Basilisk-Inspired Foldable Robot: Design and Development of a Four-Bar Mechanism for Adaptive Terrestrial Locomotion

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***Abstract*—This project aims to develop a foldable robotic system inspired by the basilisk lizard's unique locomotion, focusing on a four-bar mechanism for the hind legs that enables a transition between quadrupedal and bipedal movement on land. The design incorporates sprung dummy forelegs or linked limbs and a tail component for balance and propulsion. Drawing from key biomechanical studies of basilisk locomotion, the project applies these insights to foldable robotics, exploring the lizard's gait patterns, force generation, and balance mechanisms. This approach advances biomimetic robotics and explores new possibilities in efficient locomotion systems, with potential applications in various fields such as search and rescue operations, exploration, and entertainment. The project's relevance is underscored by recent advancements in materials and manufacturing methods, showcasing the broader impact of this research in robotics and engineering.**

***Index Terms*—Foldable Robotics, Basiliscus basiliscus, Four-bar Mechanism, Biomechanics, Gait pattern analysis.**

PART 1: GOALS OF THE PROJECT

A. Scope

The project focuses on designing a four-bar mechanism for the hind legs of a basilisk lizard-inspired robot. The primary goal is to replicate the lizard's unique ability to transition from quadrupedal to bipedal locomotion, specifically on land. The robot will use foldable robotics techniques, with the following constraints:

- Using a four-bar mechanism for hind limb movement.
- Implementing sprung dummy forelegs made of cardstock.
- Designing a tail for balance and support, either as a static or dynamic component.
- Limiting materials and components to those suitable for foldable robotics.

B. Impact

This project is timely and relevant due to the growing interest in biomimetic robotics and efficient locomotion systems:

- **Importance:** Offers insights into adaptable robotic systems that mimic biological models, potentially benefiting robotics in search and rescue, exploration, or entertainment.
- **Current Relevance:** Advancements in materials and manufacturing methods in robotics have made such projects feasible now compared to 10 years ago.
- **Broader Impacts:** Could influence designs in robotics by demonstrating efficient energy use and adaptability by using soft foldable components, inspiring innovations in various fields.

C. Team Fit

Answering this question involves a deep exploration of the lizard's biomechanics and a solid understanding of the kinematic and dynamic analysis needed for the robot's design. It provides the team with an ideal opportunity to gain hands-on experience with simulation software like MuJoCo, allowing us to simulate and refine the foldable robot effectively.

D. Topic Fit

The project is well-aligned with the principles of foldable robotics and biomimetic systems. By drawing inspiration from the basilisk lizard's unique ability to transition from quadrupedal to bipedal locomotion, the project explores innovative ways to replicate these movements in a robotic system. The use of a four-bar mechanism to mimic the lizard's gait pattern aligns with concepts taught in class and textitasizes adaptability and efficiency. This focus on transitioning between different modes of locomotion addresses key challenges in robotic mobility, making the project relevant to ongoing research in both biomimetics and robotics.

PART 2: BACKGROUND RESEARCH

To inform our project on *Basiliscus basiliscus* locomotion, we conducted extensive background research by reviewing key scientific papers. These studies utilized digital particle image velocimetry and force measurement techniques to explore how the lizard generates support and propulsive forces while running on water. By focusing on the slap and stroke phases of its stride, we gained a deep understanding of the biomechanics involved in rapid locomotion. This foundational knowledge is crucial for applying these principles to the design of the robotic systems, allowing us to replicate the lizard's dynamic movement in our project.

A. Reference Contribution

- *Glasheen and McMahon [2]:*
  Value: Provides insights into the biomechanics of basilisk lizards, particularly focusing on size and force dynamics. This informs the design of the robot's four-bar mechanism to mimic limb dynamics on land.
- *Hsieh and Lauder [1]:*
  Value: Offers detailed analysis of forces generated during

