RicMonk: A Three-Link Brachiation Robot with Passive Grippers for Energy-Efficient Brachiation

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Abstract

Brachiation (illustrated in Fig. 1), a mode common among primates like long-armed gibbons, involves swinging between tree branches using only their arms. This locomotion mode holds potential for diverse applications such as agriculture surveillance, forest exploration, and biomimetic design. This paper presents the design, analysis, and performance evaluation of RicMonk, a novel three-link brachiation robot equipped with passive hook-shaped grippers. The paper discusses the use of the Direct Collocation methodology for optimizing trajectories for the robot's dynamic behaviors and stabilization of these trajectories using a Time-varying Linear Quadratic Regulator. With RicMonk we demonstrate bidirectional brachiation, and provide comparative analysis with its predecessor, AcroMonk [1]- a two-link brachiation robot, to demonstrate that the presence of a passive tail helps improve energy efficiency.

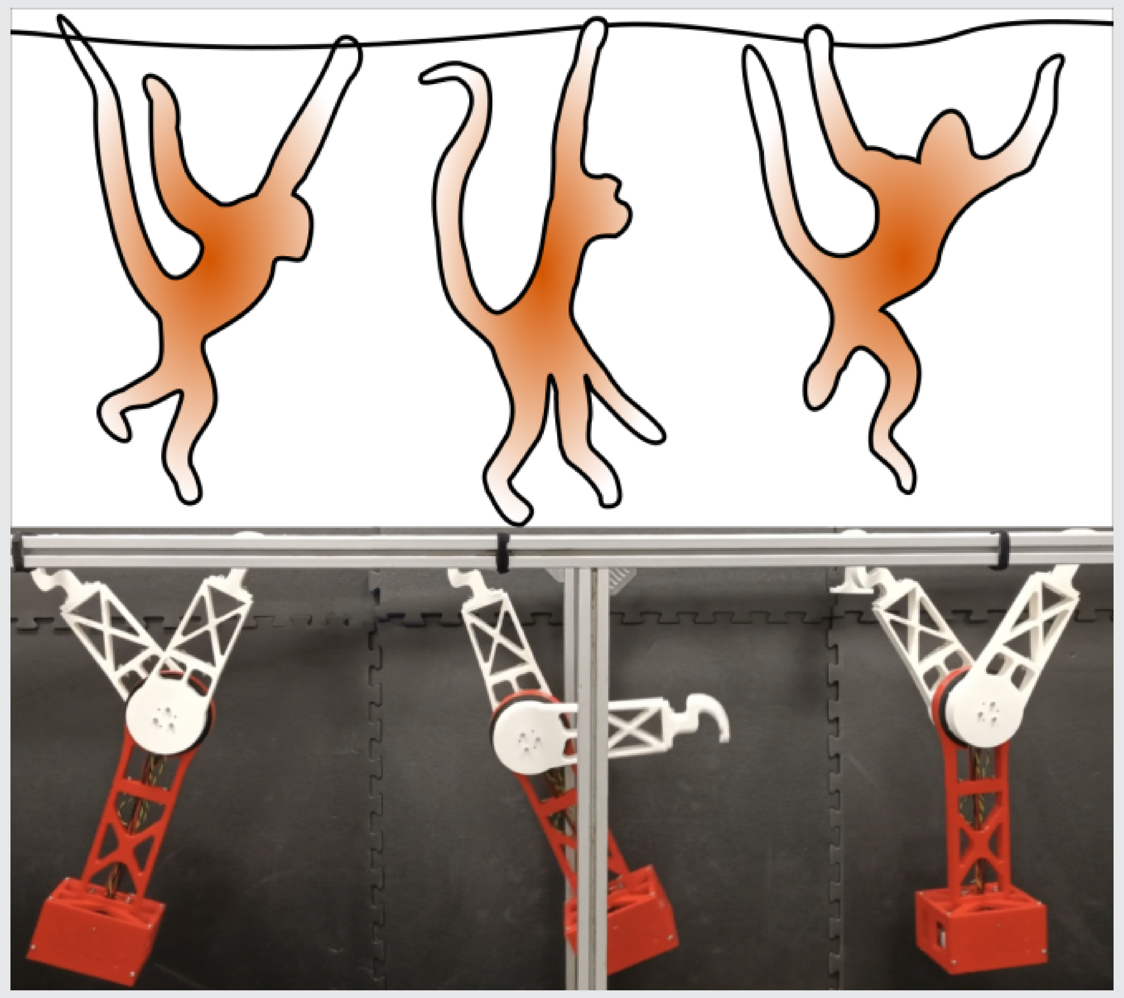

Figure: Brachiation illustration

Open-source code

The system design, controllers, and software implementation are publicly available on GitHub and the video demonstration of the experiments can be viewed on Youtube. Scan the following QR code to access the GitHub page where the link to the Youtube video is also available.

Mechatronics Design

