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RPPR Final Report
as of 07-Jan-2020

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STEM Degrees: 1 **STEM Participants:** 2

Major Goals: The objective of the project is to provide predictive models of animal and robot locomotion. We are focused on capturing the robustness and survivability of the most reliable terrestrial locomotion systems known—land-based arthropods—and transferring this essence into new mathematical representations and instantiation techniques, resulting in robotic technologies that move in fundamentally more robust ways than existing legged systems (be they for transport of soldiers and materiel in the field, or for improved prosthetic devices back home).

This work builds on fundamental advances in the theory of hybrid dynamical systems and coupled oscillators (informed by insights gained through a previous ARO YIP grant). The initial phases of this work consisted of publishing results from previous work and applying these findings to establish a new robot platform for further experimentation. We have continued to advance our methods for identifying the body dynamics of robots and animals while developing more advanced forms of instantiating and modulating dynamics. We also continued work on “connection-based” models. These methods form the foundation of a coherent methodology for producing robots whose body morphology contributes to simplifying their control, and whose software can identify and re-instantiate desired behaviors if they fail.

Our approach is grounded in oscillator theory, and accounts for both the crucial role of body morphology and mechanics in the dynamics of motion, and the interactions of the body with the environment. This fundamental progress in anchoring templates is proving to be a novel approach to control, applicable anywhere the control of high-dimensional nonlinear systems is of interest to the Army. Moreover, theoretical and computational advances in the theory of oscillators and their application may impact a range of engineering fields outside biomechanics and robotics, including vibration mitigation in mechanical and civil engineering and power systems engineering. It also shows promise in other fields, such as econometrics, where these advances could aid in the analysis of seasonality in markets.

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).

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 (featured in chapter 2 of Council PhD thesis).

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 and implemented this in a version of the RHex robot. Work on implementation of these findings relied strongly on robot components acquired through this grant and related DURIP ARO grant #W911NF-17-1-0243. (See Council PhD thesis section 3.9.)

Finished work on implementing tools for numerical computation of Bouligand derivatives of the flows of event selected vector fields (see Council PhD these section 3.5–3.7).

Documented how event-selected controllers can be used to produce reference trajectory tracking with reduced proprioceptive requirements and lower bandwidth than conventional controllers. (See section 3.8 of Council PhD thesis.)

Developed and expanded the “Multipod” family of robots (see Figure 1, left side; and Figure 5). Their modular design extends from four to 12 legs, enabling us to examine the oscillator-template covering relationship and how gaits map up and down the complexity hierarchy. Used enhanced motion tracking arena in conjunction with these robots to prepare datasets for work under this grant.

Furthered advanced RHex and BigANT 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. Continued work on the extended water-resistant corrugated-plastic plate and reinforced flexure (PARF) fabrication methodology developed under this grant.

Integrated force- and torque-transducers (purchased under DURIP Grant #W911NF-17-1-0243) into a hexapedal robot, as proposed under the DURIP grant (see Figure 1, right side). These are intended for collecting data to investigate the surprising success of the multi-legged geometric mechanics motion model developed over the last two years.

Training Opportunities: Continued support of Graduate student, George Council, who finished his PhD in December, 2019.
Continued support of Graduate student, Dan Zhao.

Results Dissemination: Bittner, B., Hatton, R., & Revzen. S,. (2018). Geometrically optimal gaits: a data-driven approach. Nonlinear Dynamics. https://dx.doi.org/10.1007/s11071-018-4466-9

Bittner, B., & Revzen, S., Optimizing gaits for coverage on lie groups, Dynamic Walking 2019, Calgary, AB, Canada, June 2019.
Council, G., Data-driven methods to build robust legged robots, PhD thesis, University of Michigan, 2019.

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Kvalheim, M., Bittner, B., & Revzen. S,. (2019). Gait modeling and optimization for the perturbed Stokes regime. Nonlinear Dynamics. https://dx.doi.org/10.1007/s11071-019-05121-3

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Revzen, S. (2019). Moving with more legs is different: a geometric mechanics perspective. Integrative and Comparative Biology, 59, pp. E191–E191

Revzen, S., How many legs become a snake? CMU-RI 2019, Carnegie Melon University, Pittsburgh, PA, July 25, 2019.

