# RAPID AND AGILE LOCOMOTION WITH POWER-DENSE MILLIROBOTS

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# MOTIVATION | DESIGN FOR ENERGETIC LOCOMOTION

Try to design highest performance robots

Use those robots as scientific tools to study locomotion

# APPROACH | DESIGN FOR POWER-DENSITY

To perform better at energetic tasks, design with power density as primary criteria

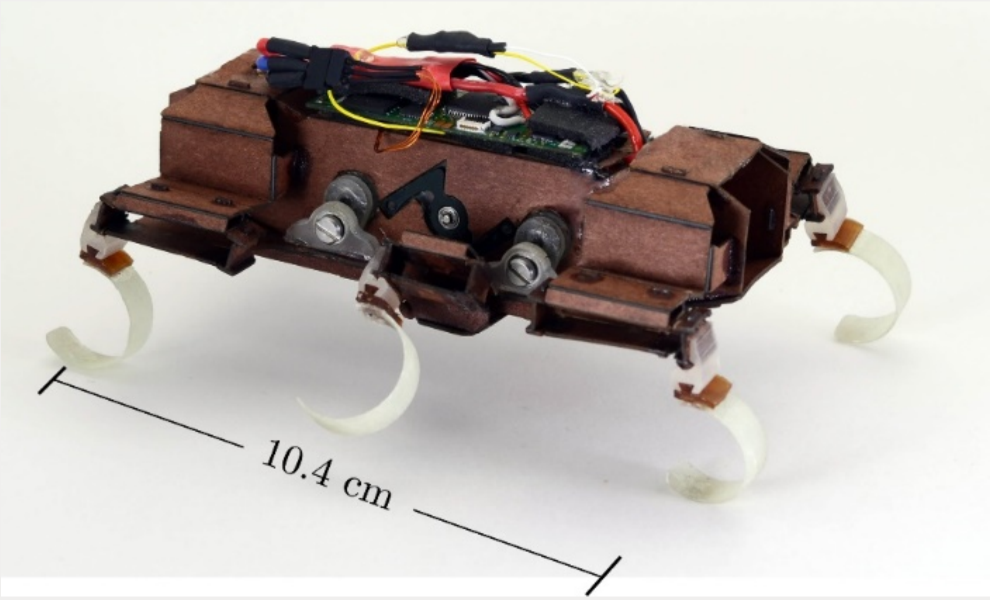
Method: Use one actuator to do all the energetic work.

This is enabled by a coupling mechanism that produces the desired behavior by default, when power is applied

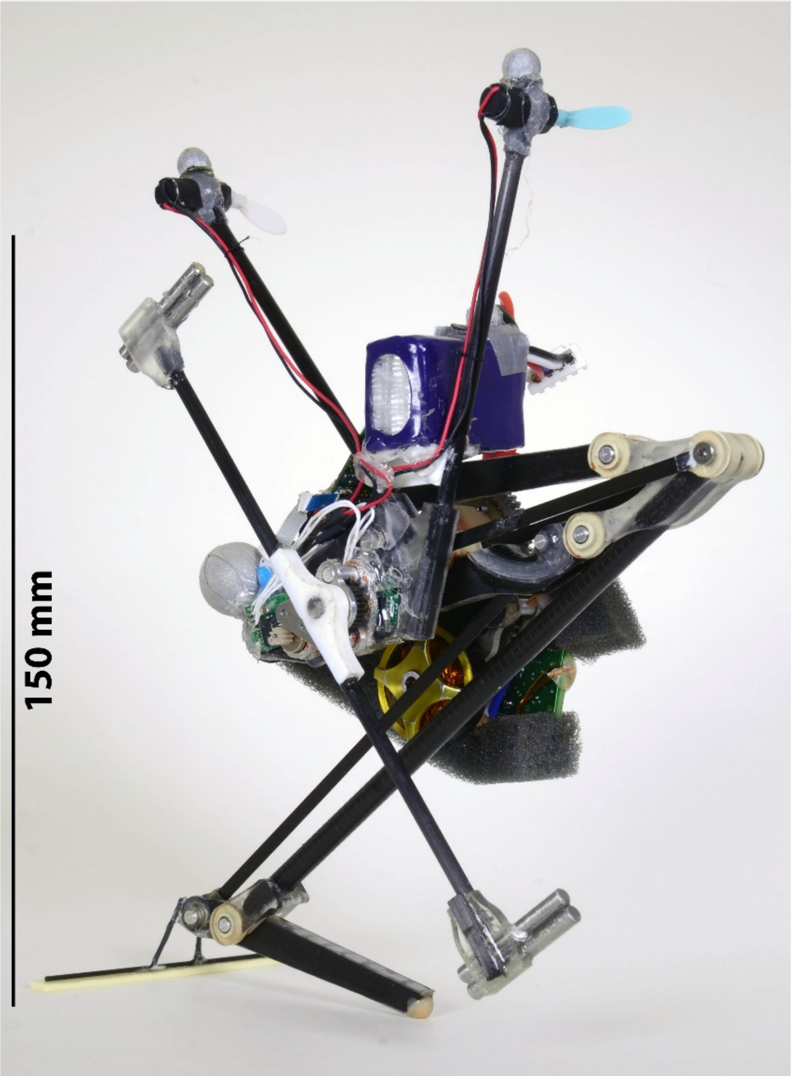
# APPROACH | DESIGN FOR POWER-DENSITY

Test power density first design with running robot and jumping robot.

Both should be best in class




X2-VelociRoACH




Salto

# OVERVIEW

## RAPID AND AGILE LOCOMOTION WITH POWER-DENSE MILLIROBOTS

**1: RAPID LOCOMOTION**

- Approach
- Result
- Stride kinematics
- Force and power
- Energetics

**2: AGILE LOCOMOTION**

- Motivation
- Agility metric
- Actuation strategies
- SE+MA actuation
- Leg mechanism
- Proof of concept
- Prototype & results

**3: SPATIAL-AGILE**

- Attitude control
- Spatial controller
- In-place jumping
- Forwards-backwards
- Jump exploration

# 1: RAPID LOCOMOTION



**1: RAPID LOCOMOTION**

Approach

Result

Stride kinematics

Force and power

Energetics

# 1: RAPID LOCOMOTION

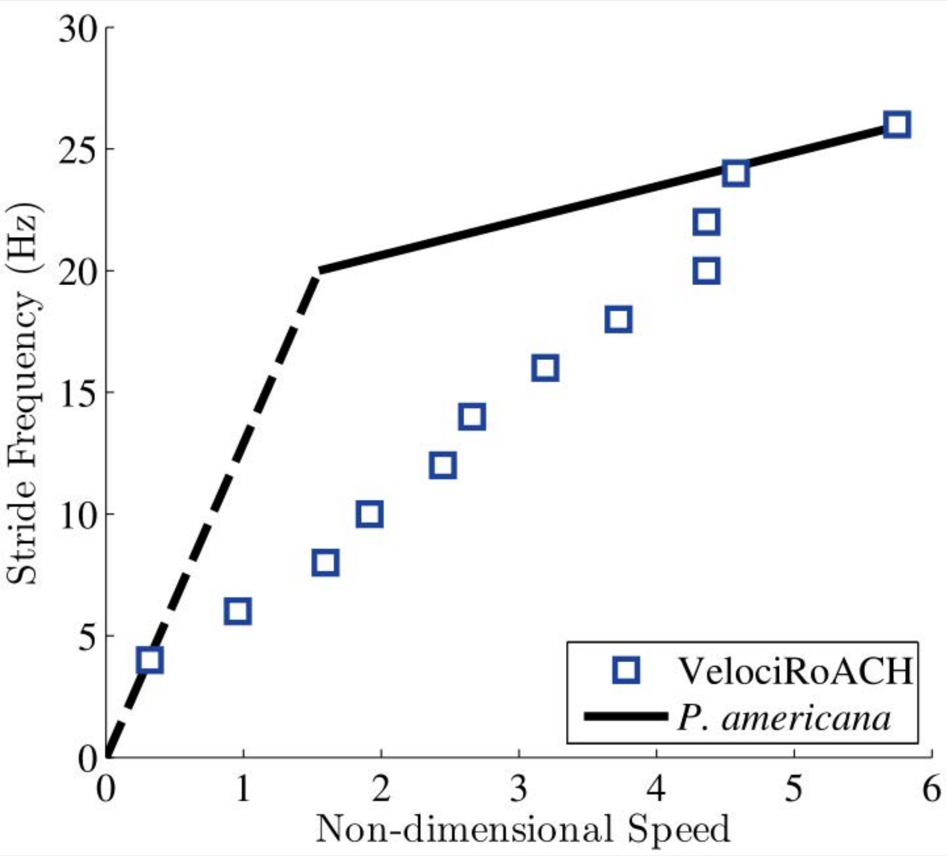
FASTER RUNNING ROBOTS VIA POWER-DENSITY

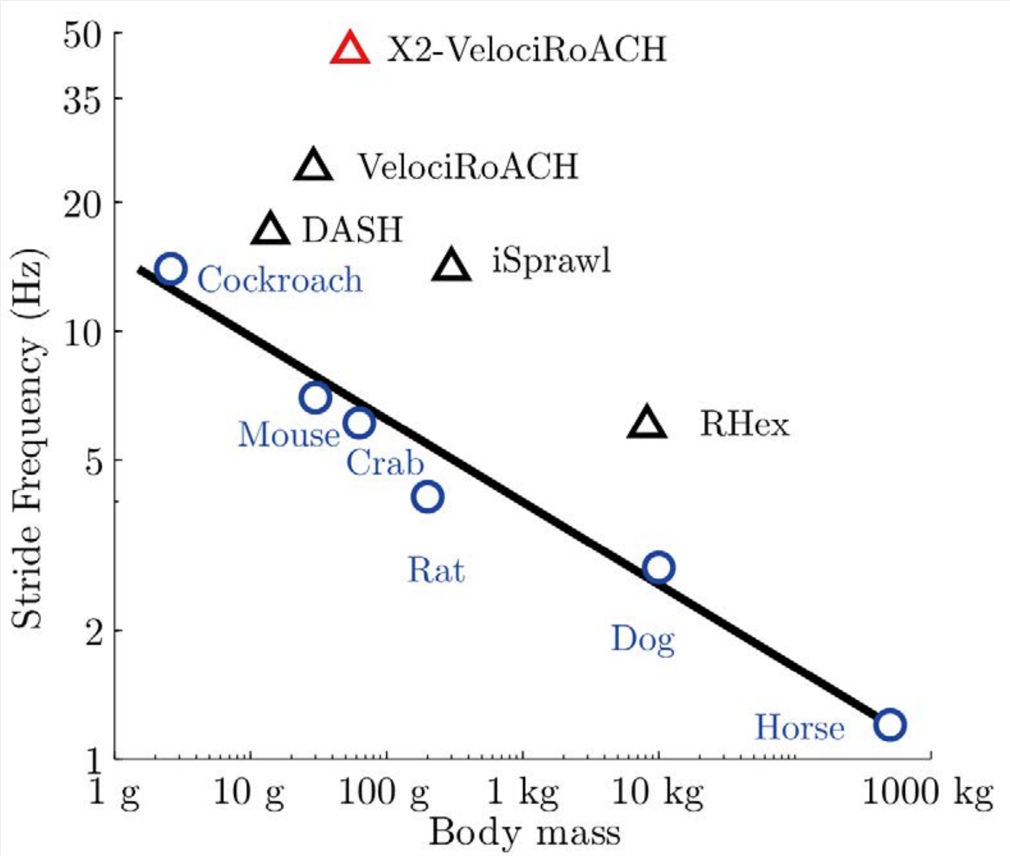
## 1: RAPID LOCOMOTION

Approach

# RAPID | MOTIVATION

Find the speed limits of legged locomotion




**What limits the top speed of a robot?**

# RAPID | APPROACH

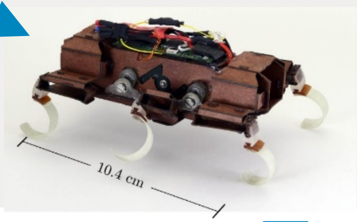
**Design for power-density first:**

Cut everything that doesn't add power

Run using a single actuator

[PhantomX Hexapod]

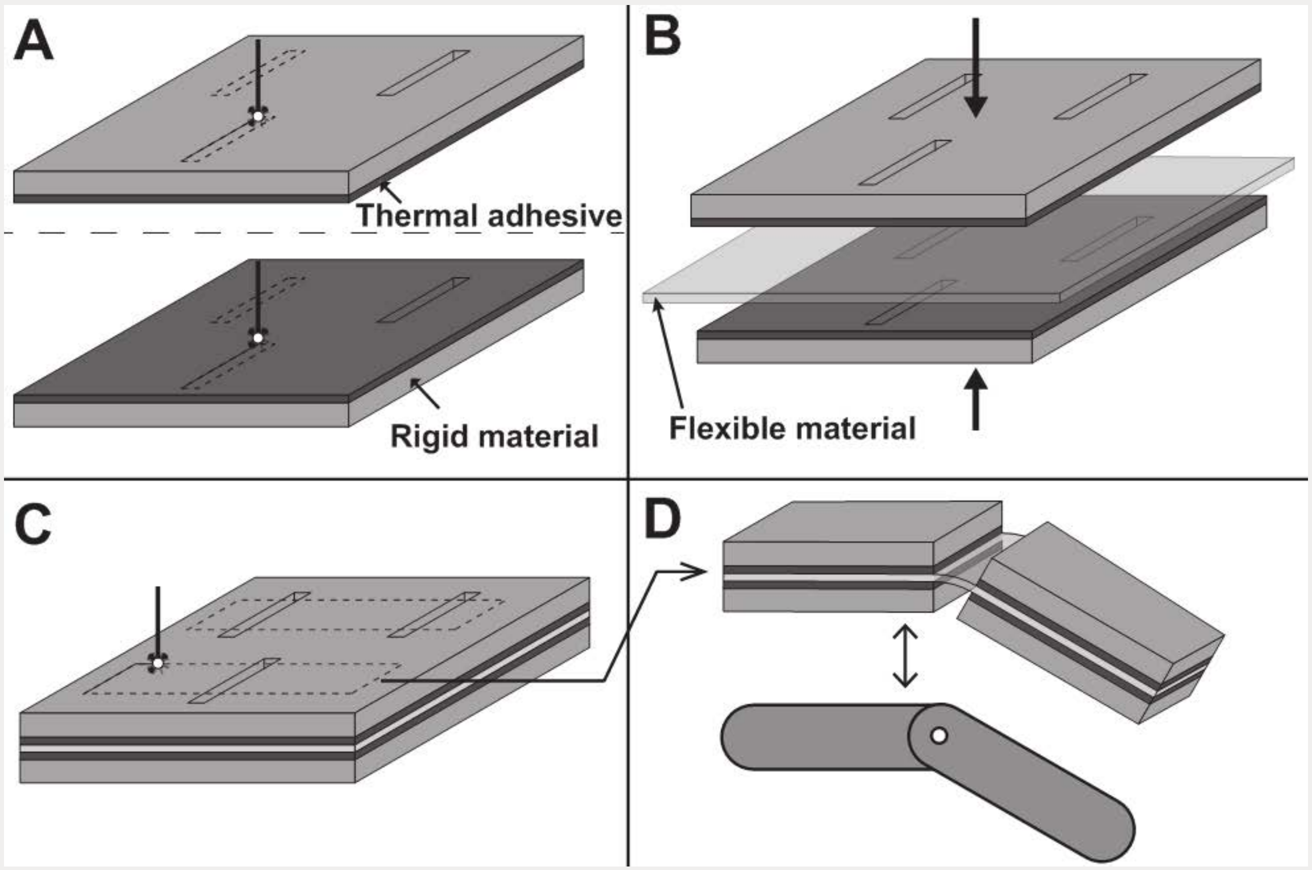
**Build faster robot by increasing power density**



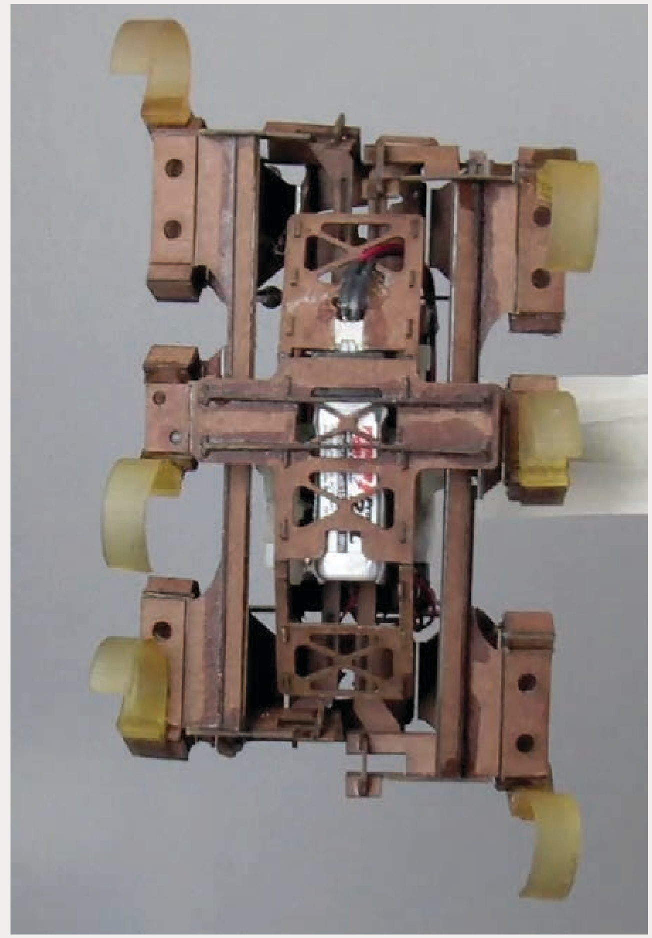
# RAPID | APPROACH

Attach single motor to running mechanism

Mechanism translates power to running




## VelociRoACH

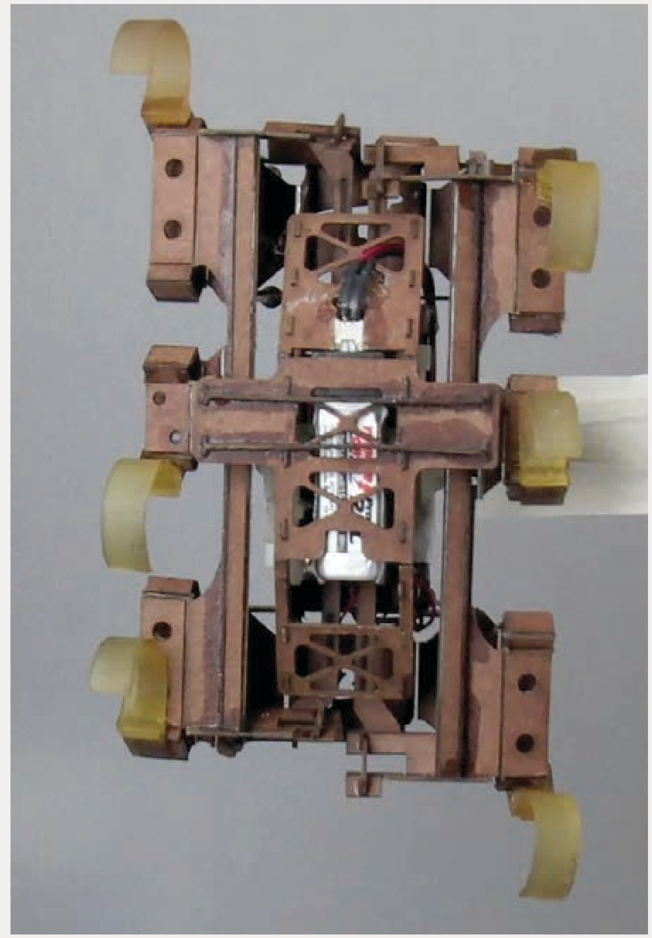


# RAPID | 2013: VelociRoACH

Prior running robot

2 DoF, 43 W/kg, 2.7 m/s top speed

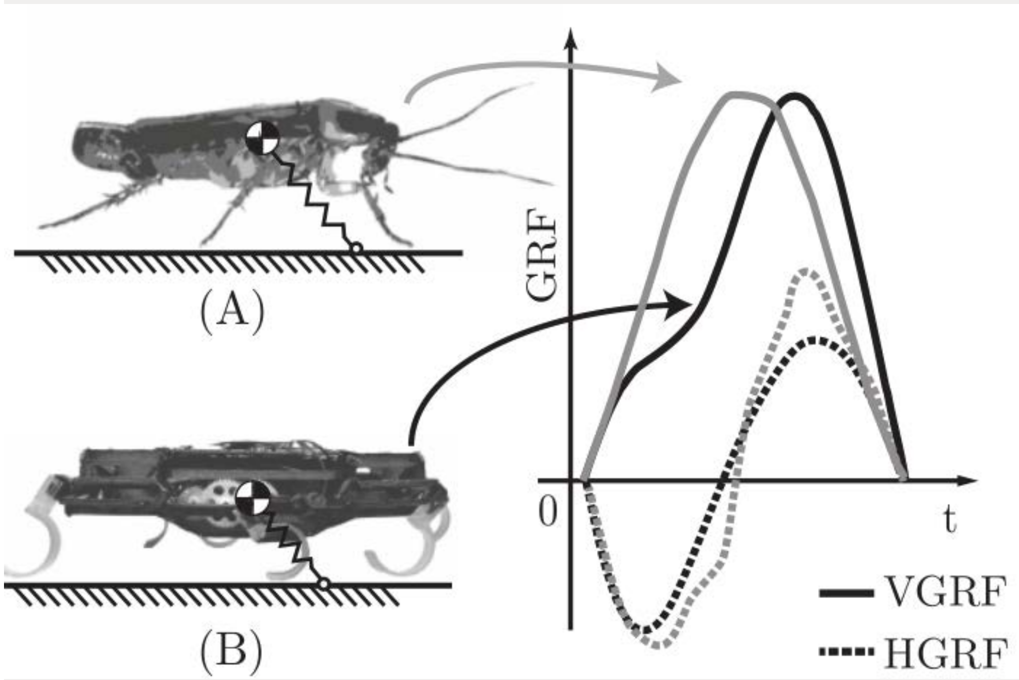

**VelociRoACH**



# RAPID | APPROACH: MECHANSIM

To get running from open-loop power input:

Tune leg kinematics and stiffness to get stable motion



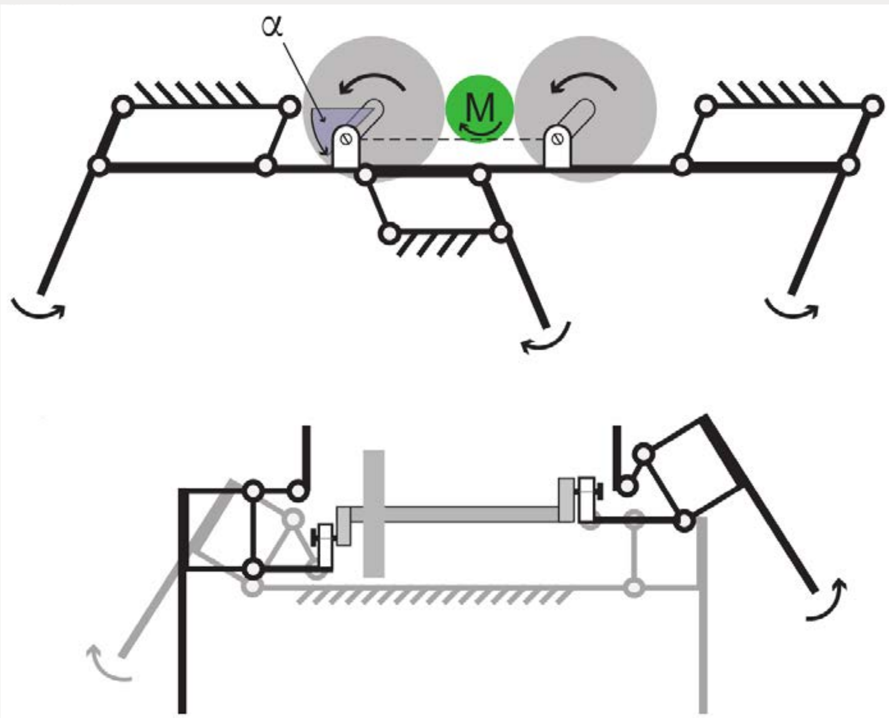

| | Scaling Factor | Value $\alpha_X$ | Cockroach | VelociRoACH Target | Actual |
|---|---|---|---|---|---|
| Length | $\alpha_L{=}\alpha_L$ | 3.3 | 3.4cm | 11.2cm | 10cm |
| Mass | $\alpha_M{=}\alpha_L^3$ | 36.1 | 0.83g | 30g | 29.1g |
| Stiffness | $\alpha_K{=}\alpha_L^2$ | – | – | – | 40 N/m |
| Frequency | $\alpha_\omega{=}\alpha_L^{-0.5}$ | 0.54 | 27 Hz | 15 Hz | 24Hz |
| Velocity | $\alpha_V{=}\alpha_L^{0.5}$ | 1.2 | 1.5 m/s | 2.72 m/s | 2.7 m/s |
| Power | $\alpha_P{=}\alpha_L^{3.5}$ | 65.3 | 1.57 mW | 103 mW | 243 mW |

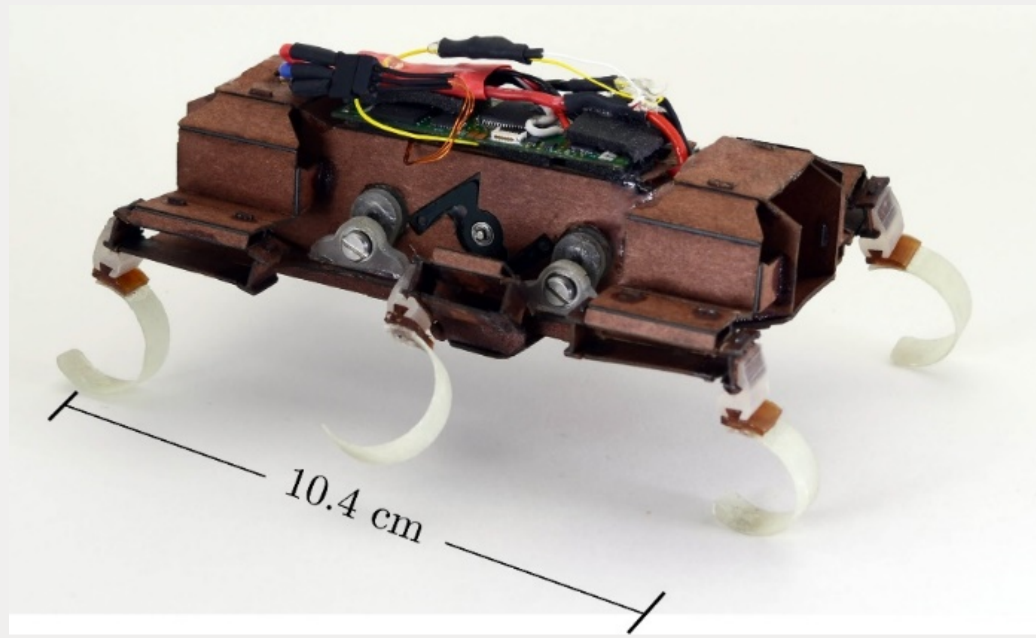
**Establish mechanical stability to get running by default**

# RAPID | APPROACH: MECHANSIM

New running robot: X2-VelociRoACH

1 DoF, 120 W/kg




**Single-motor design gets 3X power density**

# 1: RAPID LOCOMOTION

FASTER RUNNING ROBOTS VIA POWER-DENSITY

1: RAPID LOCOMOTION

Approach

Result

# RAPID | RUNNING RESULTS

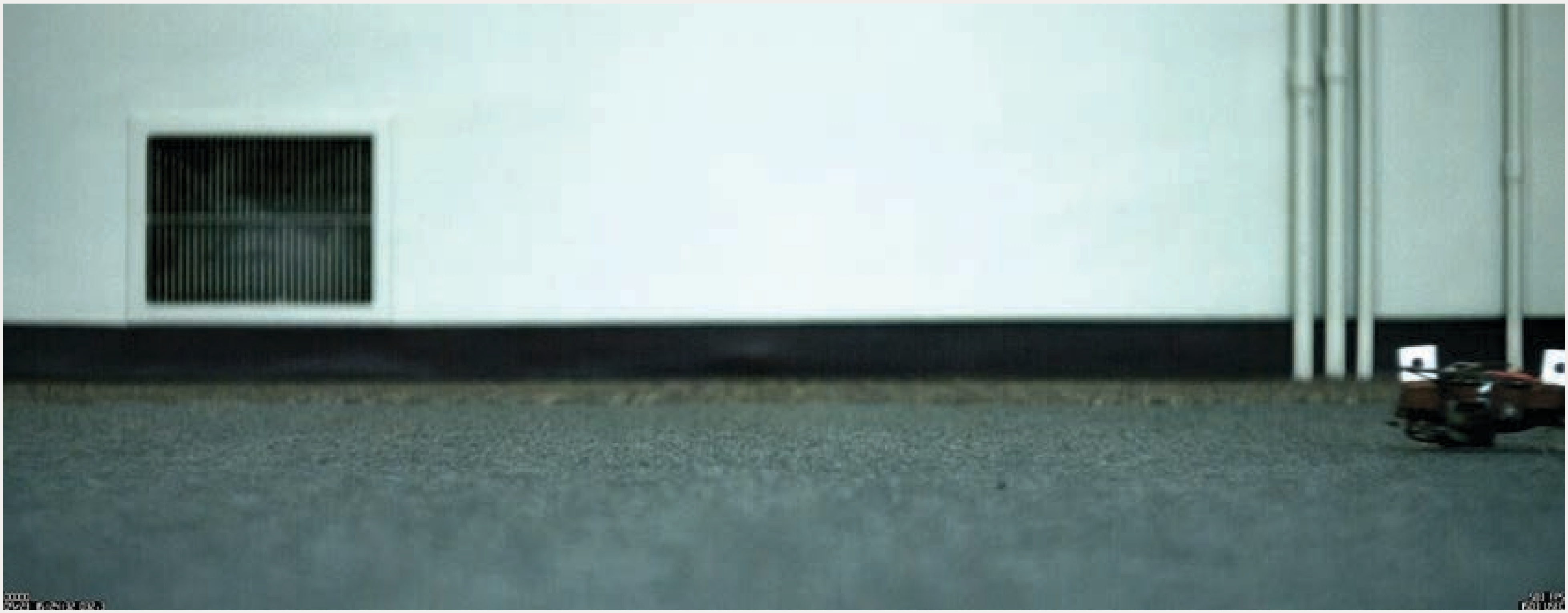
**Top speed: 4.9 m/s**

# RAPID | RUNNING RESULTS (SLOWED 5X)

# RAPID | RUNNING RESULTS (SLOWED 20X)

Footage captured at 600 fps

# RAPID | RUNNING RESULTS (SLOWED 19X)



# 1: RAPID LOCOMOTION

FASTER RUNNING ROBOTS VIA POWER-DENSITY

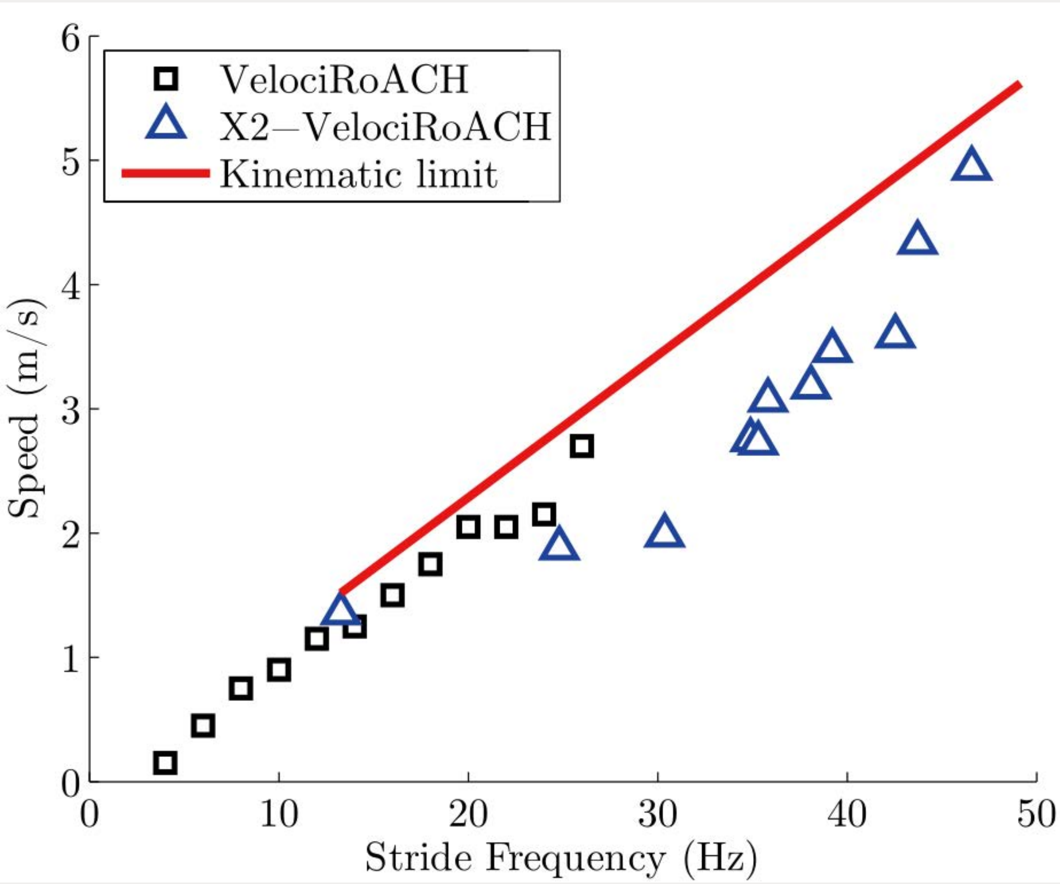
1: RAPID LOCOMOTION

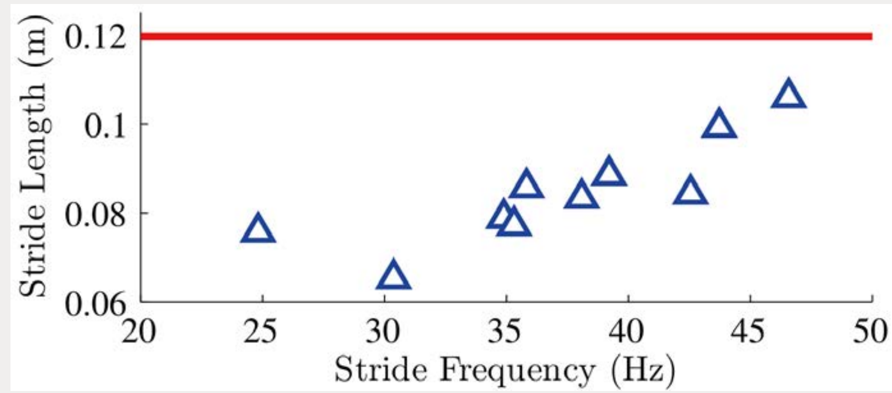
Approach

Result

Stride kinematics

# RAPID | STRIDE KINEMATICS




**Stride length increases at higher frequencies**

**Speed continues to increase with stride frequency**

# 1: RAPID LOCOMOTION



**1: RAPID LOCOMOTION**

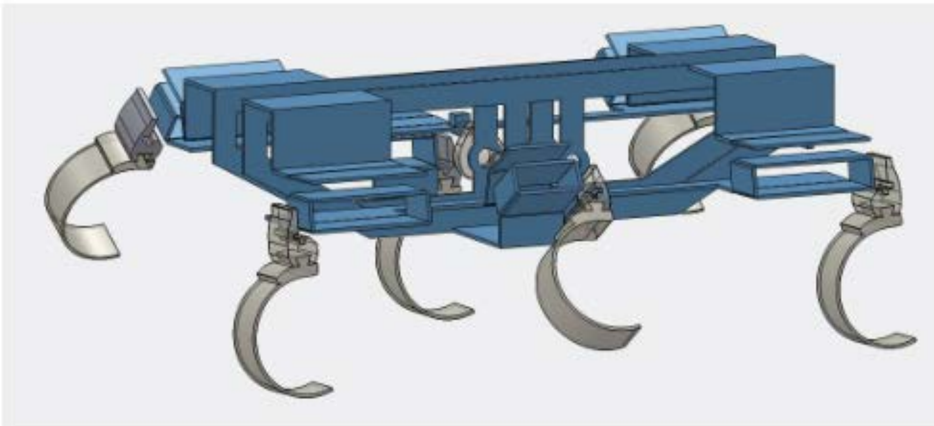
Approach

Result

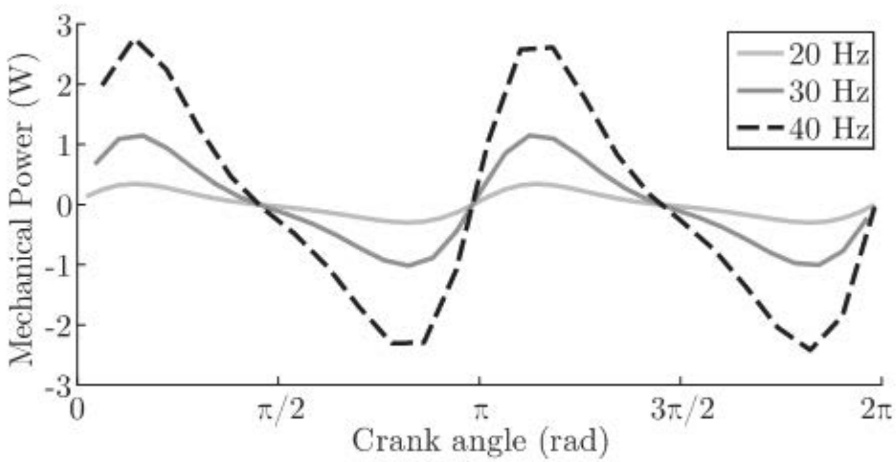
Stride kinematics

Force and power

# RAPID | PREDICTED POWER DRAW



(a) A rendering of a Solidworks model of X2-VelociRoACH. The leg mechanisms have one degree of freedom, and are driven by a single virtual motor.

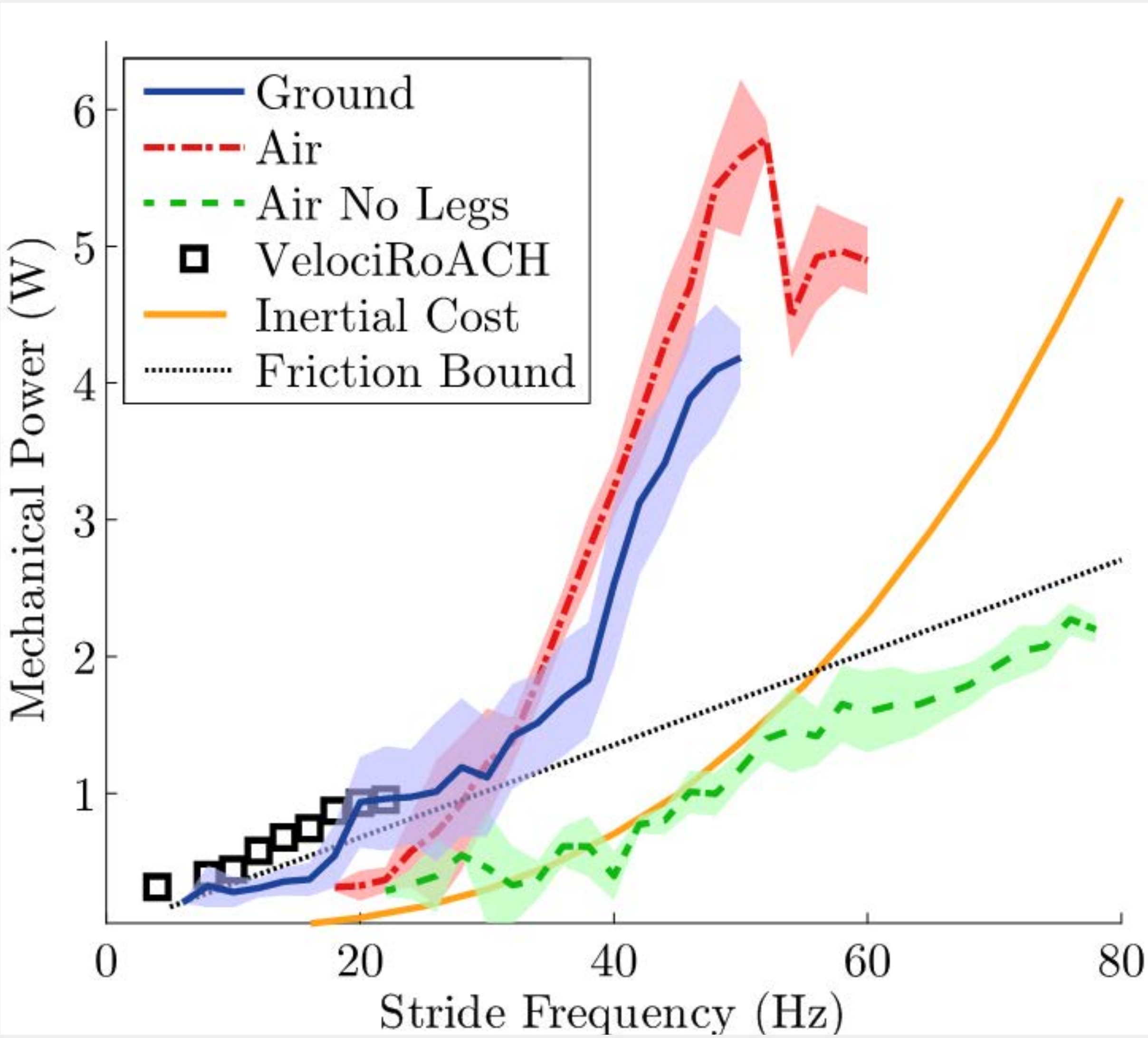



(b) Power requirements for driving the motor at constant rates, as a function of crank angle (see Fig. 4). The peak amplitude increases cubically with stride frequency.