As envisioned in the preceding generation of the RicMonk, the AcroMonk [1], the design should be compact, and wireless and needs to be made of readily available and low-cost materials. The arms and passive gripper are inspired by AcroMonk. RicMonk is equipped with two actuators and a tail that mimics a monkey's body, as depicted in Fig. 2. Electrical components and the battery reside securely in the tail's bottom box. A stable gripper design is critical during swinging. The original cylindrical pivot lacked stability due to an offset center of mass, causing sway and weak contact. This instability led to undesired motion with one arm on the ladder bar. To solve this, a conical pivotal surface was introduced, accommodating the offset. This improved stability, although a tight grip required higher release torque. Also, this gripper design results in mirroring symmetry rather than full sagittal symmetry in RicMonk.

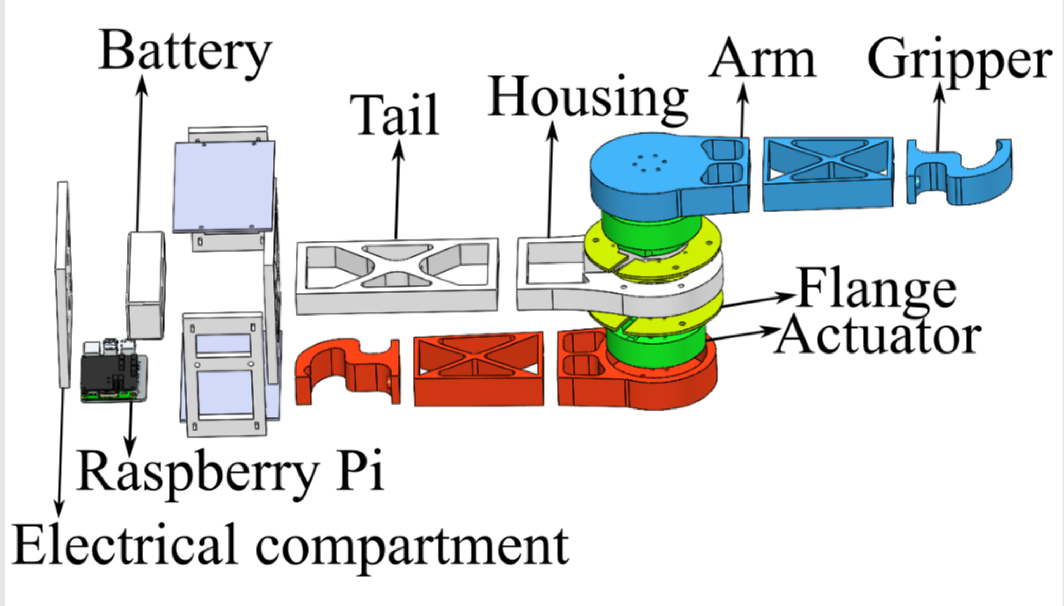

Figure: RicMonk exploded view

Trajectory Optimization

Brachiation is divided into four simple atomic behaviours - ZB (Zero - Back bar), ZF (Zero - Front bar), BF (Back bar - Front bar), FB (Front bar - Back bar); as defined in [1]. These trajectories (state variables and inputs) are optimized, for a fixed base model of RicMonk (Fig. 3, dotted red circle represents a revolute joint), using the Direct Collocation method, by minimizing a cost dependent on the energy expended during the respective maneuver.

