On the Gait Robustness of Passive Dynamic Robots, and a Novel Variable Stiffness Series Elastic Actuator

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Today's Presentation

Outline:

1. Introduction to Passive-Dynamic Robots
2. Two Definitions of Gait Robustness
3. Custom Simulator
4. Data, Conclusions
5. Novel Variable Stiffness Actuator
6. Conclusions, Future Research

What is passive dynamic walking?

- Stable limit cycle exists...but how stable?
- Three hard problems: Desigining mechanics, controllers, and actuation
- Today’s Questions:
  1. どのように受動歩行ロボットのロバスト性を測るか
  2. どのようなアクチュエータが受動歩行ロボットに適しているか

The difference between stability and robustness

Differential property vs. Disturbance Rejection:

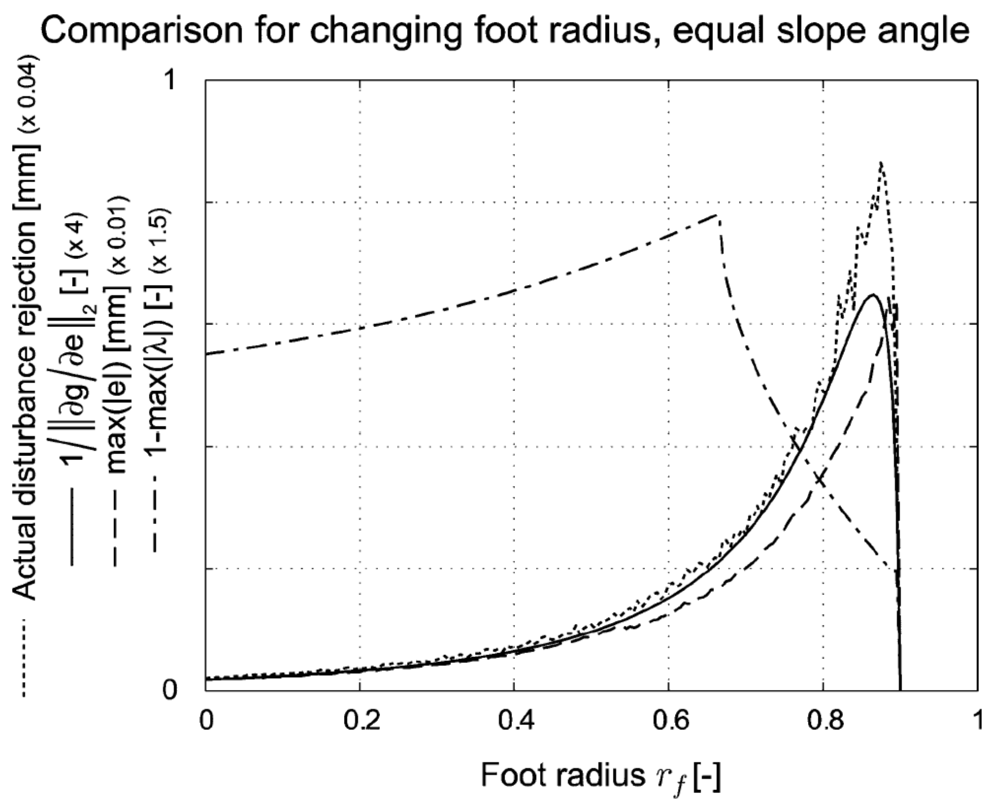
- *Gait Stability* means “It keeps walking."
- *Gait Robustness* means “It can withstand this much disturbance and keep walking"

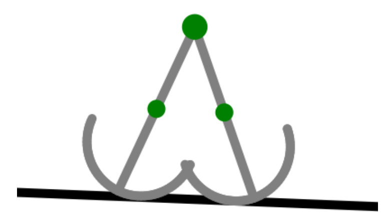
Stability is often analyzed using the spectral radius of the Jacobian of the Poincare Map

- This is fine for stability
- But does not correlate well with robustness

Prior Research

- “Real Robustness" is size of random disturbance per step such that it falls in an average of 100 steps

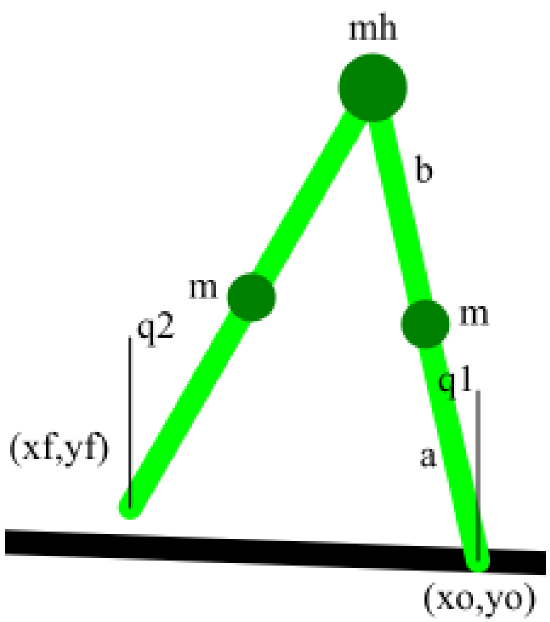


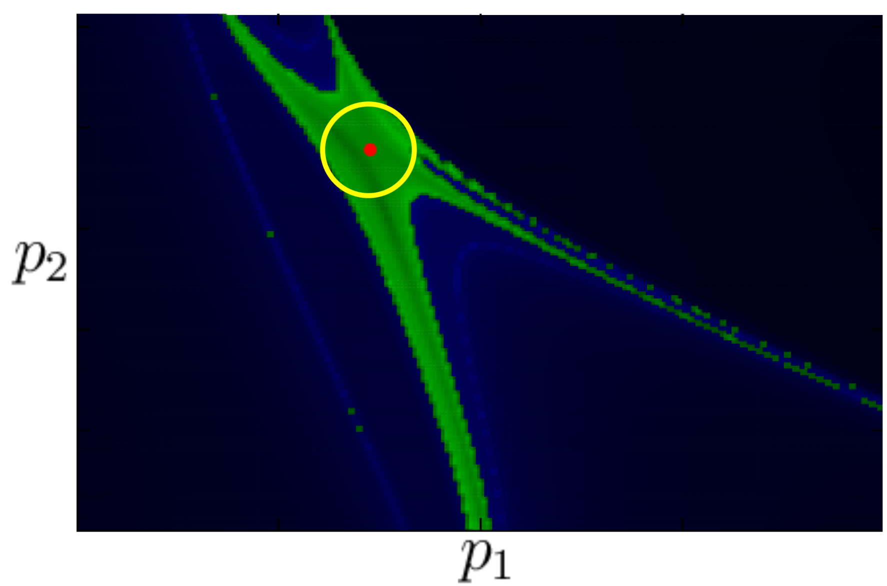


Source: “A Disturbance Rejection Measure for Limit Cycle Walkers: The Gait Sensitivity Norm" by D. Hobbelen, M. Wisse

What metric does this thesis propose?

- Any momentary disturbance can be represented as a change in generalized momenta
- We propose using the length of the smallest deterministic disturbance of generalized momenta that moves the system from the limit cycle to an unstable region.





Above: Post-heelstrike instant generalized momenta. Red dot is limit cycle, green is basin of attraction, and yellow circle represents maximum

What does “length of the disturbance" mean?

We present two definitions of gait robustness using two different definitions of length:

1. Length is measured as the magnitude of the impulse. (r_{IDR}: Impulse Disturbance Rejection)
2. Length is measured using the metric tensor. (r_{EDR}: Energy Disturbance Rejection)

Mathematical Definition of r_{IDR}

The “Impulse Disturbance Rejection" radius r_{IDR} of a system with generalized momenta p is defined as

$$
\begin{aligned}
(x^*, y^*) &= \arg\min \left\| p_x - p_y \right\|_2, x \in \mathbb{Q}_{NR},\ y \in \mathbb{Q}_{LC} \\
\Delta p_{IDR} &= x^* - y^* \\
r_{IDR} &= \min \left\| \Delta p_{IDR} \right\|_2,
\end{aligned}
$$

where $\mathbb{Q}$ is the configuration space of the system, $\mathbb{Q}_{LC} \subseteq \mathbb{Q}$ are states passed through during a circuit of the limit cycle, and $\mathbb{Q}_{NR} \subseteq \mathbb{Q}$ are states which result in the system not returning to the limit cycle. The notation $(...)_x$ means evaluated at a point x.

Mathematical Definition of r_{EDR}

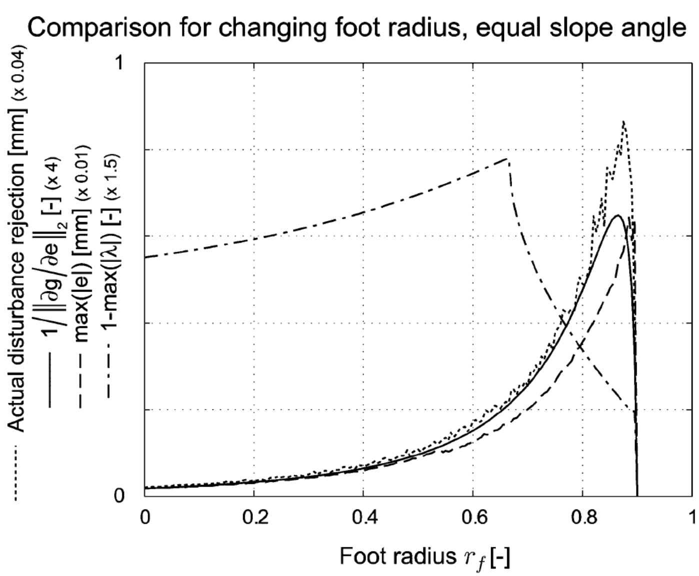
The “Energy Disturbance Radius” r_{EDR} is defined as the change of kinetic energy resulting from an impulse disturbance:

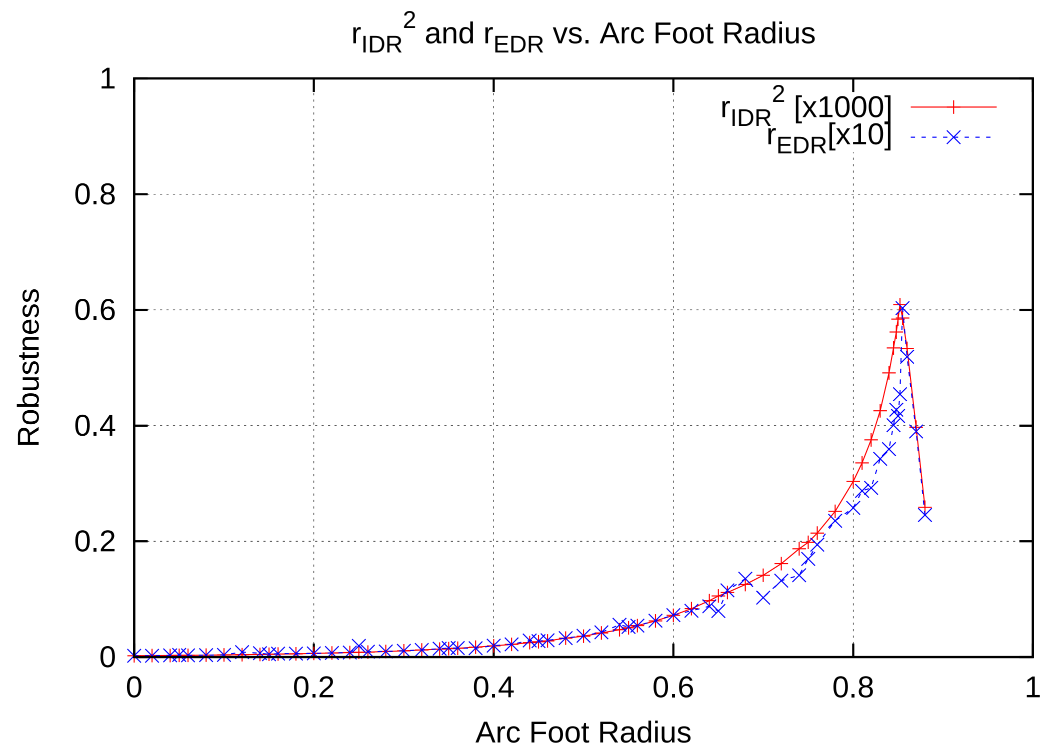
$$
\begin{aligned}
(x^*, y^*) &= \arg\min (p_x - p_y)^T M^{-1} (p_x - p_y), x \in \mathbb{Q}_{NR},\ y \in \mathbb{Q}_{LC} \\
\Delta p_{EDR} &= x^* - y^* \\
r_{EDR} &= \min \Delta p_{EDR}^T M^{-1} \Delta p_{EDR},
\end{aligned}
$$

Here M is the inertial matrix (tensor) of the Lagrangian system. Since M is a metric tensor of a Riemannian space and p is a linear space, r_{EDR} is a coordinate invariant quantity. We could also have written $r_{EDR} = \Delta\dot{q} M \Delta\dot{q}$ if we wished to express r_{EDR} in terms of generalized velocities.

How do these correlate with real robustness to disturbances?

