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University of California - Berkeley
The Regents of the University of California
1608 Fourth Street, Suite 220
Berkeley, CA 94710 -1749

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RPPR Final Report
as of 13-Feb-2024

Agency Code: 21XD

Proposal Number: 71957ME **Agreement Number: W911NF-18-1-0038**

INVESTIGATOR(S):

Name: Ronald Fearing
Email: ronf@berkeley.edu
Phone Number: 5106429193
Principal: Y

Organization: **University of California - Berkeley**
Address: The Regents of the University of California, Berkeley, CA 947101749
Country: USA

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Report Date: 05-Jun-2023 Date Received: 08-Feb-2024
Final Report for Period Beginning 06-Dec-2017 and Ending 05-Jun-2023
Title: b. Engineering Sciences i. Mechanical Sciences (3) Complex Systems and Dynamics "W911NF-17-S-0002: 3D Saltatorial Locomotion on Compliant Terrain"
Begin Performance Period: 06-Dec-2017 **End Performance Period:** 05-Jun-2023
Report Term: 0-Other
Submitted By: Ronald Fearing Email: ronf@berkeley.edu
Phone: (510) 642-9193

Distribution Statement:

STEM Degrees: 0 **STEM Participants:** 3

Major Goals: Year 1: Find models and experimental bounds for how 3D jumping on fixed piecewise planar surfaces with compliance is limited by robot performance. Begin by testing fox squirrels using ricochetal saltation on fixed piecewise planar surfaces with compliance. Determine the strategies and performance limits by measuring both the 3D kinematics and ground reaction force.

Year 2: Determine strategies and control limits for recovering from unexpected disturbances due to sliding and compliance which are outside the bounds found in Year 1. Determine strategies and control limits for fox squirrels recovering from unexpected disturbances due to sliding and compliance. Begin careful examination of foot function. Begin to explore alternative animal models such as chinchillas or jerboas.

Year 3: Understand how to transition between quasistatic and dynamic motions as needed for complex terrain or recovery from disturbances.

Year 4 (Aug. 2022 to June 5, 2023): Refine evaluation of trade-offs between force and torque for balanced landing in both squirrel and Salto, as well as sources of uncertainty in landings. Prototype new squirrel-inspired robotic feet designs. Integrate work from years 1-3.

Accomplishments: FORCE-TORQUE BALANCE STRATEGIES AND TOUCHDOWN CONDITIONS

As reported in the previous progress report, we have successfully demonstrated branch-to-branch jumping with the Salto robot, as shown in Figure 1B. In the last reporting period, the branch jumps and landings of Salto were analyzed with the pendulum leg extension model. The goal was to develop a unifying framework for arboreal locomotion in squirrels and Salto (Fig. 1). The previous work focused on the trade-offs between torque and force during landing, particularly examining the role of leg extension and the force-torque trade-off for a specific landing condition. In the present period, we examine how the limits of the landing actuation space affects the landing balance region, i.e. the initial conditions from which a balanced landing is possible. We also identify the gripper as a source of measurement uncertainty and propose a new design for a branch-landing gripper.

Figure 2 illustrates the possible balance strategies of squirrels and Salto. Three distinct balance strategies are visualized for both systems: torque only (pink, region 1), radial force only (blue, region 2), and both force and torque simultaneously (green, region 3). Fig. 2A highlights a squirrel’s trial 28, which resulted in a failed balanced landing. Fig. 2B highlights Salto's trial 13, which resulted in catching the branch but ultimately failing to achieve upright balance. Fig. 2C illustrates the squirrel's balance region for each balance strategy as well as landing data from squirrel field experiments. A torque-only balance strategy occupies a band of landing conditions, and the width of this band increases with the ability to apply more torque. However, both Salto and squirrels are limited in their torque capability. A radial leg force-only strategy occupies a larger area, though in contrast to region 1, it has a vertical offset, which helps account more for overshooting trials. The combination of both force and torque strategies yield a landing space that is bigger than the union of regions 1 and 2. Leg force control results in region 3 extending down towards trials in which squirrels undershoot. Utilizing the leg extension and effective torque model for squirrels results in all but one successful and one failed trial correctly classified by region 3, indicating the fidelity of the model and balance strategy.

In contrast to the squirrels, Salto's balance success rate is significantly lower. This could be for many reasons. First, Salto's torque capacity is 0.1, which is approximately ½ that of squirrels'. Second, although its peak force capacity is more than double that of squirrels', its control bandwidth is low, which results in low control authority along the leg. Fig. 2D illustrates a sparse and thin blue region, which is the balance region for Salto's force-only strategy. Third, Salto is limited by the time it takes for it to swing its foot forward. In practice, this means that Salto has to take steeper ballistic trajectories, which results in higher landing speeds. In our experiments, Salto utilized both force and torque to attempt a balanced landing. The two successful landings are correctly classified by region 3. However, most failures are misclassified, indicating a mismatch between Salto's simulated model and hardware experiments.

