Using Mutual Information to Analyze Adaptations to Loading, Speed, and Terrain

Izaak D. Neveln[a], Chris Dallmann[b], Simon Sponberg[c]
[a]School of Physics, Georgia Institute of Technology — *ineveln3@gatech.edu*
[b]Department of Biological Cybernetics, Bielefeld University — *cdallmann@uni-bielefeld.de*
[c]School of Physics, School of Biology, Georgia Institute of Technology — *sponberg@gatech.edu*

1 Motivation

Neuromechanical control architectures can be defined by information flow. For example, centralization has been cited as an important axis of control architecture in legged locomotion [1]. Weak or local coupling describes decentralized control while strong or global coupling describes centralized control. Centralizaton, however, has been difficult to explicitly quantify and thus far attempts to define centralization either rely on a specific model [2, 3] or only discuss centralization in qualitative terms [4].

To better analyze biological locomotor systems and inform design decision for robotic control, we developed an empirical measure of centralization which compares how much information a control signal shares with a global state of the system (global information) compared to how much is shared with a local state (local information) [5]. This measure indicates that cockroach locomotor control is more centralized than decentralized because a control muscle in the middle leg shares more information with the global kinematic state than the local kinematic state of the leg it actuates. Measuring mutual information is emerging as a useful analytic tool for comparing neuromechanical architectures empirically without the need for a model.

Using this approach to quantify centralization and information bandwidth, we can now address how changing parameters about the neuromechanical architecture in animals and robots affects information flow during movement. We first show an example of how measuring centralization in a robot can quantify how loading a robot alters information flow. Next we compare the control strategies of two similar animals (stick insects and cockroaches) that operate at different maximum speeds. We then study how cockroaches adapt the centralization of their control when encountering rough terrain. Finally, we discuss how these principles of measuring information could be applied to the control of a robot which monitors information and adjusts internal or mechanical coupling to adapt to different speeds or substrates.

2 Shifts in centralization from mechanical loading

For robots to perform useful functions, they will have to adapt to changing circumstances such as adding and removing mass (Fig. 1-1a). These changes can manifest as differences in the amount of information mechanically shared through the legs of a terrestrial robot. As the inertia of the bounding Minitaur quadruped shifts, the coupling between the front and rear leg pairs changes [6]. Our measure of centralization correctly identifies this shift in coupling for different moments of inertia (Fig. 1-1b). Furthermore, an unexpected difference between the centralization of rear legs versus front legs indicates some asymmetry about the robot, which could either be exploited or may require refinement to the control architecture. Assessing centralization can inform design choices and control strategies in robotics.

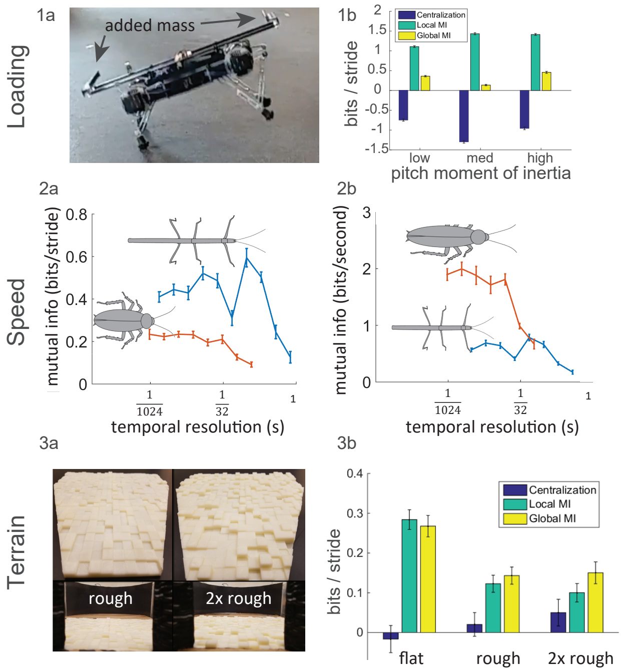

Figure 1: 1a) We tested the Minitaur robot with added mass. 1b) Centralization is minimized when there is the least transfer of information at the medium level of moment of inertia. 2a) Stick insects have greater bandwidth on a per stride basis. 2b) Cockroaches have a higher information rate on a per time basis for fine temporal resolutions. 3a) Cockroaches ran over flat and two levels of random rough terrain. 3b) Centralization increases as the roughness of the terrain increases.

3 Bandwidth of motor control for various speeds

Neurons can only transmit a finite amount of information due to noise and refractory periods. If control is required within the time course of one stride, information will become more limited as strides become faster. Furthermore, as the temporal resolution of the encoding of the neuronal spiking becomes finer, the potential amount of information increases [7]. We measure both the kinematic output of the middle legs of the stick insect and cockroach as well as the motor unit activity from a homologous coxal extensor from both animals. We measure the mutual information between the kinematic output and the muscle activity at a variety of temporal resolutions. The stick insect stride is longer (714 ms average) than the cockroach (120 ms average). More spikes occur over the course of the stride in the stick insect, and could potentially convey more information.

When considering the number of spikes over a whole stride period, the stick insect muscle conveys a similar amount of information as the cockroach unit, even though there are more possible combinations of number of spikes (Fig. 1-2a). As the temporal resolution becomes finer, the amount of information per stride increases for both animals, with a greater increase for the stick insect. However, there is an optimum resolution for the stick insect before the information starts to drop off, whereas the information continues to increase with finer temporal resolution in the cockroach.

Though the information per stride is greater in the stick insect, the information rate per second is actually greater in the cockroach as the muscle shares more information over the same time period (Fig. 1-2b). Thus we see an example of how precise timing can overcome bandwidth limitations when adapting to faster speeds.

4 Centralization over rough terrain

While increases in speed poses bandwidth problems, rough terrain produces large random perturbations to each leg that can affect stability and might require strengthened coupling. We expanded on previous flat ground running by running the cockroaches over two rough terrains that had 1 cm blocks of random heights, and the degree of roughness of one terrain was double the other (Fig. 1-3a).

We find that the variation of the kinematic states of the limbs increases with increased roughness of the terrain. The amount of mutual information between the control signal and both the local limb state and the global average state of all limbs is diminished in the rough terrain strides when compared to the flat terrain, and the strides traversing the rougher of the two rough terrains have slightly more local and global information. Centralization, or the difference between global and local information, increases slightly as the terrain moves from flat to slightly rough, and then increases again for the roughest terrain (Fig. 1-3b). Such adaptations to environmental variability are important for the design of more robust robots.

5 Discussion

Here we looked at how information theory can quantify changes to loading, speed, and terrain. First, mechanics alters information flow of a control architecture, which could either be exploited or controlled for. Next, motor control can be bandwidth limited, compounding the fact that there are significant sensory feedback delays [8]. However, though information often decreases on a per stride basis for faster movements, information rate can actually increase if precise timing of motor control can be achieved, which is possible in both vertebrate and invertebrate motor control [9].We also see that for cockroach locomotion, centralization further increases as the cockroach encounters variable terrain.

Measures of mutual information can be used as a guiding design space for robotic control. We could apply different control architectures to robotic models, and even actively control the parameters of the robot to maintain certain levels of information. For example, we can actively modify the moment of inertia of the Minitaur as different terrains are encountered to maintain centralized control. Information theoretic measures that have been used as analytic tools can then become controllable quantities to improve adaptability and robustness in robots.

6 Acknowledgements

We acknowledge funding support from NSF CAREER award to Simon Sponberg. We thank Volker Dürr and Josef Schmitz for providing stick insect data, and we thank Dan Koditschek and Avik De for aiding the robotic experiments.

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