IOP Conf. Series: Materials Science and Engineering 1261 (2022) 012017 doi:10.1088/1757-899X/1261/1/012017

Benefits and Challenges of Morphological Adaptation in Real-world Robots

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Abstract. For many years, the main target of robotics research has been how to improve control and behavior to allow robots to solve more challenging tasks. Recently, the concept of embodied intelligence has shifted this focus from pure control to a more holistic approach. The mind, body, environment, and the interactions between all these are all highly important for the performance of a robot system. This has previously been investigated in virtual robots in simulation or very simple physical robots in the lab, but the benefits for more advanced and capable real-world robots are still to be determined. We present a case study with several examples of real-world adaptation of morphology, and discuss the benefits and challenges as this direction becomes more important in the field of robotics. Taking an embodied approach promises more adaptive and robust robots, but there are many challenges that need to be addressed before wide-spread adoption in the robotics community.

1. Introduction

Robotics and computer science research has long focused on the brain of a robot, its controller, when it comes to optimization and adaptability. In recent years, however, a somewhat broader and more holistic approach has gained traction, taking inspiration from psychology. The concept of *embodied cognition* states that the brain of an organism is not its sole source of cognition, but that rather the brain, body, the environment it inhibits, and the interaction between these all serve as sources of cognition and problem solving [1]. The body of a robot has mostly been viewed as a design choice an engineer had to choose before building it, but as embodied cognition states, it can also be modified actively by the robot itself for better problem solving during operation.

There are many examples of experiments on morphology adaptation using virtual robots, allowing exploration of a large variety of designs using a physics simulator. The challenge with using virtual robots is that they might act very differently when tested in the real world. The difference in performance and behavior between simplified simulations and the physical world is referred to as the *reality gap*, (or more recently, sim-to-real gap in the reinforcement learning domain), and is considered one of the main challenges of robotics today [2, 3, 4]. There are many approaches to reducing this reality gap, but they have only had moderate success, and that is only considering simple robots, simple tasks, and simple environments. As expectations of what robots can perform, and in which environments they could operate in, rise, so will the reality gap problem. As embodied approaches become more widespread, we believe incremental efforts to reduce the reality gap through better simulators or surrogate modeling will not be enough to accurately produce robots that can exploit the natural noise and richness of interaction with

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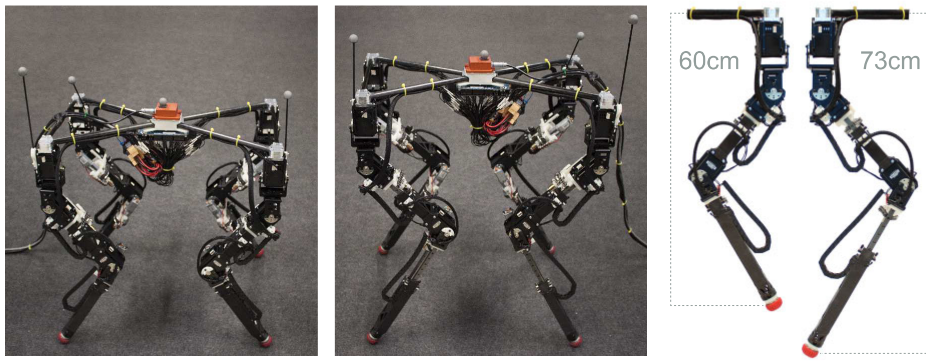

Figure 1: The DyRET robotic platform for exploring dynamic morphology adaptation. These pictures shows the minimum and maximum length of the legs of the robot. The robot stands 13cm taller when fully extended, and each link can be controlled individually.

real world environments. The only approach to completely bypass this issue is to work with the robots exclusively in hardware. Though that does come with a myriad of other challenges [5], we believe this is the right direction for future morphologically adaptive robots.

One of the sub-fields of robotics that has the most experience in embodied approaches is evolutionary robotics. This field takes inspiration from natural evolution to optimize and improve the mind (control) and body (morphology) of robots [6, 7]. A multi-objective approach optimizing both at the same time reduces the chance of premature convergence and allows more finely-tuned solutions to be found. Most work that optimizes the morphology, however, only does so in simulation [2, 3]. There are examples where the evolution of morphology is done in simulation before a select few individuals are built and tested in the real world [8], but this often comes with a large decrease in performance due to the reality gap. There are a few examples of work that combines predefined modules in new ways to build robot bodies in the real world [9, 10]. This allows adapting the bodies of robots to the environment they operate in, but this is still a bit limited due to the simple nature of the robots, relative slow process of building, and need for human intervention.

In this paper, we discuss real-world morphological adaptation in robotics in the context of artificial evolution and learning. Through our case study, we show that the concept is not only feasible with current techniques and technology, but is already at a point where it yields good results on real-world robots. Furthermore, we identify some of the benefits and challenges of a hardware-only approach, and potential ways forward.

2. Our approach

The goal of our project has been to investigate and demonstrate morphological adaptation in the real world on a capable physical robot. To do this, we designed and built DyRET, the DYnamic Robot for Embodied Testing, seen in Figure 1. It can control the length of the two lower links of its legs, the femur and tibia, which allows it to change its morphology during operation. Compared to other approaches that manufacture a population of different robots to test different morphologies, our approach simplifies the process significantly while still allowing a range of different morphologies and controllers to be tested.

