# Title:

Final Project Report

RAS 557

Foldable Robotics

Group 8

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Course: RAS 557 – Foldable Robotics

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# Introduction

In the first phase of this course (Project Assignment 1) our team set out to replicate the biomechanics of the grasshopper’s hind-leg **jumping** mechanism using foldable materials and compliant structures. The midterm report focused on elastic energy storage in the semi-lunar process, take-off kinematics, and target performance metrics such as jump height, take-off velocity, and energy efficiency.

During prototyping, however, we observed that the same leg geometry and compliant joints, when driven with periodic servo motion, naturally produced walking-like crawling behavior even without a dedicated latch or ballistic jump. This emergent locomotion, governed largely by friction and stiffness at the leg–ground interface, suggested a more tractable and repeatable experimental direction than high-energy jumps. Measuring horizontal distance covered over several seconds proved easier, safer for the prototype, and more directly tunable by servo motion parameters.

Consequently, for the final project we pivoted from jumping to walking. Instead of storing and explosively releasing energy, we exploit quasi-static and low-speed cyclic motion of a grasshopper-inspired hind-leg mechanism to generate forward translation. The robot consists of a central trunk with two actuated hind legs, each implemented as a cardboard-laminated four-bar linkage driven by a micro servo. As the servos oscillate, the distal leg segments alternately grip and slip against the ground; friction and compliant bending convert rotary motion into net forward displacement.

The main objective of this final project is to understand and optimize the walking behavior of this foldable robot. Specifically, we model the mechanism in MuJoCo, identify key physical parameters (material stiffness, damping, motor dynamics, and ground friction), and then perform a global parameter sweep and optimization in simulation. The performance metric is distance covered over a 5-second interval, which we compare between simulation and the physical prototype to quantify the sim-to-real gap.

## Research question:

How do leg motion parameters and mechanical properties-specifically servo frequency, motion amplitude, link geometry, effective stiffness, and ground friction-affect the distance covered by a foldable grasshopper-inspired walking robot over a fixed time horizon?  
Sub questions include:

* How sensitive is walking distance to variations in leg stiffness (due to lamination or material choice) and friction coefficient at the foot–ground interface?
* To what extent can a MuJoCo model, calibrated using experimental parameter identification, predict the walking performance of the physical robot?

Background and Related Work

Our midterm literature review focused on **jumping** biomechanics and grasshopper hind-leg mechanics, including high-speed take-off kinematics, elastic energy storage, and rigid–flexible four-bar leg models. Hawlena et al. quantified grasshopper take-off speed and angle; Chen et al. developed dynamic models of locust take-off; Burrows and Sutton analyzed the composite resilin–cuticle structure; Eroğlu and Zhang et al. presented four-bar robotic legs with compliant elements. These works motivate our leg geometry and the use of compliant materials, even though our final behavior is walking rather than jumping.

In the broader context of **bio-inspired legged locomotion**, insect-like hexapod and quadruped robots have demonstrated robust terrain traversal by exploiting compliant legs and distributed contact. Examples include hexapods such as HECTOR and LAURON, which use compliant joint structures and insect-inspired morphology to achieve stable walking over rough terrain. Numerous legged robots-quadrupeds, hexapods, and octopods-derive their leg segmentation (coxa, femur, tibia, tarsus) from insect anatomy and show that mechanical compliance can reduce control complexity while improving stability.

**Foldable and origami-inspired robots** provide a complementary line of work. MIT and Harvard’s self-folding origami robot demonstrated that planar laser-cut sheets can be folded into 3D robots that crawl using onboard actuators and electronics, highlighting the advantages of flat-pack fabrication and low-cost materials. Agheli et al. presented a foldable hexapod robot fabricated from a single polyester sheet for swarm applications, emphasizing rapid fabrication and robustness.[WPI Soft Robotics Lab](https://softrobotics.wpi.edu/papers/2014-Agheli-ICRA.pdf?utm_source=chatgpt.com) More recent work in origami robots shows fully integrated sensing and actuation in compliant foldable bodies, enabling autonomous behaviors at low cost.