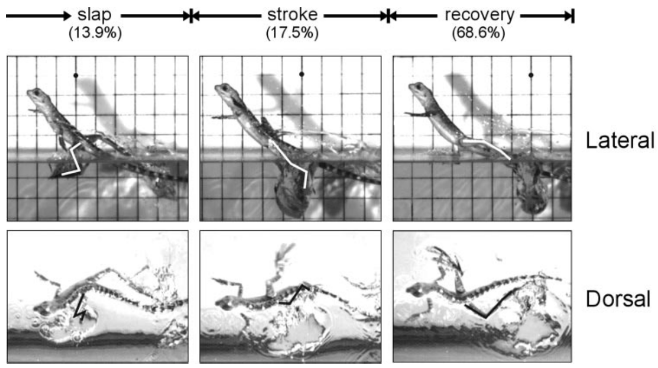

Fig. 1. Kinematic phases of stride Dorsal and Lateral views of an 18g lizard running across the water surface.[1]

water running, which is crucial for modeling robotic limb motion. The data ensures bio mechanically sound and efficient movement.

- *Floyd, Keegan, Palmisano, et al. [3]:*
  Value: Discusses bio-inspired robotic design and control, providing methodologies that can be adapted for your project. It highlights strategies for achieving dynamic balance, relevant for transitioning from quadrupedal to bipedal locomotion.
- *Floyd and Sitti [4]:*
  Value: Focuses on robotic locomotion inspired by basilisk lizards, offering insights into gait patterns and mechanical design. It supports the development of a foldable mechanism that replicates the lizard's unique movement.

B. Key Information

- **Typical Mass and Speed:** Basilisk lizards typically weigh between 2 g and 200 g, achieving speeds of about 1.6 m/s on water. This speed is facilitated by rapid limb movements and efficient energy transfer, allowing the lizard to maintain balance and propulsion across fluid surfaces [1].
- **Stride Characteristics:** The stride involves a slap phase with peak foot velocities around 3.75 m/s, generating upward forces of 15-30% of body weight. The stroke phase is crucial for propulsion, involving significant knee joint motion and coordinated limb movements to maintain stability and forward momentum [2].
- **Ground Reaction Forces:** Vertical forces during the slap phase can reach up to 225% of body weight, while transverse forces help stabilize the lizard by shifting from medial to lateral throughout the step. These forces are essential for maintaining balance and effective propulsion during rapid locomotion [2].
- **Mechanical Energy and Muscle Forces:** The hindlimb functions like a piston, textitasizing force generation over energy storage. Muscle forces are optimized for rapid movements, particularly at the knee joint, allowing quick acceleration and deceleration without losing stability [2].
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- **Biological Materials:** The tail serves as a counterweight, comprising about 18% of body mass, crucial for balance during bipedal locomotion. Toe fringes enhance foot surface area, aiding in impulse generation by improving contact with the water surface [2].

These insights are vital for designing robotic systems that mimic basilisk lizard locomotion, focusing on mechanical efficiency and dynamic stability for applications in robotics and biomechanics.

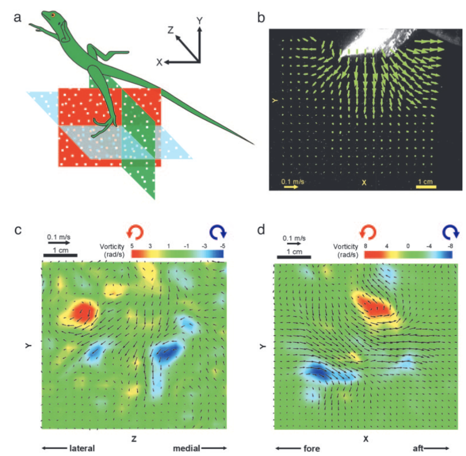

Fig. 2. Vorticity when the lizard runs on water.

C. Gait Pattern

The basilisk lizard's gait when running on water involves three distinct phases: *slap*, *stroke*, and *recovery* as shown in Figure 3.

During the *slap* phase, the lizard's foot strikes the water surface with high velocity, generating an upward force that helps support its body weight. This phase is crucial for initial lift.

In the *stroke* phase, the foot moves backward through the water, creating thrust that propels the lizard forward while maintaining lift. The foot's motion generates vortices that contribute to both propulsion and stability.

Finally, during the *recovery* phase, the foot is lifted out of the water and repositioned for the next step. This phase involves curling the toes to minimize drag as the foot exits the water cavity. The entire cycle is repeated rapidly, allowing the lizard to maintain speeds of up to 1.5 m/s across water surfaces.