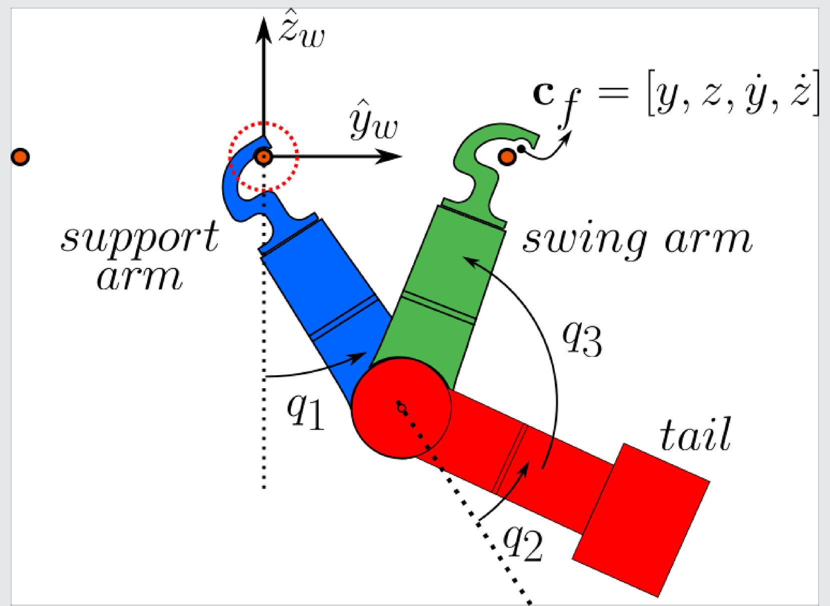

Figure: RicMonk fixed base model

Trajectory Stabilization

Each of the trajectories is stabilized using the Time-varying Linear Quadratic-Regulator (TVLQR) in simulation and reality. With the real system, TVLQR is used as an offline controller and the pre-computed optimal time-varying feedback matrix is used for online error compensation on a control loop running at approximately 400 Hz.

Experimental Validation

Atomic behaviors were executed on the real system using the TVLQR controller. State estimation accommodating the RicMonk arm's complete revolution enabled combining atomic behaviors, facilitating continuous brachiation. Fig. 4 and 5 illustrate RicMonk performing multiple forward and backward directions respectively. The controller is robust against soft disturbances in the path of the robot, and excess weight. Fig. 6 displays variation in robot's position during recovery from disturbance during brachiation.