- They appear to correlate well
- Slightly underestimate real robustness because it uses the worst-case disturbance





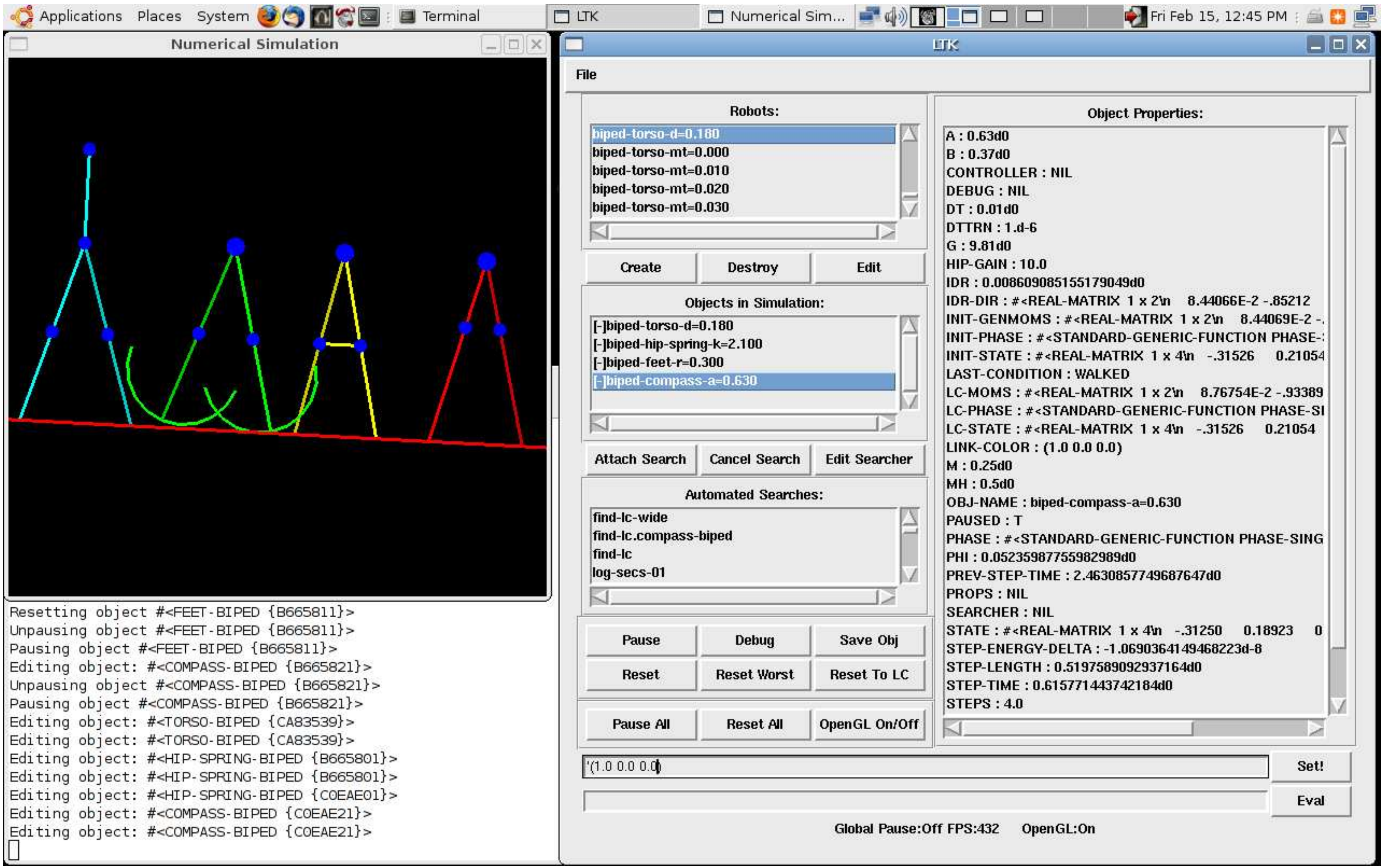
What are the advantages of r_{IDR} and r_{EDR}?

- r_{EDR} is coordinate invariant
- Both have clear physical meanings: “How hard can you bump the robot before it falls down?"
  - r_{IDR} measures change in momentum from bump
  - r_{EDR} measures change in kinetic energy from bump
- Deterministic, not stochastic
- Conservative, worst-case values that are useful for engineering and design

What are the disadvantages of r_{IDR} and r_{EDR}?

- Very difficult to analytically determine r_{IDR} or r_{EDR}.
- However, we can measure it via simulation.
- For 2DOF models, computing r_{IDR} or r_{EDR} requires approximately 3 min.
- We will now introduce the simulator

The Simulation Environment



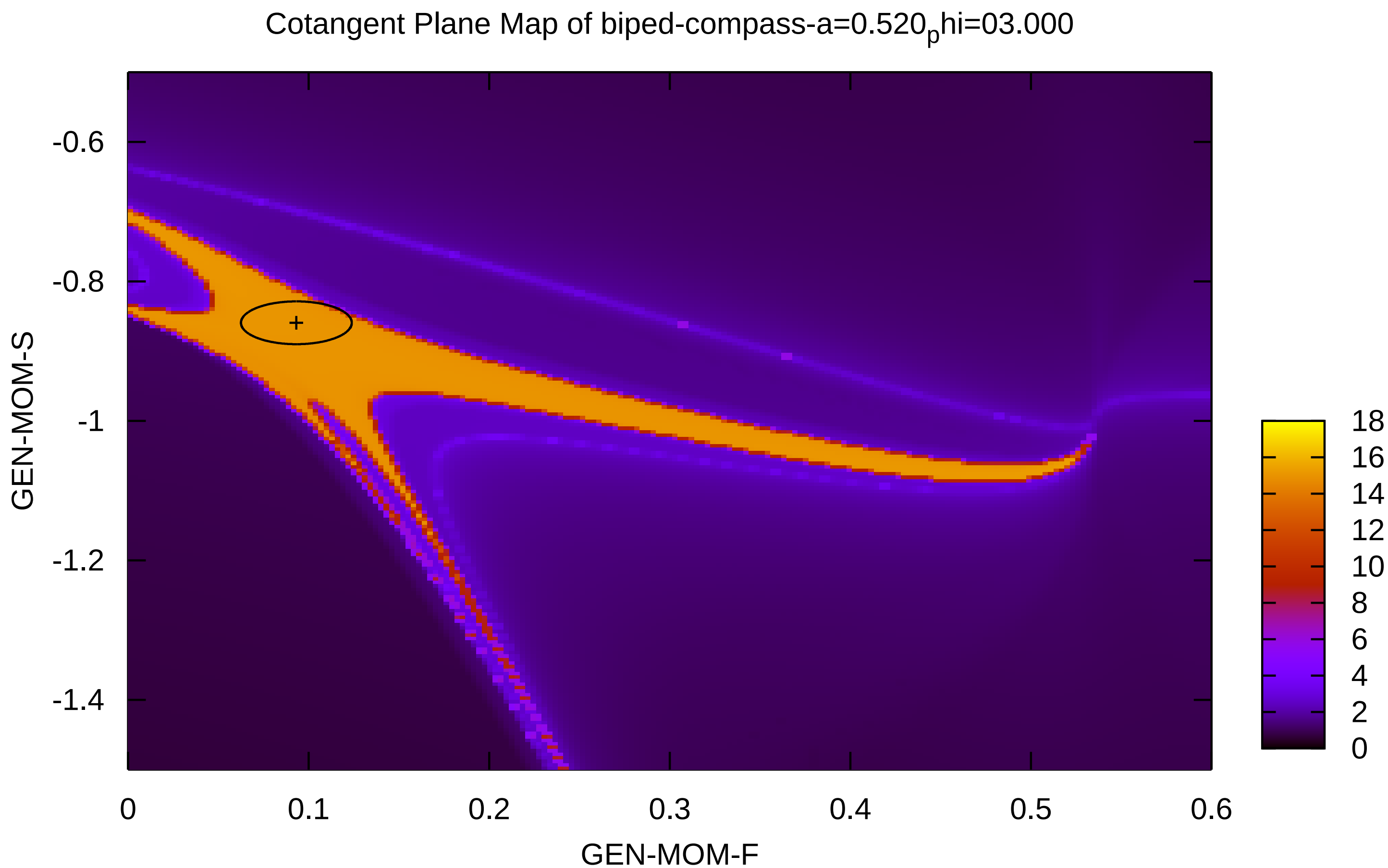
Custom Rigid Body Simulator

Simulator Features:

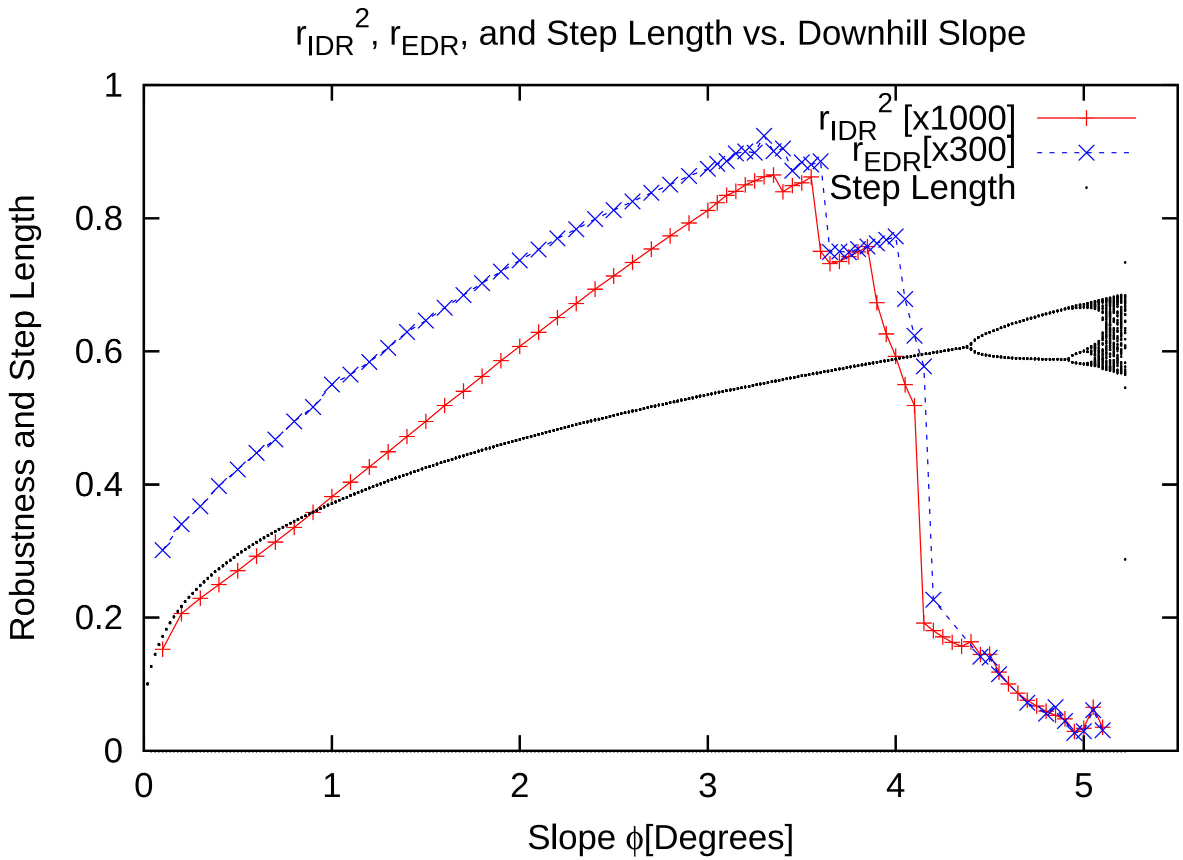
- Simulates multiple robots simultaneously
- Robots can be edited in real time
- Measures r_{IDR}, r_{EDR} automatically
- Draws PNG files of robots
- Easy saving and loading of various parameters, models
- Automatically logs and plots various quantities
- Automatically discovers limit cycle
- Plots limit cycle bifurcations
- Fast simulation using Runge-Kutta numerical integration, secant method zero finding
- Real-time debugging, compiling and interpretation of code via REPL

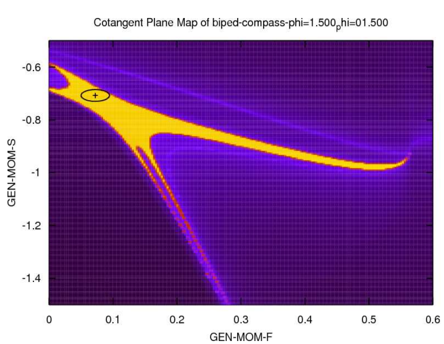
The Simulation Environment

- Automatically maps (p_1, p_2) plane, measures stability
- Yellow is stable

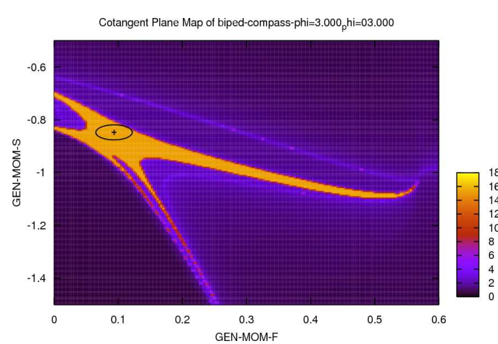


Experiment: How do r_{IDR} and r_{EDR} vary with the slope?