These phases are coordinated with precise timing to ensure that each foot completes its cycle before the air cavity created by its movement collapses, preventing sinking. This unique gait allows basilisk lizards to effectively "walk on water," a capability that has inspired biomimetic robotic designs aiming to replicate this efficient form of locomotion.

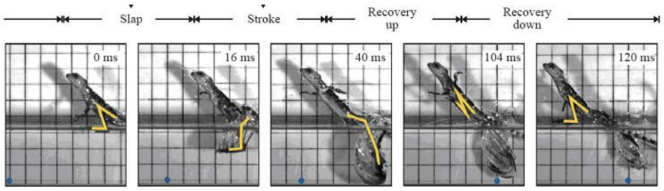

Fig. 3. Phases of a basilisk lizard's step. Time for each frame is shown in milliseconds in the upper right corner.

Fig. 4. High speed footage of robot movements as compared to the lizard.

D. Project Novelty

Our project is novel because it integrates biomimetic principles with foldable robotics to create a versatile system capable of mimicking the basilisk lizard's locomotion on land. By focusing on transitioning from quadrupedal to bipedal movement, we aim to introduce an innovative approach that prioritizes adaptability and efficiency. This design replicates complex biological movements and leverages foldable structures for enhanced compactness and functionality, offering potential applications in exploration and rescue operations in tough terrains.

Part 3: Estimation of Goal Performance Metrics

A. Average Acceleration

The average acceleration was calculated based on the ground reaction force ($F = 1.46\,\text{N}$) and the total mass ($m = 0.078\,\text{kg}$). Using the formula for acceleration:

$$a = \frac{F}{m} \tag{1}$$

Substituting the values, we get:

$$a = \frac{1.46}{0.078} \approx 18.71\,\text{m/s}^2 \tag{2}$$

This result is higher than expected for average acceleration and might represent a peak acceleration value. For a more accurate average acceleration, additional data on the lizard's movement patterns would be required.

B. Volume of Lizard

The volume was calculated using the maximum mass ($m = 0.078\,\text{kg}$) and an assumed average density for lizards ($\rho = 1200\,\text{kg/m}^3$). Using the formula for volume:

$$V = \frac{m}{\rho} \tag{3}$$

Substituting the values, we get:

$$V = \frac{0.078}{1200} \approx 6.5 \times 10^{-5}\,\text{m}^3 \tag{4}$$

This calculation assumes a uniform density, which may not be entirely accurate for a real lizard but provides a reasonable estimate.

C. Friction Coefficients

The static and kinetic friction coefficients for land and the friction coefficient for water were estimated based on typical values for lizards:

- Static friction coefficient (land): 0.87
- Kinetic friction coefficient (land): 0.67
- Friction coefficient (water): 0.38

These values are approximations and may vary depending on the specific surface conditions and the lizard's physiology.

Part 4: Specification Table

We have combined the design critical parameters from the background research into a table given below.
Please refer to Table I

Part 6: Developing an analogous mechanism

A. Making the mechanism

We have designed the mechanism with three major subcomponents. We have chosen the SVL (Snout-to-Vent-Length) of the prototype to be around 30.5cm with width and height being 6cm. We have designed the tail length to be around 1.5 times the SVL[6][5]. This gives us a tail length of approximately 46cm. The third major component is the hind limbs of the robot. We have designed a four-bar mechanism for the limbs with limb lengths as shown in Figure 6.

Fig. 5. Robot Prototype : Isometric view(left), Top view (right)

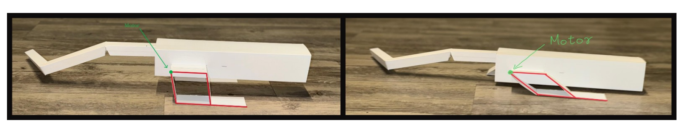

Fig. 6. Robot Prototype : Side view with motor placement and four-bar mechanism visible along with motion of the joint

B. Proposed mechanism

We propose to model a four-bar mechanism similar to the one in [3] as shown in Figure 7

We have taken inspiration from the figure 7 and designed our own four-bar mechanism as shown below.