Our first attempt at morphological adaptation looked into performing offline adaption to changing internal conditions in the robot. This allowed us to investigate the role of control and

Figure 2: The robot on the four different walking surfaces is was tested on in our work on adapting to the operating environment in the lab [12] to the left. We showed that evolution was able to utilize both control and morphology to adapt to different environments. We also showed the results could generalize to new and unseen environments. The right shows the robot during testing of our online adaptation algorithm in outdoor unstructured terrains [13]. Here, the robot was able to exploit limited training in the lab to quickly and efficiently adapt its body to new and unseen environments.

morphology without having to consider the external environment to a large degree. We applied a co-evolutionary approach of morphology and control to adapt to different battery voltages that would be present during operation, and found that the evolutionary algorithm was able to exploit both the control and morphology in its adaption [11]. The next step was to introduce the environment, and we did a similar evolutionary adaptation to different walking surfaces. There, we observed that the system was able to exploit both morphology and control to adapt to its external environment, and that the results generalized well to previously unseen walking surfaces as well [12]. Even though demonstrating that the results generalize bodes well for its applicability to real-world problems, it was still an offline approach. Even though it works in hardware, there is still a gap in performance and robot behavior between the lab environment and its final operating conditions outside. In our next experiment, we implemented an online approach to learning where minimal training in controlled environments inside helped bootstrap the learning process. We found that this allowed the robot to adapt its morphology while walking in challenging unstructured outdoor environments and continuously improve its model as it walked [13].

Through our use of the DyRET robotic platform, we have seen that morphological adaptation is not only possible to carry out in a practical way, but also leads to highly beneficial adaptations to internal and external changes. It would be natural to think that other systems implementing morphological change have the potential for similar benefits, and maybe even more so with materials and actuators allowing for more flexible changes.

3. Benefits and challenges of morphological adaptation in the real world

Benefits: Taking a hardware-only approach to morphological adaptation comes with several benefits, and we enumerate what we think are the most important ones below:

- **Bypassing the reality gap.** Working solely on real-word robots completely bypasses the reality gap problem, which is considered one of the biggest challenges in evolutionary robotics and robotic reinforcement learning today. This is not only about simplified simulations giving reduced performance in the real world, but also the algorithms exploiting the simulators and focusing on simulations that are far from realistic, often rendering solutions from simulation useless when transferred to reality.

- **Embodied intelligence.** Working with real-world robots allows investigation into and exploitation of the principles of embodied intelligence. The robot can fully utilize the natural noise and richness of the physical world, which can potentially contribute much to its performance and problem solving ability. Our own results from adapting to internal power conditions illustrate this [11]. Other robots that rely on complex dynamics [14], or interactions with the environment [15] would also be hard to exploit fully using simplified simulations.
- **Real-world platform.** Compared to the simple virtual robots typically used in simulation, we have demonstrated that this works on a highly capable robot that is applicable to a wide range of different problems and tasks. This increases the impact of the work, and might help increase the adoption of the techniques to a much higher degree as it starts being used in practical robot systems.

Challenges: Working exclusively on real-world robots also introduces some challenges, which need to be considered before initiating experiments. However identifying these challenges will also serve as a guideline for where to focus research in improving future efficiency of real-world morphology adaptation:

- **Search efficiency.** One of the main issues in the context of evolutionary optimization and other approaches to learning is the limited evaluation budget allowed by the hardware-only platform, as such algorithms typically perform optimally with a large number of evaluations. Even though the robot is able to operate on its own, our experiments have all required some form of human intervention. In addition, the evaluations typically need to be done sequentially, and necessarily in real-time. Compared to simulation experiments that can run faster than real-time, be highly parallelized, and run cheaply in the cloud, this severely limits the degree of adaptability that can be explored in hardware [16].
- **Physical wear and damage.** Another issue is damage to the robot, increasing risk significantly. Having to repair, maintain and initially build the robots also takes considerable effort, regardless of the strategy considered. This includes automated solutions like real-world assembly by an external robot or self-adaptation mechanisms. During our experiments our robot broke in many ways, and the design had to be improved and parts re-manufactured, introducing delays to the experimentation process [5].
- **Design and scale of experiments** The above-mentioned repair and design changes may be a challenge for maintaining consistency across experiments, but there are also other factors challenging the experimental design. During one single experiment, the characteristics of the robot may change, such as motors gradually heating up and leading to reduced performance. If trials are always carried out in the same order, such factors may introduce unwanted and difficult-to-identify effects in the overall results [5]. Limiting the number of individuals and replications in evolutionary experiments also reduces the applicability of the experiments for investigations into the biological principles behind evolution, which is one of the main motivations behind work in the ALIFE field [17, 18].

4. Conclusion and the way forward

In this paper, we have discussed the benefits of actively using the morphology as a part of the problem-solving space for real-world robots, grounded in our concrete application of a quadrupedal robot with dynamic leg lengths. Our previous work leveraged the dynamic morphology both with evolutionary and machine learning approaches, building upon ideas and principles from the field of embodied cognition.

While we have pointed out some challenges of real-world morphology adaptation, such as limited evaluation budgets and risk of damage, we believe that the prospect of rich real-world interaction should outweigh these, and that new materials and algorithms could alleviate existing problems. In particular, approaches which generate internal models from the real-world interactions could be a promising way to guide the real-world exploration and save trials. This would involve making or learning a model of the robot and its environment that could be used for further optimization without relying on the physical robot directly, potentially drastically reducing the number of hardware evaluations needed. Moreover, soft and compliant approaches to materials and actuators could also reduce the mechanical wear and tear of testing potentially taxing solutions.

We hope to inspire further exploration into the role of adaptive morphology for real-world robotic problem-solving and adaptation. Embodied intelligence has gained increased interest in the robotics community in the last few years, but few pursue hardware-based platforms with a dynamic morphology. The development of this concept, both in terms of methods and new materials and actuators, could lead to highly adaptive robots capable of meeting new and unforeseen situations effectively.

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