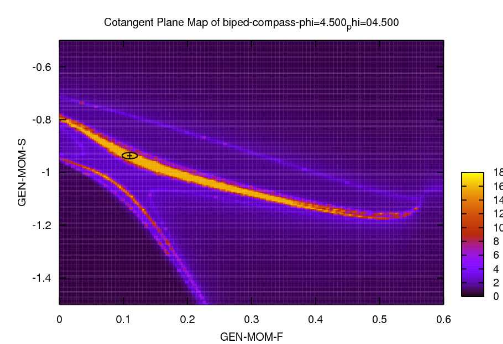




1.5 deg



3.0 deg



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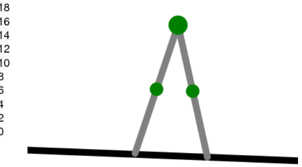
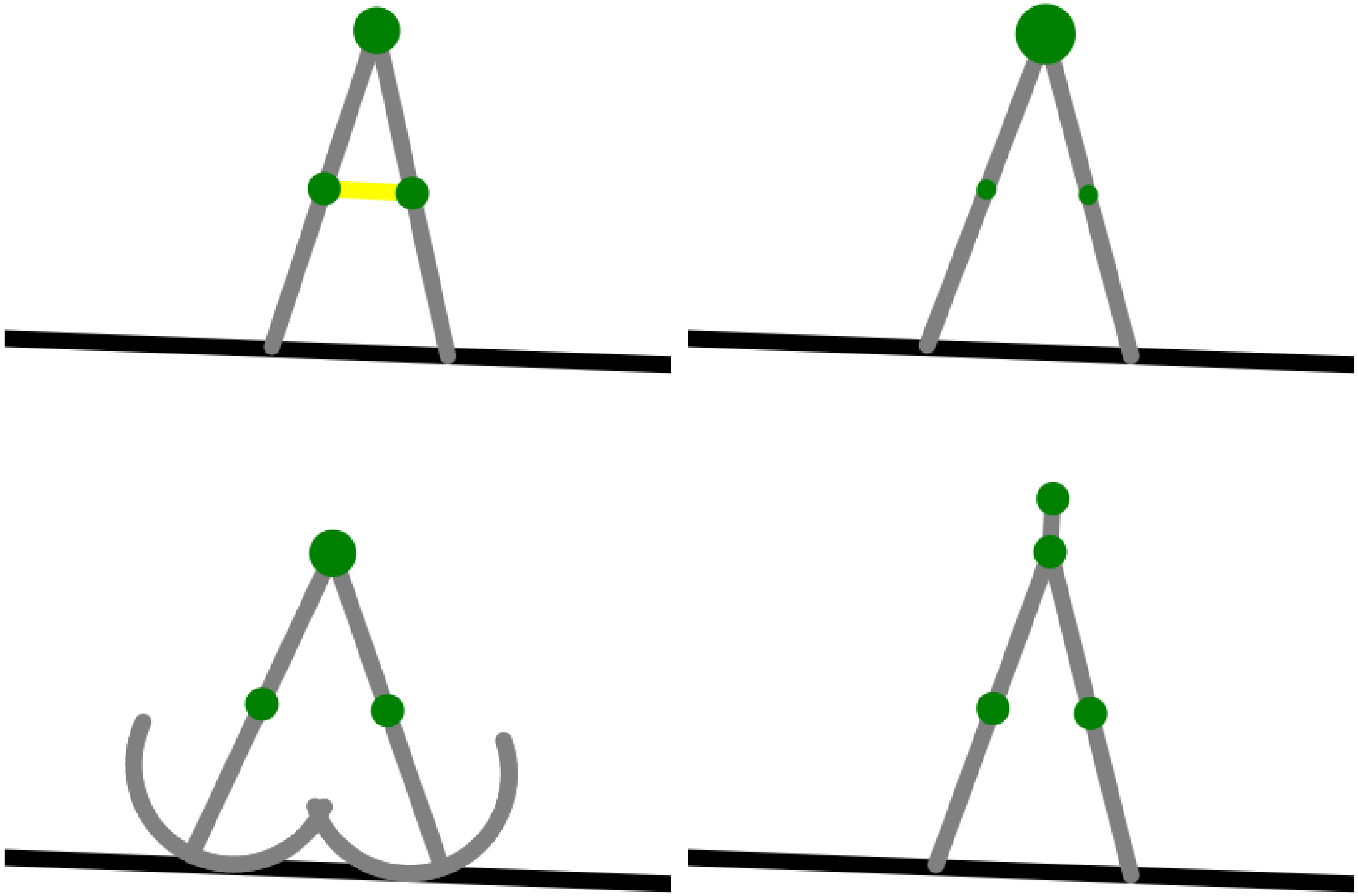


Model

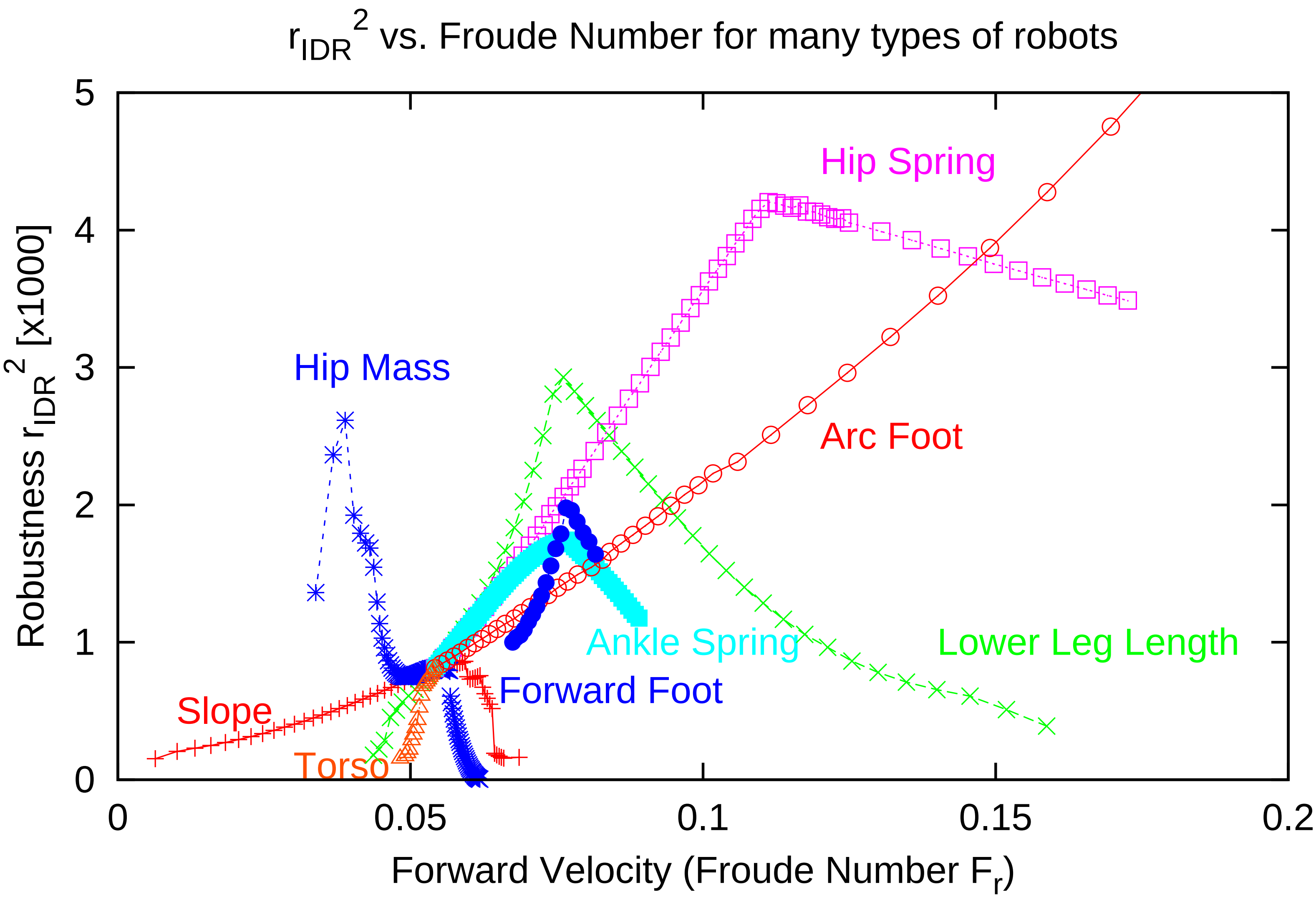
What about using these metrics to design a robot?

Let's consider the effects of several design parameters!



Summary of r_{IDR} Data

ロバスト性　vs. 無次元化した歩行速度



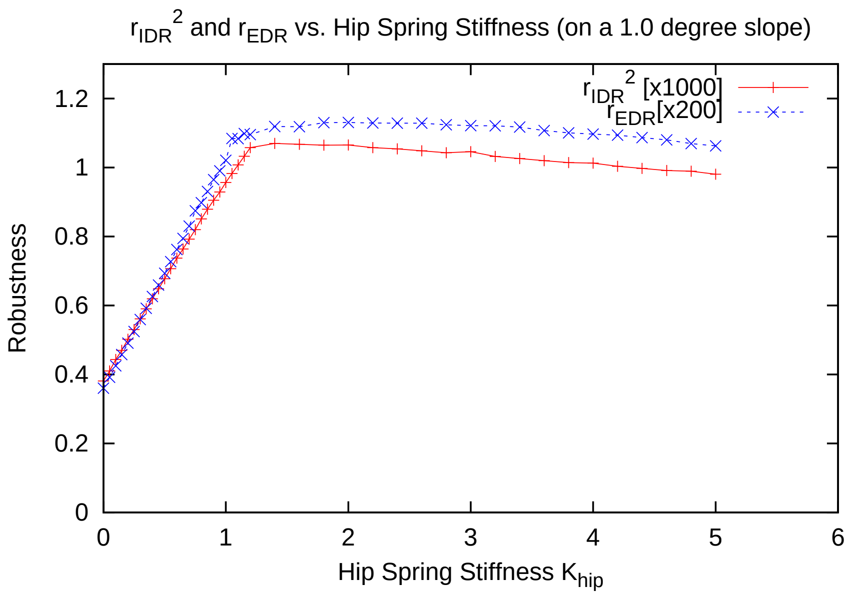
Conclusions from Data

We can make some simple conclusions

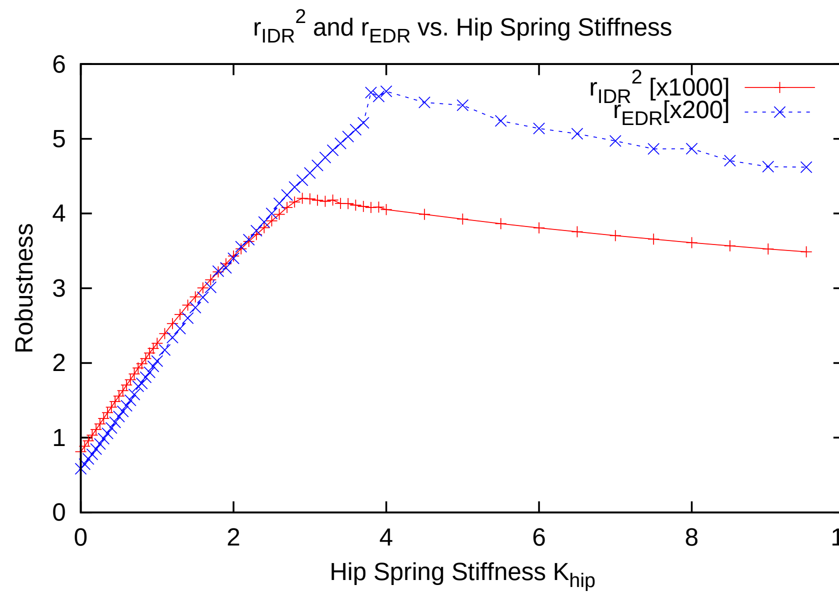
- Parameters which affect natural leg swing period have a great effect on robustness (e.g. hip springs)
- Larger feet are always beneficial
- Unlike what prior research has shown, torsos don’t always improve robustness
- There seems to be an optimal hip spring stiffness for a given forward speed

Is there an optimal hip spring stiffness for a given forward speed?

- For different slopes, optimally robust hip spring stiffness are different
- If we could change stiffness, we could maximize natural mechanical gait robustness
- Next, we will present such a variable stiffness mechanism