Revzen, S., Geometric mechanics and robots with multiple contacts, LCSR Seminar, John Hopkins University, Baltimore, MD, April 24, 2019.

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Zhao., D., Li., H., & Revzen., S., Design and undulatory gait tests of a meter-size modular centipede robot, Dynamic Walking 2019, Calgary, AB, Canada, June 2019.

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Technology Transfer: Nothing to Report

PARTICIPANTS:

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Participant: Shai Revzen
Person Months Worked: 2.00 **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: Graduate Student (research assistant)
Participant: Dan Zhao
Person Months Worked: 6.00 **Funding Support:**
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Other Collaborators:

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Authors: George Council, Shai Revzen
Acknowledged Federal Support: **Y**

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Authors: George Council
Acknowledged Federal Support: **N**

RPPR Final Report
as of 07-Jan-2020

PROJECT SUMMARY - GRANT #W911NF-14-1-0573

(Reporting Period: September 2018 – August 2019)

Morphologically Modulated Dynamics

Shai Revzen
EECS
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Major goals

The objective of the project is to provide predictive models of animal and robot locomotion. We are focused on capturing the robustness and survivability of the most reliable terrestrial locomotion systems known—land-based arthropods—and transferring this essence into new mathematical representations and instantiation techniques, resulting in robotic technologies that move in fundamentally more robust ways than existing legged systems (be they for transport of soldiers and materiel in the field, or for improved prosthetic devices back home).

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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).
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(as these can draw 6kW), preparatory to pursuing more ambitious gait development. Continued work on the extended water-resistant corrugated-plastic plate and reinforced flexure (PARF) fabrication methodology developed under this grant.

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Dissemination

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- Zhao., D., Li., H., & Revzen., S., *Design and undulatory gait tests of a meter-size modular centipede robot,* Dynamic Walking 2019, Calgary, AB, Canada, June 2019.

Honors

—*na*—

Tech Transfer

—*na*—

Products

- “Multipod” family of robots: Modular design extends from four to 12 legs, enabling investigation of how gaits map up and down the complexity hierarchy
- Advanced RHex robot: A simplified model of the RHex robot enhanced with trajectory-based control and gait recovery, thermal safety circuits for individual RHex leg motors, new 3D printed leg mounts with specialized electronics that optically couple leg contact sensors to the main body of the robot

- “Enepod”: Implements the measurement of dominant energy flows within the body of the robot, significantly enhancing the robot’s ability (and developing novel methods) to recover from damage
- BigANT 6: Water-resistant corrugated-plastic plate and reinforced flexure (PARF) construction, with integrated force- and torque-transducers
- 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)

