REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
28-10-2019	Final Report	3-May-2017 - 2-May-2019

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Dynamics, Robotics, And Kinematics Experiments (DRAKE): Measuring fast Legged Robots as Oscillators	W911NF-17-1-0243
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611103
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Michigan - Ann Arbor 3003 South State Street Ann Arbor, MI 48109 -1274	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 70098-EG-RIP.10

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Shai Revzen
UU	UU	UU	UU		19b. TELEPHONE NUMBER 734-763-3561

RPPR Final Report
as of 07-Jan-2020

Agency Code:

Proposal Number: 70098EGRIP **Agreement Number: W911NF-17-1-0243**

INVESTIGATOR(S):

Name: Shai Revzen
Email: shrevzen@umich.edu
Phone Number: 7347633561
Principal: Y

Organization: **University of Michigan - Ann Arbor**
Address: 3003 South State Street, Ann Arbor, MI 481091274
Country: USA
DUNS Number: 073133571 EIN: 386006309

Report Date: 02-Aug-2019 Date Received: 28-Oct-2019
Final Report for Period Beginning 03-May-2017 and Ending 02-May-2019
Title: Dynamics, Robotics, And Kinematics Experiments (DRAKE): Measuring fast Legged Robots as Oscillators
Begin Performance Period: 03-May-2017 **End Performance Period:** 02-May-2019
Report Term: 0-Other
Submitted By: Michele Feldkamp Email: careymrz@umich.edu
Phone: (734) 647-1813
Distribution Statement: 1-Approved for public release; distribution is unlimited.

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

Major Goals: There are critical gaps in the roboticists' current understanding of effective gaits for robots with more than two legs. Our goal through this DURIP grant was to significantly enhance the instrumentation available in the BIRDS lab of the University of Michigan for researching, investigating, and developing legged robots, and training students in such development and analysis.

By building specially instrumented robots (using equipment purchased via this DURIP grant), we were able to directly measure and understand the contributions of individual legs to the motion of the body. This advances:
The theory of limit-cycle oscillators which describe these gaits
The practical Army goal of building all-terrain robots
The educational goal of training robotics engineers to conduct cutting-edge multidisciplinary research.

DURIP funds served this goal in three ways:

Enhanced rapid fabrication instrumentation—Heretofore, our modular plate-and-reinforced-flexure (PARF) approach to rapid design iteration has been limited to low-cost, low-strength flat materials (such as foam board), which can be precision-cut using a 36” × 24” bed 120 Watt CO2 laser cutter. (Other machining was limited, as it must be done in a centralized machine shop with limited student access.) Adding a Markforged Mark One Professional 3D printer to the BIRDS lab allowed us to produce high-strength specialty parts. This specific 3D printer allows fibers (e.g., carbon, kevlar, fiberglass) to be embedded into the 3D printed object, creating components with remarkable structural strength. Having such a cutting-edge fabrication ability allows us to train our robotics students in the design of 3-printed fiber reinforced structures - a technical skill of emerging value.
Enhanced Motion tracking instrumentation—Motion tracking in the lab reference frame is a key tool for biomechanical research and robotics. The addition of four new Qualisys motion tracking cameras substantially improved our ability to reliably track our robots through the arena. The active marker systems we tested for purchase under this grant did not meet our performance requirements and were subsequently returned to the vendor.
Robot parts for studying dynamic motion—Studying dynamic motion in robots is considerably more challenging than studying quasi-static or kinematic motions. Building up high momentum in a dissipative system requires actuators with high mass-specific power densities, and a body which is tough and strong enough to handle impacts with the ground. In collaboration with University of Pennsylvania, we have already built a RHex-like robot with a mass specific power density 3 to 7 times that of any previous RHex models. With DURIP support, we replaced damaged actuators, added thermal safeties to the motor controllers, and developed an optically coupled ground contact sensor system.

Robot parts for force measurement — using DURIP funds we developed and constructed a robot with full 6DOF force sensing on each leg. This allows us to tease apart the contributions of individual legs to the robots' motion, leading to significant advances in our understanding of the ground interactions that produce multilegged gaits.

Accomplishments: Used our enhanced motion tracking arena to collect new data sets on BigANT 6, Enepod (highly flexible legs, for investigating dynamic motion), and Multipods (especially pertaining to gaits and backbone morphology options in 12-legged Multipod).

Based on earlier work, and enhanced with instrumentation acquired through this DURIP grant, we built "Enepod," a robot that implements the measurement of dominant energy flows within the body of the robot, significantly enhancing the robot's ability to recover from damage. The deformations of the Enepod's highly flexible legs can be measured directly using motion tracking systems improved through this grant. The results were used to develop a novel method for allowing robots to recover locomotion ability after being damaged; publication in preparation.

Extended previous work on event-selected vector fields, showing that a broad class of hybrid oscillators exhibit the same topological dynamics as smooth oscillators through a piecewise smooth conjugacy. Demonstrated that the interaction of legs with the ground can, in and of itself, serve to synchronize legs, without need for any additional control. This class of controllers has reduced proprioceptive requirements and requires lower bandwidth than conventional controllers. Work on implementation of these findings relied strongly on robot components acquired through this grant.