GRIPPER DESIGN AND SQUIRREL INSPIRATION

A big source of measurement uncertainty comes from Salto's gripper. Fig. 3 illustrates the ideal open and closed state of the gripper, while Fig. 4 plots the gripper's tolerance to lateral and angular offsets (kinematic misalignment) as a polytope. Fig. 4B shows where all the trials fall. Considering only these two parameters, within these bounds, all trials meet these conditions for successful catches (not necessarily balanced landings). As not all these landings were successful catches, it is clear that other state variables at touchdown are also critical. This misalignment model does not take into account the impulse dynamics that take place upon the high-speed contact. Since all trials fall near an edge of the polytope, it is possible that the uncertainty induced by high touchdown speed results in a theoretical catch becoming a miscatch in hardware. Further analysis is required.

From our learnings and observations of squirrel and Salto landings, we developed a simple, articulated mechanism to imitate the way that squirrels grasp branches. The design can be seen in Fig. 5 both in neutral and flexed positions. The mechanism is tendon-driven and could be actuated with a motor, but it is actuated manually to start with, and eventually will be actuated by the weight of the system to which it is attached. Additionally, to reduce misalignment from high-speed impact, damping pads will be added to examine the effect that damping has on landing balance success. An advantage that this design may have is that unlike Salto's gripper, this new gripper design could adapt to both flat and curved surfaces, enabling a system to transition from the ground to a trunk to a branch. With the gripper's passive ability to close, we hypothesize that control can be simplified in a similar way that Salto's current low-friction gripper simplified control.

Training Opportunities: Sebastian Lee mentored two undergraduate students over the summer by meeting with them weekly to design their own squirrel-inspired feet.

Results Dissemination: 1. Journal manuscript in preparation on comparison of squirrel and Salto jumping using pendulum extension model. Current title: ``Monopedal robot branch-to-branch leaping and landing inspired by squirrel balance control'' Paper in collaboration with Prof. Nate Hunt, Univ. of Nebraska, and Prof. Justin Yim, University of Illinois. Expected completion Spring 2024.

2. Abstract Submission in preparation on gap distance effect on squirrel landing kinetics. Expected presentation in Jan 2024 at SICB.

3. Journal manuscript in preparation on gap distance effect on squirrel landing kinetics. Current title: “Stabilization of above-branch landing by free-ranging squirrels using nonprehensile, palmar foot grasps”. Paper in collaboration with Prof. Nate Hunt and Prof. Justin Yim. Expected completion Spring 2024.

Honors and Awards: Nothing to Report

RPPR Final Report
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PARTICIPANTS:

Participant Type: PD/PI
Participant: Ronald S Fearing
Person Months Worked: 1.00 **Funding Support:**
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National Academy Member: N

Participant Type: Co PD/PI
Participant: Robert Full
Person Months Worked: 1.00 **Funding Support:**
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National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Sebastian Lee
Person Months Worked: 3.00 **Funding Support:**
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National Academy Member: N

Participant Type: Undergraduate Student
Participant: Stanley Wang
Person Months Worked: 2.00 **Funding Support:**
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Participant Type: Undergraduate Student
Participant: Tina Kuang
Person Months Worked: 2.00 **Funding Support:**
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Date Submitted: 8/28/20 12:00AM Date Published: 4/1/20 9:00PM
Publication Location:
Article Title: Precision Robotic Leaping and Landing Using Stance-Phase Balance
Authors: Justin K. Yim, Bajwa Roodra Pratap Singh, Eric K. Wang, Roy Featherstone, Ronald S. Fearing
Keywords: legged robots, dynamics, jumping
Abstract: Prior work has addressed control of continuous jumping using touchdown angle from flight, but greater precision can be obtained by directing individual leaps using liftoff angle from stance. We demonstrate targeted leaping as well as balanced landing on a narrow foot with a small, single leg hopping robot, Salto-1P. Accurate and reliable leaping and landing are achieved by the combination of stance-phase balance control based on angular momentum, a launch trajectory that stabilizes the robot at a desired launch angle, and an approximate expression for selecting touchdown angle before landing. Dynamic transitions between standing, hopping, and standing again are now possible in a robot with a narrow foot. We also present approximate bounds on acceptable velocity estimate and angle errors beyond which balanced landing is infeasible. Compared to a prior (SLIP)-like gait, the jump distance s.d. is reduced from 9.2 cm to 1.6 cm.
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CONFERENCE PAPERS:

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Conference Location: Madrid, Spain
Paper Title: Precision Jumping Limits in Salto-1P from Flight-phase Control
Authors: Justin Yim, Ronald Fearing
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Authors: Justin K. Yim, Ronald S. Fearing
Acknowledged Federal Support: **Y**

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Authors: Justin Yim, Eric Wang, Ronald Fearing
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WEBSITES:

URL: https://people.eecs.berkeley.edu/~ronf/Biomimetics.html
Date Received: 12-Aug-2018
Title: Biomimetic Millisystems Lab
Description: Overview of recent results from Biomimetic Millisystems Lab, including research and publcations.
URL: http://polypedal.berkeley.edu/
Date Received: 12-Aug-2018
Title: Polypedal Lab
Description: Prof. Robert Full's Polypedal Lab.

Partners

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I certify that the information in the report is complete and accurate:
Signature: Ronald S. Fearing
Signature Date: 2/8/24 8:53PM

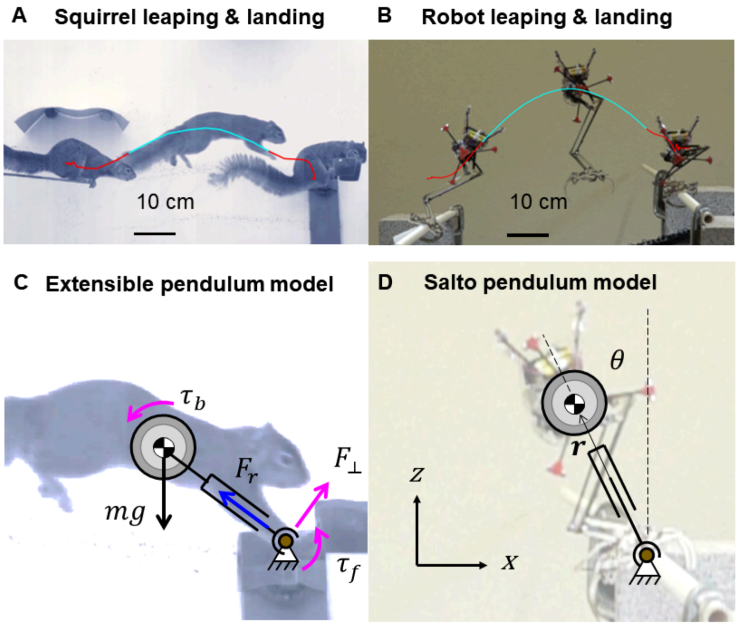

Figure 1. Overview of successful squirrel and SALTO branch-to-branch leap, and simplified extensible pendulum model (from August 2022 Annual report).

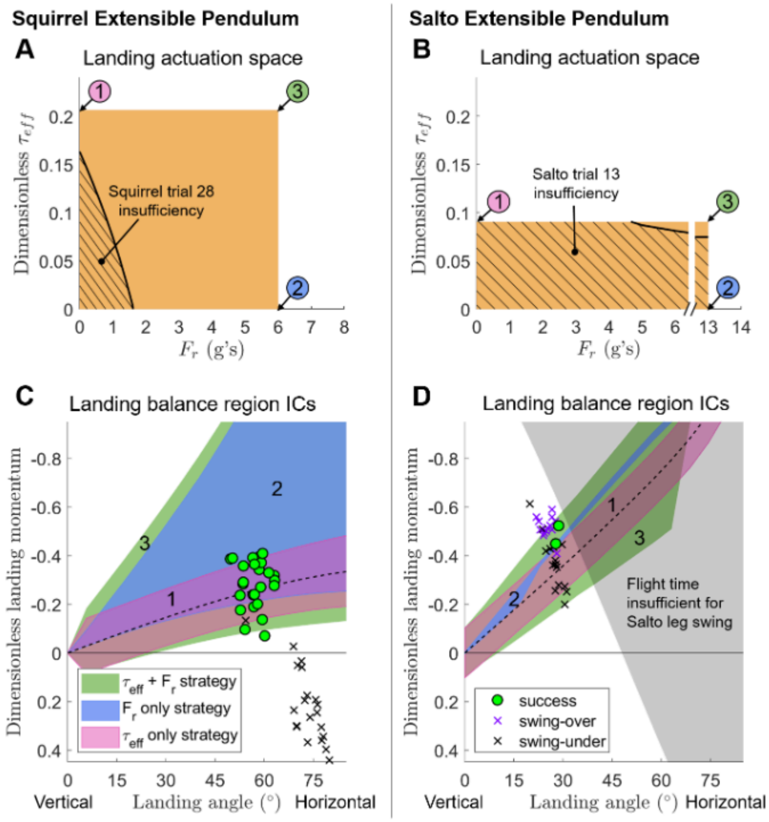

Figure 2: Balance strategies using different amounts of force and torque from the actuation space can balance a range of touchdown conditions.