FIGURES

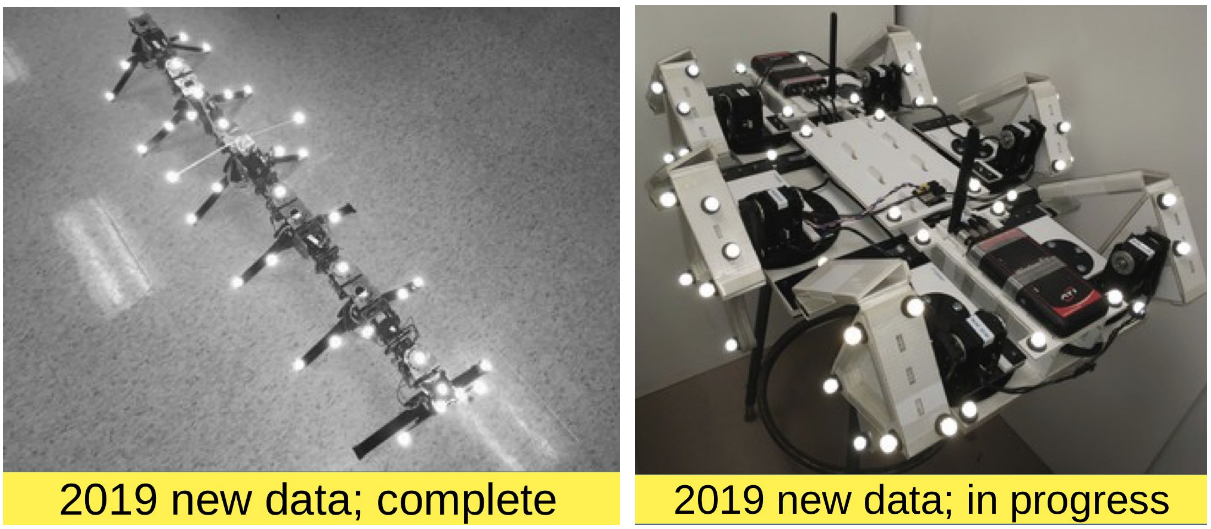

Figure 1. *Robotic platforms producing model data. Multipod with 12 legs used to study gaits at various levels of morphological complexity (left); Mechapod instrumented with force and torque measurement capabilities (right).*