1.0 deg 斜面



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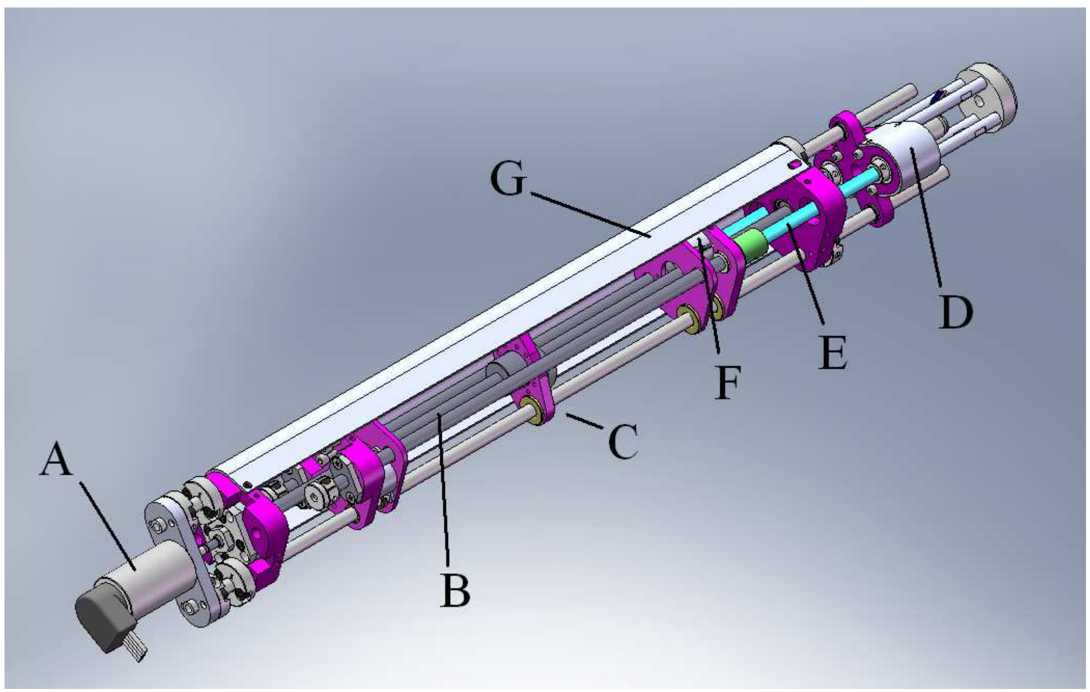
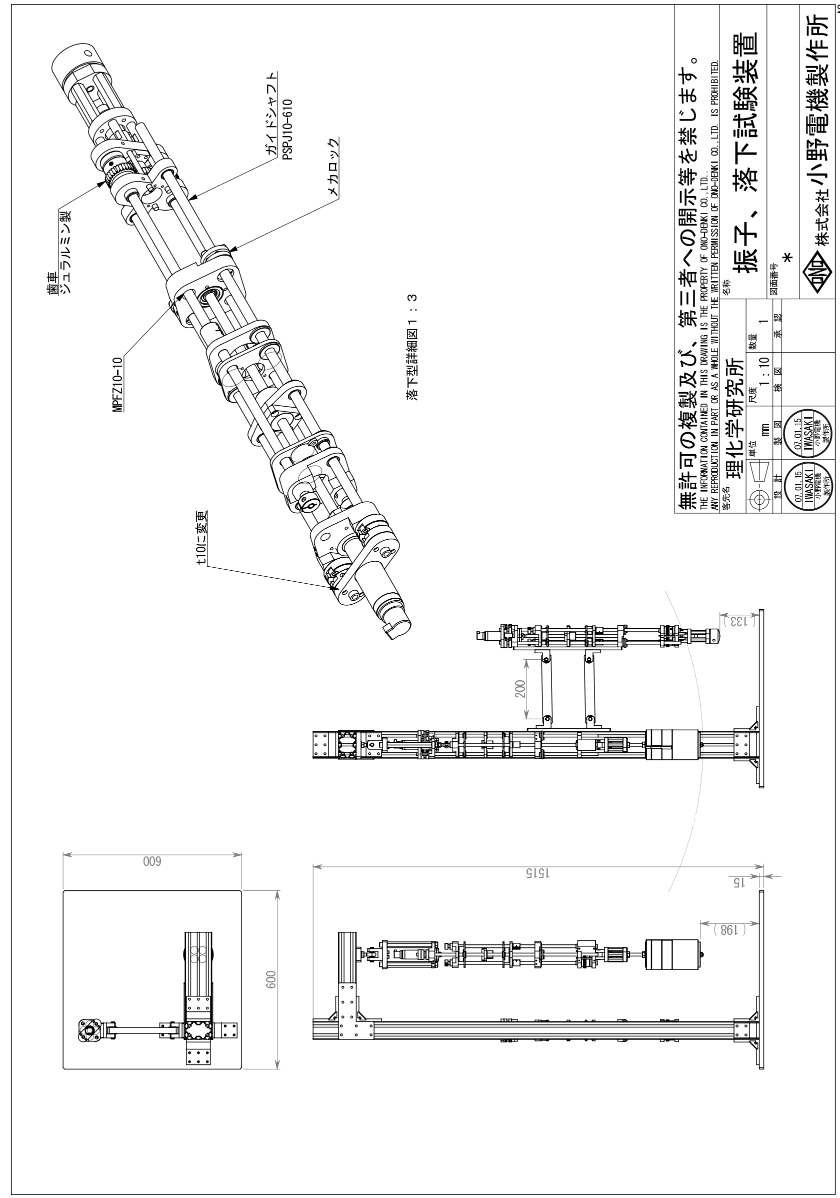
Introducing a New Actuator: The VSSEA

VSSEA: Variable Stiffness Series Elastic Actuator

- An actuatoor which does not destroy passive dynamic behavior
- Two nonlinear springs act as variable linear spring
- Two motors, (A) adjusts position, (D) adjusts stiffness



VSSEA photos



Conclusions

We have designed, implemented, and presented:

- Two new definitions of gait robustness: r_{IDR} and r_{EDR}, applicable to systems with/without control. Latter is coordinate invariant.
- A new simulator to measure these quantities
- A new actuator which can
  - Provide power without overwhelming natural dynamics
  - Adapt its stiffness to an operating environment to maximize gait robustness

Future Research

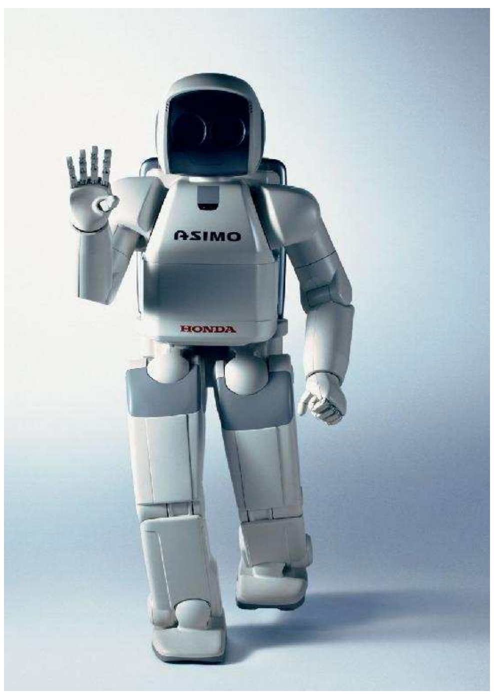
- Construct the proposed biped using the developed method
- Investigate which has better correlation to real-life robustness, r_{IDR} or r_{EDR}?
- Improve the engineering of the VSSEA to make it lighter, have less friction
- Consider using theory of manifolds and numerical optimization to design controllers for these bipeds

Questions?

What is the state of the art for bipedal robots?

Stiffly-actuated, position-controlled robots

- Strengths: General method, easily understood
- Weaknesses: Trying to constraining position via control is bad for efficiency, poor shock tolerance, dangerous, can't run.



Asimo (Honda)

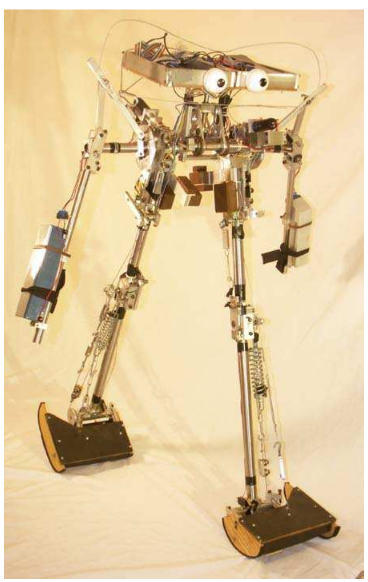
HRP-2 (AIST)

QRIO (Sony)

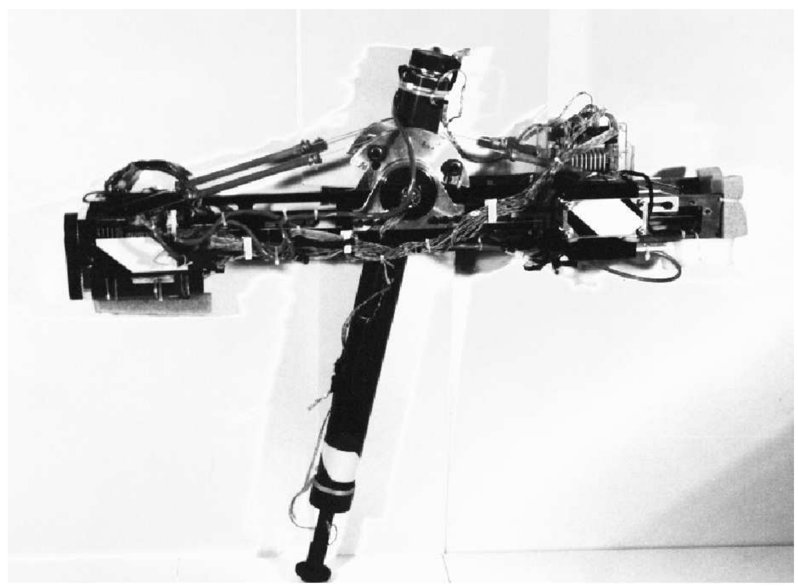
How can we improve on existing robots?

We advocate basing robots on passive dynamic walking and running

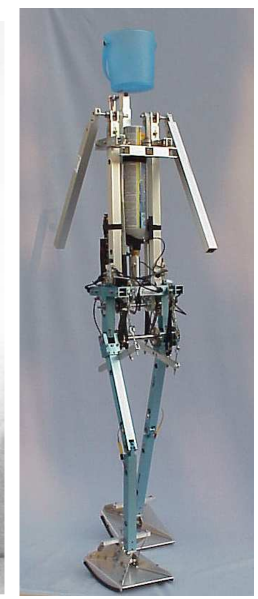
- Strengths: Energy efficiency, natural looking motion, good shock tolerance, safer
- Weaknesses: Hard to analyze robustness to disturbances, hard to design controllers, hard to actuate. (Can we solve these problems?)



Cornell Biped



Monopod-II (McGill)



Denise (Delft U.)

How much more efficient are Passive Dynamic robots?

Cost of Transport: $c_t = \frac{energy}{weight \cdot distance}$.
c_{et}はバッテリーあるいはmetabolicの消費したエネルギー, c_{mt}は機械的な仕事

Name	Mfg	c_{et}	c_{mt}	Passive-Dynamic?
Asimo	Honda	3.2	1.6	no
Denise	Delft	5.3	0.08	yes
Monopod II	McGill	0.22	-	yes
Cornell Biped	Cornell	0.20	0.055	yes
Human Walking	God	0.20	0.05	-
Dynamite	McGeer	-	0.04	yes

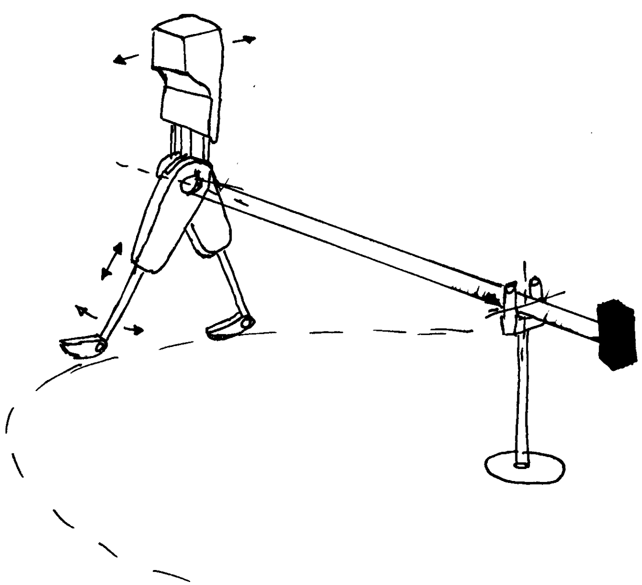
Reasons for high c_{et} of passive-dynamic robots are thought to be mostly engineering-related problems.

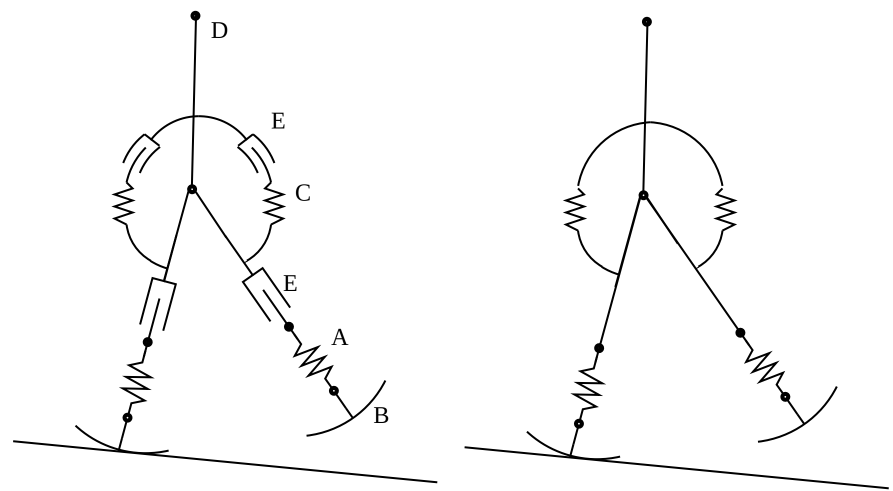
Turning now to the other weaknesses of Passive Dynamic Bipeds

- We can now calculate robustness and design theoretical bipeds
- But what about the practical requirements of control and actuation?
- How do we actuate these robots without destroying their passive dynamics?