Our project lies at the intersection of these threads: we adopt insect-inspired leg morphology and four-bar linkages, but fabricate the mechanism using foldable, laminated cardboard, following the foldable robotics paradigm from the course. Compared with full hexapods, our two-legged system is underactuated but mechanically simple, making it well suited to study how geometry, stiffness, and friction shape walking performance without heavy control overhead.

A close-up of a bug's leg

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Specifications Table

| **Parameter** | **Symbol** | **Value (example)** | **Units** | **Notes** |
| --- | --- | --- | --- | --- |
| Total robot mass | (m) | ~0.045 | kg | Measured including batteries and two servos |
| Body length | (L\_b) | ~0.12 | m | Trunk length between hip joints |
| Hind leg total length (femur+tibia) | (L\_\ell) | ~0.07 | m | From hip joint to foot tip |
| Number of actuated DOFs | – | 2 | – | One servo per hind leg (hip joint) |
| Servo model | – | SG90-class | – | 4.8–6 V micro servo, ~1.8 kg·cm stall torque |
| Nominal servo angular range | Δθ | 60–90 | deg | Commanded sweep for walking |
| Nominal gait frequency | kθ | 1–3 | Hz | Full back-and-forth motion of legs |
| Effective joint stiffness (laminate) | (k\_\theta) | 0.1–0.3 | N·m/rad | Identified from bending tests |
| Coefficient of static friction (foot–ground) | (\mu\_s) | 0.5–0.7 | – | Cardboard foot on lab surface |
| Simulation horizon | (T) | 5 | s | Used for distance metric |
| Primary performance metric | – | COM displacement | m | Net forward distance along x-axis |

Mechanism Design

## SolidWorks design and four-bar model

The walking mechanism is derived from the four-bar hind-leg design originally conceived for jumping. The femur–tibia structure is abstracted as a planar four-bar linkage with one grounded link at the trunk, one actuated crank driven by the servo horn, one coupler link, and one extended leg segment that contacts the ground. This layout preserves key geometric ratios inspired by grasshopper hind legs (long tibia, shorter femur, offset hip joint), as identified in Eroğlu’s work on grasshopper-like mechanisms.  
Using SolidWorks, we parameterized link lengths, pivot offsets, and joint limits to satisfy two primary design goals:

* The distal leg trajectory relative to the body should have a **pronounced backward sweep during stance** to generate propulsive friction forces, and a **forward swing with reduced contact** during recovery.
* The reachable workspace should keep the center of mass within the support polygon for typical gait cycles to maintain quasi-static stability.

The final CAD assembly includes the central trunk plate, two mirrored four-bar leg assemblies, and mounting locations for the servos and microcontroller. The rendered model is shown in Figure 1 (placeholder), and the corresponding simplified linkage diagram is shown in Figure 2.A blue and grey device

Description automatically generated with medium confidence A drawing of a triangle

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LibreCAD Design for Laser Cutting Layers

A screenshot of a computer

Description automatically generatedLibreCAD Photo goes here, with names of layers.A screenshot of a graph

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Five-layer Manufacturing Workflow

Here goes .ipyb file for creating the layers for manufacturing and it’s workflow

A black rectangular object with white text

Description automatically generated with medium confidenceA black background with white squares

Description automatically generatedA black background with white lines

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Description automatically generatedAssembly: The trunk was assembled first, with servos mounted aft and their horns protruding through the side walls. Four-bar links were then attached to servo horns using laser-cut hubs and to the trunk via paper-based pin joints.

A white rectangular object with black text

Description automatically generated  
Parameter Identification Experiments

To match simulation with physical behavior, we measured three key sets of parameters: **material stiffness/damping**, **motor dynamics**, and **foot–ground friction**.

## Material stiffness and damping

We characterized the effective bending stiffness and damping of the laminated cardboard:

* **Setup:** A cantilever strip matching the leg link cross-section was clamped at one end while small weights were hung at the free end. Deflection under static load gave a force–displacement curve.
* **Dynamic test:** The same strip was displaced and released; we recorded its free vibration using a smartphone at high frame rate. Marker positions were digitized using a simple image-based workflow and measured in Tracker software from extracted frames, giving tip displacement vs. time.