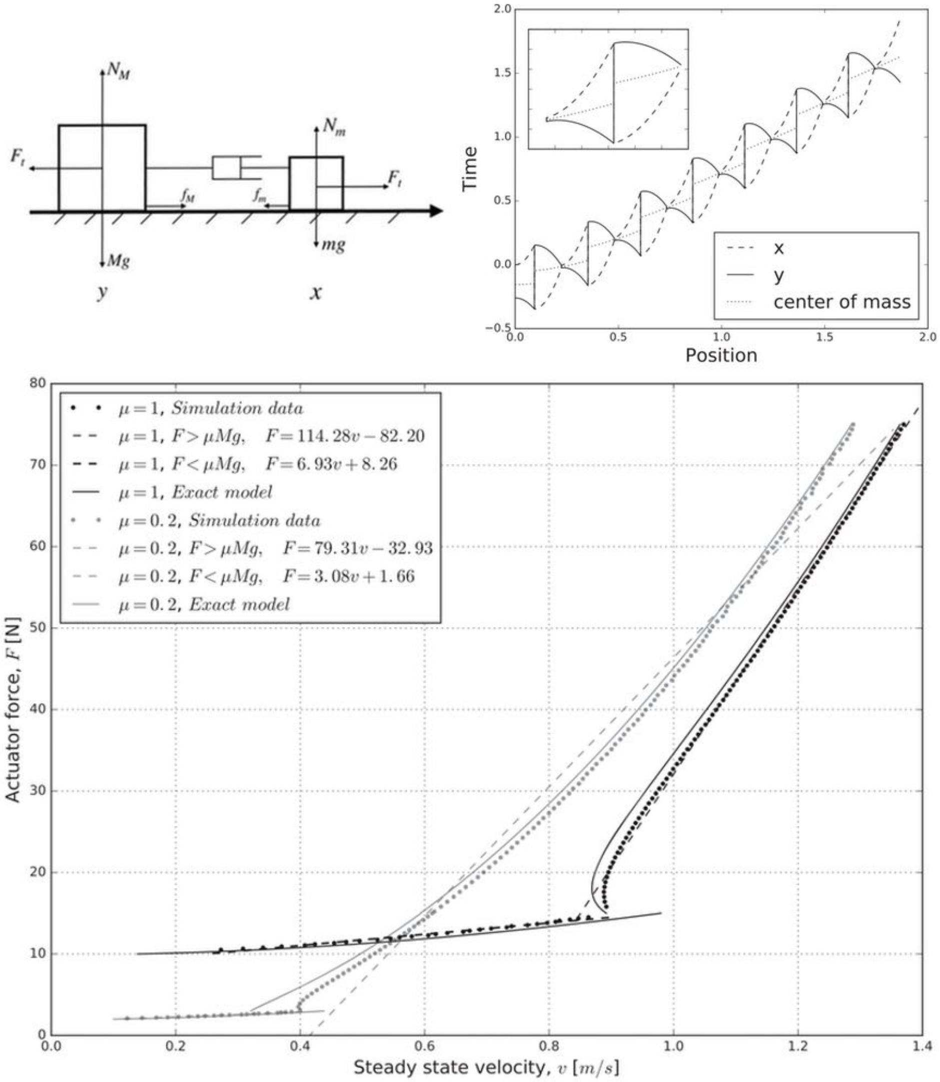

Figure 2. upper left: *Schematic representation of the mechanical model. M and m are the larger and smaller point masses, respectively, with y and x their positions. The friction forces acting on the point masses are fm and fM. Ft is the actuator force, which is positive when pushing the masses apart and negative when pulling them together. g is the gravitational acceleration.* ***upper right:*** *Position of m, M, and the center of mass versus time in an example simulation. The positions of m (dashed line), M (solid line), and center of mass (mx+My)/(m+M) (dotted line) over time are shown. Inset graph shows an enlarged cycle starting at y − x = Lmin.* ***bottom:*** *Constant force versus steady-state velocity under Coulomb friction model, μ=1, and μ=0.2. Our notable result is that in each regime, the F to vss relationship can be described fairly accurately as linear, as demonstrated by the high values of regression R2. Note that intermediate values of μ interpolate those plotted and were omitted for clarity.*