Design Concept for a Biped Based on Passive-Dynamics

- Mechanical robustness can be examined separately by locking the motors
- Stiffness tunable to match forward speed
- Mechanical robustness reduces control complexity

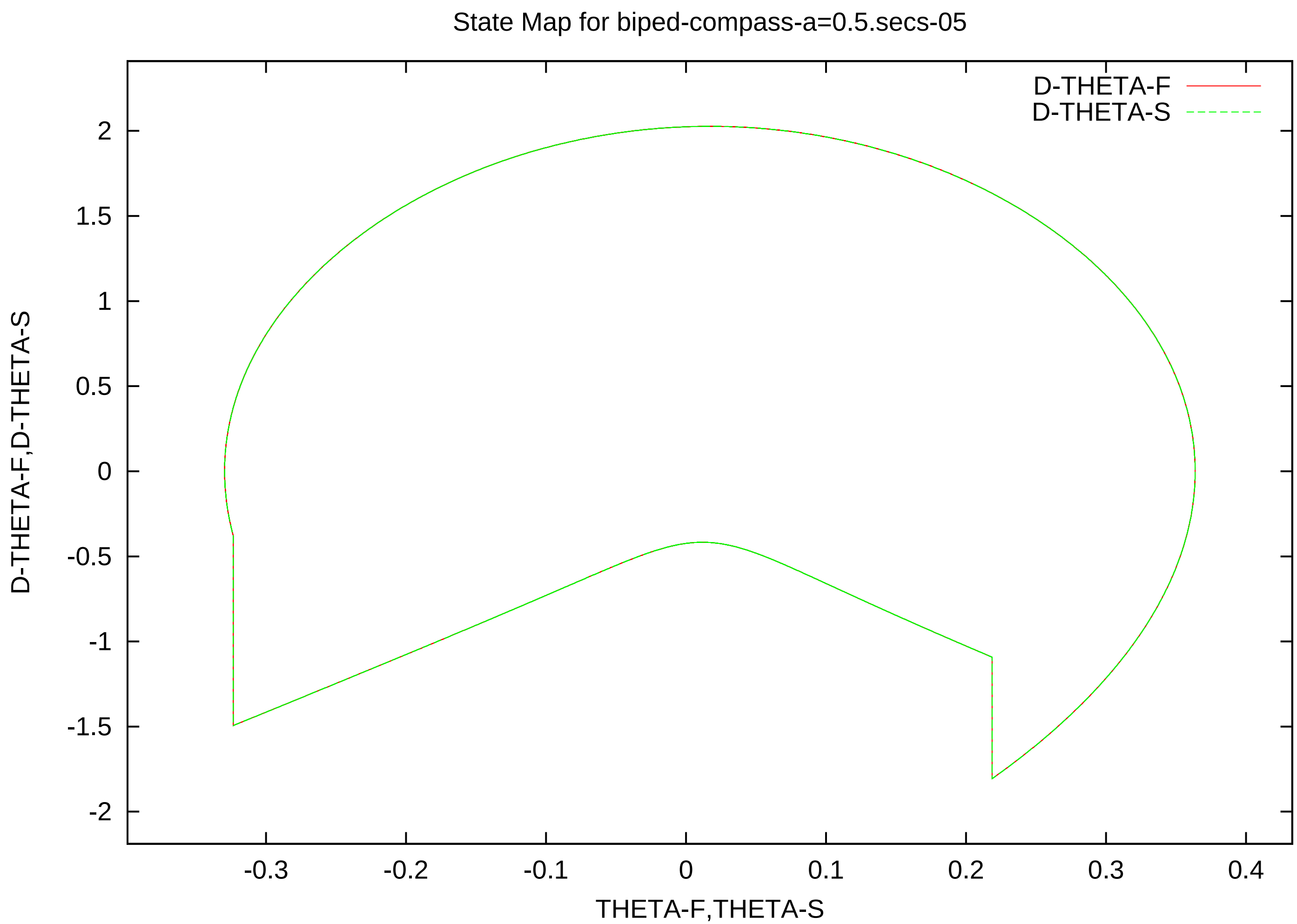




(a) (b)

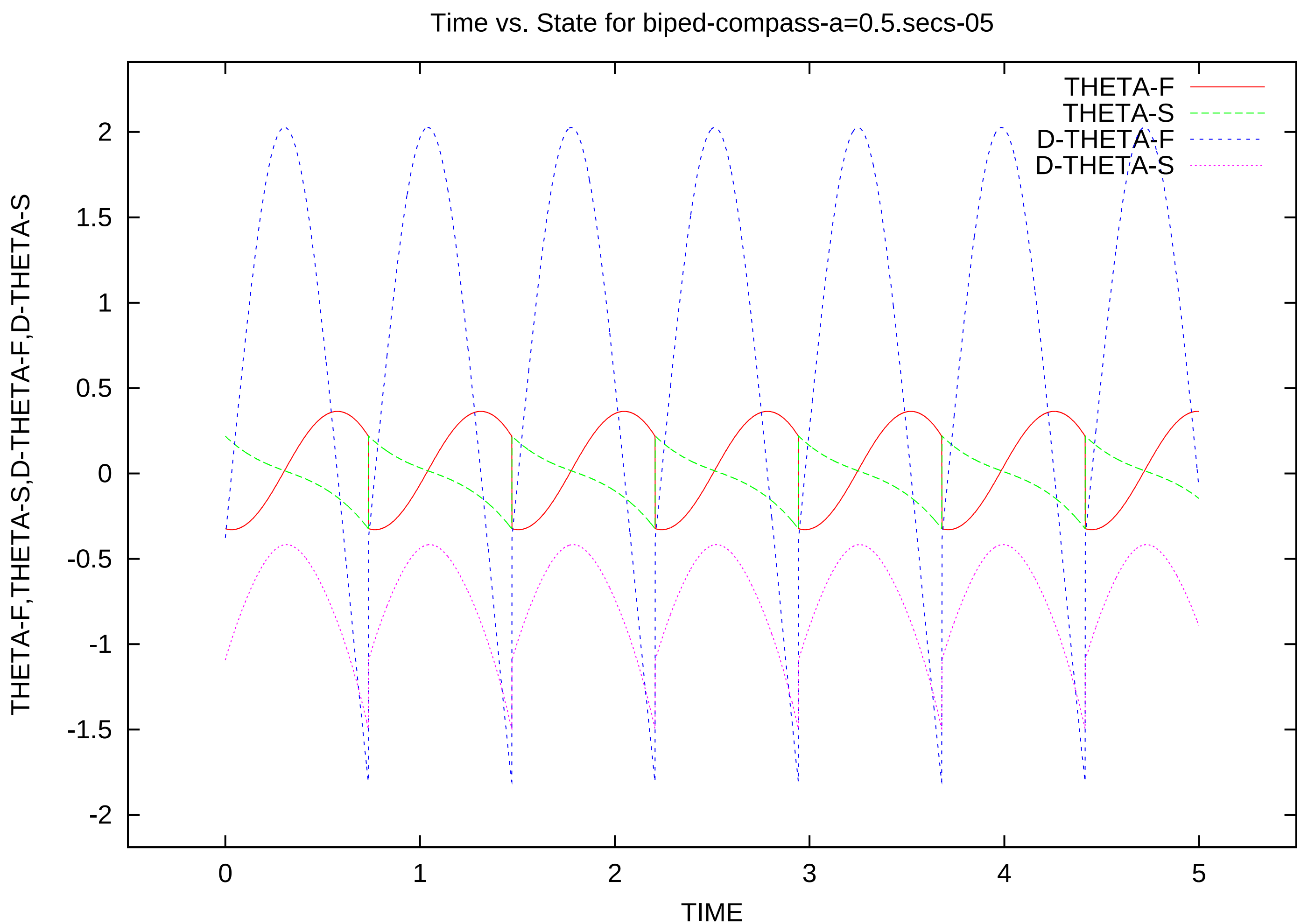
The Simulation Environment

- Automatically discovers limit cycle



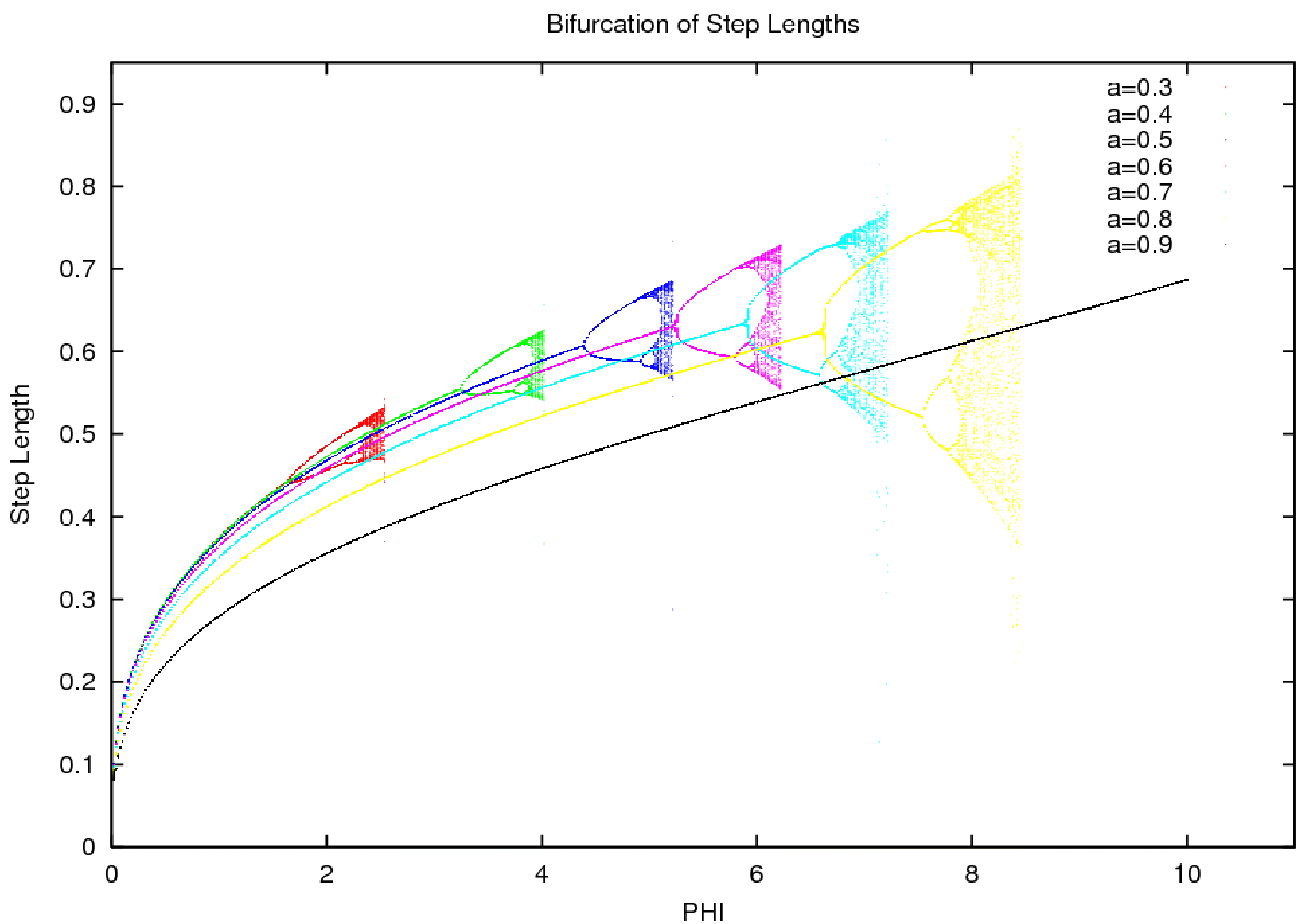
The Simulation Environment

- Automatically logs and plots various quantities



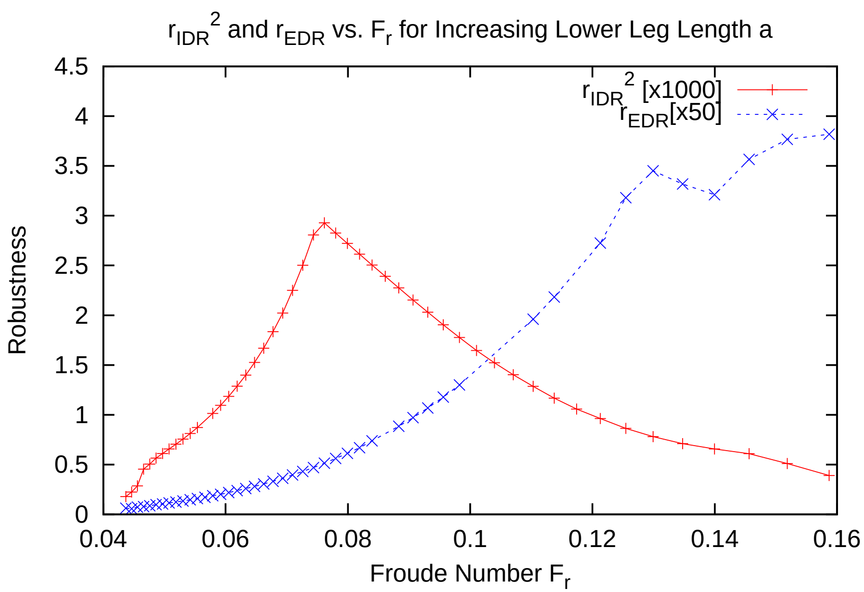
The Simulation Environment

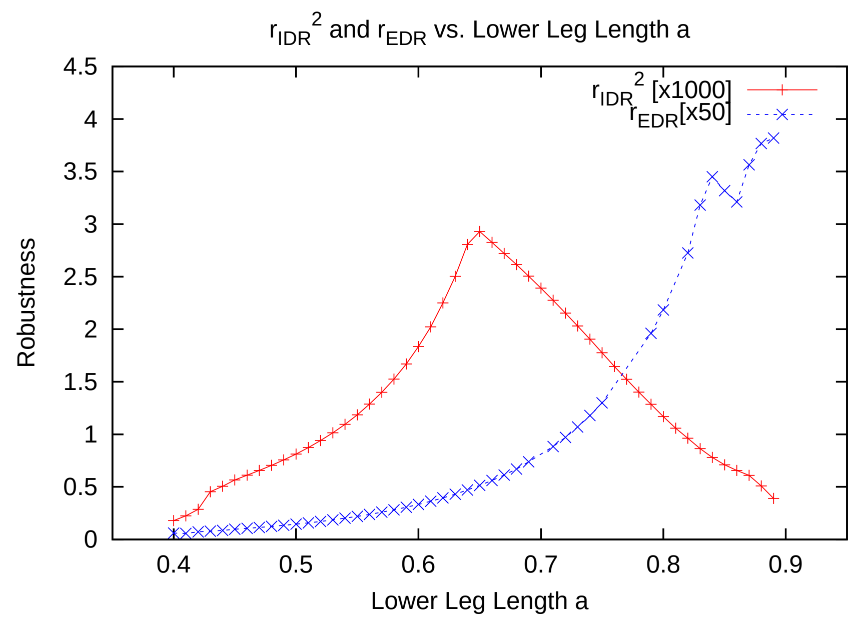
- Plots limit cycle bifurcations

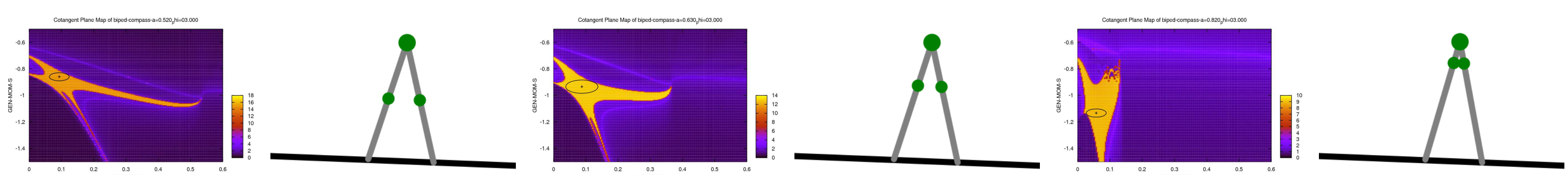


Effect of Varying Lower Leg Length

Greatly affects robustness. This is the only graph where r_{IDR} and r_{EDR} do not agree.