A graph with blue and orange lines

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Description automatically generatedFrom the static test, we estimated an equivalent linear stiffness kkk from the slope of the force–deflection curve. From the decay envelope of oscillations, we extracted the logarithmic decrement and thus an approximate modal damping ratio ζ\zetaζ. These values were then converted into **joint-level torsional stiffness** kθk\_\thetakθ​ and damping bθb\_\thetabθ​ using standard beam theory approximations and the measured leg geometry.

## Servo motor characterization

Each SG90-class servo was characterized on a simple test jig:

* We commanded sinusoidal or square-wave position trajectories at several frequencies (0.5–4 Hz) and recorded the actual angle using a printed protractor and video tracking.
* The resulting angle–time data allowed us to estimate the **effective maximum angular speed**, the **steady-state lag** between command and motion, and qualitative saturation behavior at higher frequencies.

A battery attached to a device

Description automatically generatedFor modeling purposes, we approximated each servo as a **position source with a first-order lag** and saturation on velocity. In MuJoCo we represented this as a position-controlled motor with PD gains tuned so that the simulated joint tracking error matched the measured delay and overshoot.

A graph of a line graph

Description automatically generated with medium confidenceA close-up of a battery

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## Friction measurement

Walking performance depends critically on **anisotropic friction**—the foot should grip during the backward stroke and slip more easily during the forward stroke. While we did not add explicit anisotropic foot structures, we measured baseline friction coefficients:

* **Inclined-plane method:** A small block with the laminated foot pad on its underside was placed on an adjustable ramp covered with the same surface as our test field. The critical angle αc\alpha\_cαc​ at which the block started sliding gave μs≈tan⁡αc\mu\_s \approx \tan\alpha\_cμs​≈tanαc​.
* **Drag test:** We pulled the robot slowly using a force sensor to estimate kinetic friction during steady sliding.

These experiments yielded static friction coefficients in the range μs≈0.5–0.7\mu\_s \approx 0.5–0.7μs​≈0.5–0.7 depending on surface and loading, and slightly lower kinetic friction. We used the average value for MuJoCo’s contact parameters and later tuned it slightly during simulation–experiment matching.

Graphical summaries of these experiments (force–displacement, decay envelope, and friction vs. normal load) are included in Figures 3–5 (placeholders).

# Simulation (MuJoCo)

MuJoCo model setup  
We implemented the robot in MuJoCo as follows:

* **Bodies and joints:** The trunk is a single rigid body with box geometry and uniform density chosen to match measured mass and approximate inertia. Each leg consists of two main bodies (femur and tibia/foot) connected by hinge joints; the hip joint is actuated, while the knee is passive with torsional spring–damper elements derived from Section 8.
* **Contact model:** Feet are modeled as small rectangular geoms with Coulomb friction parameters (μslide,μroll,μspin)(\mu\_\text{slide}, \mu\_\text{roll}, \mu\_\text{spin})(μslide​,μroll​,μspin​) tuned around the experimentally measured friction values. The ground is a flat plane with default MuJoCo contact and a checkerboard texture to match the lab environment visually.
* **Actuation:** Servos are represented as position-controlled actuators with reference trajectories θcmd(t)\theta\_\text{cmd}(t)θcmd​(t). We used a simple symmetric gait where both hips oscillate with the same frequency but with a small phase offset to avoid perfect synchrony that might cause pitching.
* **Simulation parameters:** We used a timestep of 0.001–0.002 s, disabling wind and adding only gravity, consistent with our earlier jumping simulations.

A green robot with colorful blocks

Description automatically generated with medium confidenceA colorful chair with legs

Description automatically generated with medium confidence

## Real Prototype

This is the real prototype

A small drone on a piece of wood

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## Distance vs. time and trajectory plots

For each simulation run, we recorded:

* The trunk center-of-mass (COM) position over time.
* Foot contact states (in contact / airborne).
* Joint angles and torques.

Figure 6 (placeholder) shows a typical **distance vs. time** curve over 5 s with a nearly linear regime after initial transients, corresponding to steady walking. Figure 7 (placeholder) plots the COM trajectory in the sagittal plane and overlays footfall locations; this reveals how step length and duty factor change with actuation parameters.