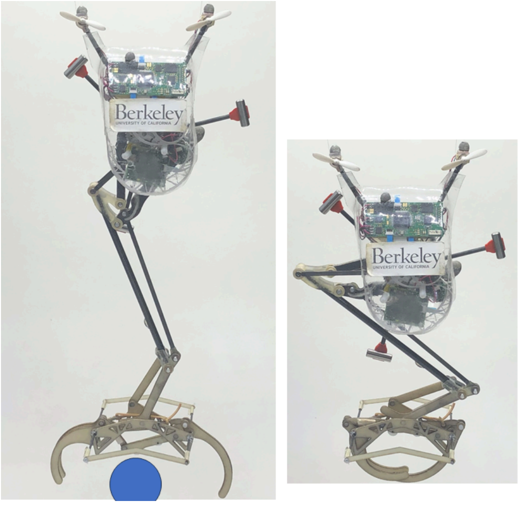

Figure 3. SALTO passive gripper before and after engagement.

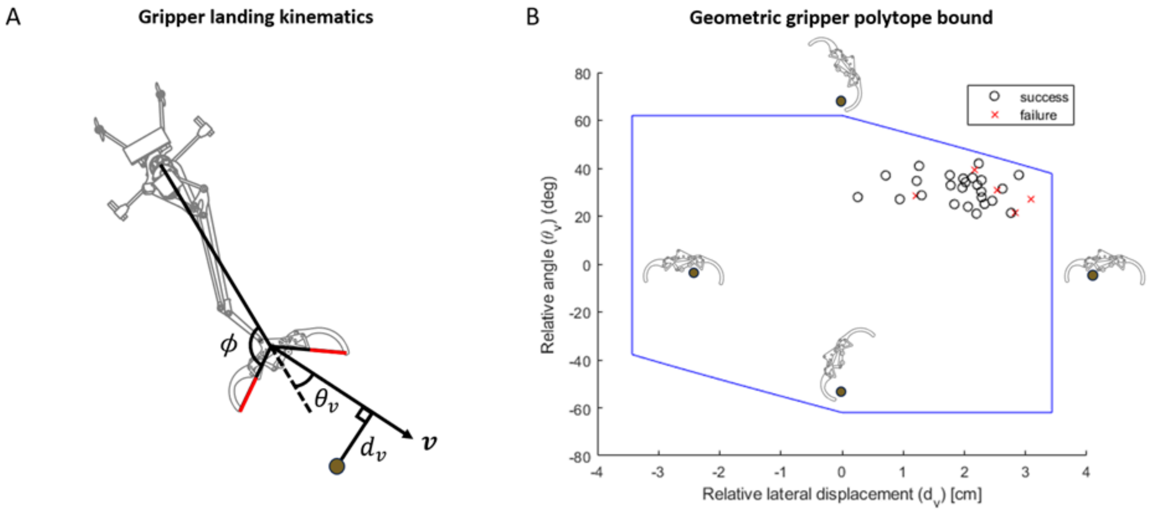

Figure 4. Model of gripper landing kinematics and subset of some necessary landing conditions for gripper engagement.

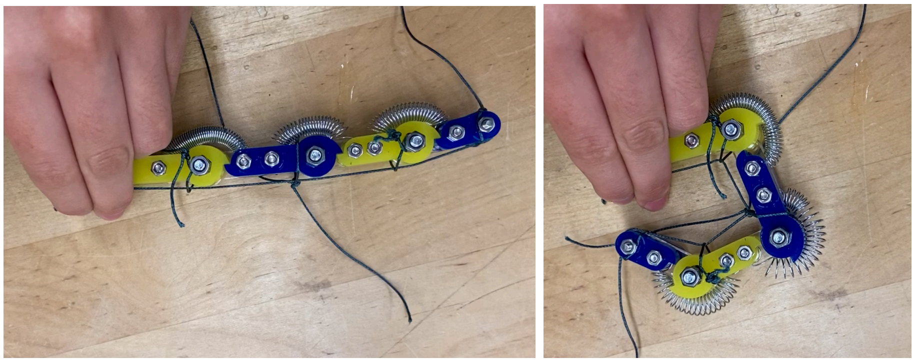

Figure 5: Early segmented foot design for passive dynamic lander. Photos show two states: neutral position (left) and tendon-pulled flexion (right).