RicMonk: A Three-Link Brachiation Robot

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Brachiation and Brachiation Robots

Brachiation (illustrated in Fig. 1), a mode common among primates like long-armed gibbons, involves swinging between tree branches using only their arms. Gibbons brachiate at speeds up to $25\,\mathrm{km\,h^{-1}}$, demonstrating remarkable agility. This locomotion mode holds potential for diverse applications such as agriculture surveillance, forest exploration, and biomimetic design. Robots capable of brachiating and walking, termed Multi-locomotion robots (MLR), offer intriguing opportunities for study and implementation [1]. Brachiation includes "Slow Brachiation," where the robot swings between branches without a free-flight phase, and "Fast Brachiation" or "Ricochetal Brachiation," involving dynamic free-flight phases. This unique locomotion bears similarity to walking and running, relying on arm-leg coordination for balance and propulsion.

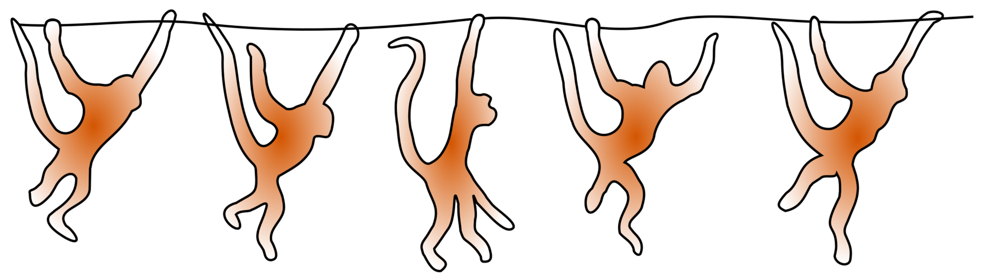

Figure: Brachiation illustration

AcroMonk Inspiration

AcroMonk [2] (shown in Fig. 2), is a two-link underactuated brachiation robot weighing 1.6 kg, capable of performing continuous brachiation cycles robustly. The AcroMonk is underactuated and has a single actuator. Its efficient design makes it a light, portable, and robustly strong robot. The AcroMonk is the most simplified system that mimics the behavior of a Gibbon. However, it currently lacks a part that represents the body (or tail) of the Gibbon. As a result, the AcroMonk cannot inject large enough momentum into its motion to perform ricochetal brachiation. Also, since it has only a single actuator, it cannot robustly perform multiple backward brachiation maneuvers. To overcome such challenges, RicMonk comes to life.

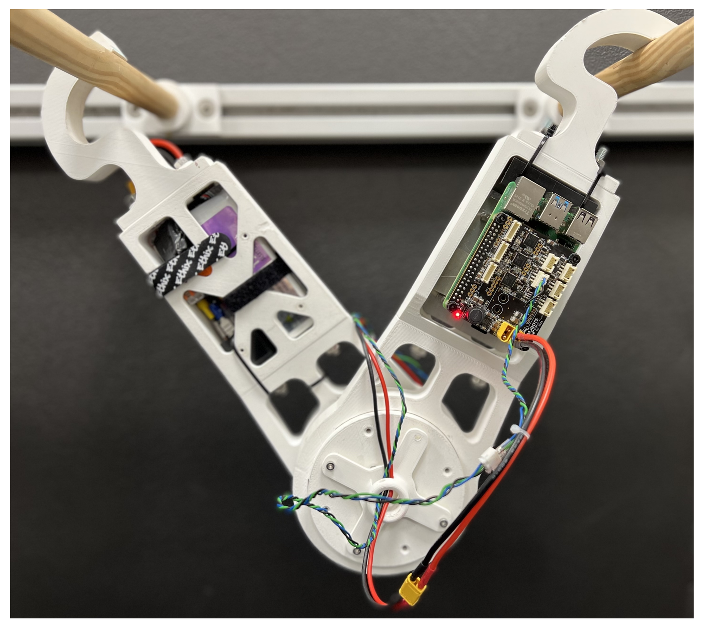

Figure: AcroMonk [2]

RicMonk

RicMonk (Fig. 3) is a three-link underactuated brachiation robot emulating gibbon movements. It embodies portability and agility while using a modular approach for adaptability, swiftly replacing parts after collisions. 3D-printed parts ensure robust yet lightweight construction. The arms and passive gripper are inspired by AcroMonk[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 (Fig. 4), 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.