Developed and expanded the "Multipod" family of robots, whose modular design extends from four to 12 legs, enabling us to examine how gaits map up and down the complexity hierarchy. Used enhanced motion tracking arena in conjunction with these robots to prepare datasets for the ARO MURI W911NF-17-1-0306 and for work under ARO W911NF-14-1-0573.

Further advanced RHex robot development. This included applying trajectory-based control and gait recovery to a simplified model of the RHex robot, and developing thermal safety circuits for individual RHex leg motors (as these can draw 6kW), preparatory to pursuing more ambitious gait development. This required the use of the 3D printed leg mount (printed on DURIP-funded printer) to interface these motor to existing legs and mount specialized electronics to optically couple leg contact sensors to the main body of the robot.

Integrated force- and torque-transducers (purchased under this DURIP) into a hexapedal robot, as proposed.

Training Opportunities: Nothing to Report

Results Dissemination: Council, G., & Revzen, S., “Recovering a Gait Using Energy and Phase,” Dynamic Walking 2016, June 2016.

Council, G., & Revzen, S., “Gait Synthesis with Reduced Proprioceptive Requirements,” IEEE International Conference On Intelligent Robots and Systems, Workshop on Robotics Inspired Biology, Vancouver, Canada, September 2017.

Fitzner, I., Sun, Y., Sachdeva, V., & Revzen, S. (2017). “Rapidly Prototyping Robots: Using Plates and Reinforced Flexures.” IEEE Robotics & Automation Magazine, 24(1), 41-47.

Kvalheim, M., & Revzen, S., “Testing an Extended ‘Posture Principle’,” Yearly Meeting of the Society for Integrative and Comparative Biology, San Francisco, CA, January 2018.

Revzen, S., “In Defense of Aristotle: Is There a Connection for Multi-legged Locomotion?” MBI workshop 4: Sensori-Motor Control of Animals and Robots, Columbus, OH, November 2017.

Sachdva, V., Zhao, D., Revzen, S., “Slipping Matters,” Dynamic Walking 2017, Mariehamn, Finland, June 2017.

Zhao, D., & Revzen, S., “Slip Matters in Hexapedal Steering,” IEEE International Conference On Intelligent Robots and Systems, Workshop on Robotics Inspired Biology, Vancouver, Canada, September 2017.

Zhao, D., & Revzen, S., “Slipping Helps Steering in a Multilegged Robot,” Dynamic Walking 2016, June 2016.

Zhao, D., Sachdva, V., Revzen, S., “Modeling Multilegged Locomotion: The Friction Dominated Limit,” Yearly Meeting of the Society for Integrative and Comparative Biology, San Francisco, CA, January 2018.

Also gave six talks in Israel, Washington, California, and Pennsylvania.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Shai Revzen
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Arun Bishop
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Brian Bittner

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Dan Zhao
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Duncas Ross Abbot
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: George Council
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Hao Luo
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Haotian Li
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Marion Anderson
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Michael Kolakowski
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Steven Gerry Murray
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Taylor Daniel McLaughlin
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Non-Student Research Assistant
Participant: Vrushali Patil
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Ziyou Wu
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
as of 07-Jan-2020

PROJECT SUMMARY - ARO/DURIP Final Report

ARO GRANT #W911NF-14-1-0573

DURIP Opportunity ID: PA-AFRL-AFOSR-2016-0001

(Reporting Period: May 2017 – May 2019)

Dynamics, Robotics, and Kinematics Experiments (DRAKE): Measuring Fast Legged Robots as Oscillators

Shai Revzen
EECS
U. Michigan, Ann Arbor, MI, 48109

Major goals

There are critical gaps in the roboticists' current understanding of effective gaits for robots with more than two legs. Our goal through this DURIP grant was to significantly enhance the instrumentation available in the BIRDS lab of the University of Michigan for researching, investigating, and developing legged robots, and training students in such development and analysis.

By building specially instrumented robots (using equipment purchased via this DURIP grant), we were able to directly measure and understand the contributions of individual legs to the motion of the body. This advances:

1. The theory of limit-cycle oscillators which describe these gaits
2. The practical Army goal of building all-terrain robots
3. The educational goal of training robotics engineers to conduct cutting-edge multidisciplinary research.

DURIP funds served this goal in three ways:

- **Enhanced rapid fabrication instrumentation**—Heretofore, our modular plate-and-reinforced-flexure (PARF) approach to rapid design iteration has been limited to low-cost, low-strength flat materials (such as foam board), which can be precision-cut using a 36” × 24” bed 120 Watt CO2 laser cutter. (Other machining was limited, as it must be done in a centralized machine shop with limited student access.) Adding a Markforged Mark One Professional 3D printer to the BIRDS lab allowed us to produce high-strength specialty parts. This specific 3D printer allows fibers (e.g., carbon, kevlar, fiberglass) to be embedded into the 3D printed object, creating components with remarkable structural strength. Having such a cutting-edge fabrication ability allows us to train our robotics students in the design of 3-printed fiber reinforced structures - a technical skill of emerging value.