**Forces increase cubically with stride rate**

**Power increases cubically**

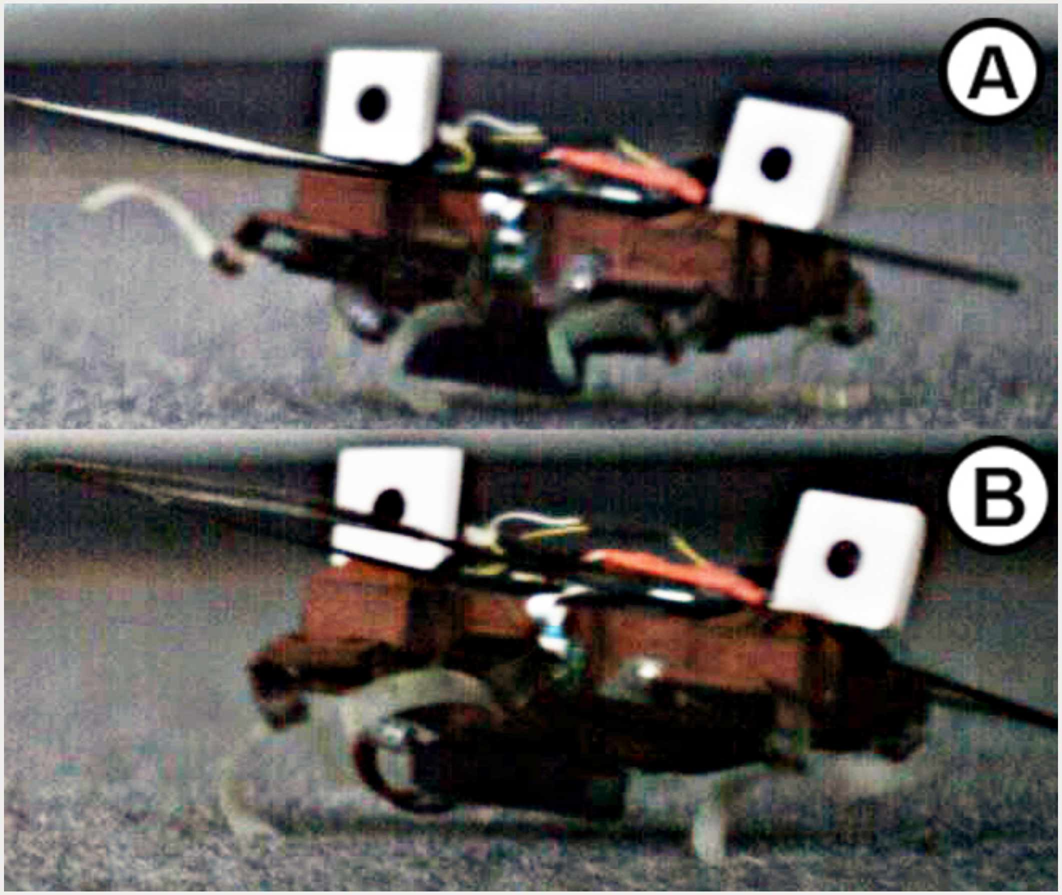
# RAPID | MEASURED POWER DRAW

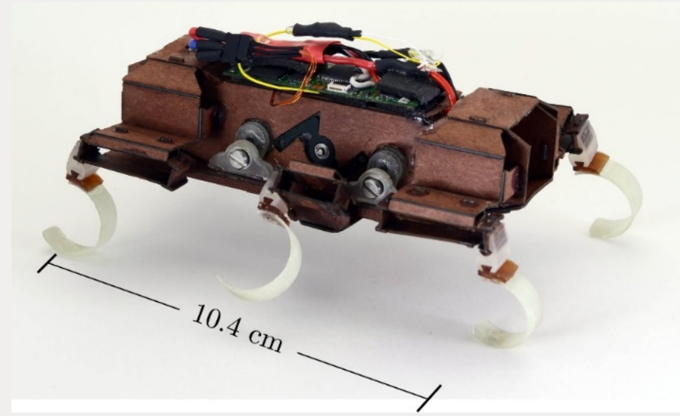



**Inertial forces drive power consumption**

**Power increases cubically, as predicted**

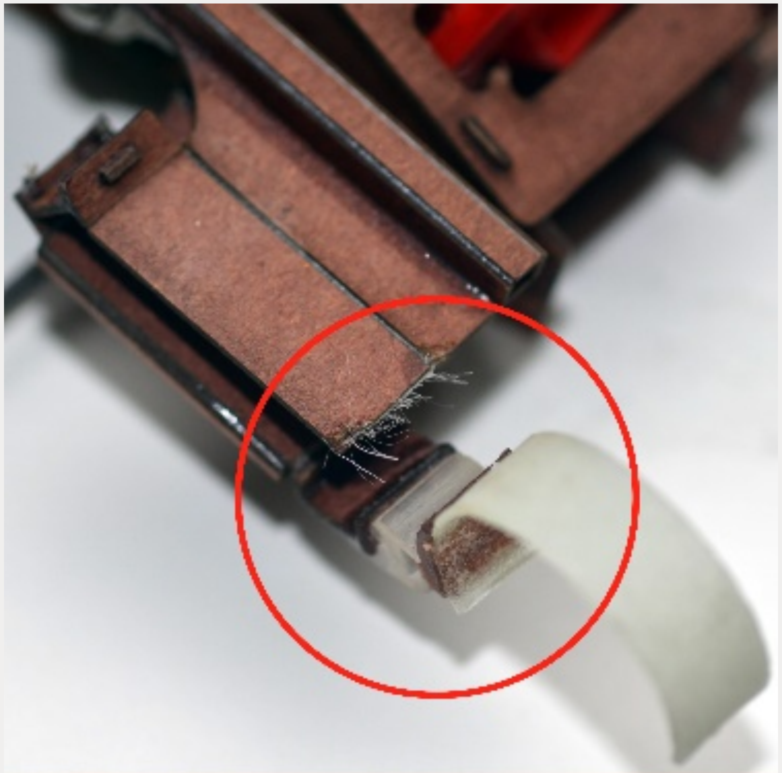
# RAPID | LEG FORCES



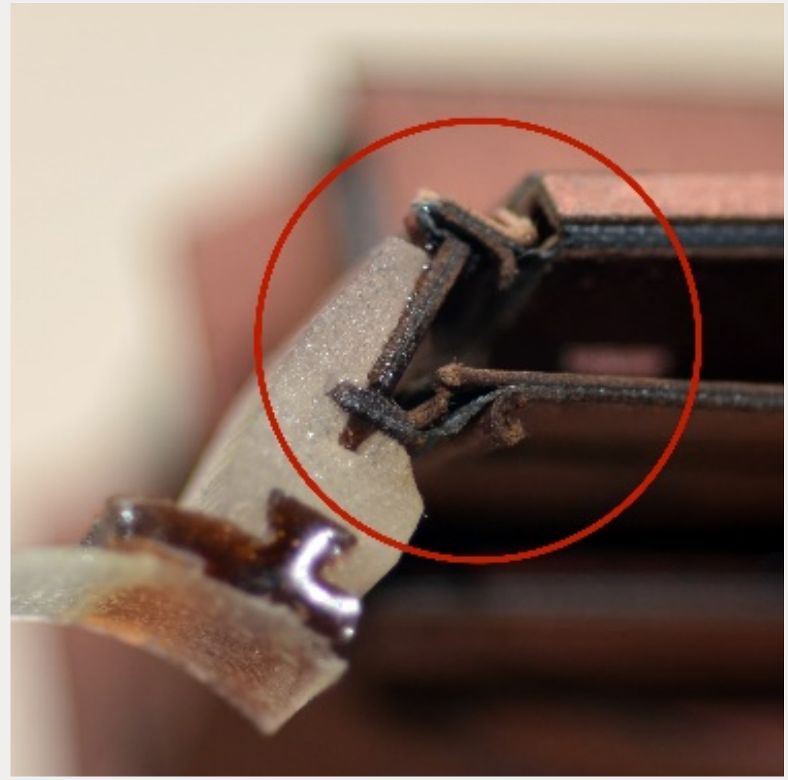




**Increased stride length caused by leg deformation**

# RAPID | MATERIAL FAILURE LIMIT



35 Hz



45 Hz

**Top speed limited by self-destruction**

# 1: RAPID LOCOMOTION

FASTER RUNNING ROBOTS VIA POWER-DENSITY


1: RAPID LOCOMOTION

Approach

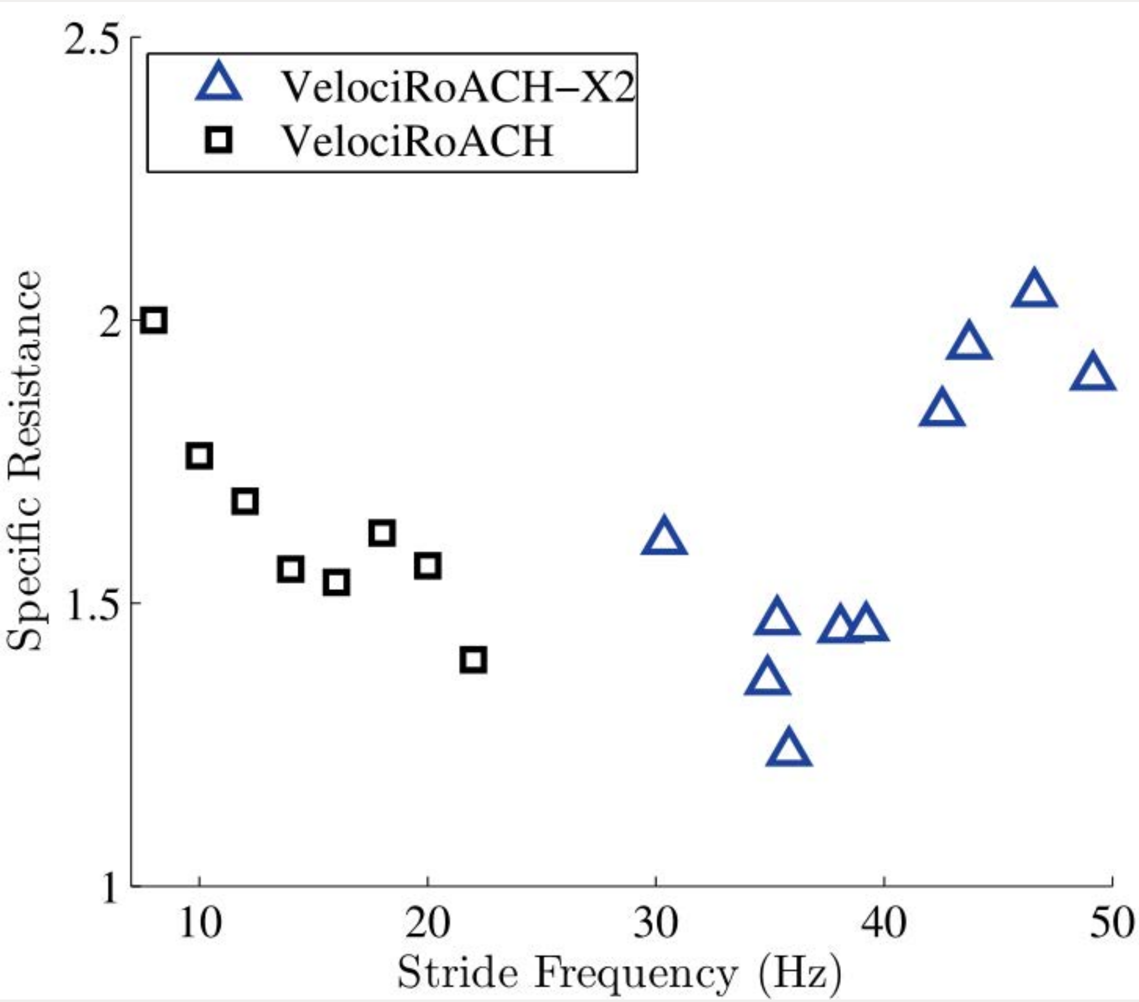
Result

Stride kinematics

Force and power

Energetics

# RAPID | SPECIFIC RESISTANCE




**Usually monotonically decreasing**

**Cubic power costs mean diminishing returns on efficiency**

# RAPID | CONCLUSIONS

Demonstrated power-density first design strategy

- 1 Actuator driving specialized mechanism
- 3X increase in power density

X2-VelociRoACH is fastest running robot relative to size

Geometrically increasing power and damage motivate other methods for increasing speed

# 2: AGILE LOCOMOTION

## INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

**1: RAPID LOCOMOTION**

Approach

Result

Stride kinematics

Force and power

Energetics

**2: AGILE LOCOMOTION**

Motivation

Agility metric

Actuation strategies

SE+MA actuation

Leg mechanism

Proof of concept

Prototype & results

# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

**1: RAPID LOCOMOTION**

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**2: AGILE LOCOMOTION**

- Motivation

# AGILE | MOTIVATION

**FEMA USAR Training Site, Menlo Park**

# AGILE | MOTIVATION

# AGILE | MOTIVATION

## Ability to traverse rubble

- Not unstructured, but sparse

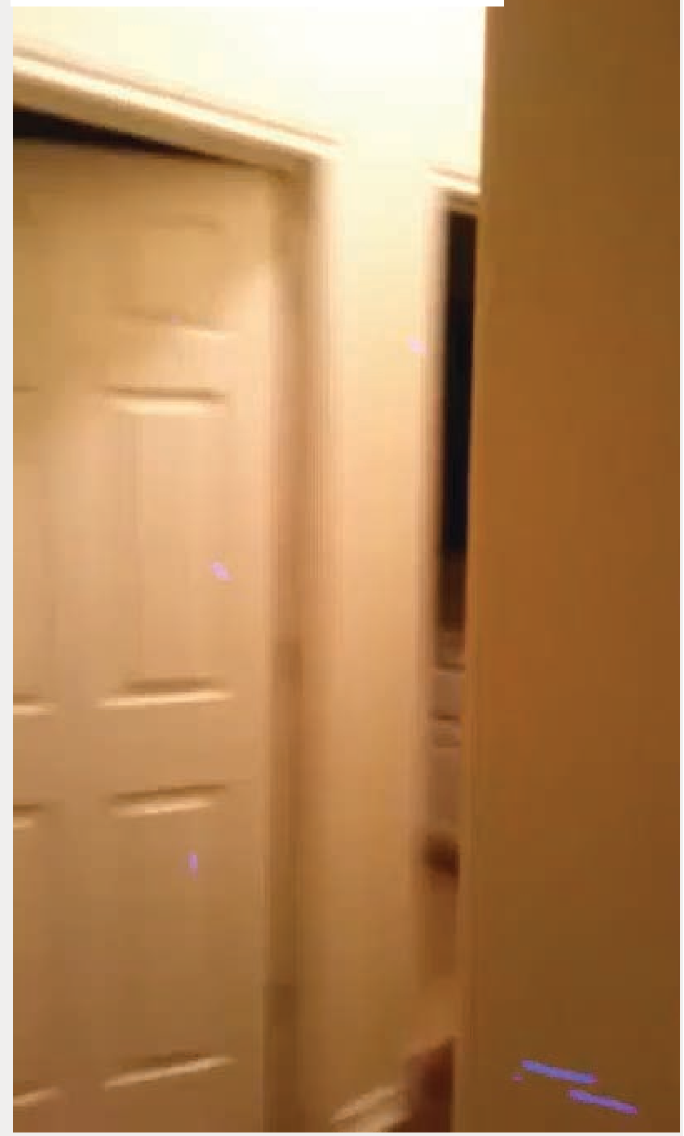
## Small platform size

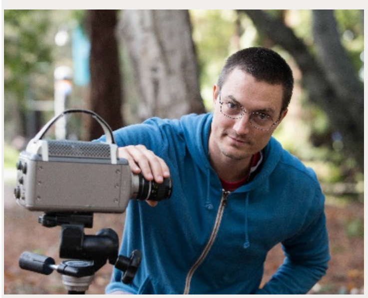
- More robust
- Won't disturb site
- Cheaper

**Implies leaping (saltatorial) locomotion**

# AGILE | ANIMAL SALTATORIAL LOCOMOTION

https://youtu.be/-O0V3Pw0UBg



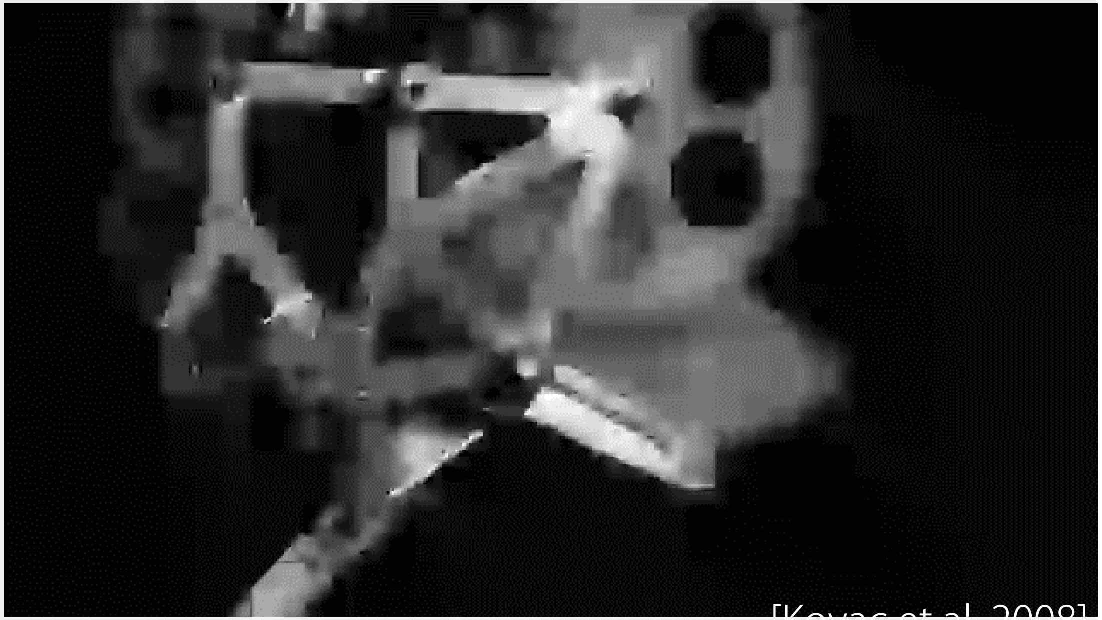


Video by Nate Hunt

# AGILE | ROBOTIC SALTATORIAL LOCOMOTION

Running


Jumping




**Controlled continuous locomotion**

**Low amplitude hops**

**Uncontrolled intermittent jumps**

**High-power jumps**

**OPEN AREA:**
**Controlled high-power jumps**

# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

| 1: RAPID LOCOMOTION | 2: AGILE LOCOMOTION |
| --- | --- |
| Approach | Motivation |
| Result | Agility metric |
| Stride kinematics | |
| Force and power | |
| Energetics | |

# AGILE | AGILITY METRIC

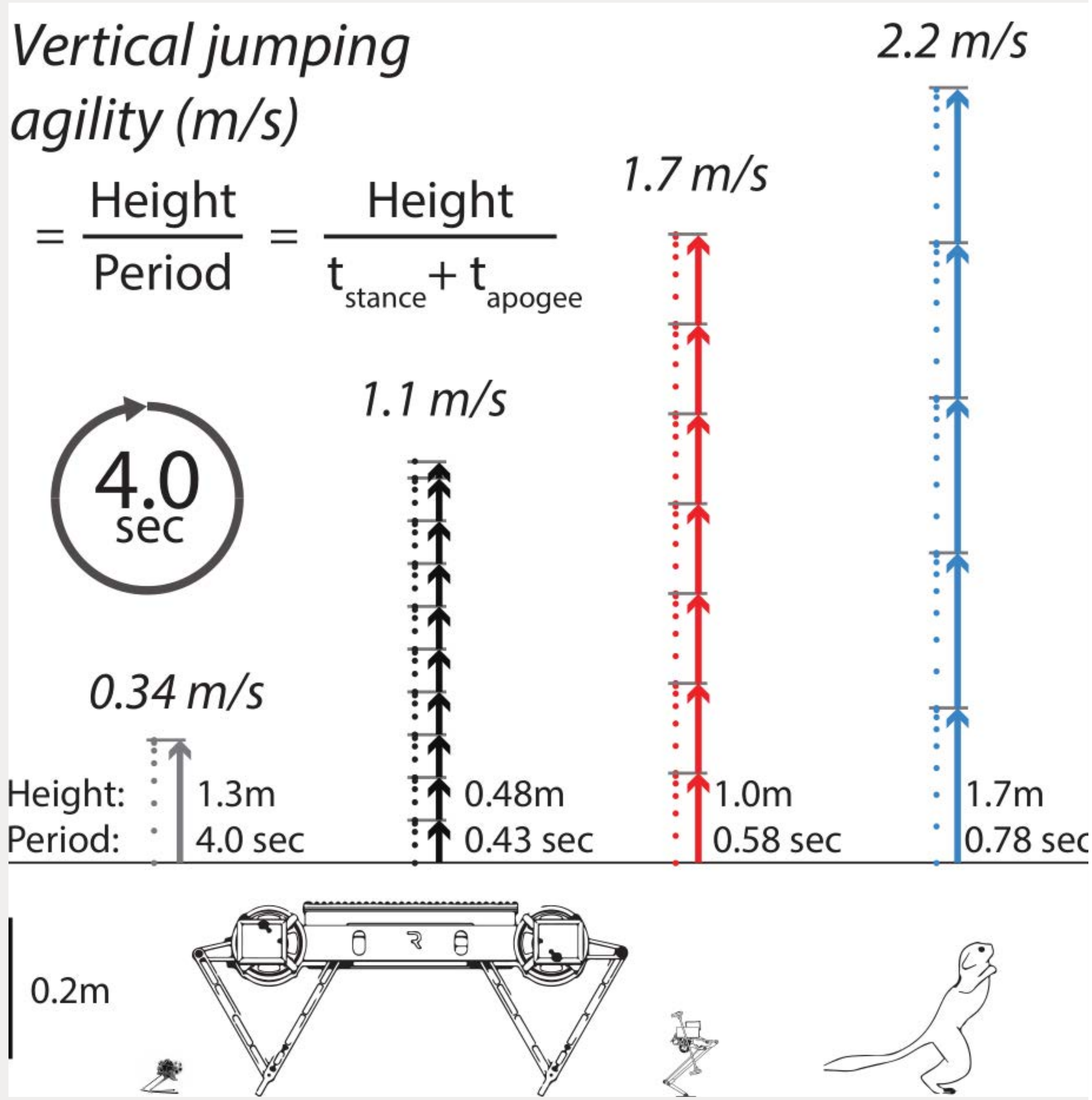
To find animal that will inspire new robot:

## Find metric that describes behavior

- Jump high
- Jump quickly

Metric:

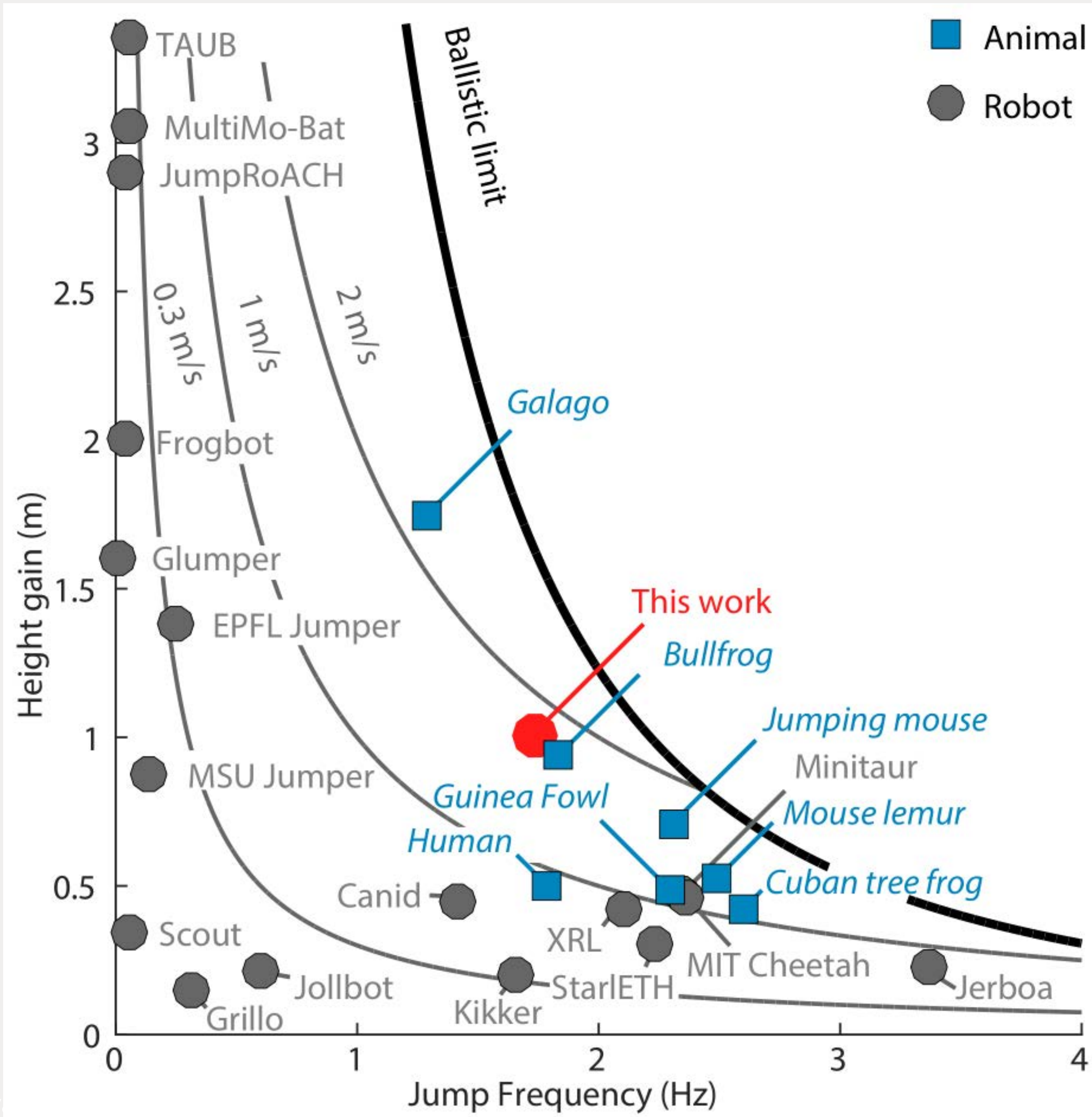
## Vertical Jumping Agility



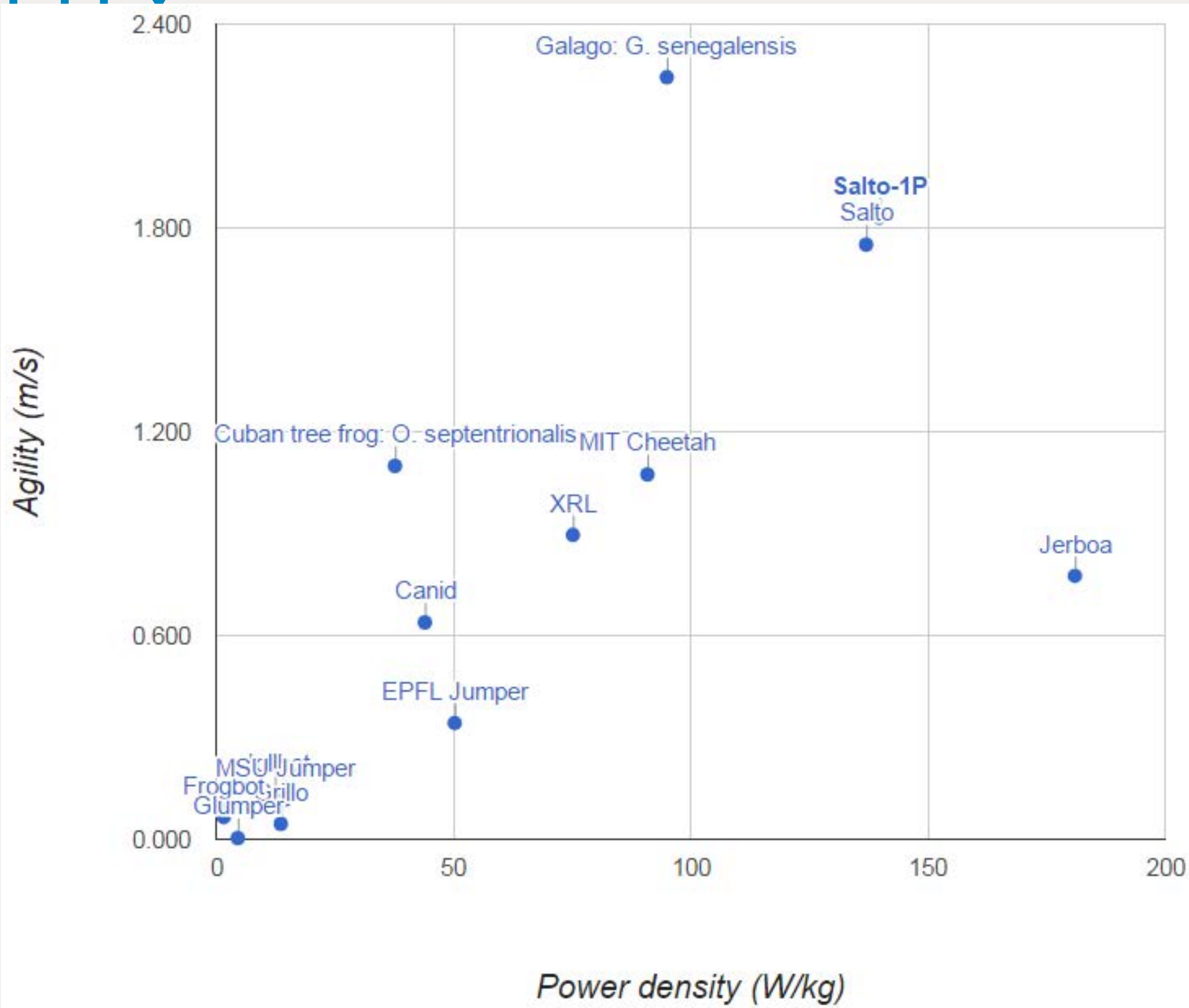
# AGILE | MODEL ANIMAL: GALAGO

# AGILE | MODEL ANIMAL: GALAGO


# AGILE | AGILITY METRIC



# AGILE | POWER DENSITY AND AGILITY



# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

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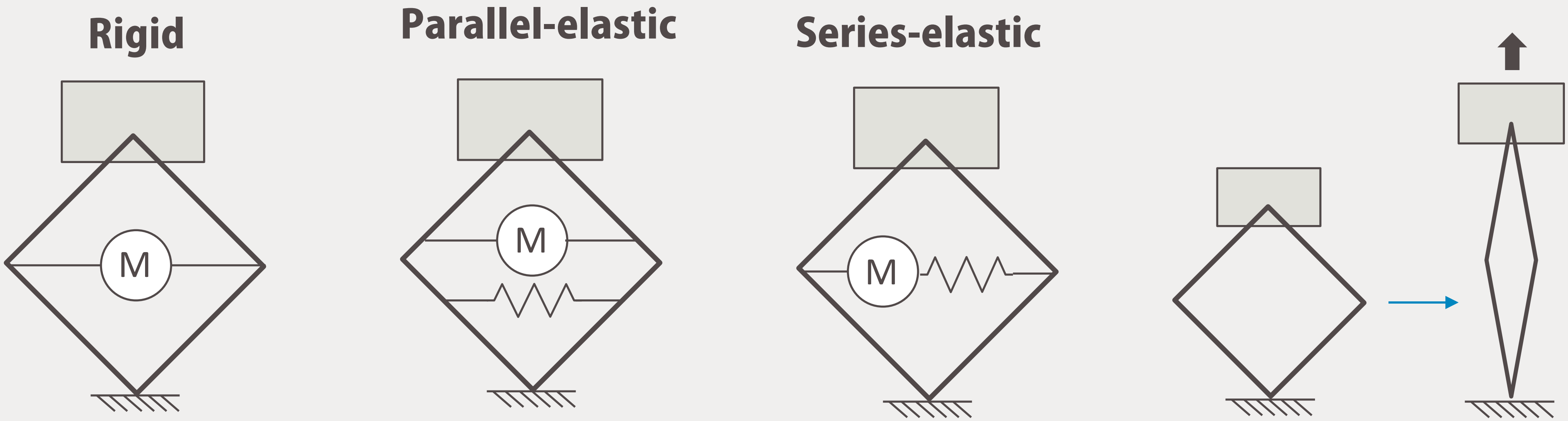
**2: AGILE LOCOMOTION**

- Motivation
- Agility metric
- Actuation strategies

# AGILE | ACTUATION STRATEGIES

Energetic goal: deliver as much jumping energy as possible

Approaches:

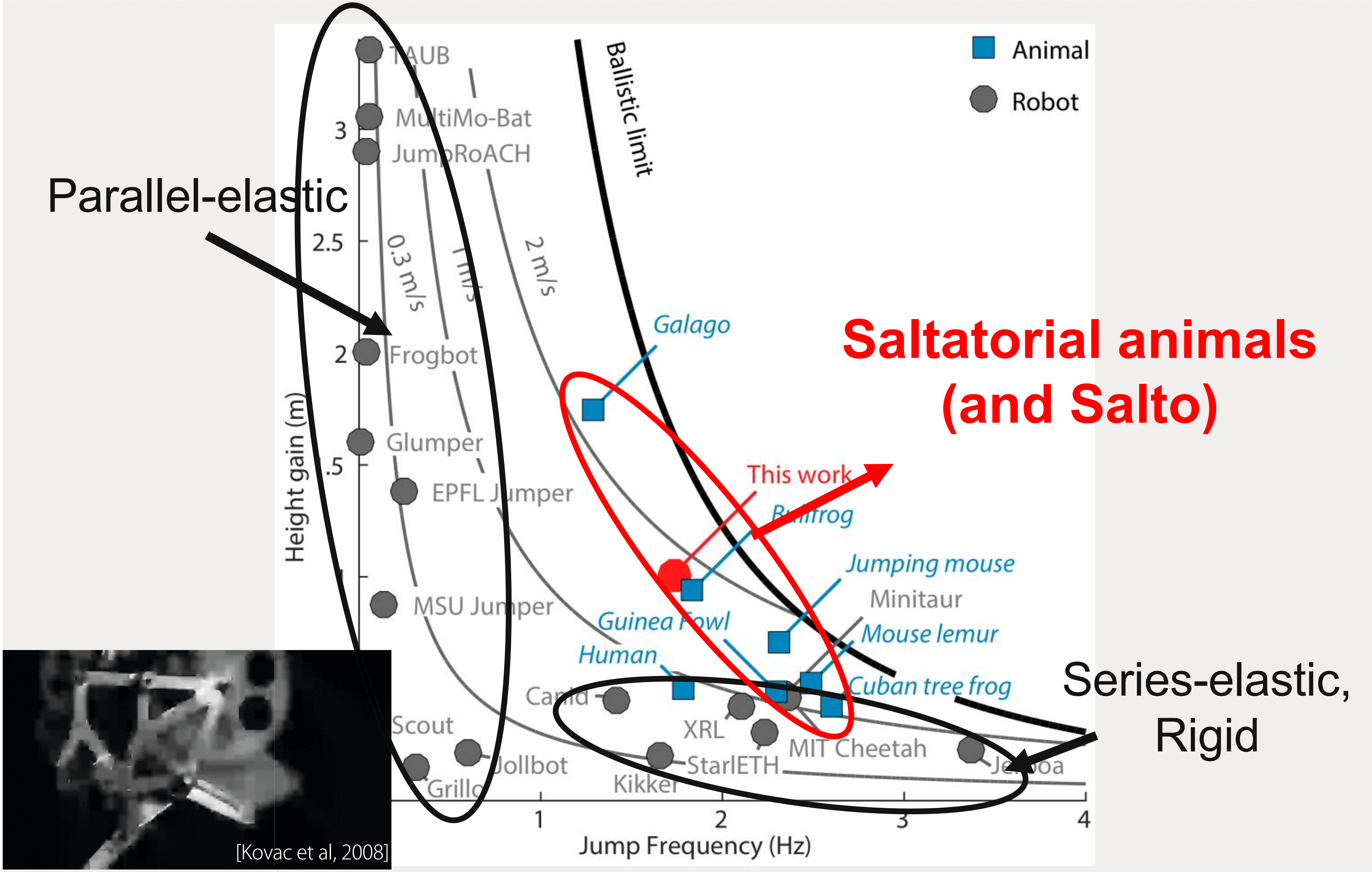



**Rigid maximum power determined by motor**

**Parallel-elastic can store/return energy. No maximum power limit (with latch)**

**Series-elastic can passively store/return energy.**
**Increase max power by factor of 1.436**

# AGILE | AGILITY METRIC



# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

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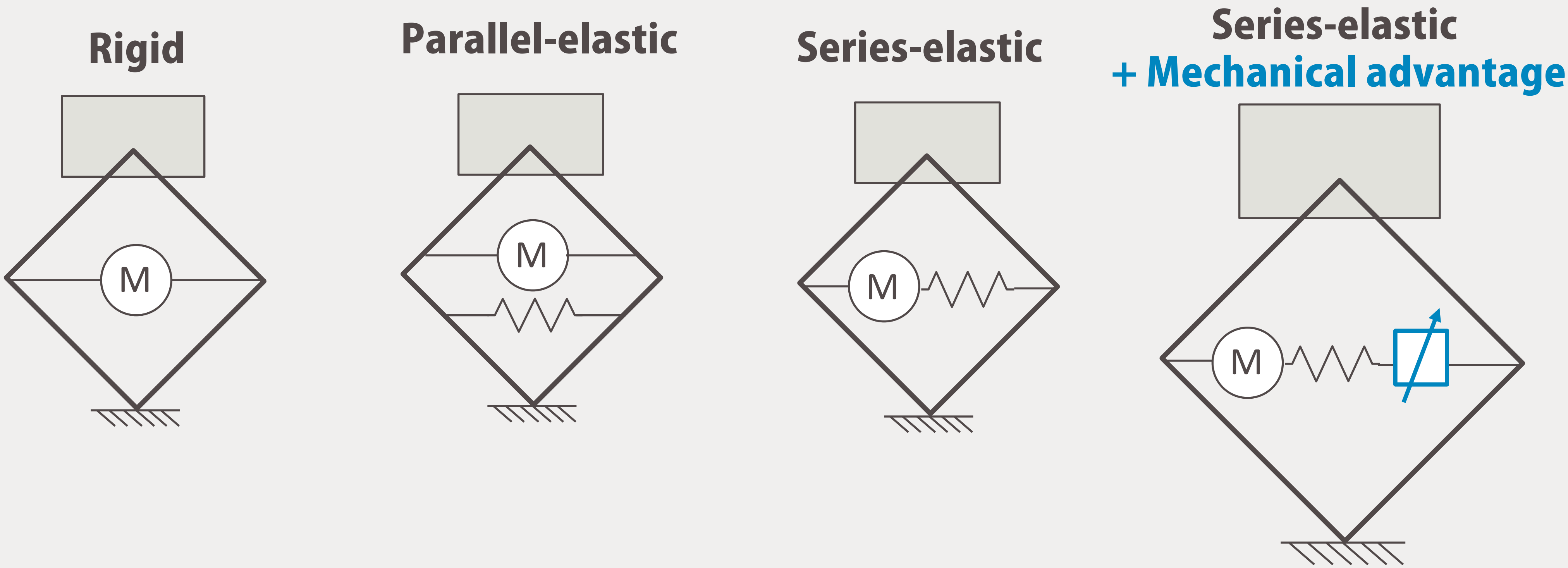
| Force and power | SE+MA actuation |
| Energetics | |

# AGILE | ACTUATION STRATEGIES

Energetic goal: deliver as much jumping energy as possible

Approaches:

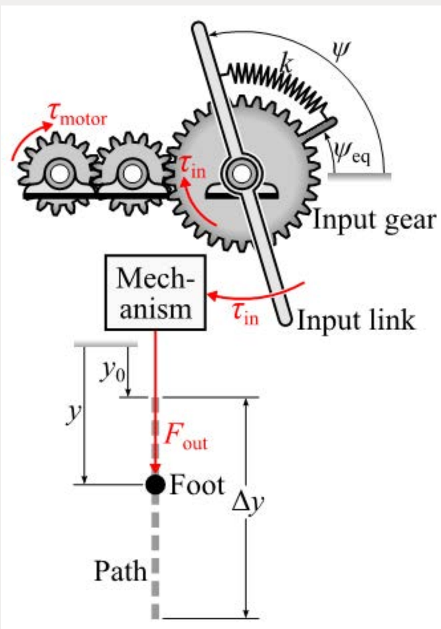



**SE+MA strategy: add variable mechanical advantage to increase peak power**

# AGILE | DESIGN OF TRANSMISSION

A variable mechanical advantage profile *increases* power modulation factor of series-elastic systems (Bullfrog study [Roberts, Marsh 2003])