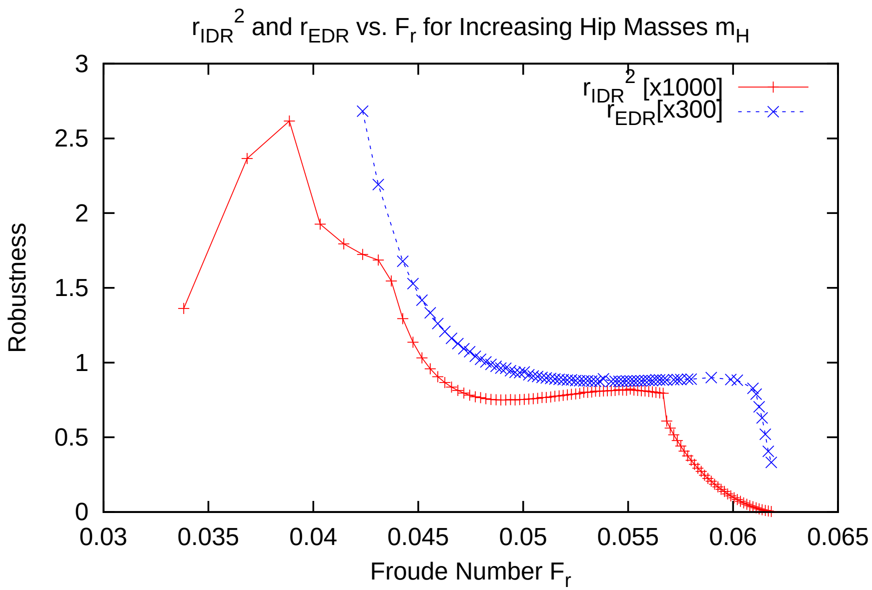


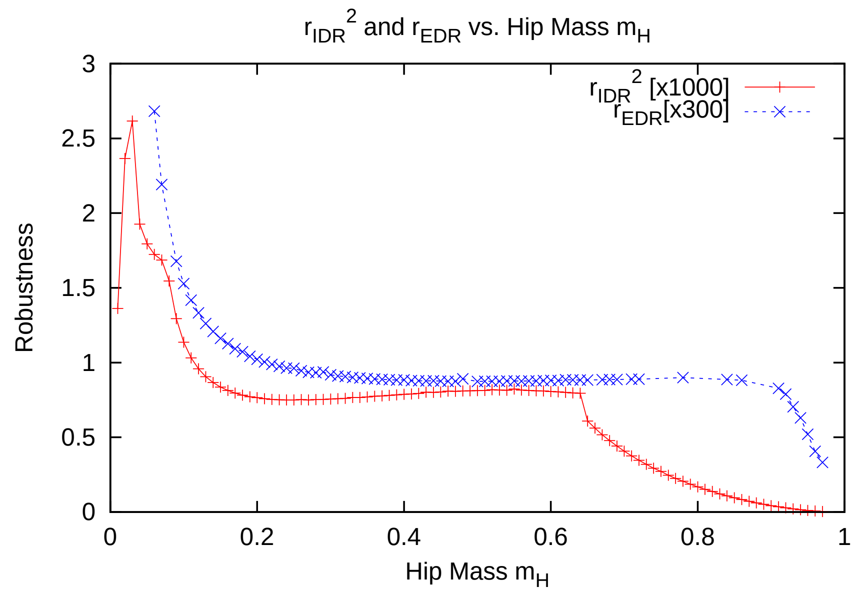


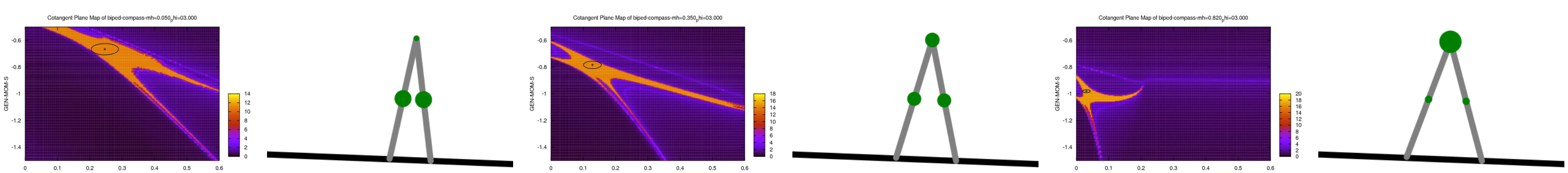


Effect of Mh

Little effect on robustness.

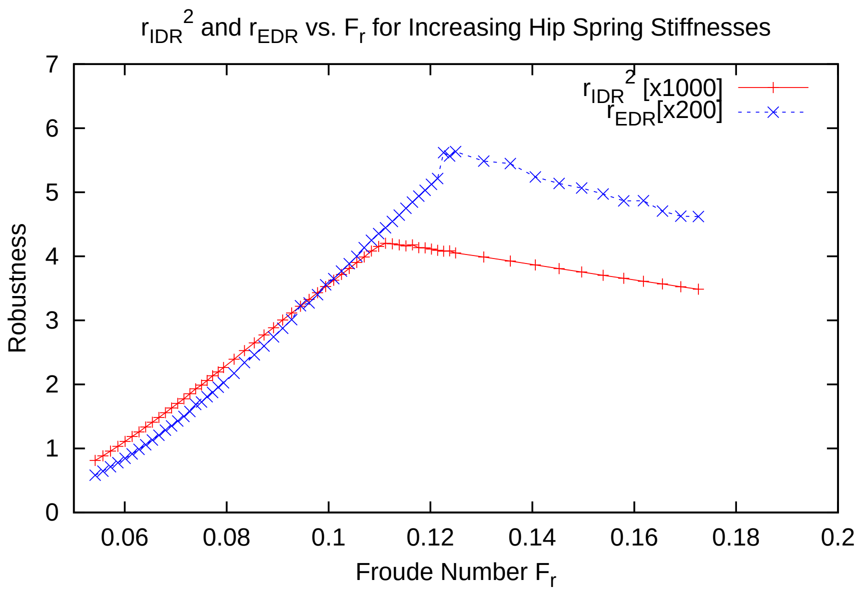


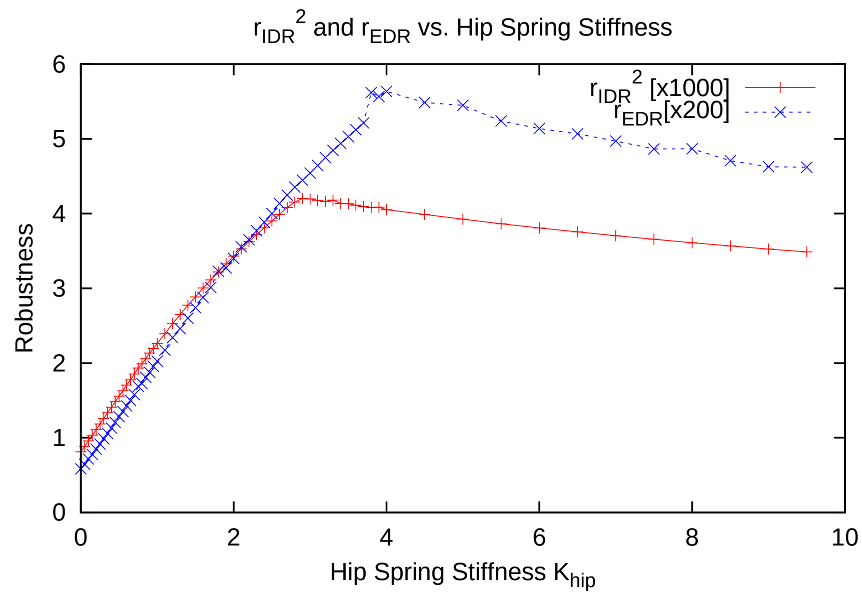




Effect of k_{hip}

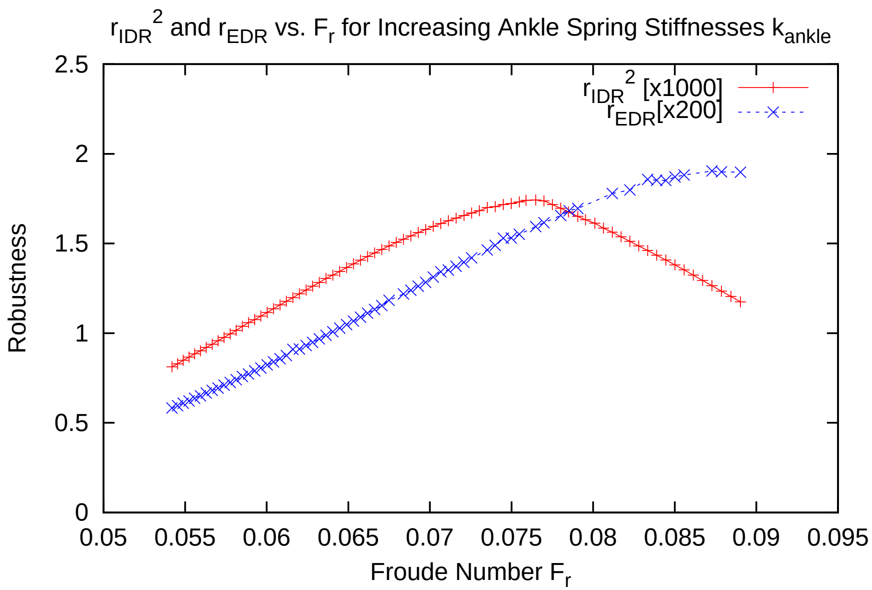
Great effect on robustness, peaking behavior interesting.

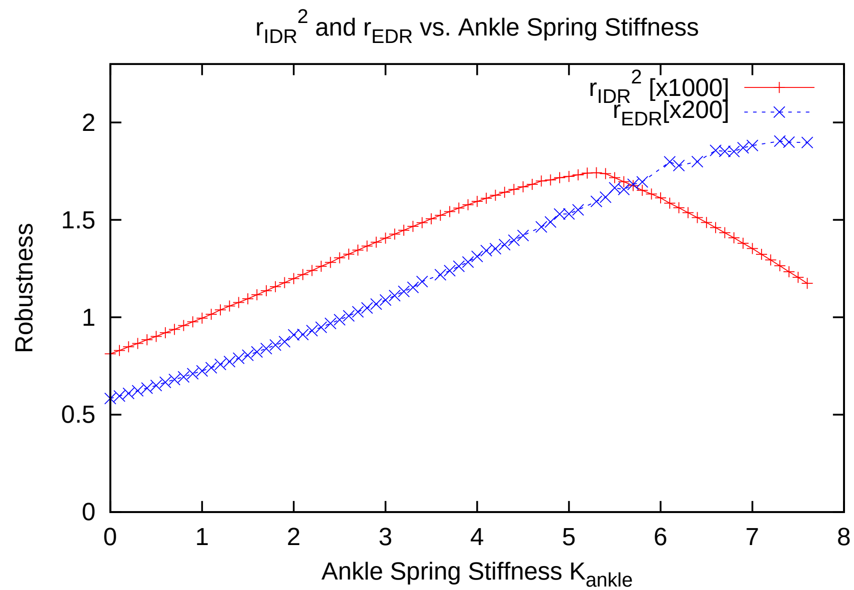




Effect of k_{ankle}

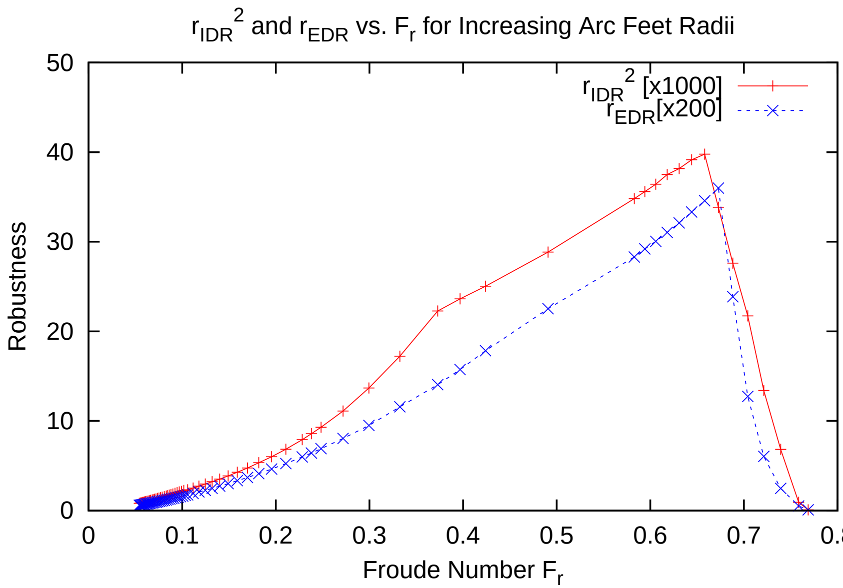
Slightly unphysical, but improves robustness

