Fig. 2.

We have shown how the speed adaptation task in a legged robot can be simplified to the maximum and hence learned online. Let us analyze the components that are responsible for this behavior. First, the characteristics of

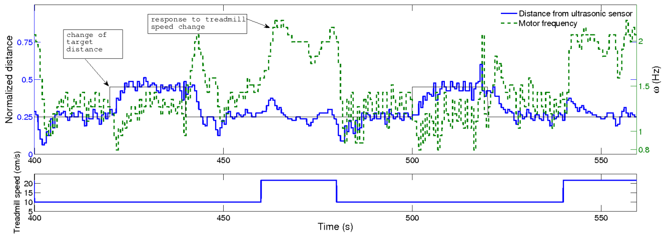

Fig. 2 **Speed adaptation performance.** The top graph shows the target (target distance - black line) tracking performance by the robot (actual distance measured by sensor in blue; distance had a range 10-90 cm and was normalized). When the target moves, the robot needs to respond with an appropriate change in frequency (green dotted line). The same applies when the treadmill speed (bottom graph) changes.

the gait - linear relationship of frequency to speed plays a key part. Second, the optimization algorithm has come up with a high gain controller, which allows for quicker responses and better tracking performance. However, it also results in oscillations of the control parameter (cf. Fig. 2, top). Interestingly, the system could absorb the large perturbations. We hypothesize that this was possible due to mechanical self-stabilization of our system [2]. Third, the fact that a new control parameter can be introduced at any time further simplifies the situation and allows for quicker responses.

5. ACKNOWLEDGMENTS

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