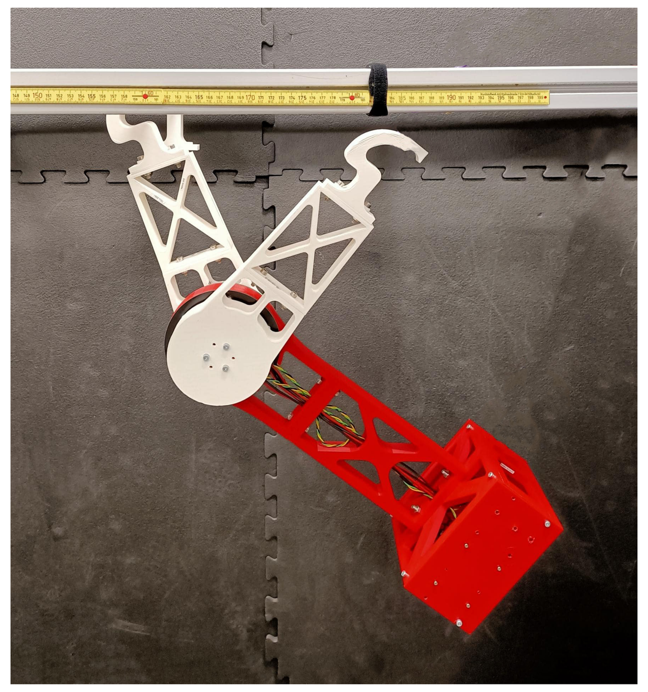

Figure: RicMonk

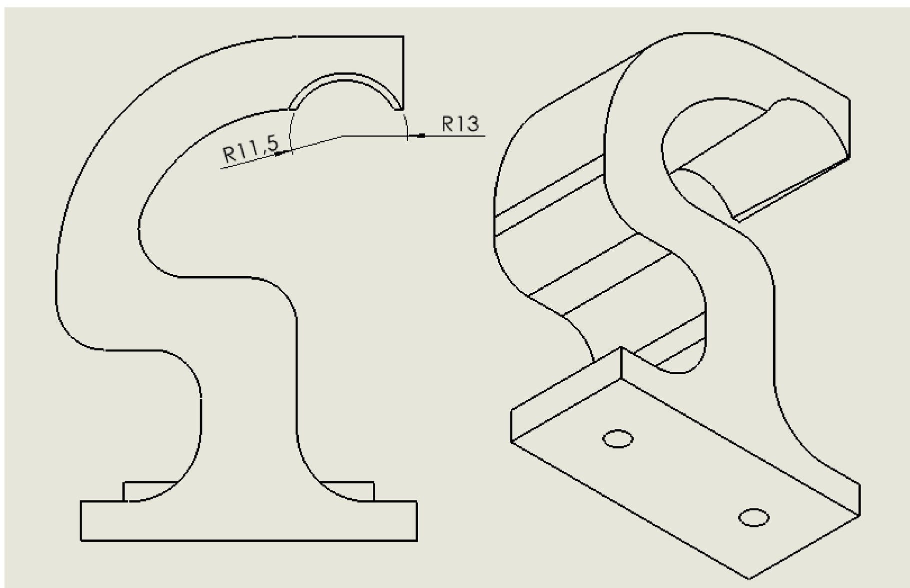

Figure: Current gripper design

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 [2]. These trajectories (state variables and inputs) are optimized using the Direct Collocation method, by minimizing a cost dependent on the energy expended during the respective maneuver.

Trajectory Stabilization

Each of the trajectories is stabilized using the Proportional-Derivative (PD) controller and the Time-varying Linear Quadratic-Regulator (TVLQR) in simulation. However, in reality, model-free PD controller faces difficulty in tracking the unactuated joint. Model-based TVLQR is successful in tracking all the trajectories.

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. 5 and 6 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. 7 displays variation in robot's position during recovery from disturbance during brachiation.