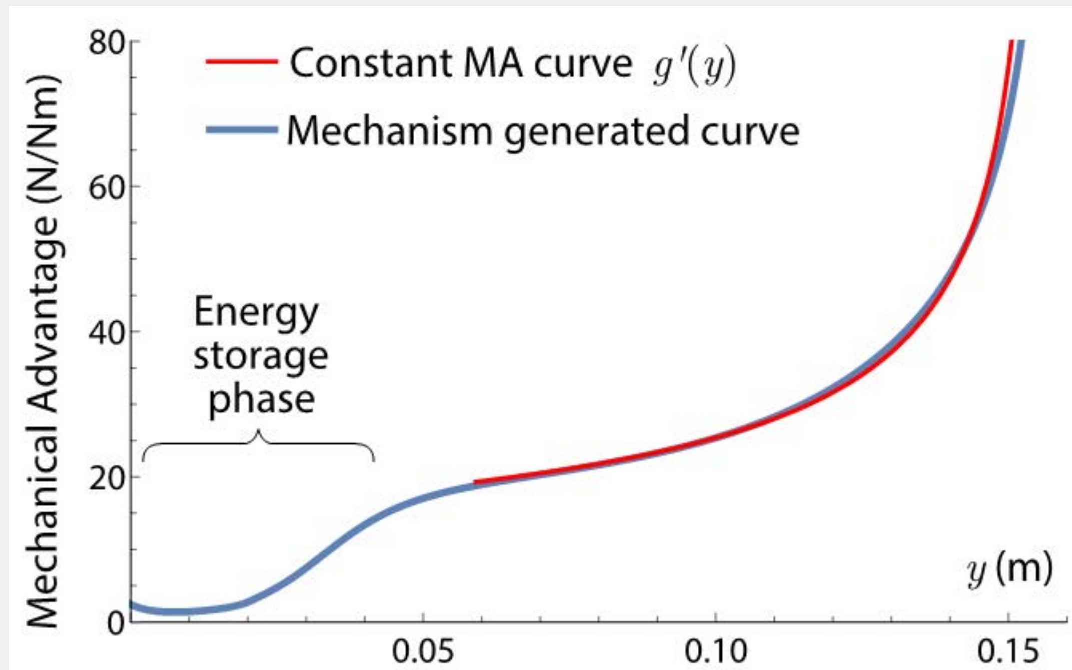
Power modulation
$P_{MAX} > P_{MOTOR}$



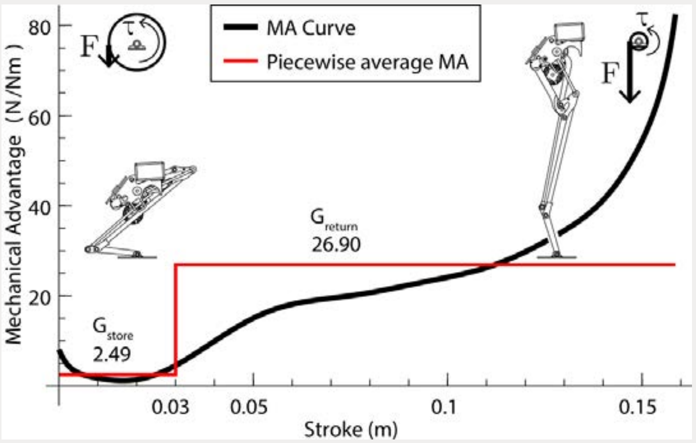

Robotic system

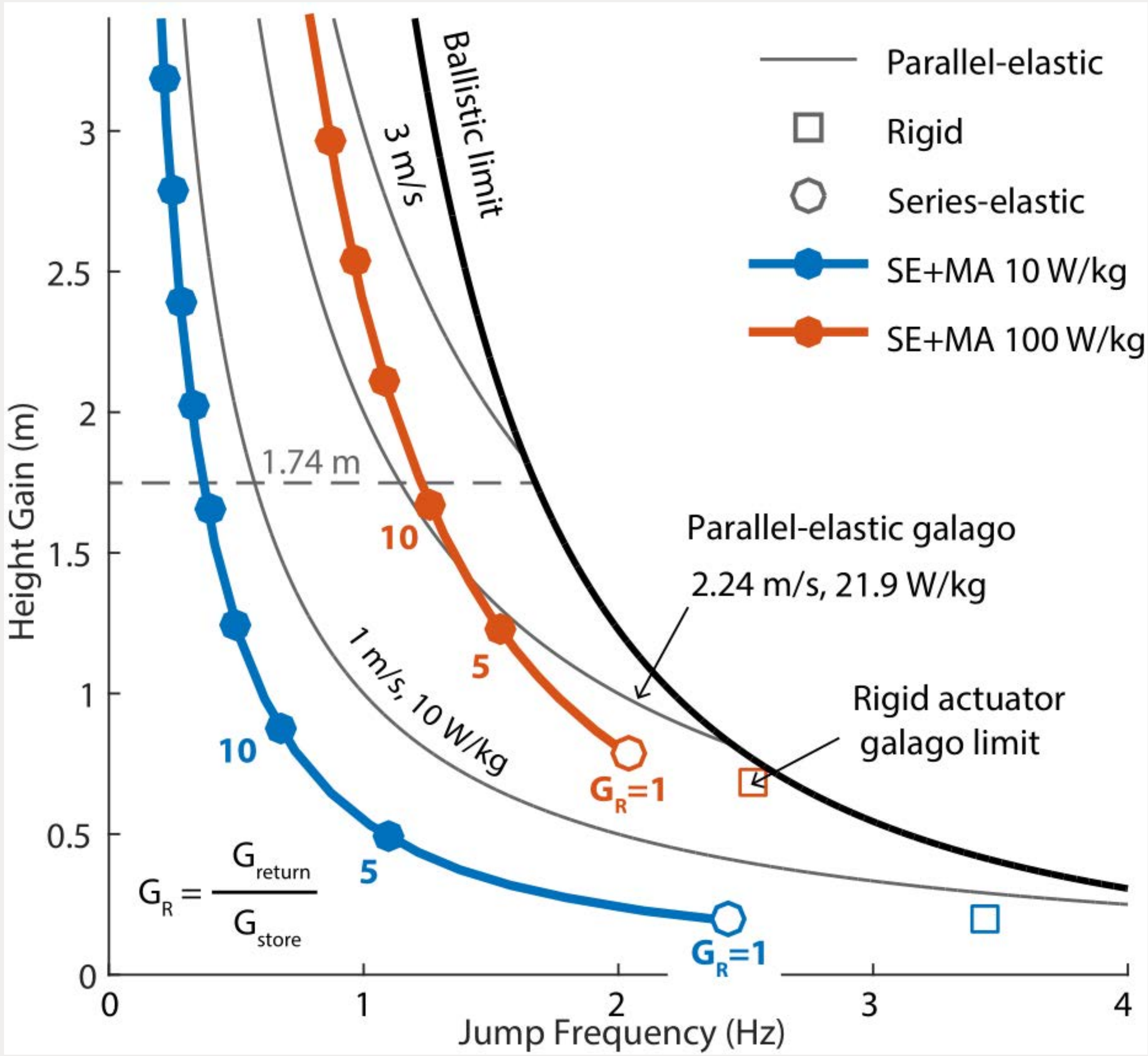
Mechanical advantage:

$$\frac{\text{Output force}}{\text{Input torque}}$$



# AGILE | ACTUATION STRATEGIES



# AGILE | ACTUATION STRATEGIES

Create hypothetical galago-sized robot, determine necessary power density

| | Galago | Hypothetical rigid | Hypothetical series-elastic | Hypothetical parallel-elastic | Hypothetical SE+MA | EPFL Jumper | Salto |
|---|---|---|---|---|---|---|---|
| Mass (kg) | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.007 | 0.100 |
| Leg Length (m) | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.10 | 0.150 |
| Maximum jump height (m) | 1.74 | 1.74 | 1.74 | 1.74 | 1.74 | 1.38 | 1.008 |
| Jump Frequency (Hz) | 1.29 | 1.66 | 1.59 | 1.29 | 1.29 | 0.248 | 1.74 |
| Vertical jumping agility (m/s) | 2.24 | 2.89 | 2.78 | 2.24 | 2.24 | 0.34 | 1.75 |
| Power density (W/kg) | 92.7 | 343 | 325 | 21.9 | 90.0 | 50 | 137 |

**SE+MA strategy reduces required power density by factor of 3.8**

**Parallel-elastic has lowest theoretical power density**

# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

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| Approach | Motivation |
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| Force and power | SE+MA actuation |
| Energetics | Leg mechanism |

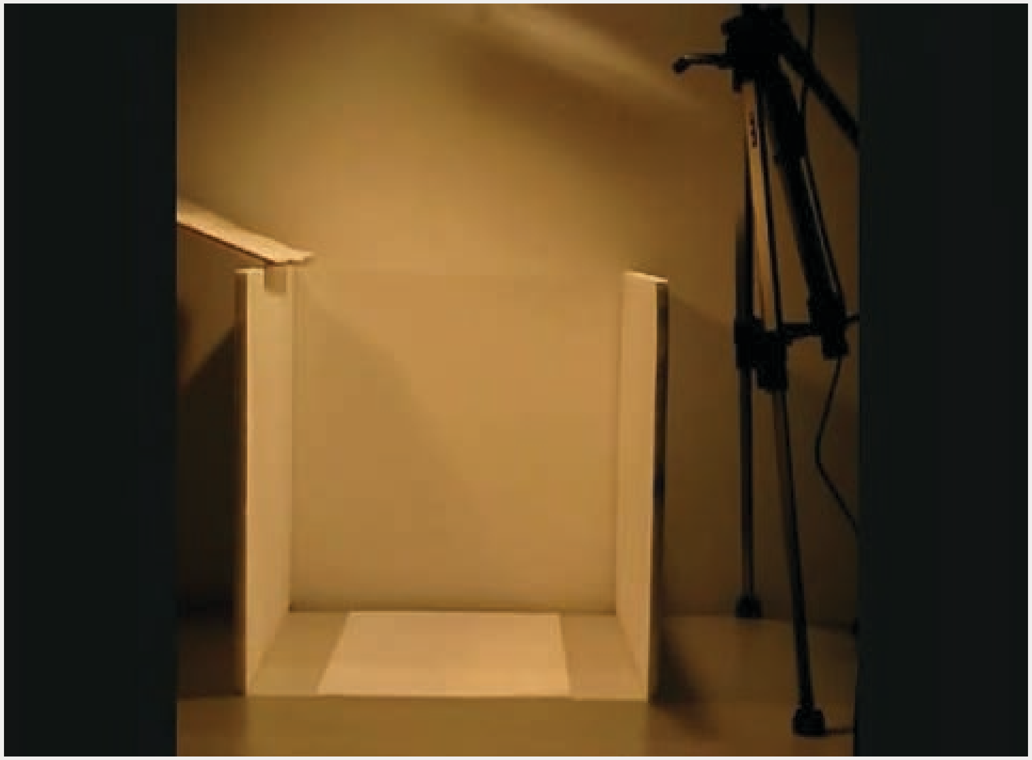
# AGILE | LEG MECHANISM

Design for power density: drive jump with single actuator

Leg mechanism has MA profile for power-modulation

*and*

Produces rotation-free jumps by default



# AGILE | MECHANISM REQUIREMENTS

1. The mechanism constrains a foot point to a vertical straight line, the line-of-action, in the frame of the robot.

2. Translation of the foot point, or stroke, is long relative to the size of the robot.

3. All pivots are located above the foot point at all times, with an input pivot near to the line-of-action.

4. Link lengths are compact.

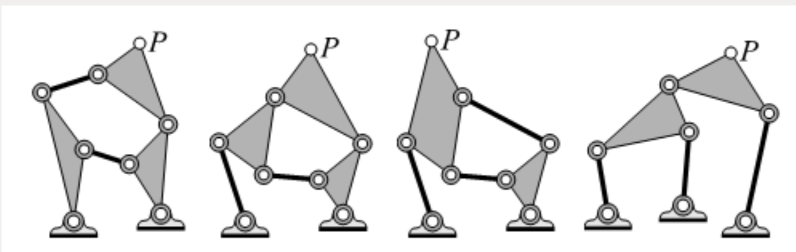
5. The input link that attaches to the series elastic actuator rotates over a large range.

6. The leg possesses low mechanical advantage at the top of stroke.

7. Mechanical advantage defines a constant ground force for the remainder of stroke.

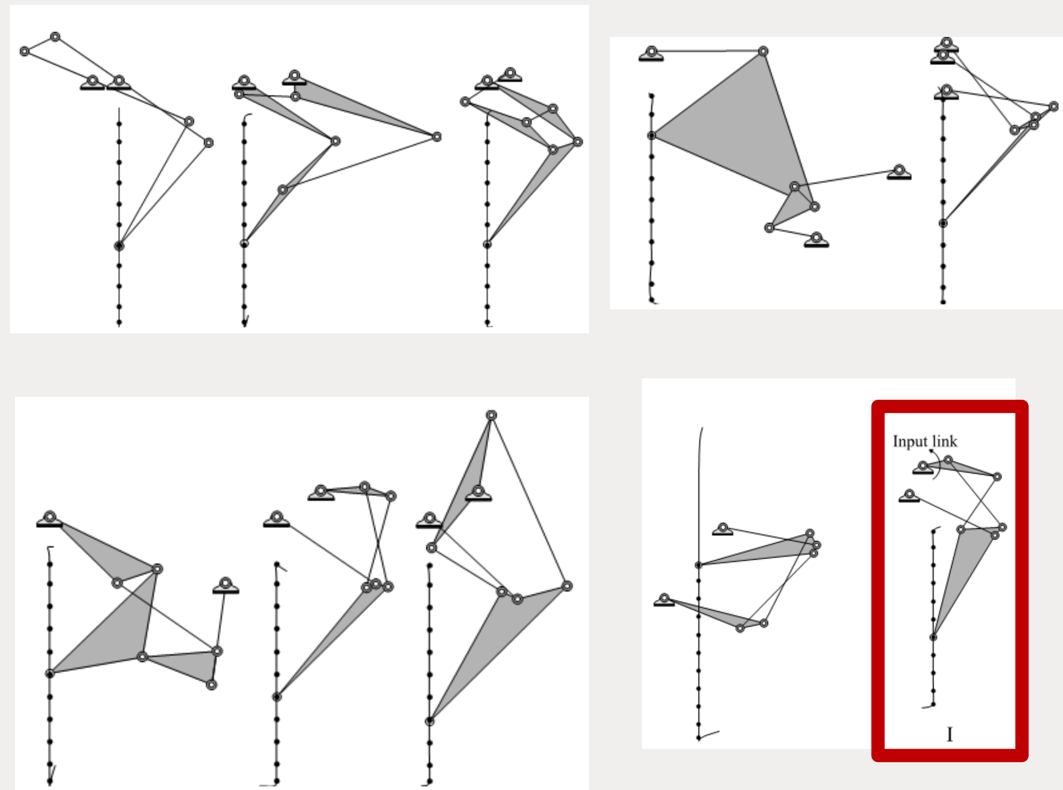
8. Moments exerted on the body of the robot by the mechanism are minimized.

# AGILE | MECHANISM SYNTHESIS




Find all Stephenson linkages that trace a straight line

- Homotopy continuation method
- 4478 good solutions

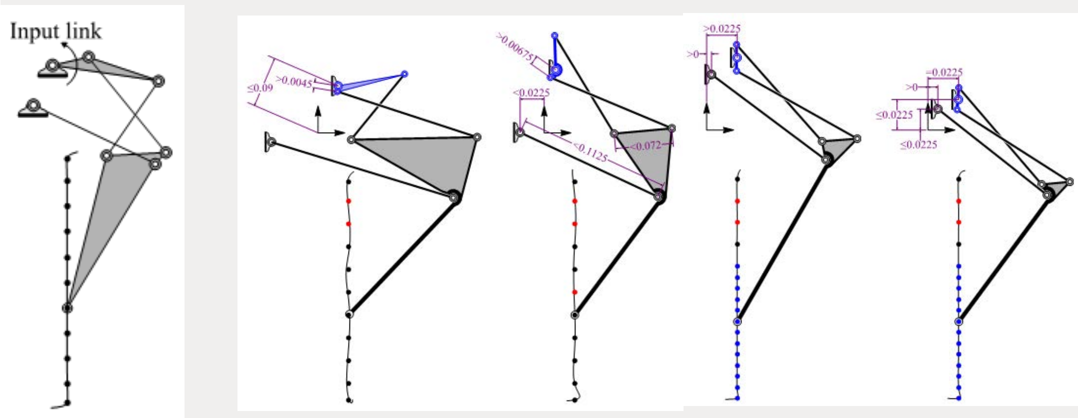



Choose solution best matching specifications

Details: M. M. Plecnik, D. W. Haldane, J. K. Yim, R. S. Fearing, Design exploration and kinematic tuning of a power modulating jumping monopod, *J. Mech. Robot.* (2016).

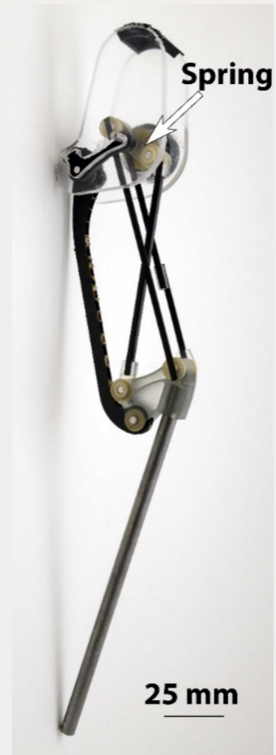
# AGILE | MECHANISM SYNTHESIS

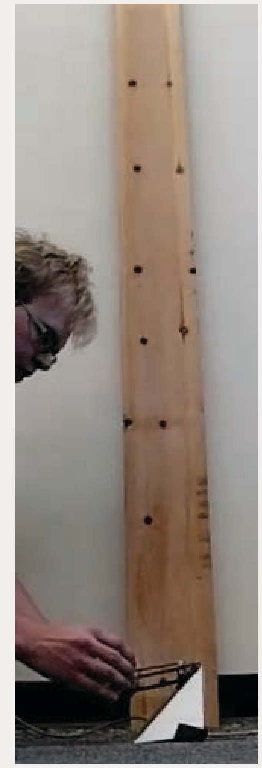
Start　　　　　　　　　　End




Optimize start point from design space exploration to meet requirements

<u>Details:</u> M. M. Plecnik, D. W. Haldane, J. K. Yim, R. S. Fearing, Design exploration and kinematic tuning of a power modulating jumping monopod, *J. Mech. Robot.* (2016).



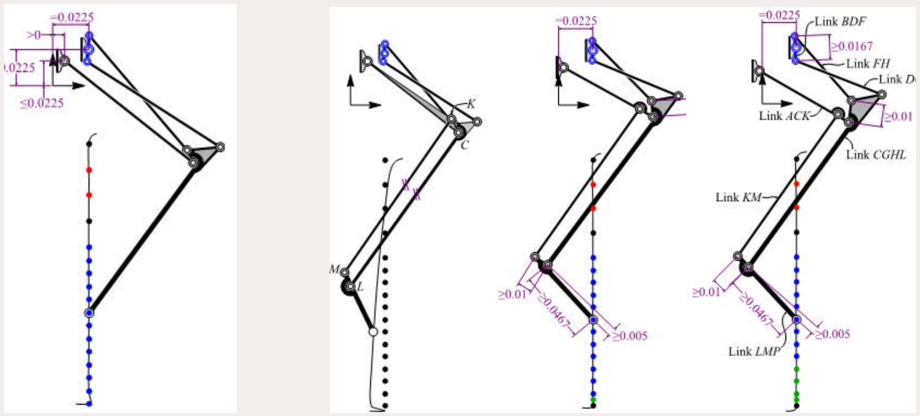



Prototype spins!

- Inaccurate mass models
- 6-bar hard to balance

# AGILE | MECHANISM SYNTHESIS

Start End




6-bar hard to balance
⇒ Add two more links
⇒ Reoptimize

<u>Details:</u> M. M. Plecnik, D. W. Haldane, J. K. Yim, R. S. Fearing, Design exploration and kinematic tuning of a power modulating jumping monopod, *J. Mech. Robot.* (2016).