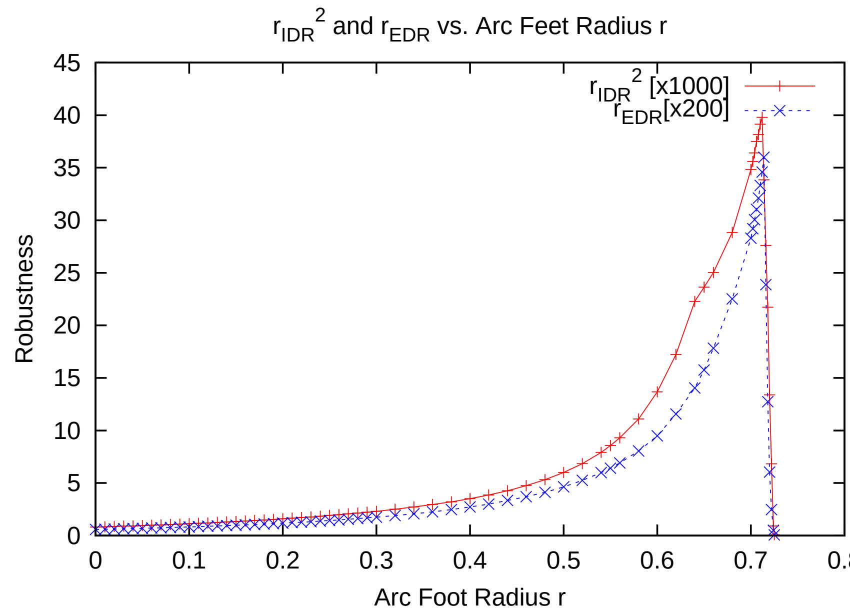


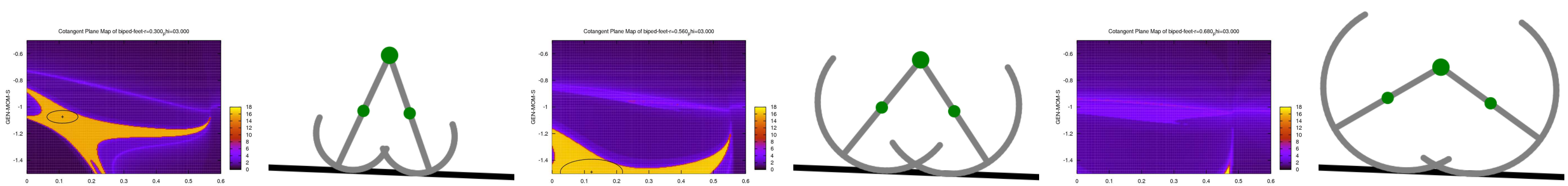


Effect of Arc Feet

Increasing arc radius improves speed and robustness

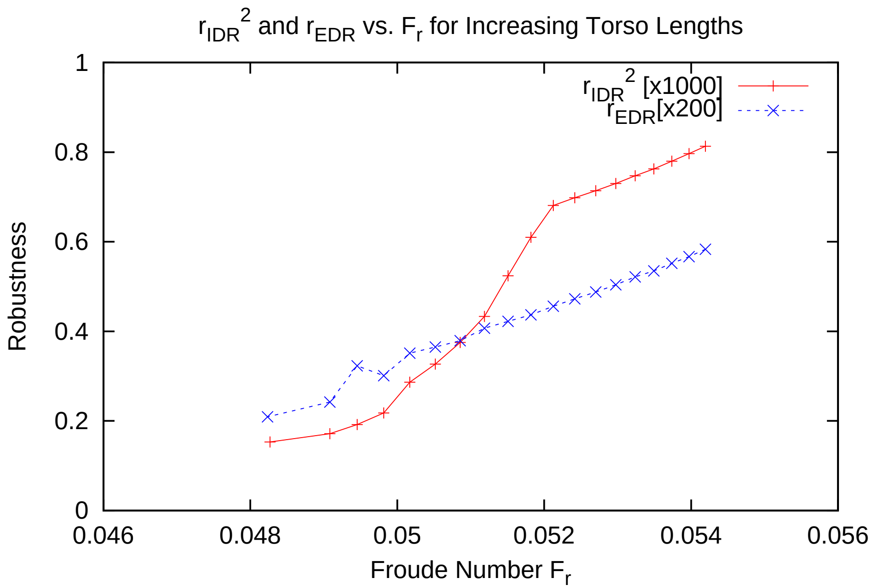


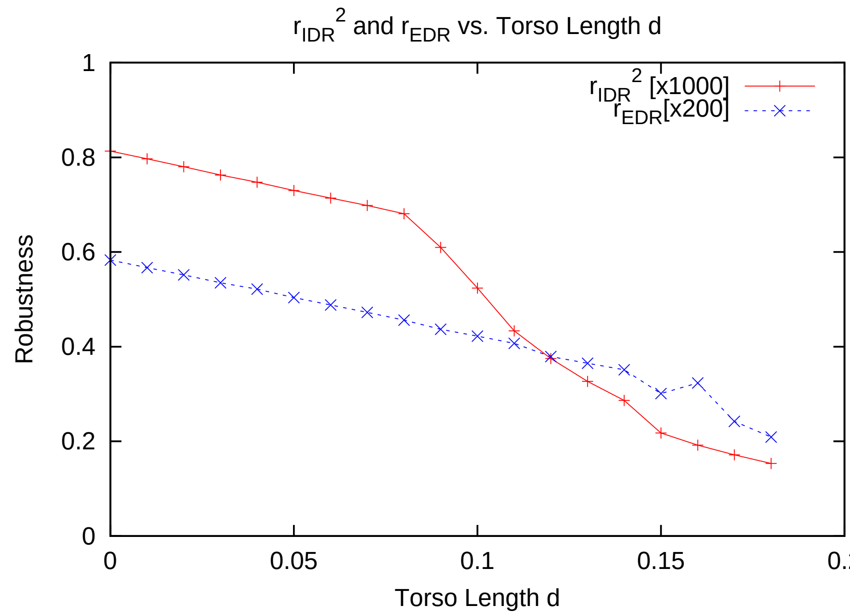


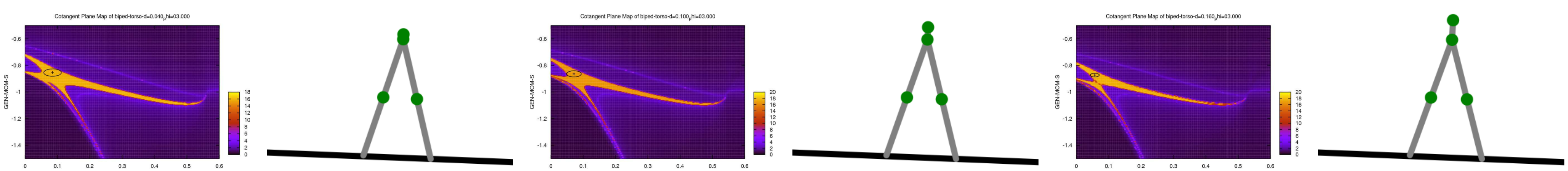


Effect of Torso

Adding a torso made robot less robust

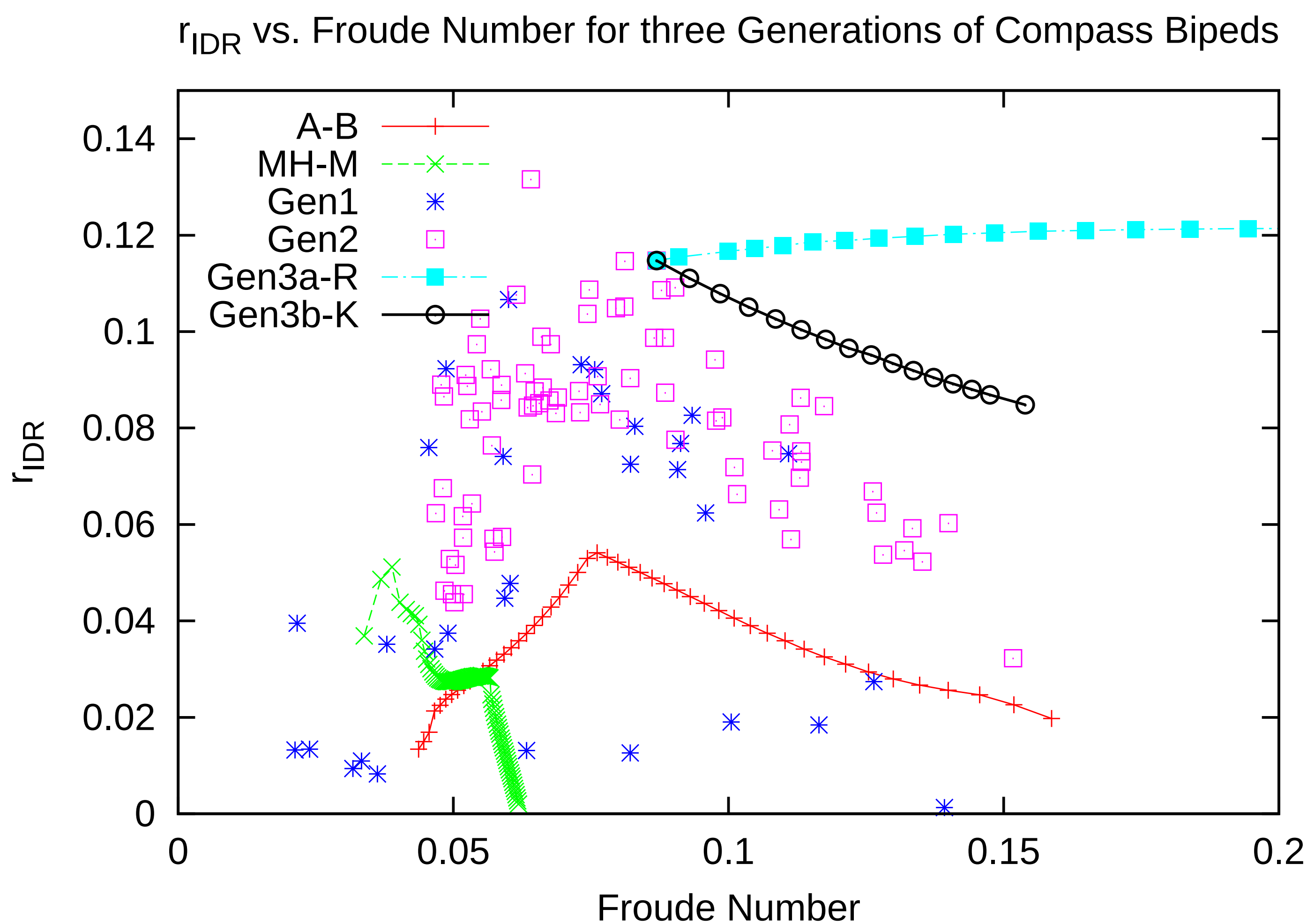




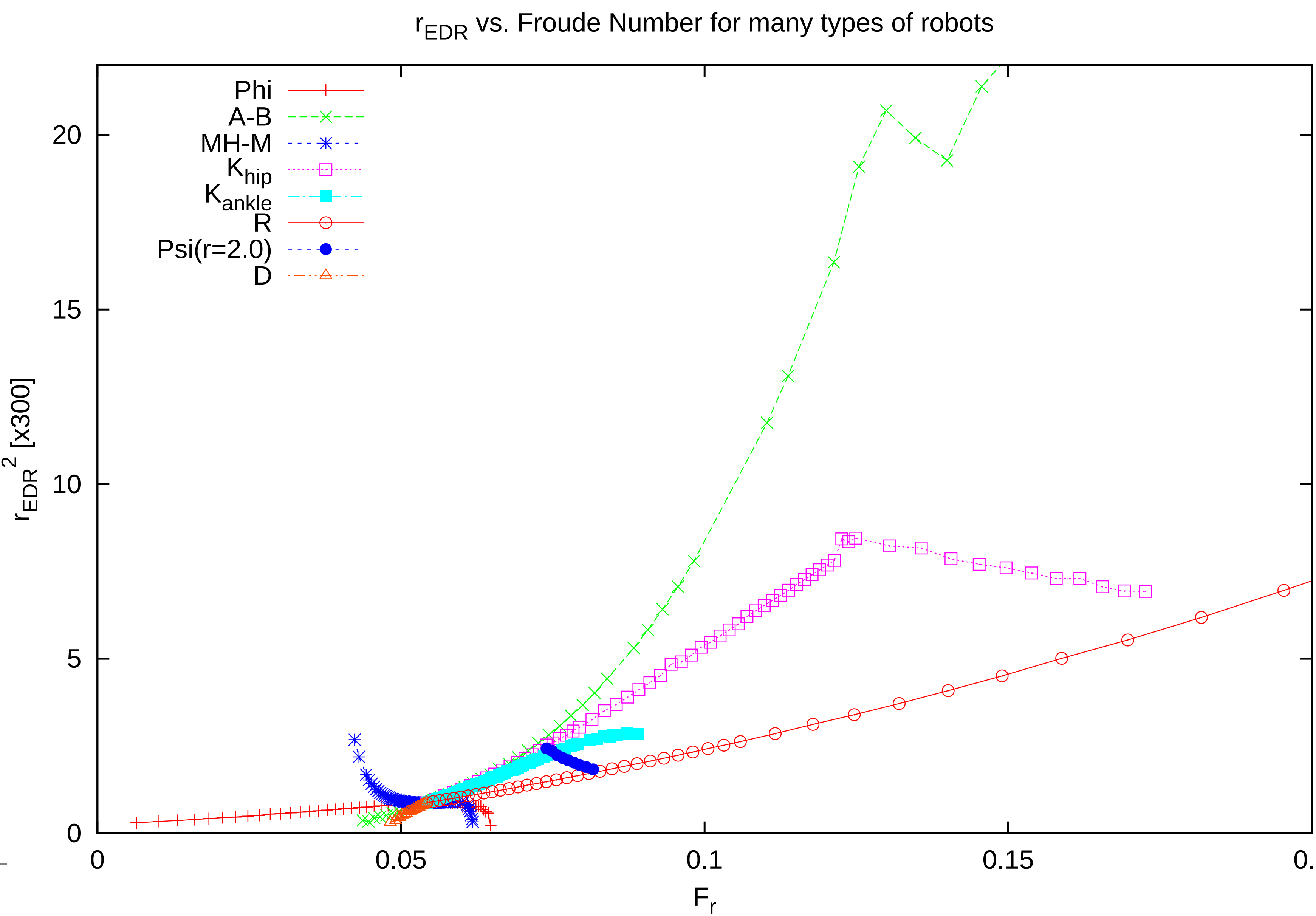


What about varying more than one parameter?