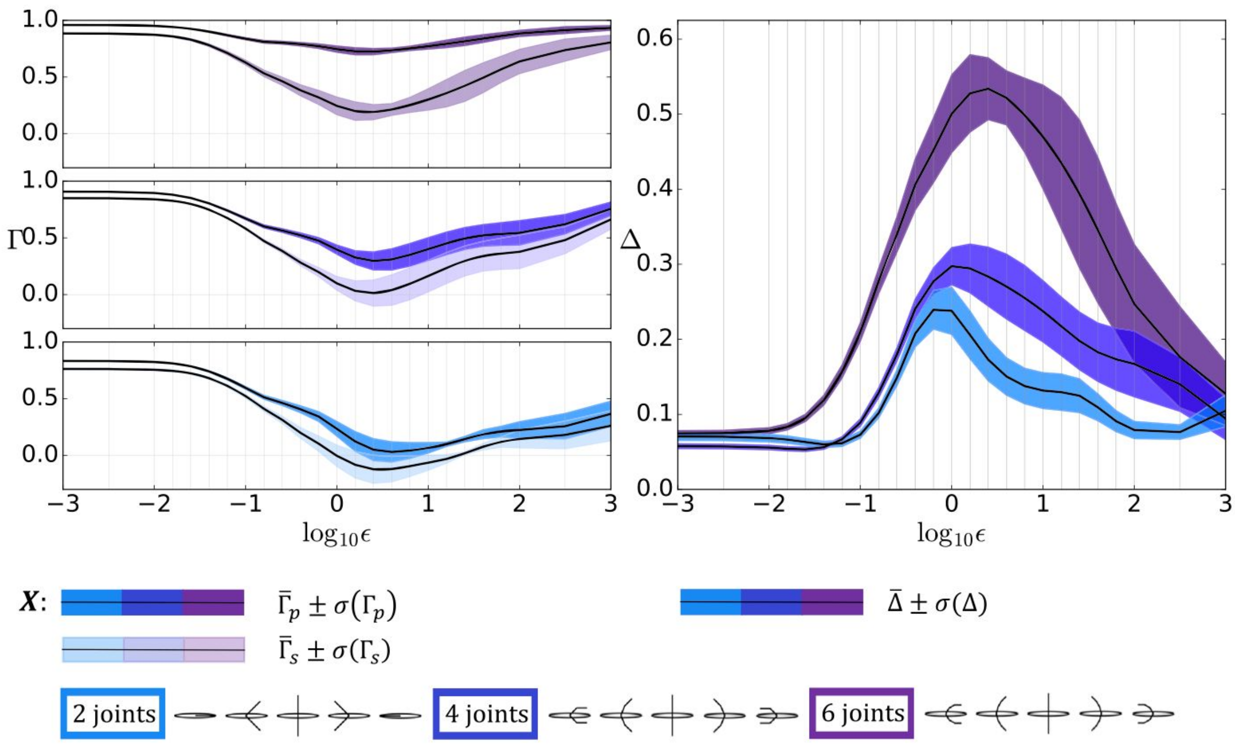

Figure 3. *Comparison of model prediction quality when using the perturbed Stokes regressors versus the Stokes regressors on paddles with different dimensions of the shape space, shown in terms of the Γ and Δ quality metrics. We plotted Γ and Δ of three swimmers with different numbers of paddle segments: one segment per paddle (light blue), two segments (blue), and three segments (purple). We used a symmetric flapping gait. The paddles moved symmetrically with total angles of all joints summing up to a sinusoid of amplitude π. We plot the X components of Γ_p (left column; one plot per model; saturated colors Γ_p; pale colors Γ_s) and Δ (right column). Results show that over the two orders of magnitude range of $10^{-0.5} < \varepsilon < 10^{1.5}$, the perturbed Stokes regressors consistently provide improvements. The relative improvement Δ increased markedly with shape space dimension, by as much as 0.5 in Δ.*

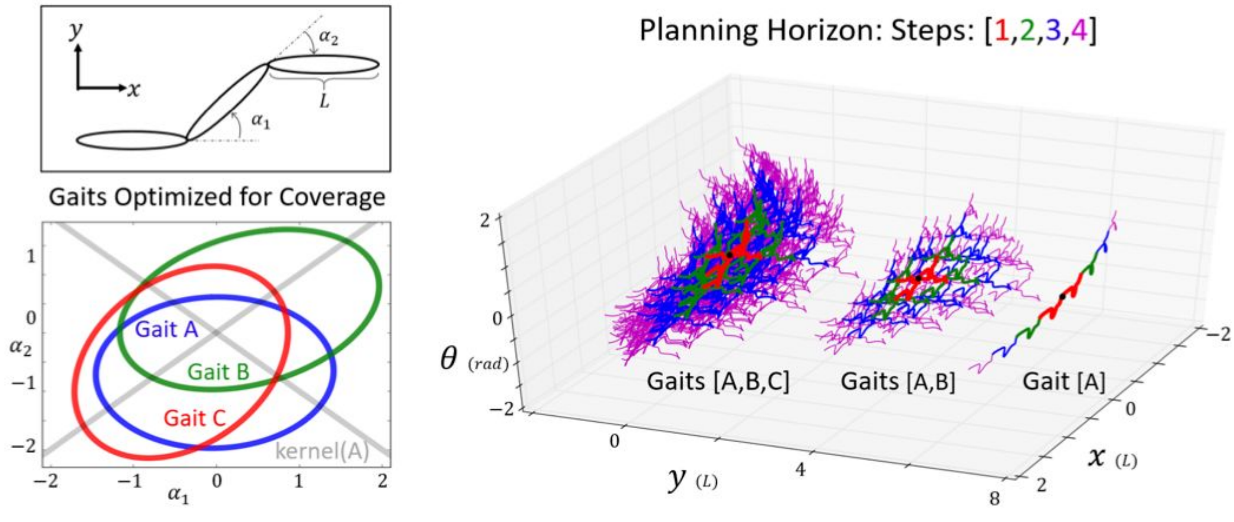

Figure 4. *We constructed G from randomly sampling 100 points of unit ballon SE(2). Ten iterations of gradient descent on the loss function (seeded with a unit circle gait), resulted in the gaits (bottom left) for the 3-link Purcell swimmer (top left). Gaits can be connected along the kernel of A(·) (grey), preserving the exactness of the four step planner (right). The two and one gait planners are shifted in y by 5L and 7L respectively.*

