Design and Comparative Morphology for Inertial Reorientation

Thomas Libby, Aaron M. Johnson, Robert J. Full, and D. E. Koditschek

Fig. 1. Inertial reorientation is not limited to tails – motion of limbs, wheels and abdomen may generate orientation change during a fall.

The remarkable aerial agility of long-tailed lizards [2] has sparked significant interest in Inertial Reorientation (IR) – the induced rotation of a 'body' by inertial forces arising from opposed internal motion of an appendage – resulting in a proliferation of robots with varying capability and morphology. Likewise, IR capability has been identified in animals as diverse as moths and prosimians (Fig. 1), and hypothesized in cheetahs and other large vertebrates. Motivated by a need for principled design tools in the face of this complexity, we used a generalization of the Templates and Anchors framework [1] to develop a formal structure for the selection, design and comparison of IR systems across a diverse range of morphology.

We defined the Inertial Reorientation template, the simplest model of an IR maneuver, equipped with a DC motor-like model parameterized by peak output power. The model's linear dynamics, along with a bang-bang controller, enabled analytic (optimal) solution of the template's single-switch reorientation behavior, revealing a simple relationship between morphology and performance in the form of two design constraints which ensure completion of the task (here, a planar, aerial rotation in finite time, see Fig. 2). Increasing the template's appendage inertia relative to its total inertia increases body rotation per unit appendage stroke and decreases power required to reorient in a fixed time; we therefore define "Inertial Effectiveness" as the ratio of internal to total inertia.

Practicable IR morphology (tails, reaction wheels, and flailing limbs) can be 'anchored' to the template constraints through a family of mappings describing the dimensional reduction to the simpler system. In a tailed robot, the only nontrivial map is the "morphological reduction" – the mapping from tailed body design space to that of the template – which enables use of the aforementioned task-preserving design constraints. While approximate in general, the reduction is low in error for all known tailed robot designs, and many animals as well. Our template-anchor relations revealed advantages to each type of morphology, with the tailed design prevailing in cases where large, rapid reorientations are desired. In turn, our robot-centric design approach produced powerful tools for comparative biomechanics, enabling evaluation of performance across the diversity of natural IR morphology, and testing long-open questions on the scaling of the mechanism to larger animals like therapod dinosaurs. The specific power to reorient in one body length of fall scales as $M^{1/6}$, suggesting broad utility of IR across scales, from 3 gram geckos to 30 kilogram theropod dinosaurs and beyond.

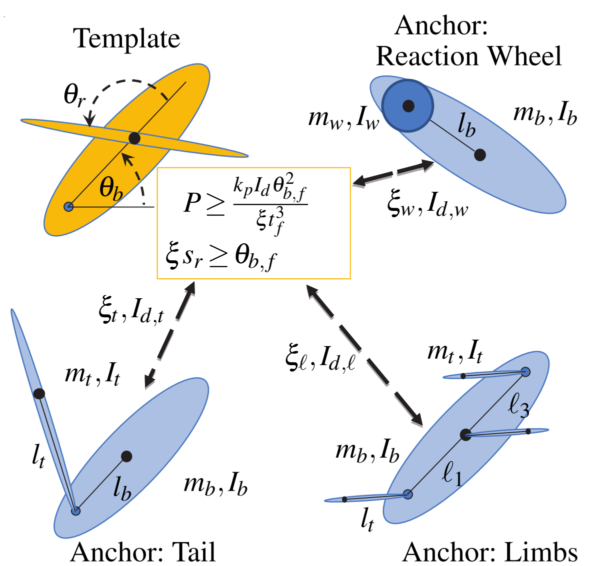

Fig. 2. The IR Template is parameterized by Power, P, Effectiveness, ξ, Appendage Stroke, s_r, and Inertia, I_d. Several inertial reorientation systems (anchors) map onto the template through equivalent values of appendage effectiveness ξ_i and inertia $I_{d,i}$.

References

[1] Robert J. Full and D.E. Koditschek. Templates and anchors: neuromechanical hypotheses of legged locomotion on land. *Journal of Experimental Biology*, 202(23):3325–3332, 1999.

[2] Thomas Libby, Talia Y. Moore, Evan Chang-Siu, Deborah Li, Daniel J. Cohen, Ardian Jusufi, and Robert J. Full. Tail-assisted pitch control in lizards, robots and dinosaurs. *Nature*, 481(7380):181–184, 2012.