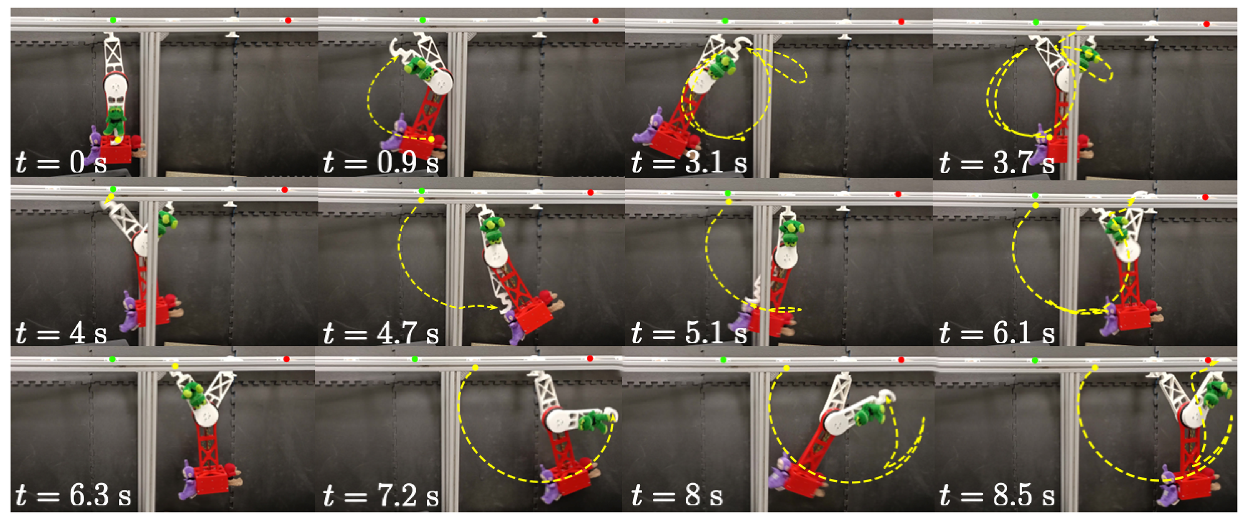

Figure: RicMonk performing multiple forward brachiation cycles. Row one - ZF maneuver (left to right), row two and three - BF maneuvers (left to right)

Comparative analysis

Cost of Transport (CoT) [2] is a dimensionless measure for energy efficiency, allowing comparison across sizes and structures. Formulated as Eq. 1, it factors in energy input (E), mass (m), distance (d), and gravity acceleration (g).

$$CoT = \frac{E}{mgd} \quad (1)$$

The lower the CoT value, the more energy-efficient a given system is. Table 1 compares total energy consumed (TE), CoT, and time taken(t) during five continuous forward brachiation maneuvers for AcroMonk and RicMonk. RicMonk, with the tail, is more energy efficient compared to AcroMonk. However, AcroMonk consumes a lower amount of energy in total.

Table: Comparitive analysis

	TE (J)	CoT	t (s)
AcroMonk	8.9547	0.3355	11
RicMonk	15.1947	0.2760	17

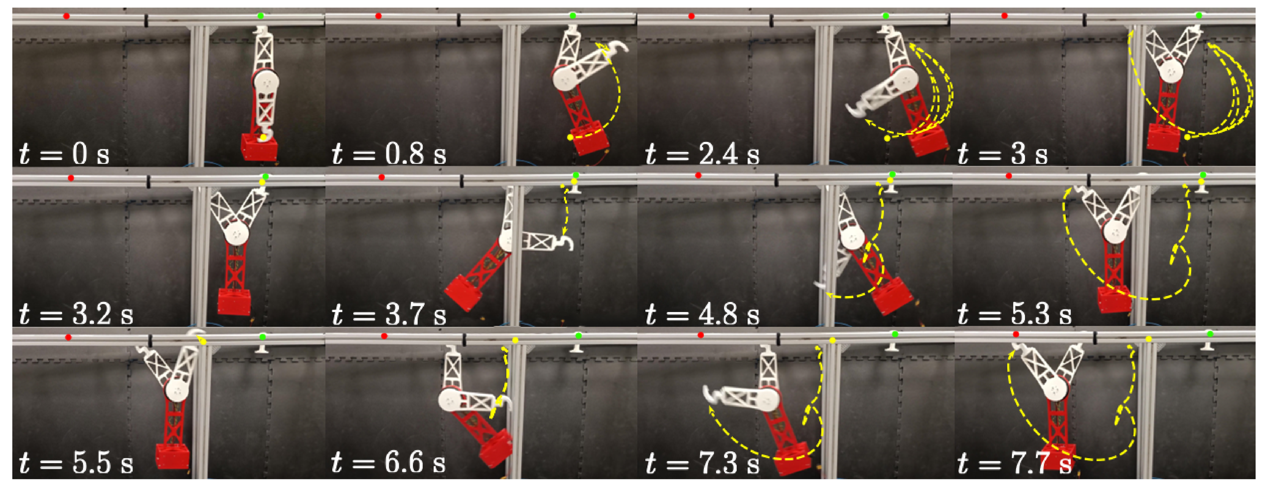

Figure: RicMonk performing multiple backward brachiation cycles. Row one - ZB maneuver (left to right), row two and three - FB maneuvers (left to right)