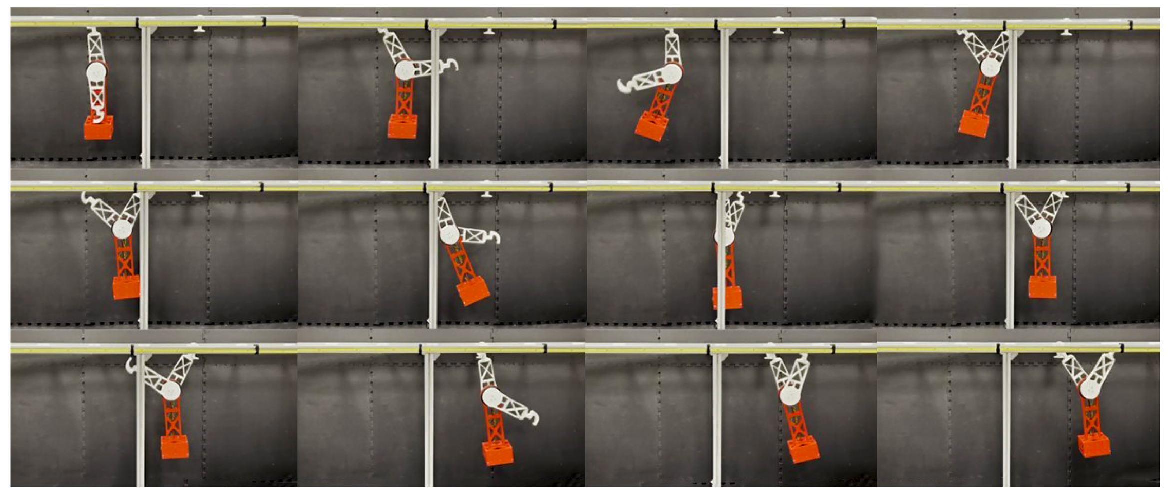

Figure: RicMonk performing multiple forward brachiation cycles. Row one - ZF maneuver (left to right), row two & three - BF maneuvers (left to right)

Energy efficiency analysis

Cost of Transport (CoT) [3], [4] 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).

$$CoT = \frac{E}{mgd} \tag{1}$$

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 & three - FB maneuvers (left to right)

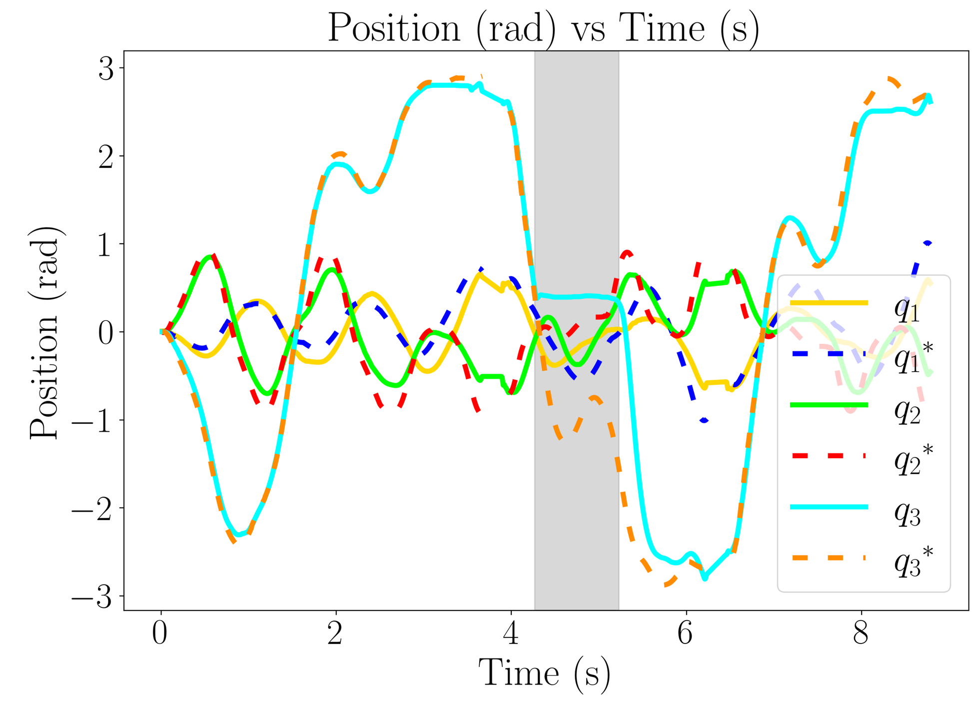

Figure: Position plot of RicMonk performing multiple brachiation in face of disturbances in its path. Shaded region of the plots signify disturbance in robot motion

Acknowledgment

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[3] Wiki. https://en.wikipedia.org/wiki/Cost_of_transport.

[4] Sangbae Kim, Patrick M Wensing, et al. "Design of dynamic legged robots". In: *Foundations and Trends® in Robotics* 5.2 (2017), pp. 117–190.