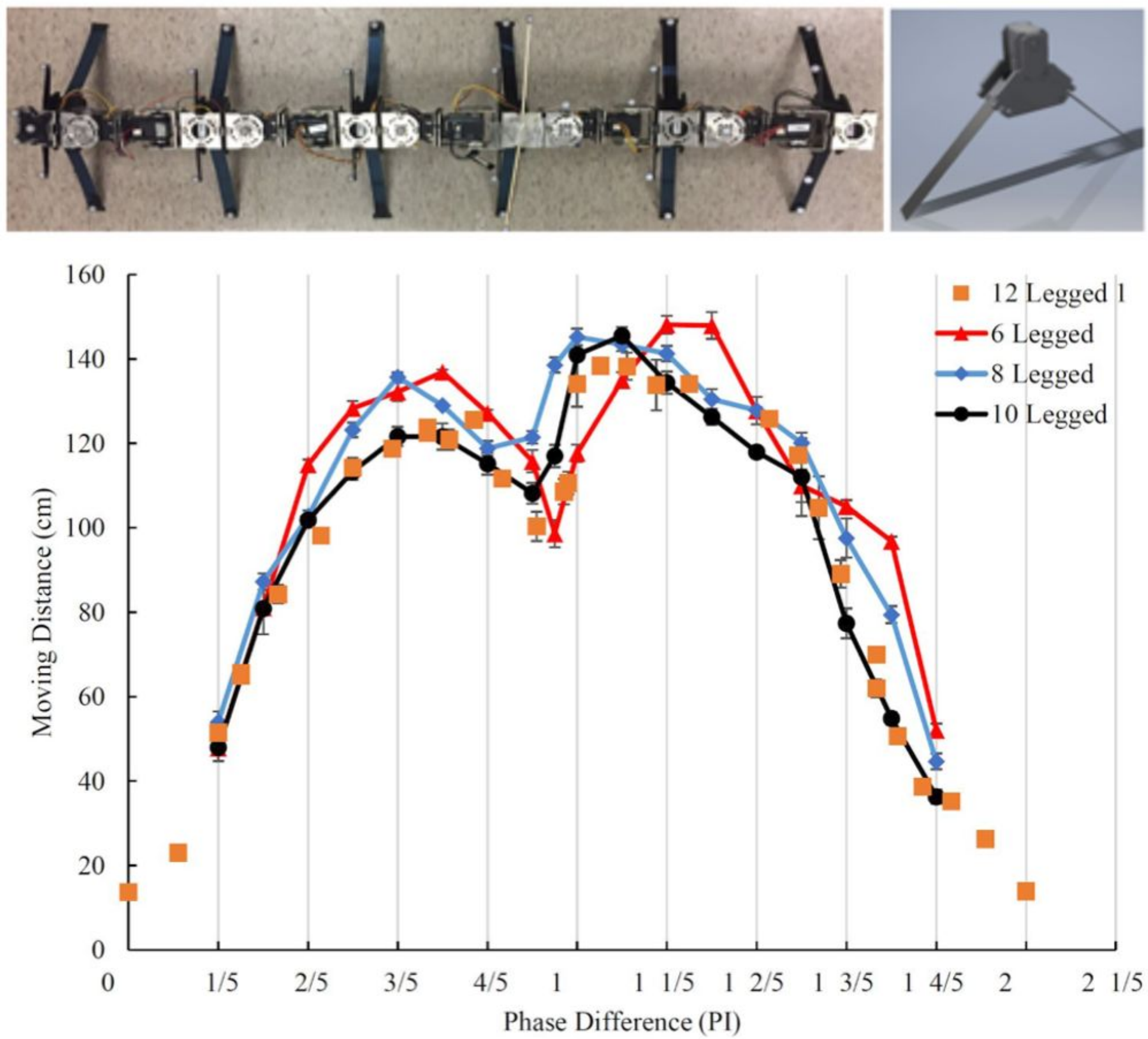

***Figure 5. top:** Multipod robot and leg segment CAD.* ***bottom:** Moving distance at 5 strides (N=3 trials) vs. phase difference between segments. Different numbers of legs produce similar motion.*

