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Quantifying embodiment towards building more adaptive legged robots

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1 Motivation

Legged robots benefit from compliance to handle perturbations such as impulsive contact forces from different terrains, or from other obstacles. In that respect, modelling system dynamics using active control becomes challenging due to uncertainty caused by environmental interactions and with system parameters changing over time due to external conditions. Biological systems use a blend of active control and using the body as a computing resource to adapt to such changing environments. Designing legged robots that exploit the combination of active control and embodied responses remains under-explored [1]. This paper, as part of wider research on designing more adaptive robots using this inter-play, demonstrates the quantification of the extent of such embodiment, which can provide useful input during the design process.

2 Introduction

Recently, the importance of the embodied responses and behaviours for effective operation of intelligent machines has been recognised through the study of a wide range of biological systems such as insects [2], dogs and other mammals [3] in muscle-driven systems. Haghshenas-Jaryani [4] and Mohseni et al. [5] have developed bio-inspired muscle-driven legged robots which exploit their embodiment blended with Active Control (AC). To study the extent of embodiment in muscle-driven systems quantitatively, various information-theoretic methods have been proposed by a number of researchers, including by Ghazi-Zehadi et al. [6], Polani et al. [7], and Rückert and Neumann [8]. In this work, we quantify embodiment to measure Morphological Computation (MC) in a simulated quadruped robot using a method from [6] due to its suitability for muscle-driven models. MC refers to processes, which are conducted by the body (and environment) that otherwise would have to be performed by the brain [6]. This measure quantifies the contribution of MC as compared to AC for a specific gait or trajectory. The following sections describe the experiments, their results and finally, we discuss the possibilities of designing robots using an inter-play of MC and AC.

3 Measuring Morphological Computation

The sensorimotor loop [9] is essentially the basic control loop used in robotics, comprising a brain or controller, which sends signals to the system's actuators, thereby generating force and motion which may interact with the system's environment. The body and environment are encapsulated in a single random variable named 'world'. There are three (stochastic) processes $S(t), A(t), W(t)$ that constitute the sensorimotor loop (see Figure 1), which take values s, a, w, in the sensor, actuator, and world state spaces respectively. The world dynamics kernel $\alpha(w'|w,a)$ captures the influence of the actuator signal A and the previous world state W on the next world state W'. An absence of MC would mean that the behavior of the system is entirely determined by the system's controller, and hence, by the actuator state A. In this case, the world dynamics kernel reduces to $p(w'|a)$. The discrepancy of these two distributions can be measured with the average of the Kullback-Leibler divergence $D_{KL}(\alpha(w'|w,a)||p(w'|a))$, which is also known as the conditional mutual information $I(W';W|A)$ [6], and computed by:

$$MC = \Sigma p(w',w,a) log_2 \frac{\alpha(w'|w,a)}{p(w'|a)} \tag{1}$$

4 Method

A quadruped robot was simulated (Figure 2) using the Solo8 design from the Open Dynamic Robot Initiative (ODRI) [11] [12], which is an open-source, impedance-controlled robot with 8 degrees of freedom (DoF). MATLAB Simscape^{TM} was used to build a high level of mod-

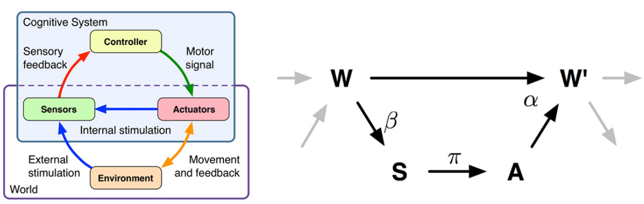

Figure 1: Sensorimotor loop showing the intrinsic and the world states, and the directed graph showing the causal nature of the sensorimotor loop, redrawn from [10]

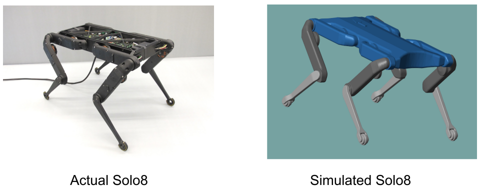

Figure 2: Solo8 actual (reproduced from [12]) and simulated robot

elling fidelity in the simulation, with the ability to control close to 500 different variables including stiffness, damping, and material properties.

5 Experiment and Results

A hopping gait was simulated and the displacement, contact forces and the angular velocity plotted for different values of stiffness and damping. Furthermore, the continuous data was discretised, followed by computation of joint and conditional probabilities, to ultimately calculate the MC, per Equation 1. The MC is measured at different states in the hopping gait, and the plot is shown in Figure 3. During most of the flight phase, the behavior of the system

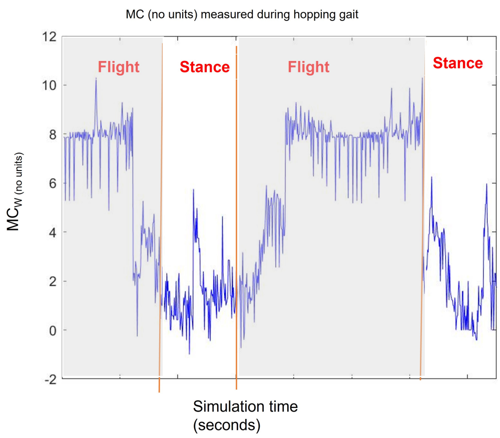

Figure 3: Extent of MC at various points in the jumping gait, which shows that the MC increases during flight and is maximum at the highest point.

is governed primarily by the interaction of the body (mass, velocity) and the environment (gravity), and less so by the actuator models. This behaviour is consistent with the biomechanics of walking described using the Spring Loaded Inverted Pendulum (SLIP) model [13].

6 Conclusion and future work

By measuring the MC, the advantage of passive dynamics and morphology can be considered as an 'enabler' as part of the robot's architecture and design, rather than aiming to control every aspect. Another interesting area of research where quantification of embodiment will be useful is in the development of highly re-configurable intelligent systems with adaptive morphologies [14]. As these elements are developed, their embodiment can be quantified to evaluate their behaviour before adding further building blocks, to lower the risk during design process. This could enable higher resilience in robots that could recover more effectively from damage with adaptive morphologies.

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