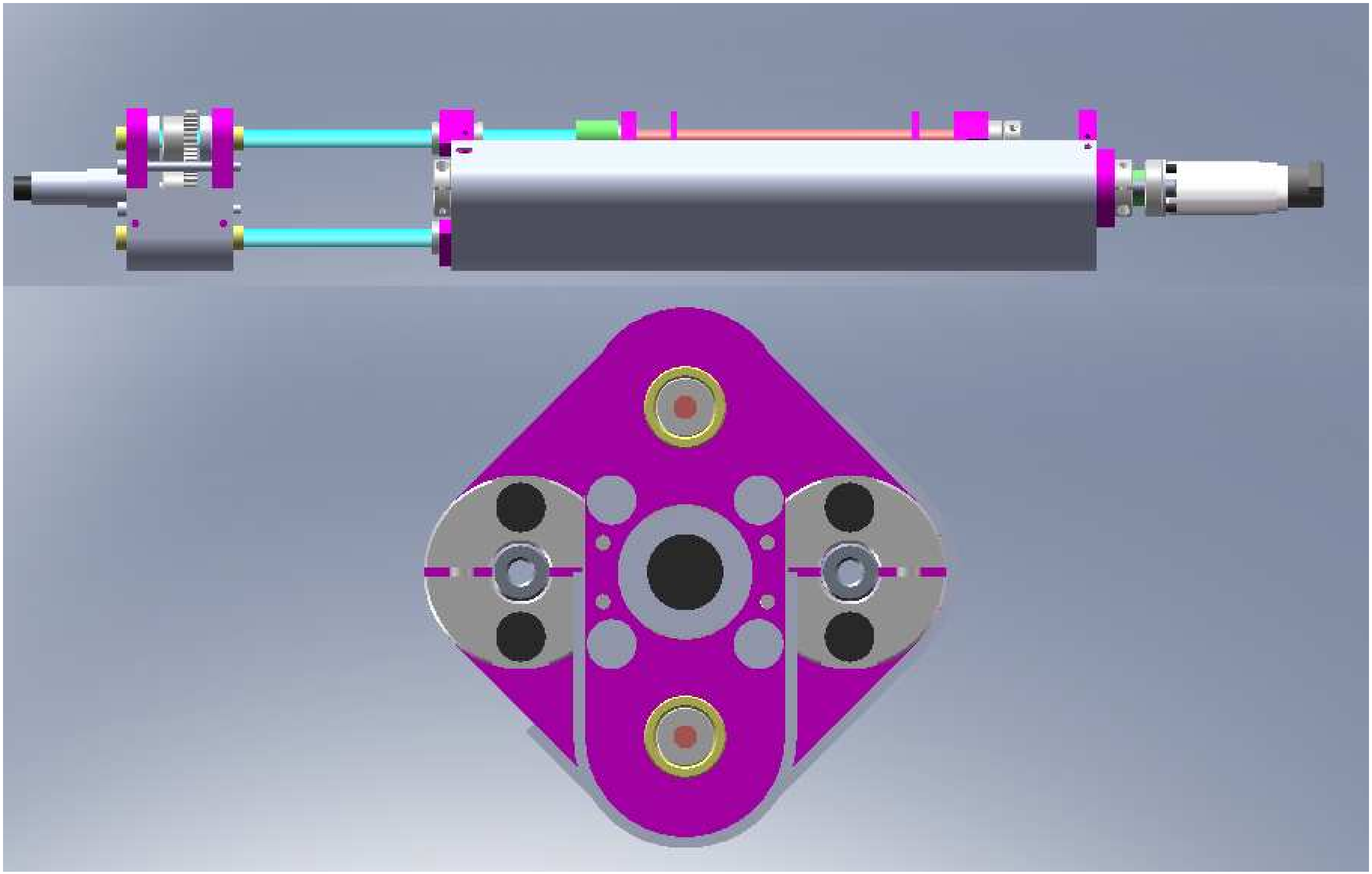
Let's pick some design parameters randomly and evolve a biped



Summary of r_{EDR} Data



VSSEA schematics



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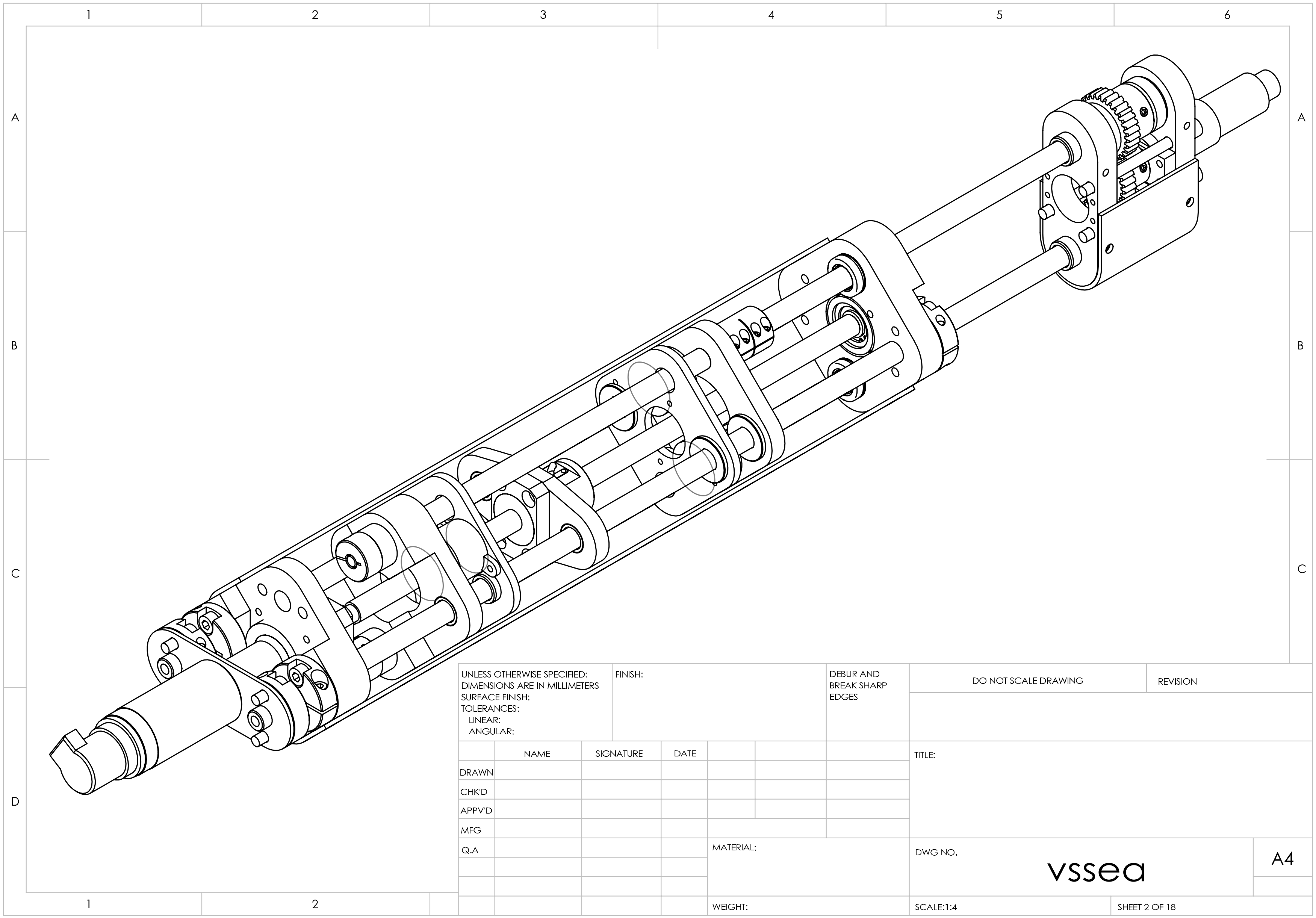
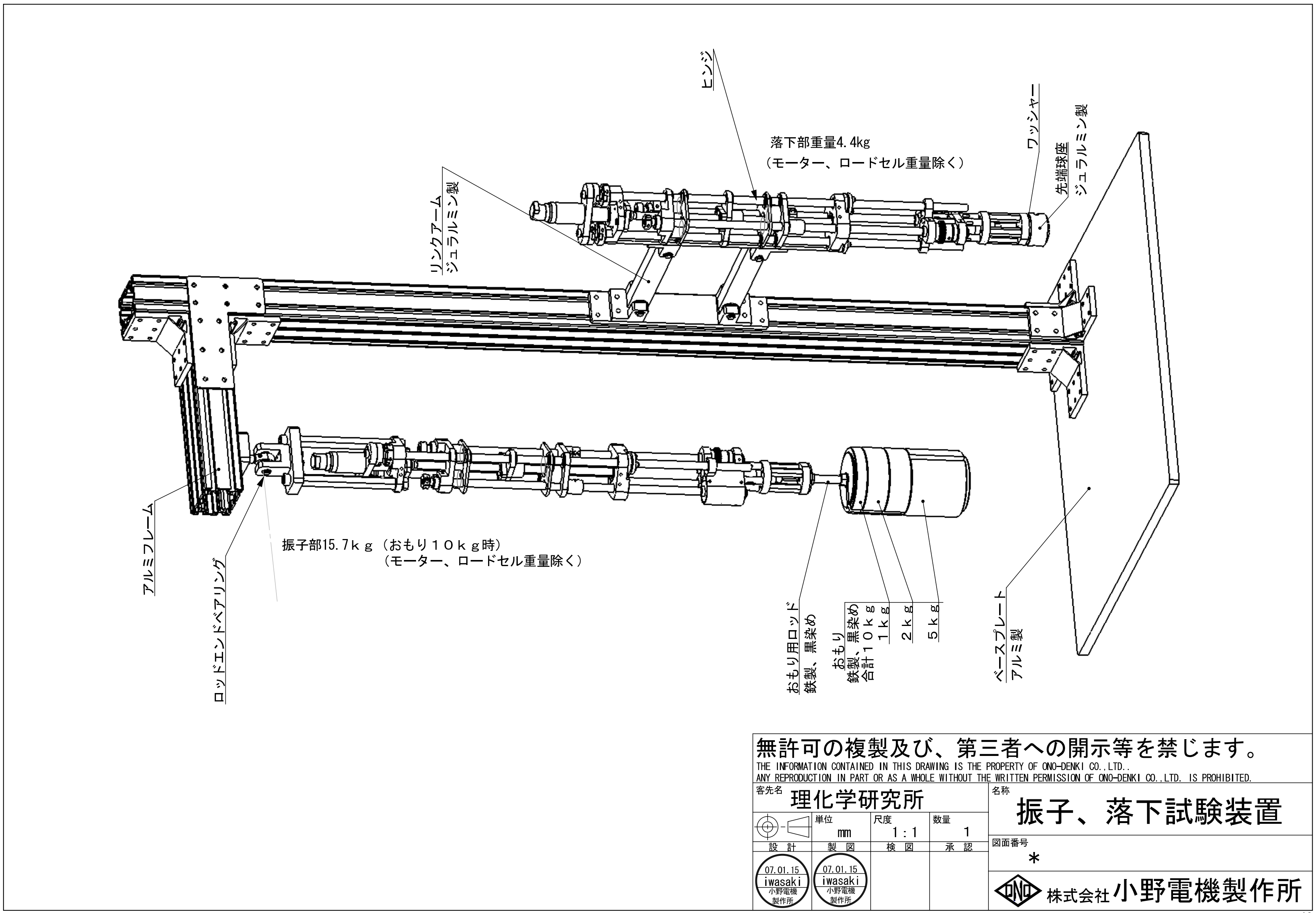


VSSEA schematics



The Simulation Environment

- ...or total kinetic energy.