Parameter	Unit (SI)	Value	Reference
Reaction forces (Vertical)	N	43 - 54	[1]
Hind limb length	m	0.048 - 0.137	[1]
Body Length	m	0.203	[5]
Tail Length	m	0.800	[5]
Hip joint angle range	degrees	55 - 140	[6]
Knee joint angle range	degrees	60 - 140	[6]
Ankle joint angle range	degrees	70 - 170	[6]
Walking speed (on water)	m/s	1.3 - 1.6	[1]
Ground reaction force (peak)	N	0.015 - 1.46	[1]
Stride frequency	Hz	5.3 - 12.8	[1]
Duty factor	-	0.18 - 0.37	[1]
Stride length	m	0.11 - 0.29	[6]
Foot slap duration	s	0.020 - 0.035	[1]
Foot stroke duration	s	0.035 - 0.060	[1]
Foot area	m^2	$0.00016 - 0.0016$	[6]
Total mass	kg	0.2 - 0.078	[2]
Reaction forces (vertical)	% body weight	110 - 225	[2]
Average acceleration	m/s^2	18.71	Equation (2)
Volume of lizard	m^3	6.5×10^{-5}	Equation (4)
Static friction coefficient (land)	-	0.8	[2]
Dynamic friction coefficient (land)	-	0.6	[2]
Friction coefficient (water)	-	0.3	[2]

TABLE I
BIOMECHANICAL PARAMETERS FOR THE BASILISK LIZARD

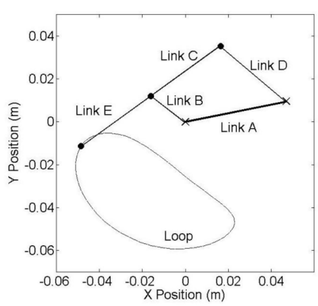

Fig. 7. Four bar mechanism modeling lizard limb movement as seen in [3]

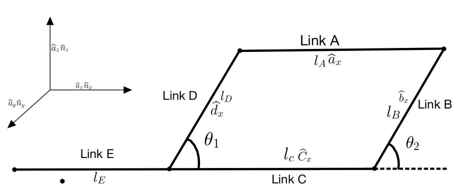

Fig. 8. Four-bar mechanism designed for the prototype robot

PART 7: SYSTEM IDENTIDFICATION

We plan to conduct a series of critical experiments to optimize our design parameters and performance metrics and assign key experiments to team members as shown in Table II. Our experimental protocol encompasses the following key investigations:

A. Servo Characterization

We'll characterize our servo motors, focusing on those for the hind limbs, which are crucial for locomotion.

Experimental setup:

- Simple lever arm attached to the servo horn
- Various weights for load application
- Protractor for angle measurement
- Multimeter for current measurement

Measurements:

- Maximum torque output at different angles
- Speed-torque curve
- Positioning accuracy and repeatability
- Power consumption under various loads

We'll apply known weights at different distances from the rotation axis, recording the servo's ability to hold position and move under load. We'll also measure current draw to calculate power consumption. This data will help determine if our chosen servos can handle the robot's weight and perform the four-legged to two-legged transition.

B. Link Stiffness Experiment

We'll test the stiffness of our links made from cardstock and thin plastic film to ensure structural integrity.

Experimental setup:

- Sample links of various designs and material combinations

- Secure mounting point
- Weights for load application
- Ruler or digital caliper for deflection measurement

We'll apply known loads to the free end of secured links and measure the resulting deflection. By plotting load vs. deflection, we'll determine the stiffness of different link designs, optimizing for the right balance of strength and flexibility.

C. Joint Stiffness Experiment

We'll measure the stiffness of our joints, particularly for the 4-bar mechanism in the hind limbs and potentially for an active tail.

Experimental setup:

- Prototype joints mimicking our robot's design
- Weights and lever arm for torque application
- Protractor or IMU for angular deflection measurement

We'll apply known torques to our joints and measure the resulting angular deflection, repeating for different joint configurations and materials. This data will help fine-tune joint stiffness for optimal performance during stance transitions.

D. MuJoCo Model Experiment

We'll create a detailed MuJoCo model of our robot to simulate and refine the design before physical prototyping.