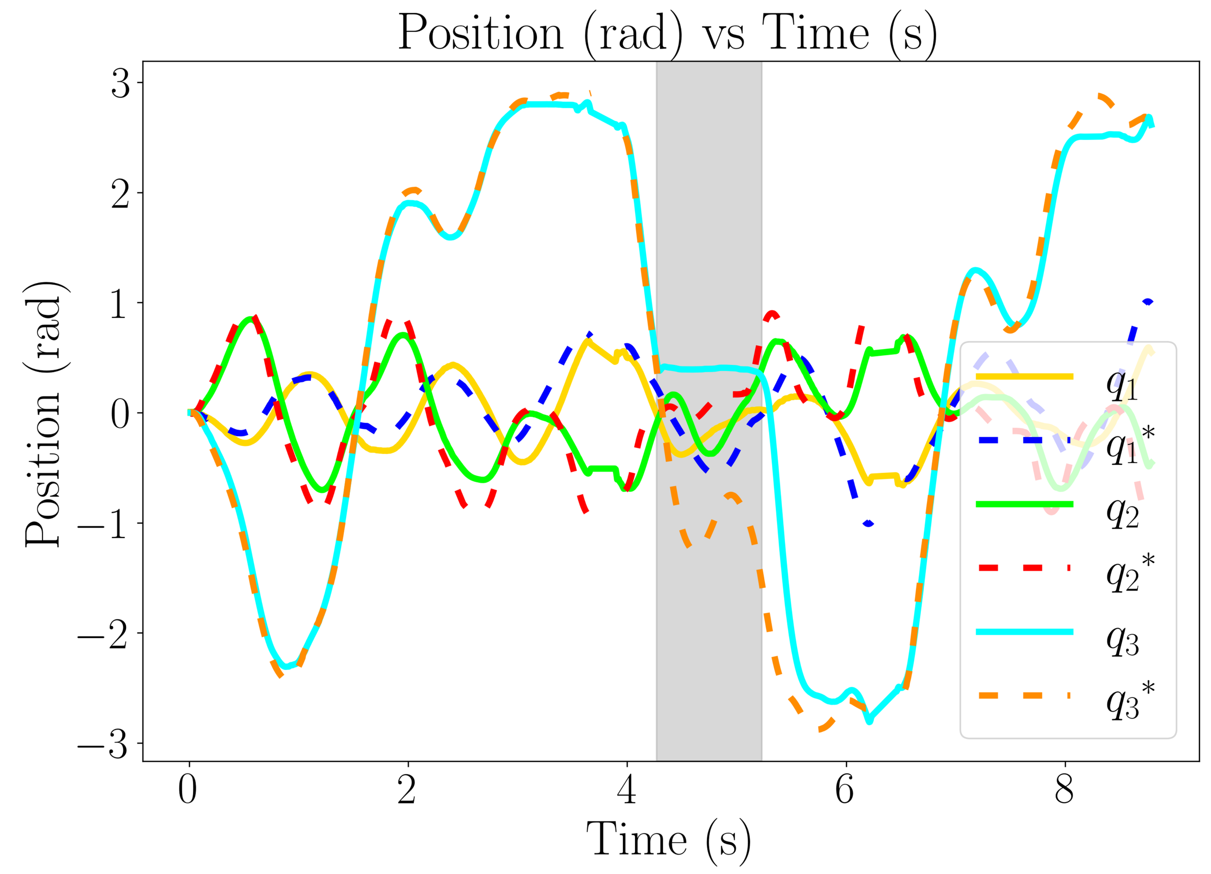

Figure: Position plot of RicMonk performing multiple brachiation in face of disturbances in its path. Shaded region of the plots signify disturbance in robot motion

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