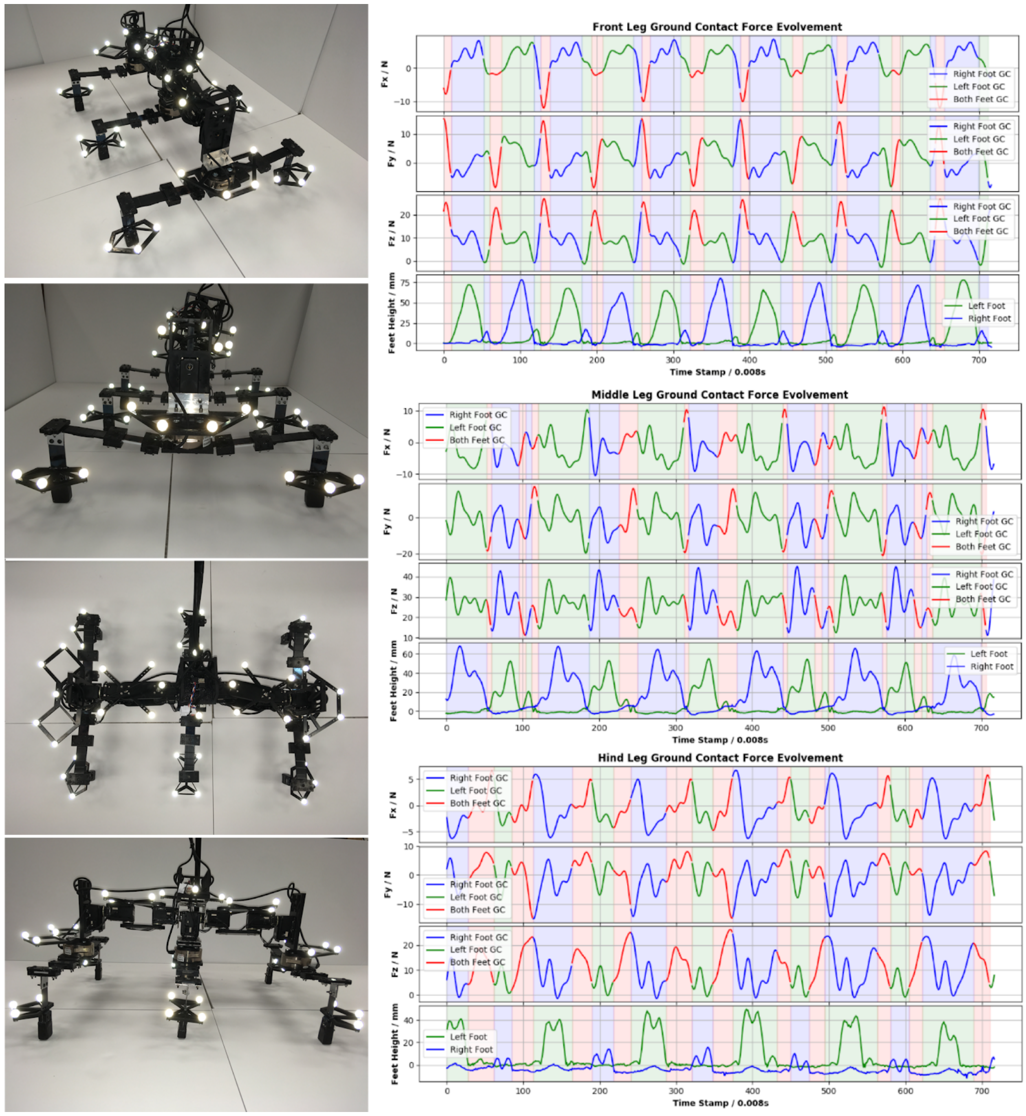

Figure 6. left: *The constitutive equations governing multi-legged contact with the ground, although known in theory, are rarely used in practice. This hexapodal robot is equipped with integrated force- and torque-transducers, allowing us to track the actual contact forces and validate and extend this new class of models.* ***right:*** *Ground contact force evolvement. The colors represent the type of ground contact (left foot: green; right foot: blue; both feet: red). Subfigures illustrate the ground contact forces decomposition along x, y, z-axis of the world frame. The bottom chart in each plot shows the height of the feet.*