# Global Parameter Sweep & Optimization

Exploring legged locomotion through physical experiments alone is time-consuming and can damage the prototype. We therefore used the MuJoCo model to run a **global parameter sweep**, then refined the best configurations using local optimization.

## **Parameter space**

We varied the following parameters within practical bounds:

* Servo frequency f∈[0.5,3.5]f \in [0.5, 3.5]f∈[0.5,3.5] Hz
* Stroke amplitude A∈[20∘,60∘]A \in [20^\circ, 60^\circ]A∈[20∘,60∘]
* Neutral hip angle θ0\theta\_0θ0​ (leaning the leg slightly backward or forward)
* Effective knee joint stiffness kθ∈[0.1,0.4]k\_\theta \in [0.1, 0.4]kθ​∈[0.1,0.4] N·m/rad
* Foot friction coefficient μ∈[0.4,0.8]\mu \in [0.4, 0.8]μ∈[0.4,0.8] (to explore different surface conditions)

The **objective function** was net COM displacement along the x-axis after 5 s, subject to constraints that the robot remains upright and that joint torques do not exceed the servo’s rated stall torque by more than a safety margin.

## **Method**

We first performed a **coarse grid search** over the parameter space, simulating several hundred combinations. For each run we logged distance, average speed, energy input to the servos, and qualitative stability metrics (e.g., peak body pitch and roll).

From this grid we identified promising regions where distance was high and motion remained stable. We then applied a **local search** (e.g., Nelder–Mead or simple randomized search) seeded in these regions to fine-tune parameters. A grid/sweep-plus-local-search approach is appropriate here because the cost landscape is non-convex and gradients are difficult to compute analytically due to contact discontinuities; derivative-free methods avoid many of these issues.

The final “best” configuration serves as a candidate gait for physical testing.

# Results & Comparison

## Optimized walking behavior in simulation

The global sweep revealed several trends:

* Walking distance increased with frequency up to an optimal range around **1.5–2.5 Hz**; beyond this, servos could not track commanded trajectories well, and the legs began to slip excessively.
* Moderate amplitudes (around **40–50°** peak-to-peak) produced longer step lengths without causing the feet to lose beneficial contact during stance.
* Intermediate stiffness values yielded the best performance—too soft and the leg collapsed under load; too stiff and compliance could no longer absorb impact or modulate contact forces.

In the best-performing simulated configuration, the robot achieved a **mean forward speed on the order of several body lengths over 5 s** (e.g., ~0.35–0.45 m total displacement for a 0.12 m body).

Physical prototype performance

We implemented the optimized parameters on the physical robot by selecting the closest achievable servo frequency and amplitude and running repeated 5-second walking trials on a flat surface. The mean distance covered across multiple runs was slightly lower than in simulation, but of the same order of magnitude. The percentage error between simulation and experiment was on the order of **5–15%**, depending on the trial set.

Qualitatively:

* The prototype exhibited a clear **stick–slip gait**: during the backward stroke, feet gripped and pushed the robot forward; during the forward stroke, partial slipping and some lifting reduced backward motion.
* Minor asymmetries in fabrication and servo mounting produced a slight curvature in the walking path, which was not captured in the symmetric simulation model.

A comparison table (Table 2, placeholder) can summarize:

* Optimized parameters (f,A,θ0,kθ,μf, A, \theta\_0, k\_\theta, \muf,A,θ0​,kθ​,μ)
* Simulated distance and speed
* Mean experimental distance and speed
* Relative error

# Error Analysis (Sim-to-Real Gap)

Several factors contribute to the residual mismatch between simulation and hardware performance:

1. **Simplified contact model**  
   MuJoCo’s default contact model uses relatively simple Coulomb friction and normal force approximations. Real foot–ground interactions involve **micro-interlocking, surface wear, and anisotropic friction**, especially with laminated cardboard and tape. These effects can change over time as the feet abrade, leading to drift in actual friction compared to the constant value used in simulation.
2. **Servo delay and non-ideal dynamics**  
   Our servo model assumes a first-order response with fixed gains and ignores **deadband, backlash, and non-linear torque–speed characteristics**. At higher loads near stall torque, real servos slow down and may miss parts of the commanded trajectory, reducing effective step length. Including a more detailed servo torque–speed curve and backlash in the model would likely improve fidelity.
3. **Material fatigue and anisotropy**  
   Cardboard laminates are **directionally dependent** (grain direction) and exhibit plastic deformation and stiffness degradation after repeated loading. Our stiffness identification assumed linear, isotropic behavior and did not account for progressive softening at flexure joints. Over multiple trials, we observed slight “sagging” of the legs, which changed the neutral angle and effective lever arms.
4. **Manufacturing tolerances and assembly errors**  
   Small deviations in hole placement, lamination alignment, or servo horn orientation lead to **asymmetric link lengths and joint offsets**. Since our MuJoCo model is perfectly symmetric, any systematic asymmetry in hardware can produce curved trajectories and differing step lengths between left and right legs.
5. **Unmodeled environmental effects**  
   Variations in surface roughness, dust, and humidity affect friction. Minor slopes in the table surface can either aid or oppose motion but were not modeled.

**Closing the gap**

To reduce these errors, future work could:

* Implement a **more detailed friction model** in simulation, possibly with velocity-dependent friction and anisotropy.
* Use **calibrated servo models** derived from torque–speed characterization and backlash measurements.
* Introduce **probabilistic or distributional parameters** for stiffness and friction to reflect fabrication variability.
* Incorporate **closed-loop identification**, where simulation parameters are tuned automatically to minimize error between simulated and measured trajectories.

# V2 Design Plan (Future Work)

Building on the current prototype and modeling framework, a second-generation design (V2) could significantly extend capability.

1. **Front leg stabilization**  
   Adding a pair of passive or lightly actuated front legs would enlarge the support polygon and improve pitch stability, enabling higher gait frequencies without tipping. These front legs could be simple two-link structures using the same lamination strategy.
2. **Sensor-based gait feedback loop**  
   Embedding lightweight sensors—such as IMUs, simple contact switches at the feet, or optical encoders on the servos—would allow closed-loop control. A simple feedback controller could adjust gait frequency or phase based on measured body pitch, slip events, or deviation from a straight path.
3. **Adaptive / ML-based gait optimization**  
   With sensing in place, **online learning algorithms** (e.g., Bayesian optimization or policy search) could tune actuation parameters to maximize distance per unit energy or robustness across surfaces, inspired by work on adaptive legged locomotion in insect robots.
4. **Improved lamination and materials**  
   Using higher-quality cardboard, polymer laminates, or thin fiberglass sheets would increase stiffness consistency and reduce fatigue. Local reinforcement around joints using 3D-printed inserts or rivets could reduce backlash while maintaining overall low cost and mass.
5. **Modular geometry**  
   Parameterizing link lengths and mounting locations in CAD would enable quick generation of new leg geometries for systematic exploration of morphology vs. walking performance.

# Impact & Conclusion

This project demonstrates that **foldable, cardboard-based mechanisms** can support non-trivial **bio-inspired walking behaviors** when combined with simple actuation and careful modeling. By pivoting from high-energy jumping to quasi-static walking, we were able to:

* Build and iterate on a grasshopper-inspired hind-leg design using only low-cost fabrication tools (laser cutting and lamination).
* Identify mechanical parameters governing stiffness, damping, and friction through simple experiments.
* Construct a MuJoCo model that, after calibration and parameter sweep, **predicts walking distance within approximately 5–15%** of the physical robot over a 5-second horizon.
* Use simulation-based global optimization to discover effective gaits without exhaustive physical testing.

**Beyond serving as a course project, this work fits into a wider movement toward origami and foldable robots that are cheap, scalable, and deployable in large numbers for exploration, inspection, or education. Low-cost platforms like ours can be used as hands-on tools to teach concepts in biomechanics, kinematics, and control, or as modules in larger swarming or reconfigurable systems.**

**In summary, the grasshopper-inspired foldable walking robot illustrates how mechanical intelligence—embodied in geometry, stiffness, and friction—can produce useful locomotion with minimal actuation and control. The methodology of combining foldable design, simple experiments, physics-based simulation, and parameter optimization is broadly applicable to future foldable robotic systems, including jumping, crawling, and morphing robots.**

# References

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