- **Enhanced Motion tracking instrumentation**—Motion tracking in the lab reference frame is a key tool for biomechanical research and robotics. The addition of four new Qualisys motion tracking cameras substantially improved our ability to reliably track our robots through the arena. The active marker systems we tested for purchase under this grant did not meet our performance requirements and were subsequently returned to the vendor.
- **Robot parts for studying dynamic motion**—Studying dynamic motion in robots is considerably more challenging than studying quasi-static or kinematic motions. Building up high momentum in a dissipative system requires actuators with high mass-specific power densities, and a body which is tough and strong enough to handle impacts with the ground. In collaboration with University of Pennsylvania, we have already built a RHex-like robot with a mass specific power density 3 to 7 times that of any previous RHex models. With DURIP support, we replaced damaged actuators, added thermal safeties to the motor controllers, and developed an optically coupled ground contact sensor system.
- **Robot parts for force measurement** — using DURIP funds we developed and constructed a robot with full 6DOF force sensing on each leg. This allows us to tease apart the contributions of individual legs to the robots’ motion, leading to significant advances in our understanding of the ground interactions that produce multilegged gaits.

Accomplished

- Used our enhanced motion tracking arena to collect new data sets on BigANT 6, Enepod (highly flexible legs, for investigating dynamic motion), and Multipods (especially pertaining to gaits and backbone morphology options in 12-legged Multipod).
- Based on earlier work, and enhanced with instrumentation acquired through this DURIP grant, we built “Enepod,” a robot that implements the measurement of dominant energy flows within the body of the robot, significantly enhancing the robot’s ability to recover from damage. The deformations of the Enepod’s highly flexible legs can be measured directly using motion tracking systems improved through this grant. The results were used to develop a novel method for allowing robots to recover locomotion ability after being damaged; publication in preparation.

- Extended previous work on event-selected vector fields, showing that a broad class of hybrid oscillators exhibit the same topological dynamics as smooth oscillators through a piecewise smooth conjugacy. Demonstrated that the interaction of legs with the ground can, in and of itself, serve to synchronize legs, without need for any additional control. This class of controllers has reduced proprioceptive requirements and requires lower bandwidth than conventional controllers. Work on implementation of these findings relied strongly on robot components acquired through this grant.
- Developed and expanded the “Multipod” family of robots, whose modular design extends from four to 12 legs, enabling us to examine how gaits map up and down the complexity hierarchy. Used enhanced motion tracking arena in conjunction with these robots to prepare datasets for the ARO MURI W911NF-17-1-0306 and for work under ARO W911NF-14-1-0573.
- Furthered advanced RHex robot development. This included applying trajectory-based control and gait recovery to a simplified model of the RHex robot, and developing thermal safety circuits for individual RHex leg motors (as these can draw 6kW), preparatory to pursuing more ambitious gait development. This required the use of the 3D printed leg mount (printed on DURIP-funded printer) to interface these motor to existing legs and mount specialized electronics to optically couple leg contact sensors to the main body of the robot.
- Integrated force- and torque-transducers (purchased under this DURIP) into a hexapedal robot, as proposed.

Training

**** TK insert list of students and post-docs funded through this grant ****

Dissemination

- Council, G., & Revzen, S., “Recovering a Gait Using Energy and Phase,” Dynamic Walking 2016, June 2016.
- Council, G., & Revzen, S., “Gait Synthesis with Reduced Proprioceptive Requirements,” IEEE International Conference On Intelligent Robots and Systems, Workshop on Robotics Inspired Biology, Vancouver, Canada, September 2017.
- Fitzner, I., Sun, Y., Sachdeva, V., & Revzen, S. (2017). “Rapidly Prototyping Robots: Using Plates and Reinforced Flexures.” *IEEE Robotics & Automation Magazine*, 24(1), 41-47.
- Kvalheim, M., & Revzen, S., “Testing an Extended ‘Posture Principle’,” Yearly Meeting of the Society for Integrative and Comparative Biology, San Francisco, CA, January 2018.
- Revzen, S., “In Defense of Aristotle: Is There a Connection for Multi-legged Locomotion?” MBI workshop 4: Sensori-Motor Control of Animals and Robots, Columbus, OH, November 2017.

- Sachdva, V., Zhao, D., Revzen, S., “Slipping Matters,” Dynamic Walking 2017, Mariehamn, Finland, June 2017.
- Zhao, D., & Revzen, S., “Slip Matters in Hexapedal Steering,” IEEE International Conference On Intelligent Robots and Systems, Workshop on Robotics Inspired Biology, Vancouver, Canada, September 2017.
- Zhao, D., & Revzen, S., “Slipping Helps Steering in a Multilegged Robot,” Dynamic Walking 2016, June 2016.
- Zhao, D., Sachdva, V., Revzen, S., “Modeling Multilegged Locomotion: The Friction Dominated Limit,” Yearly Meeting of the Society for Integrative and Comparative Biology, San Francisco, CA, January 2018.

Also gave six talks in Israel, Washington, California, and Pennsylvania.

Honors

—*na*—

Tech Transfer

—*na*—