Process:

- Create 3D models of robot components
- Define joints, particularly the 4-bar mechanism
- Input material properties from stiffness and friction experiments
- Implement actuator models based on servo characterization
- Simulate various environments, including water-like interfaces

Starting with a basic model, we'll gradually increase complexity, testing different gaits for four-legged and two-legged locomotion. We'll simulate stance transitions and adjust parameters to optimize stability and efficiency.

E. Balance Point Experiment

To determine the optimal posture for a two-legged stance, we will conduct a balance point experiment.

Experimental setup:

- Robot with adjustable limb positions
- IMU attached to the body
- Flat, stable surface (later, a water-like interface)

We'll adjust the robot's posture, focusing on:

- Hind limb angles
- Center of mass position
- Body orientation
- Forelimb position and angle (if not dummy)
- Tail position and angle

For each configuration, we'll measure:

- Balance duration
- Stability metrics from the IMU
- Servo energy consumption

Using servo control to adjust joint angles incrementally, we'll record IMU data for each configuration to identify the optimal posture for stable two-legged locomotion.

F. Tail Effectiveness Experiment

To optimize our robot's tail design, we'll test its contribution to balance and locomotion.

Tail designs:

- Varying lengths
- Different materials (rigid and flexible)
- Static and actuated designs

Testing:

- Static balance in two-legged stance
- Dynamic stability during locomotion
- Transition from four-legged to two-legged stance
- Simulated water-running motion

Measurements:

- Balance duration in two-legged stance
- Stability metrics from the IMU during motion
- Energy consumption (for actuated designs)
- Success rate of stance transitions

Starting with a static tail as a baseline, we'll test different lengths and materials. For actuated tails, we'll experiment with various movement patterns synchronized with leg motion. IMU data analysis will quantify the tail's contribution to stability in different scenarios.

Part 8: 'Part 2' Roadmap

We list below a detailed roadmap of all the activities and responsibilities assigned to the team members along with the specific tasks assigned and the explanation of each task. We have chronologically categorized the table to perform one task and experiment after the other. Please refer to Table III

Item	Pranay	Puneet
Servo Characterization	x	
Link Stiffness Experiment	x	
Joint Stiffness Experiment		x
Mujoco model Experiment		x
Tail effectiveness Experiment	x	
Balance Point Experiment		x

TABLE II
TEAM LEAD FOR EACH EXPERIMENT

Task Category	Specific Task	Assigned To	Explanation
Materials & Design	Select/procure materials	Puneet	Choose and obtain cardstock, plastic film, servos, ESP32, IMU for robot structure and control.
	Design 4-bar mechanism	Pranay	Create hind limb mechanism for basilisk-like locomotion.
Prototyping	Construct prototype	Pranay	Build foldable structure as physical basis of robot.
	Integrate electronics	Puneet	Install servos, ESP32, IMU for control and data collection.
Component Testing	Servo characterization	Puneet	Measure servo performance to meet design requirements.
	Stiffness tests	Pranay	Test link/joint stiffness for structural integrity.
System-Level Testing	Motion capture setup	Pranay	Prepare IMU/video for detailed movement analysis.
	Balance experiment	Puneet	Test stability for two-legged stance.
	Tail effectiveness	Pranay	Evaluate tail's role in balance/locomotion.
Data Analysis	Process motion data	Pranay	Extract information from IMU/video for quantitative analysis.
	Analyze metrics	Puneet	Evaluate stability/efficiency to optimize design.
Simulation	Develop MuJoCo model	Puneet	Create virtual model for rapid design testing.
	Optimization routines	Pranay	Fine-tune parameters for improved performance.
Refinement	Iterate on design	Both	Improve based on tests/simulations.
Final Testing	Water-running tests	Both	Simulate water-running to mimic basilisk lizard.
Reporting	Compile results	Pranay	Organize data for final report.
	Prepare final report	Puneet	Summarize project findings and outcomes.
Version Control	Manage Git repository	Puneet	Maintain files and track changes for collaboration.

TABLE III
PROJECT ROADMAP FOR BASILISK LIZARD-INSPIRED FOLDABLE ROBOT

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