Final design satisfies all specifications

# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

**1: RAPID LOCOMOTION**

Approach

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Energetics

**2: AGILE LOCOMOTION**

Motivation

Agility metric

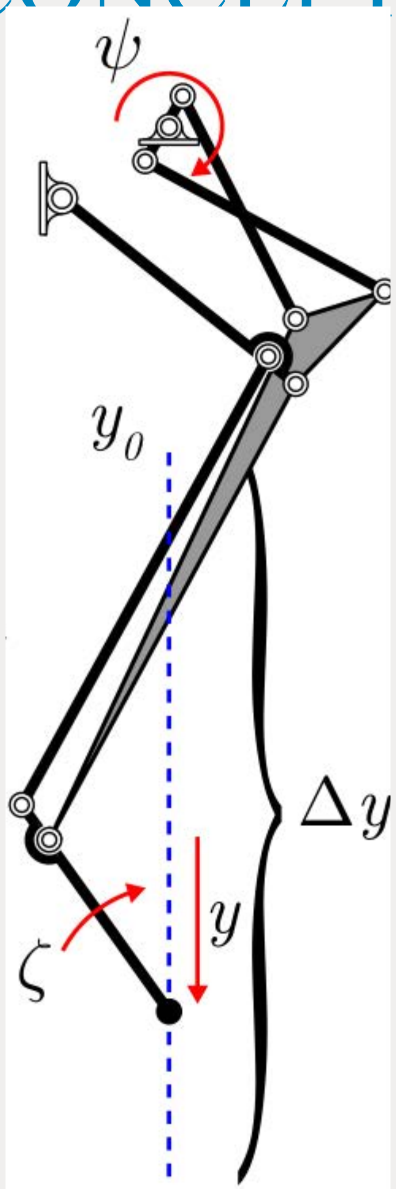
Actuation strategies

SE+MA actuation

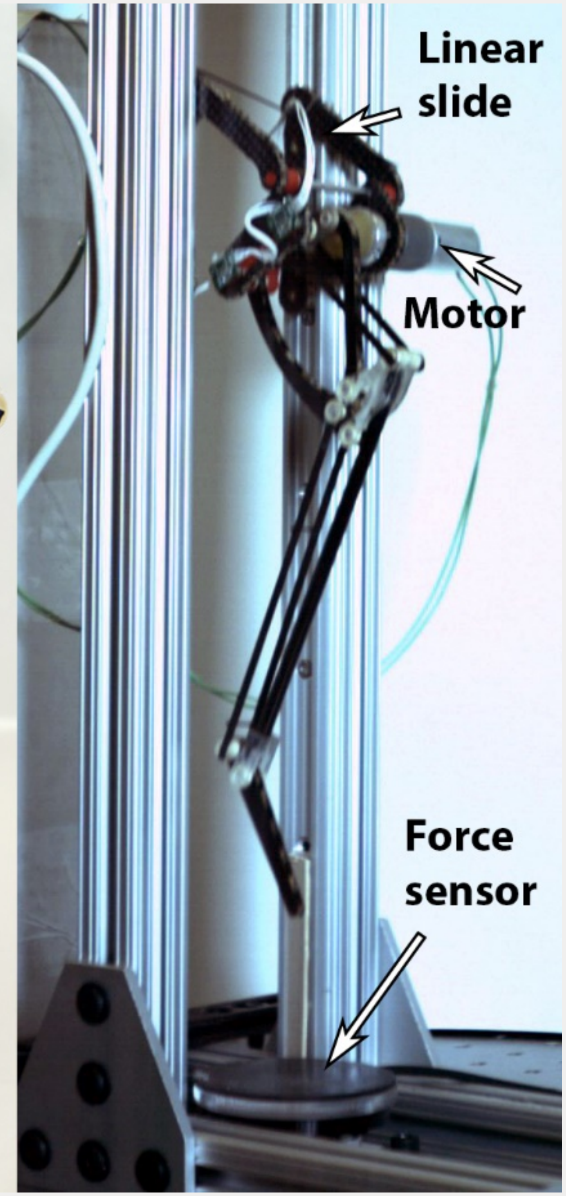
Leg mechanism

Proof of concept

# AGILE | ACTUATED PROOF OF CONCEPT







# AGILE | ACTUATED PROOF OF CONCEPT

<u>Mechanism</u>

Binary tension links: *CF tie-rod*

Binary compression link, ternary links, body*: Pre-fab CF honeycomb panel*

Joints: *IGUS polymer bushings*

Connected by molded polyurethane

Panel and molds cut using *Othermill*


<u>Spring</u>

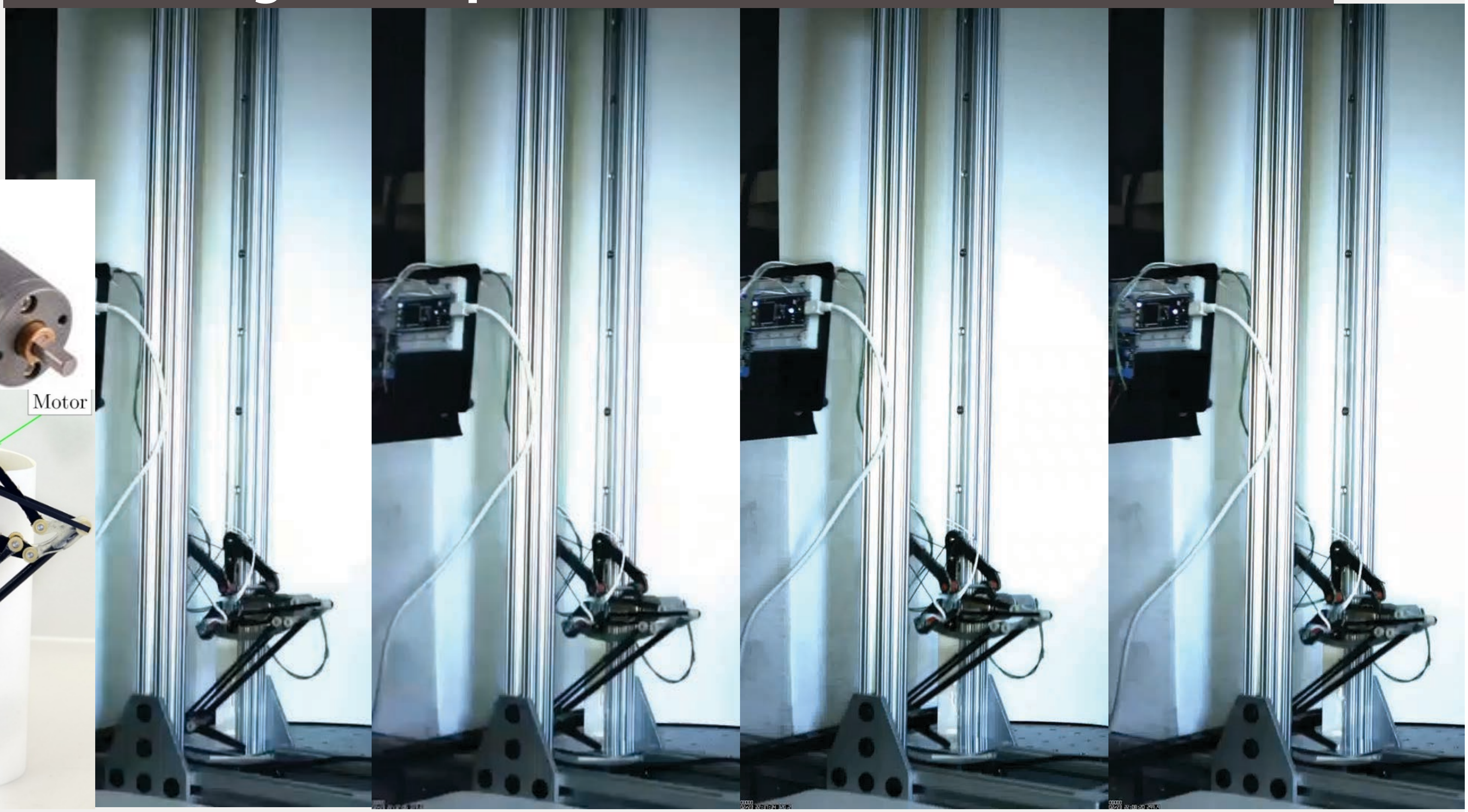
Torsional conic-sectioned latex

<u>Actuator</u>

COTS 3W DC gearhead

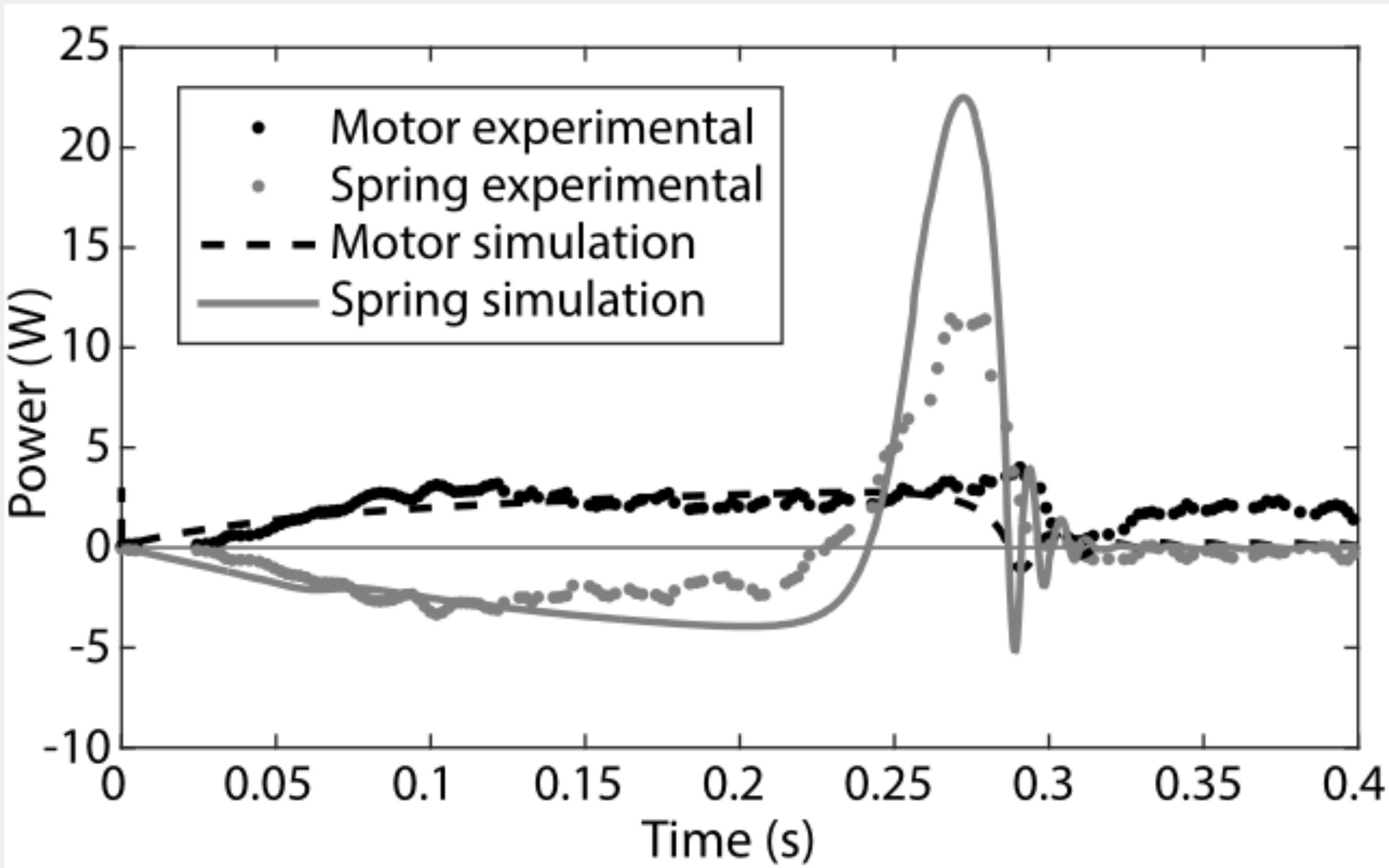
# AGILE | JUMPING EXPERIMENTS

**Increasing motor power → (Videos slowed 10X)**



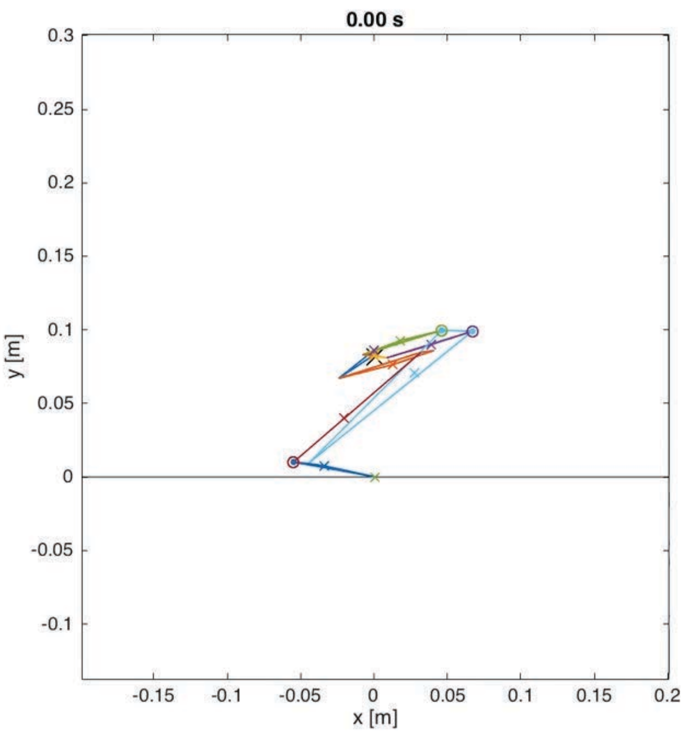
# AGILE | POWER MODULATION

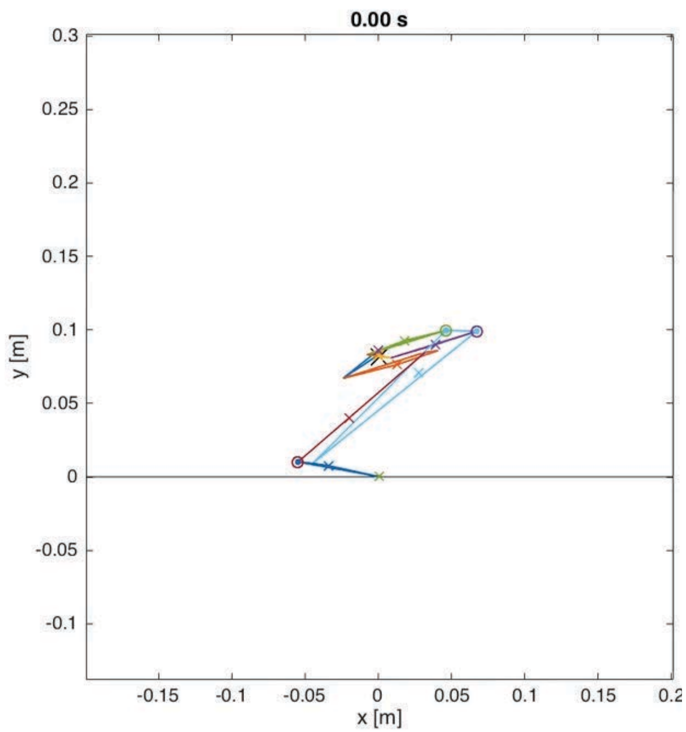
Power modulation
$P_{MAX} > P_{MOTOR}$

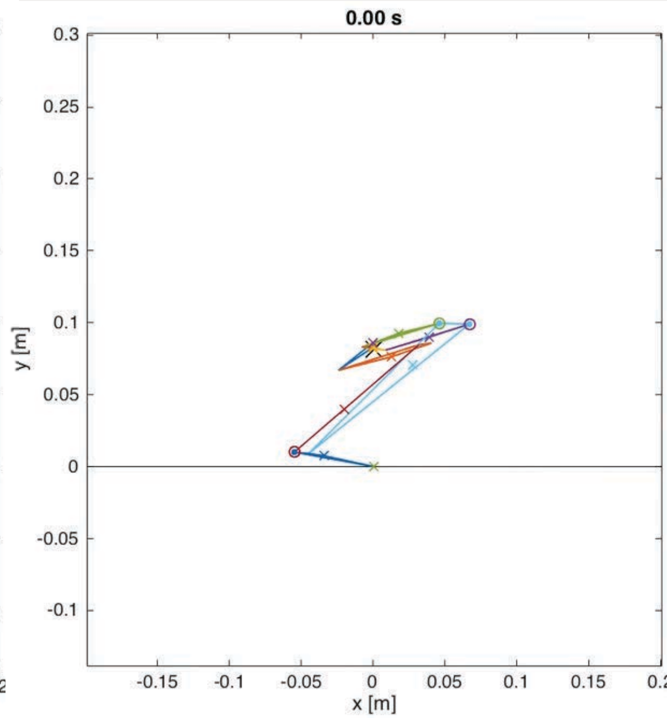



**Power modulation factor: 3.63**

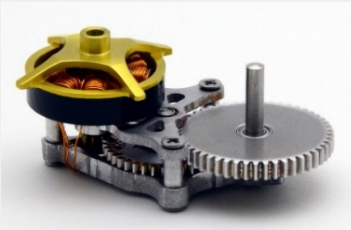
# AGILE | EFFECT OF POWER DENSITY




**23.5 W/kg** **58.8 W/kg** **176 W/kg**



# 2: AGILE LOCOMOTION

INCREASING ROBOTIC AGILITY VIA POWER-DENSITY

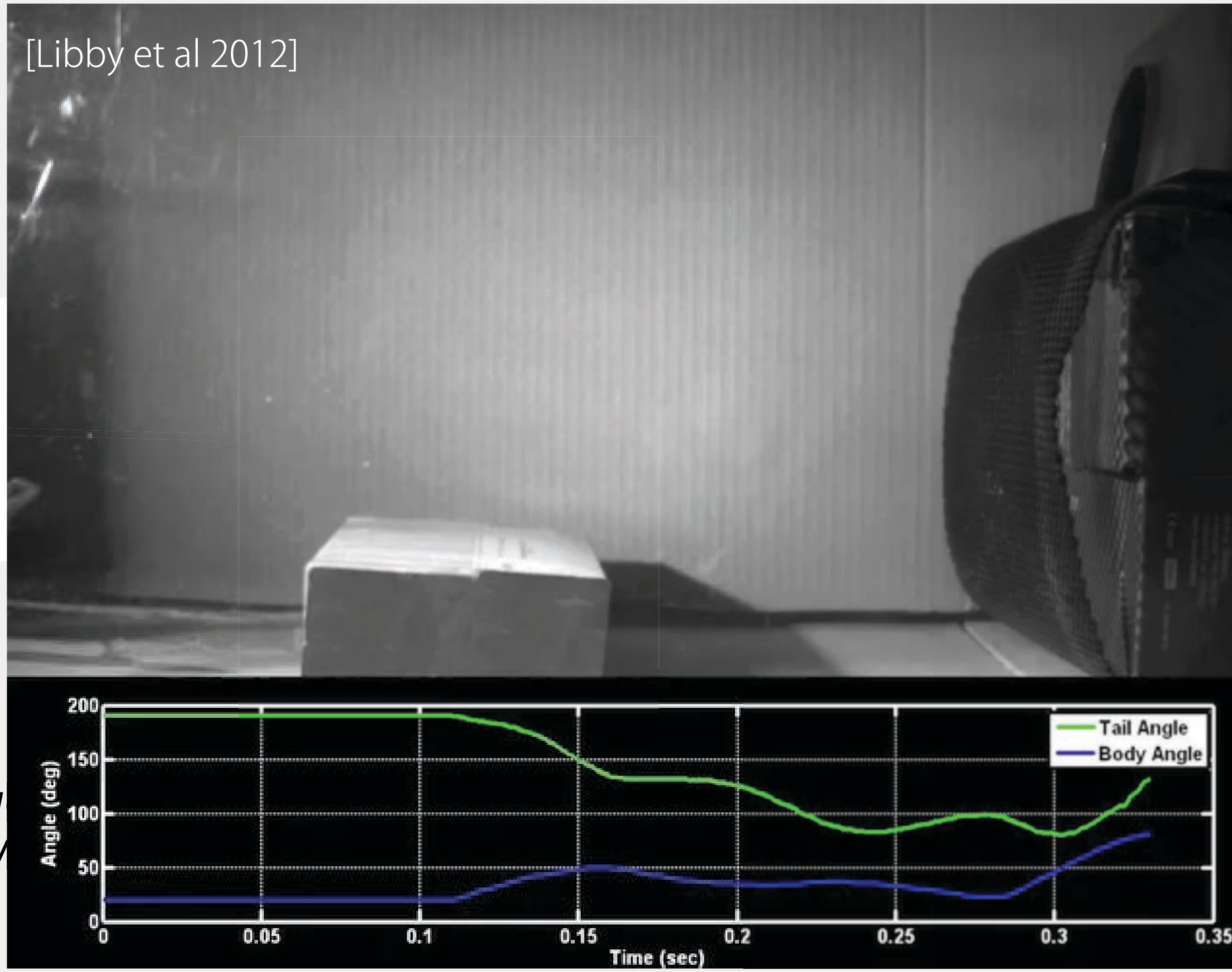
**1: RAPID LOCOMOTION**

- Approach
- Result
- Stride kinematics
- Force and power
- Energetics

**2: AGILE LOCOMOTION**

- Motivation
- Agility metric
- Actuation strategies
- SE+MA actuation
- Leg mechanism
- Proof of concept
- Prototype & results

**Integrate high-power actuator, spring, inertial tail, and foot with jumping mechanism**

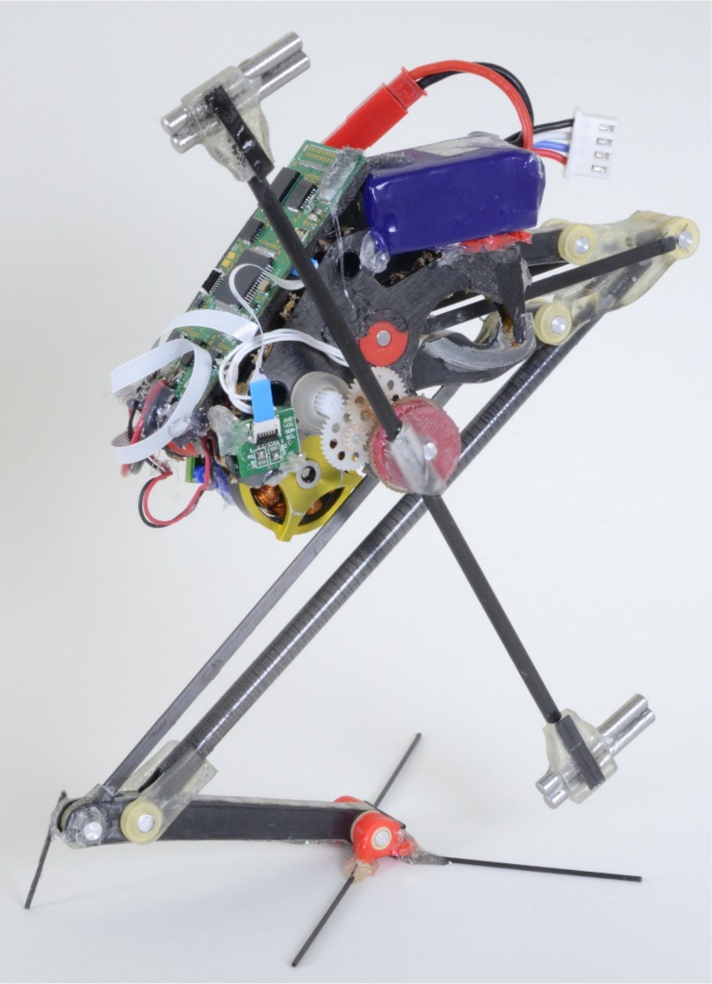



*Upgra*
*to 15V*

# AGILE | VERTICAL JUMPS

**1.008±0.007m vertical jumps,**

**Highest robotic vertical jumping agility of 1.75m/s**

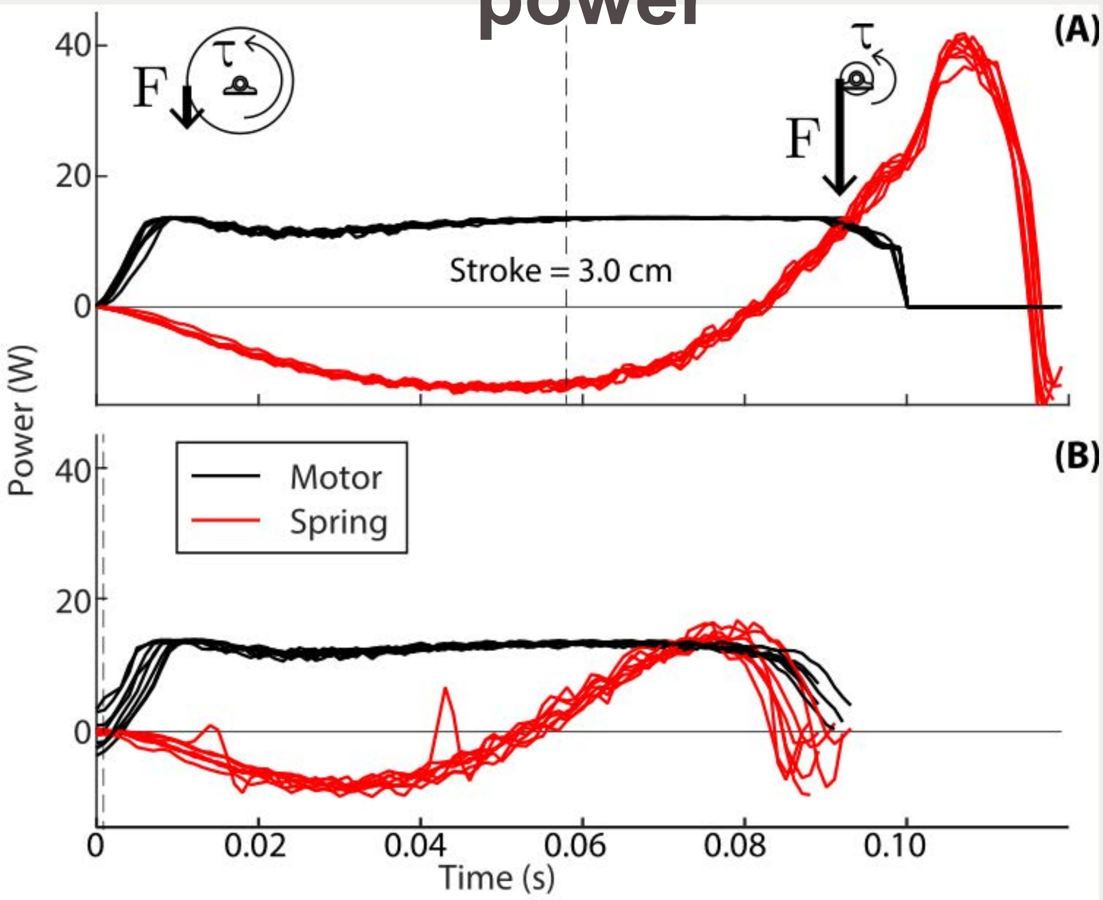



# AGILE | VERTICAL JUMPS

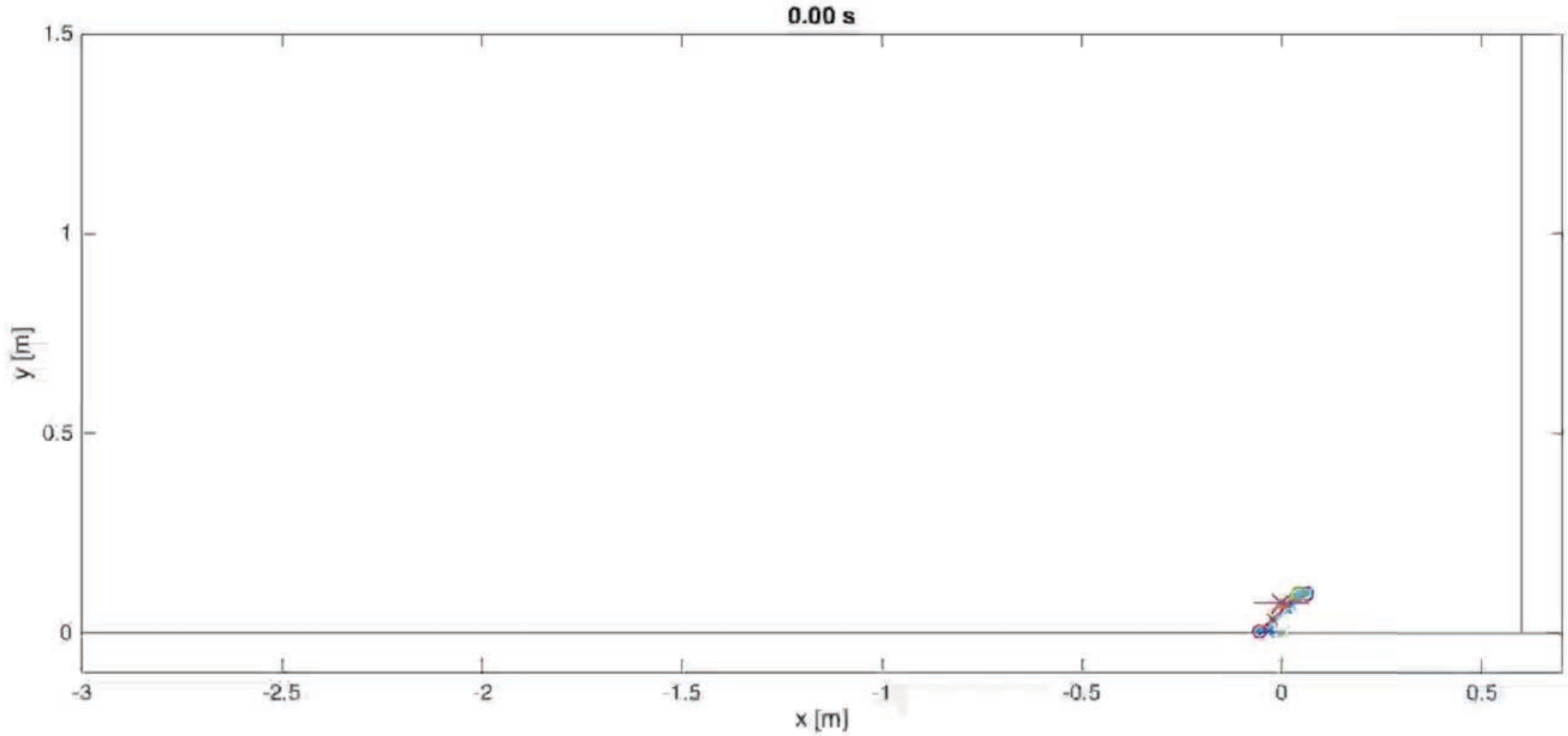
**1.008±0.007m vertical jumps,**

**Highest robotic vertical jumping agility of 1.75m/s**

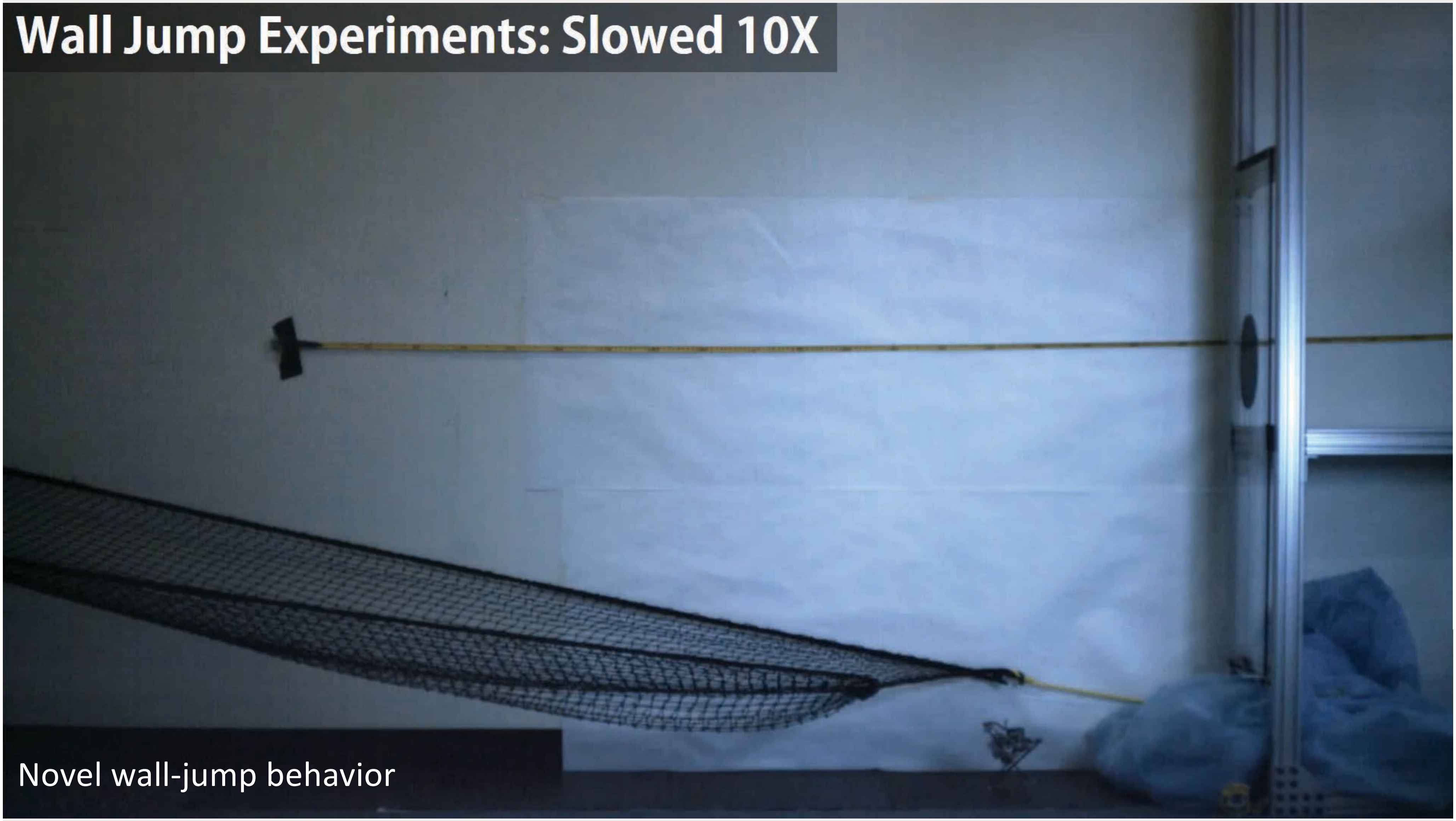

**2.94x Greater peak power**



# AGILE | WALL JUMPS

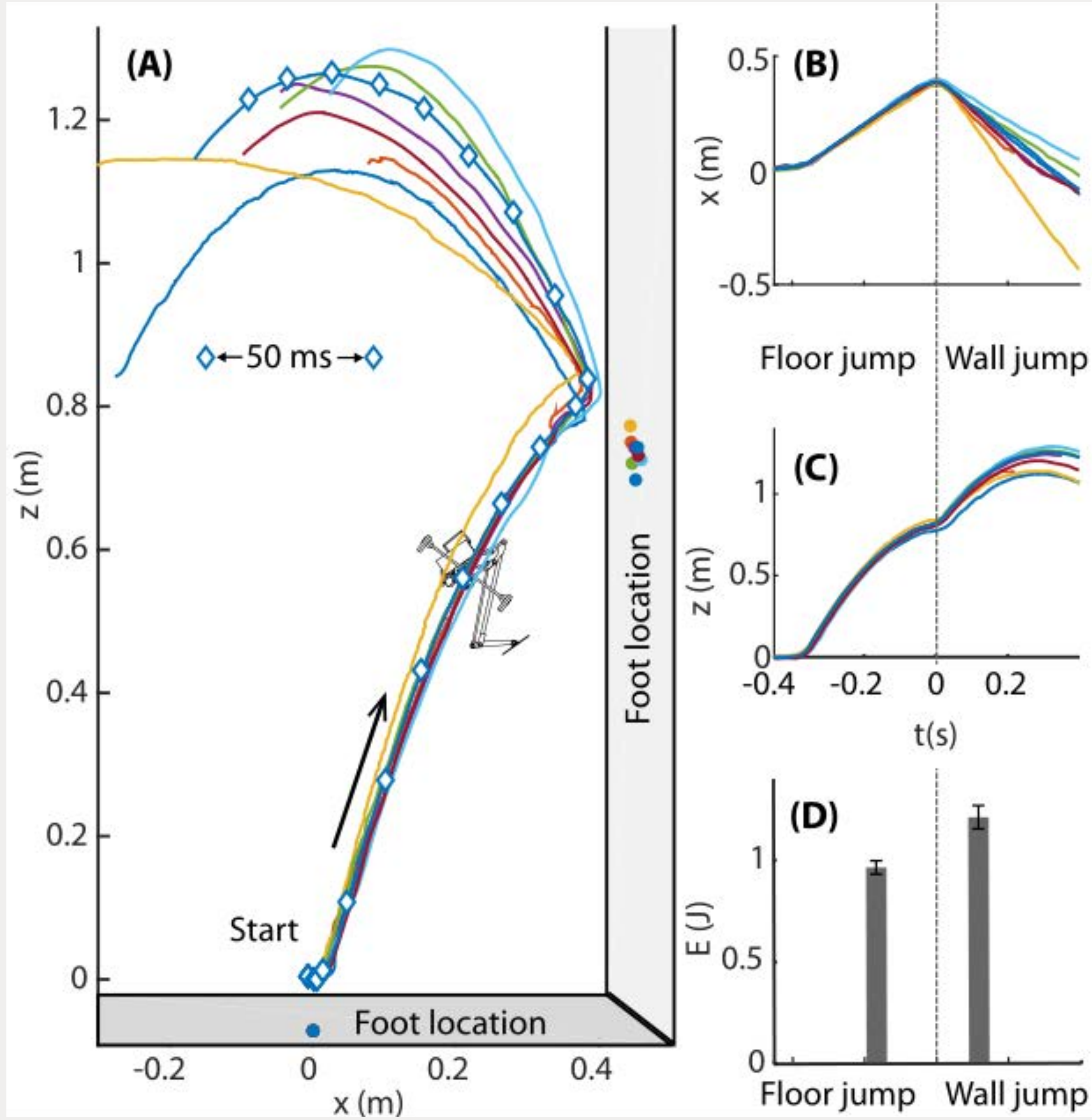


# AGILE | WALL JUMPS



# AGILE | WALL JUMPS

**Wall jump height higher than max vertical from ground**




Novel wall-jump behavior

# AGILE | CONCLUSIONS

Agility metric able to compare animal and robot jumpers

Bio-inspired SE+MA strategy increases peak power

SE+MA can be done with singly-actuated mechanism

Salto has highest vertical jumping agility

High agility enabled the new wall-jump

Novel wall-jump behavior

# 3: SPATIAL AGILE LOCOMOTION

## EXPANDING LOCOMOTORY CAPACITY WITHOUT COMPROMISING POWER DENSITY

**1: RAPID LOCOMOTION**

- Approach
- Result
- Stride kinematics
- Force and power
- Energetics

**2: AGILE LOCOMOTION**

- Motivation
- Agility metric
- Actuation strategies
- SE+MA actuation
- Leg mechanism
- Proof of concept
- Prototype & results

**3: SPATIAL-AGILE**

- Attitude control
- Spatial controller
- In-place jumping
- Forwards-backwards
- Jump exploration

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- Attitude control

# AGILE | SPATIAL STABILIZATION

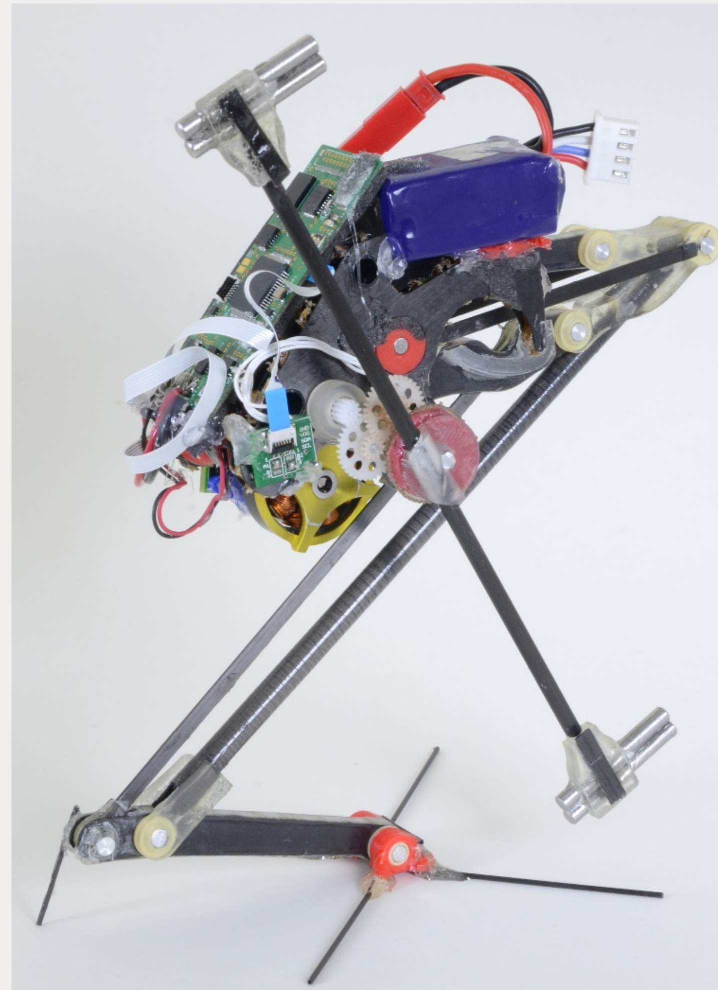
Salto is only controllable in-plane

Unstable out of plane

To stabilize without compromising power density – Add thrusters (4.4 g)

| | Salto | Salto-1P |
|---|---|---|
| Mass (kg) | 0.1000 | 0.0981 |
| Active leg Length (m) | 0.138 | 0.144 |
| Maximum jump height (m) | 1.007 | 1.252 |
| Vertical jumping agility (m/s) | 1.75 | 1.83 |
| *Max control torque (Nm):* | | |
| Pitch | 0.029 | 0.034 |
| Roll | 0 | 0.0078 |
| Yaw | 0 | 0.0039 |

**Salto-1P**



Novel wall-jump behavior

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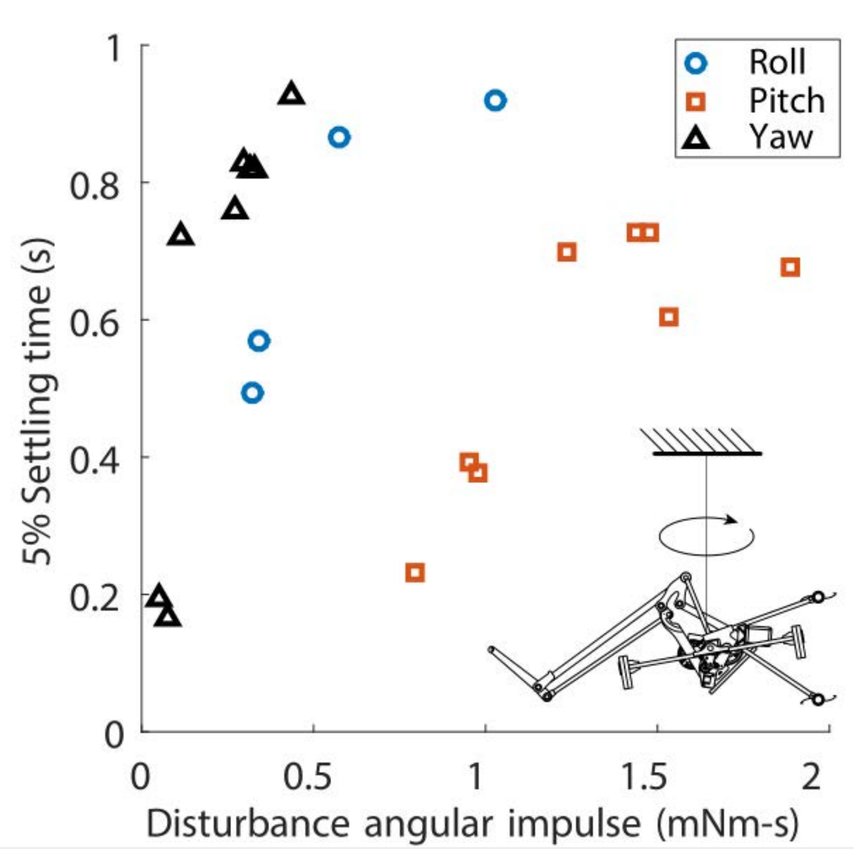


Novel wall-jump behavior

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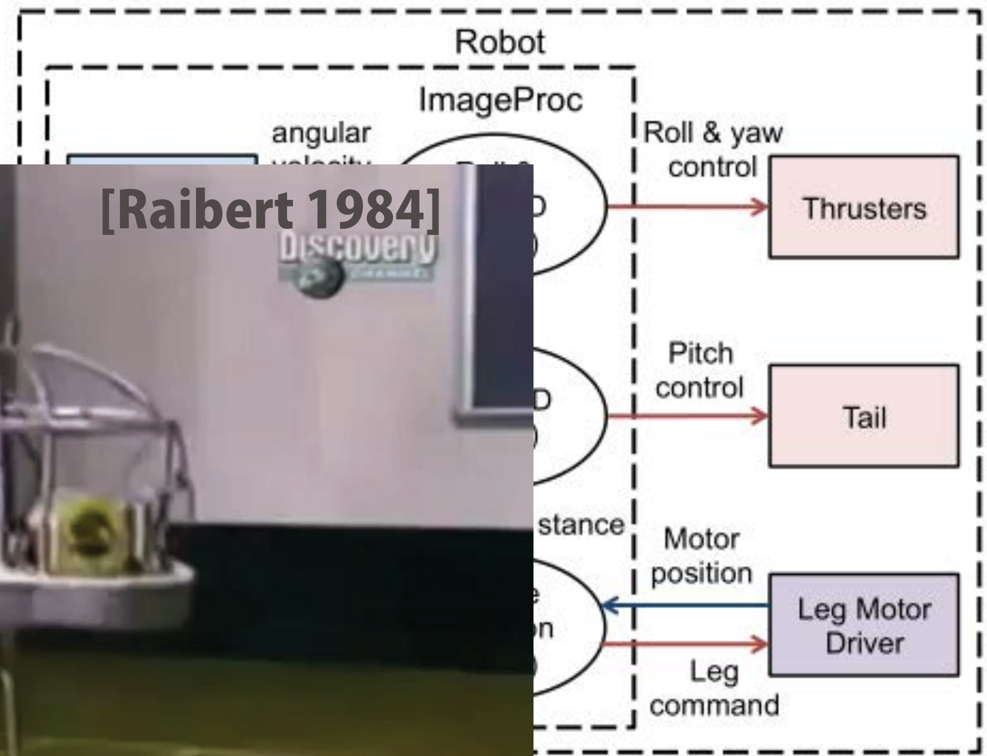
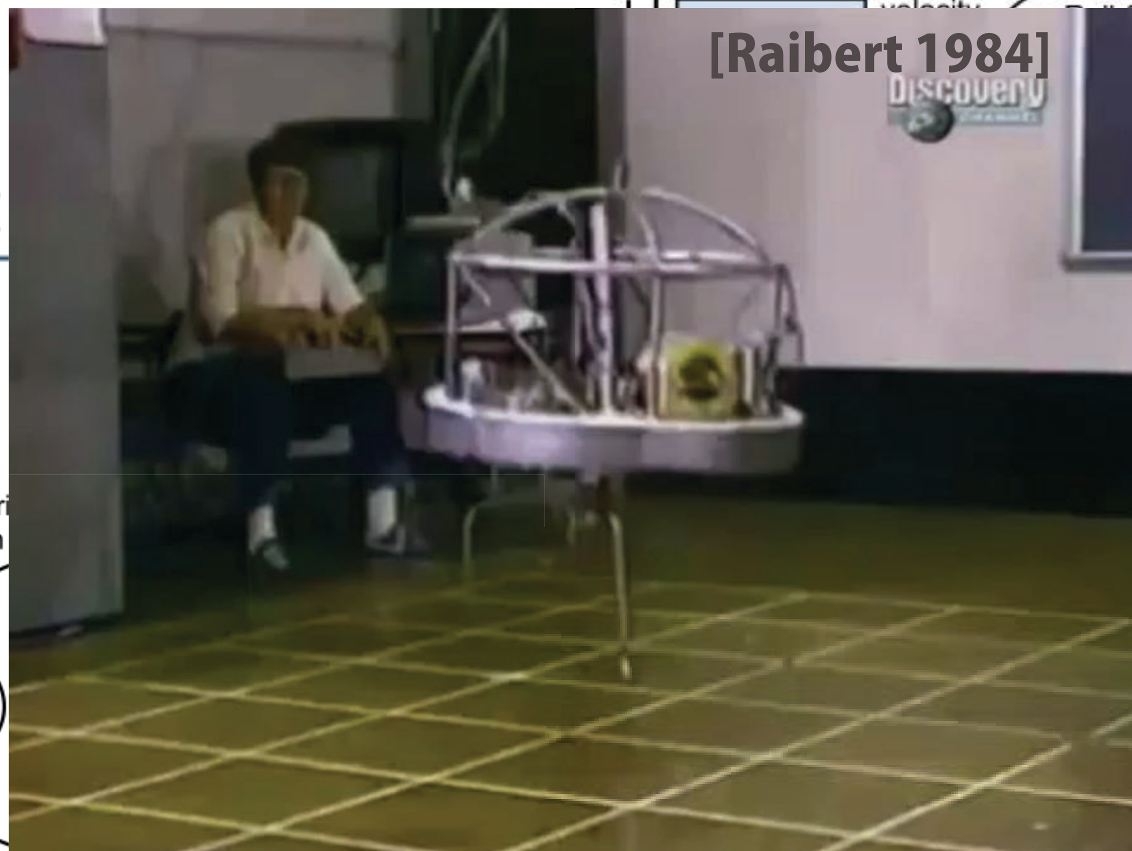
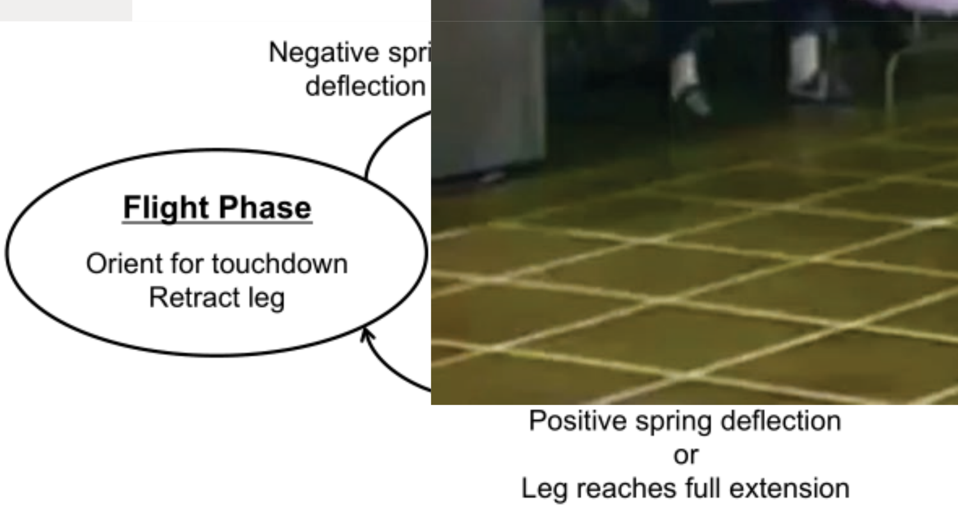
# AGILE | SPATIAL LOCOMOTION CONTROLLER




$$\ldots_{max}) - k_{Vx}(\dot{x}_d - \dot{x})$$

$$\theta = k_{Py} sat(y_d - y, y_{max}) + k_{Vy}(\dot{y}_d - \dot{y})$$

Novel wall-jump behavior

# 3: SPATIAL AGILE LOCOMOTION

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Prototype & results

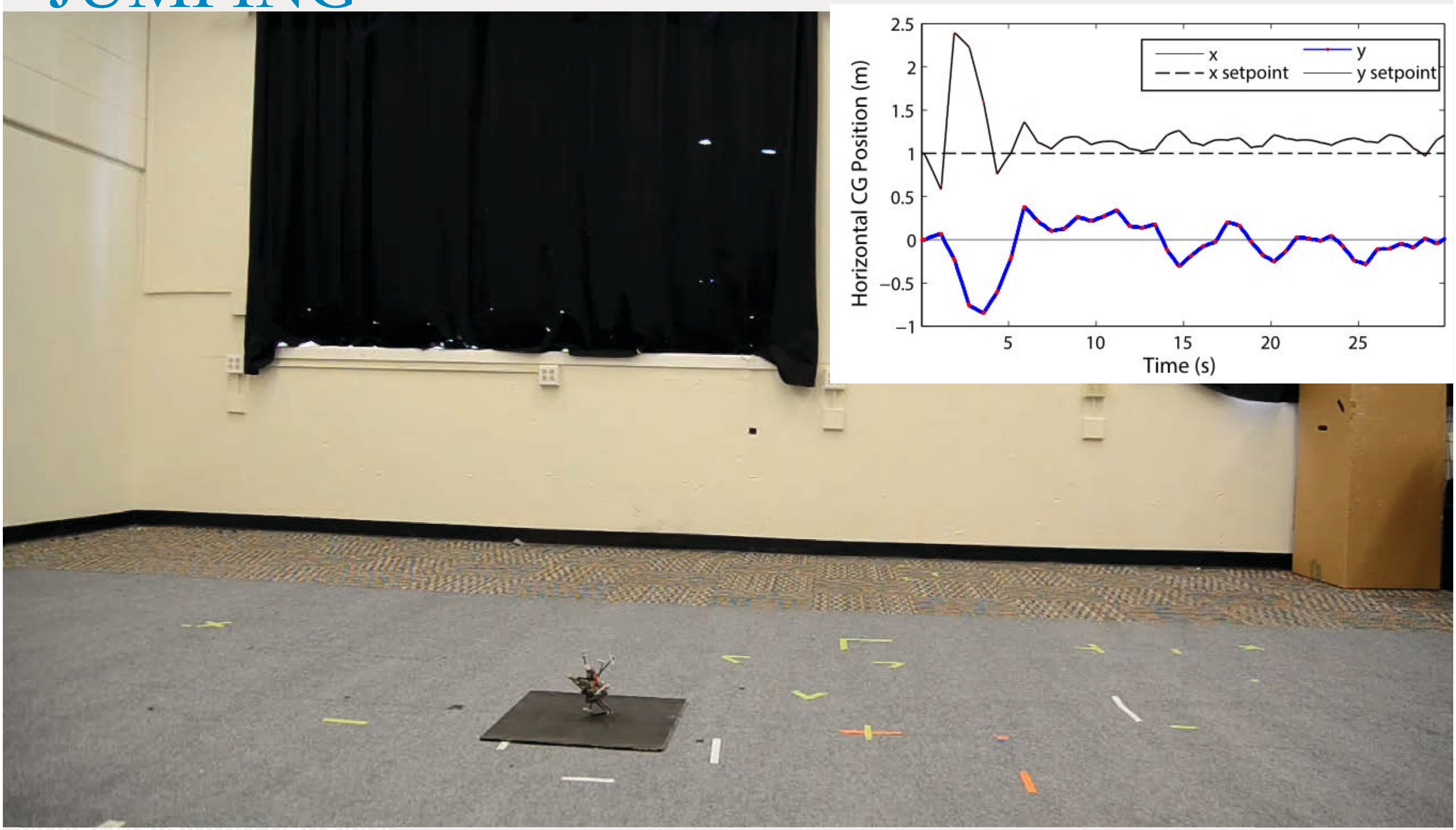
**3: SPATIAL-AGILE**

Attitude control

Spatial controller

In-place jumping

# AGILE | SPATIAL IN-PLACE JUMPING



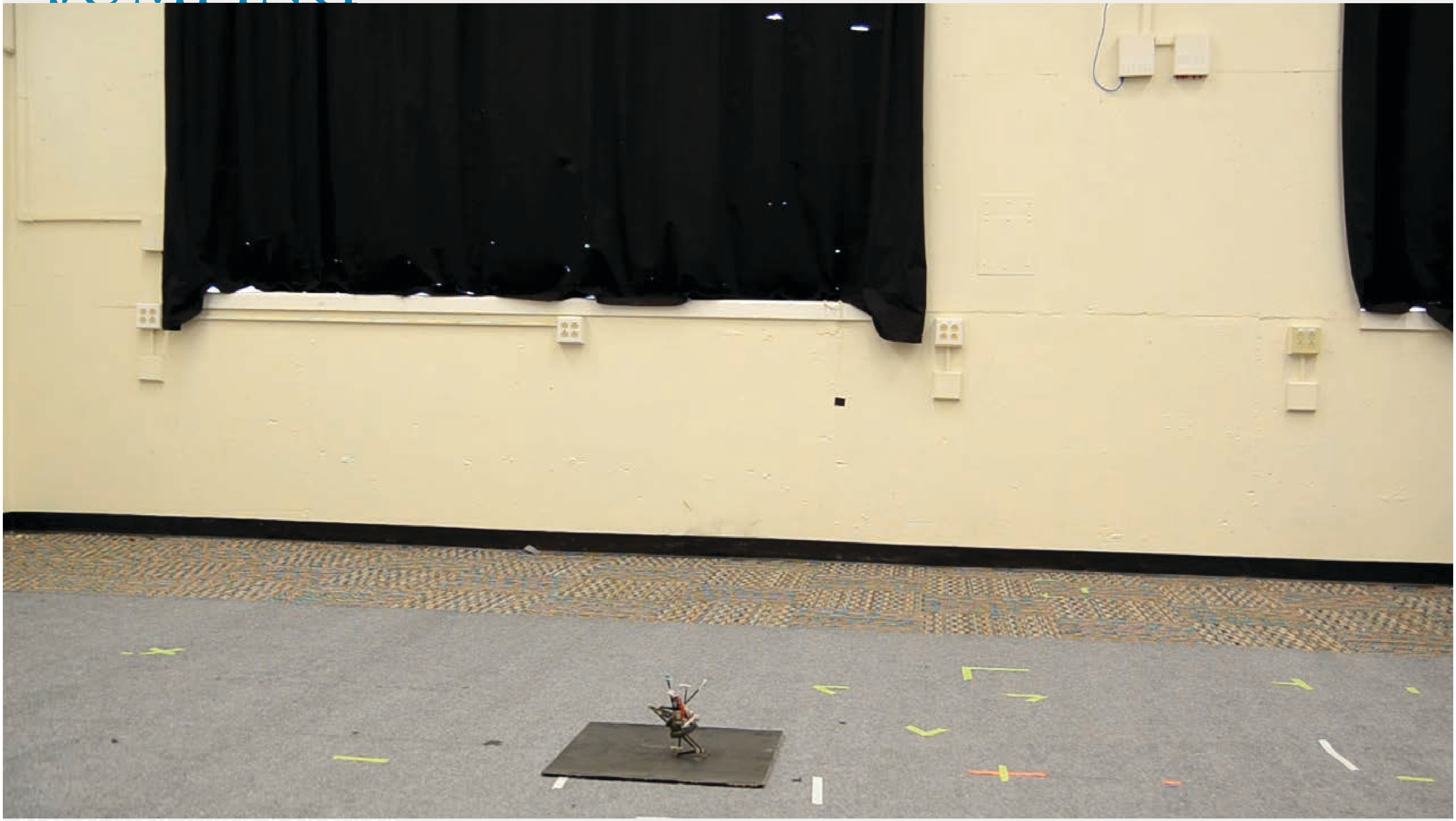

Novel wall-jump behavior

# AGILE | SPATIAL IN-PLACE JUMPING

**Footage slowed 10X**

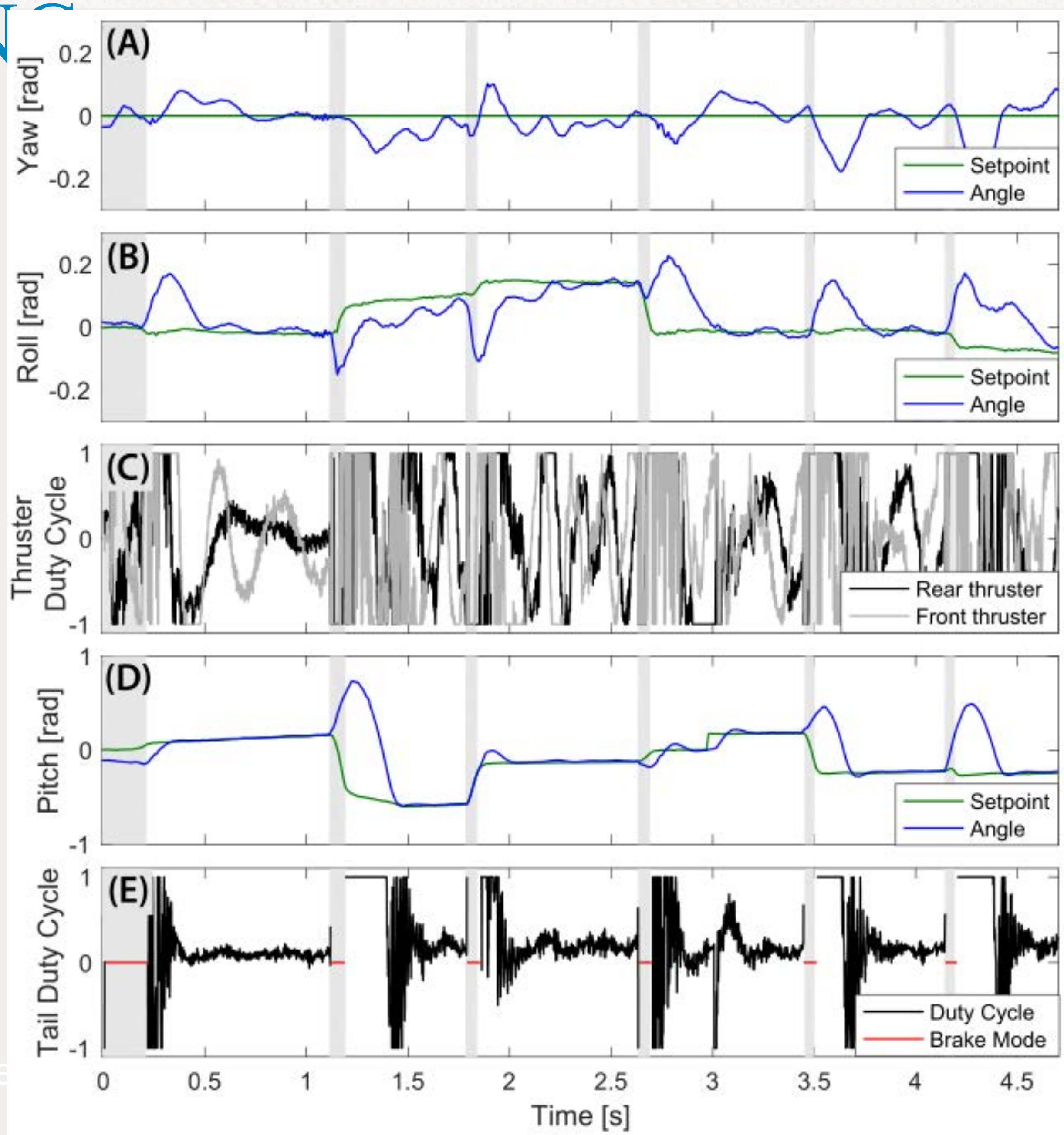
Novel wall-jump behavior

# AGILE | SPATIAL IN-PLACE JUMPING



Novel wall-jump behavior

# AGILE | SPATIAL IN-PLACE JUMPING




Novel wall-jump be

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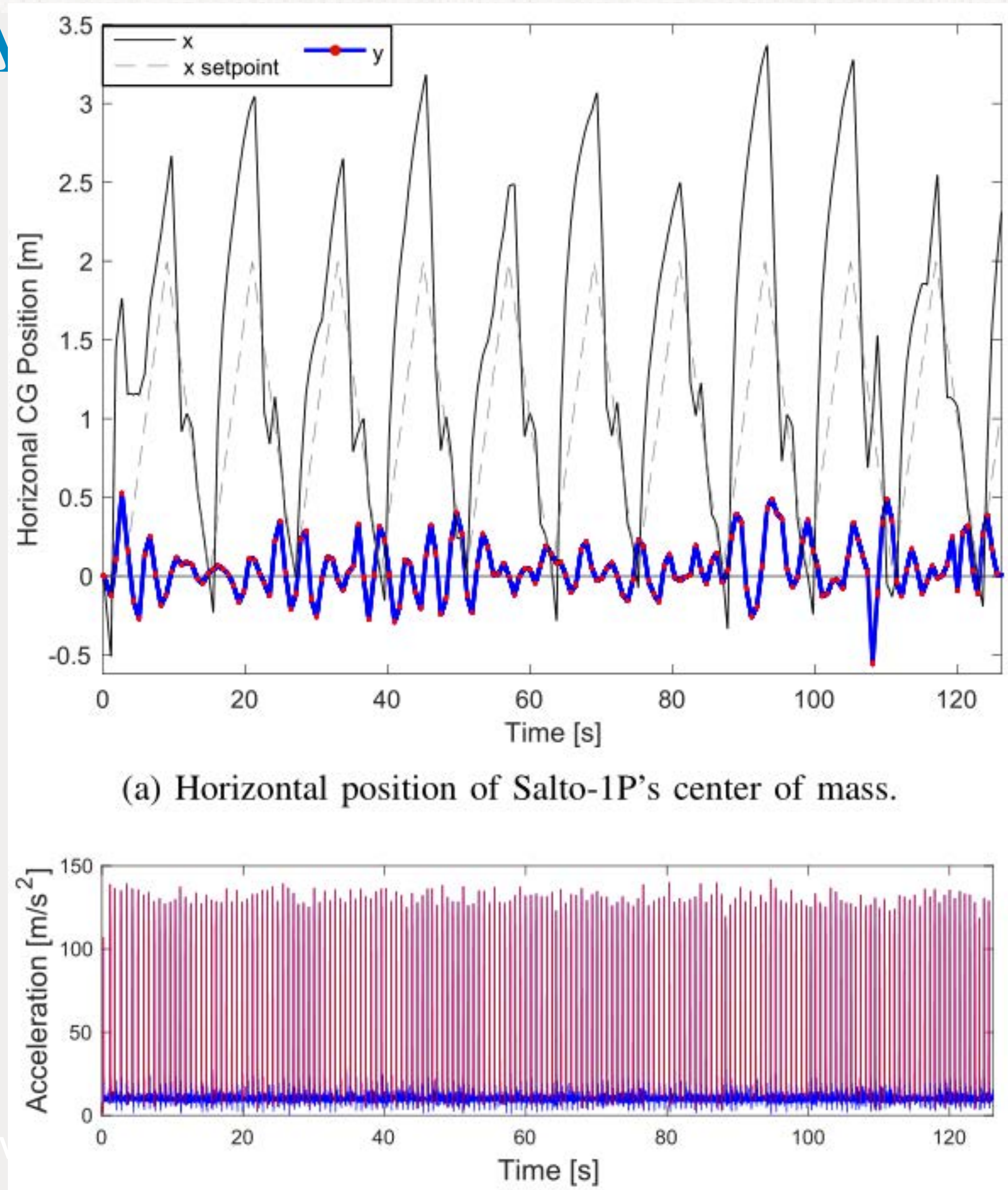
# AGILE | SPATIAL FORWARDS-BACKWARDS JUMPING

Novel wall-jump behavior

# AGILE | SPATIAL FORWARDS-BACKWARDS JUMPING

Novel wall-jump behavior

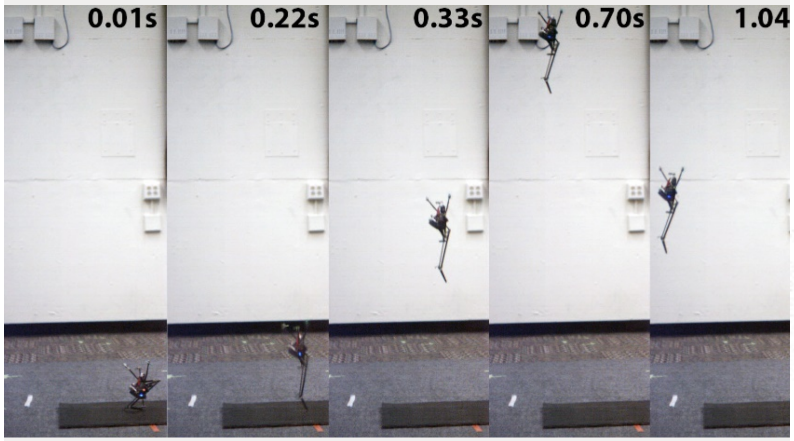
# AGILE | SPATIAL FORWARDS-BACKWA

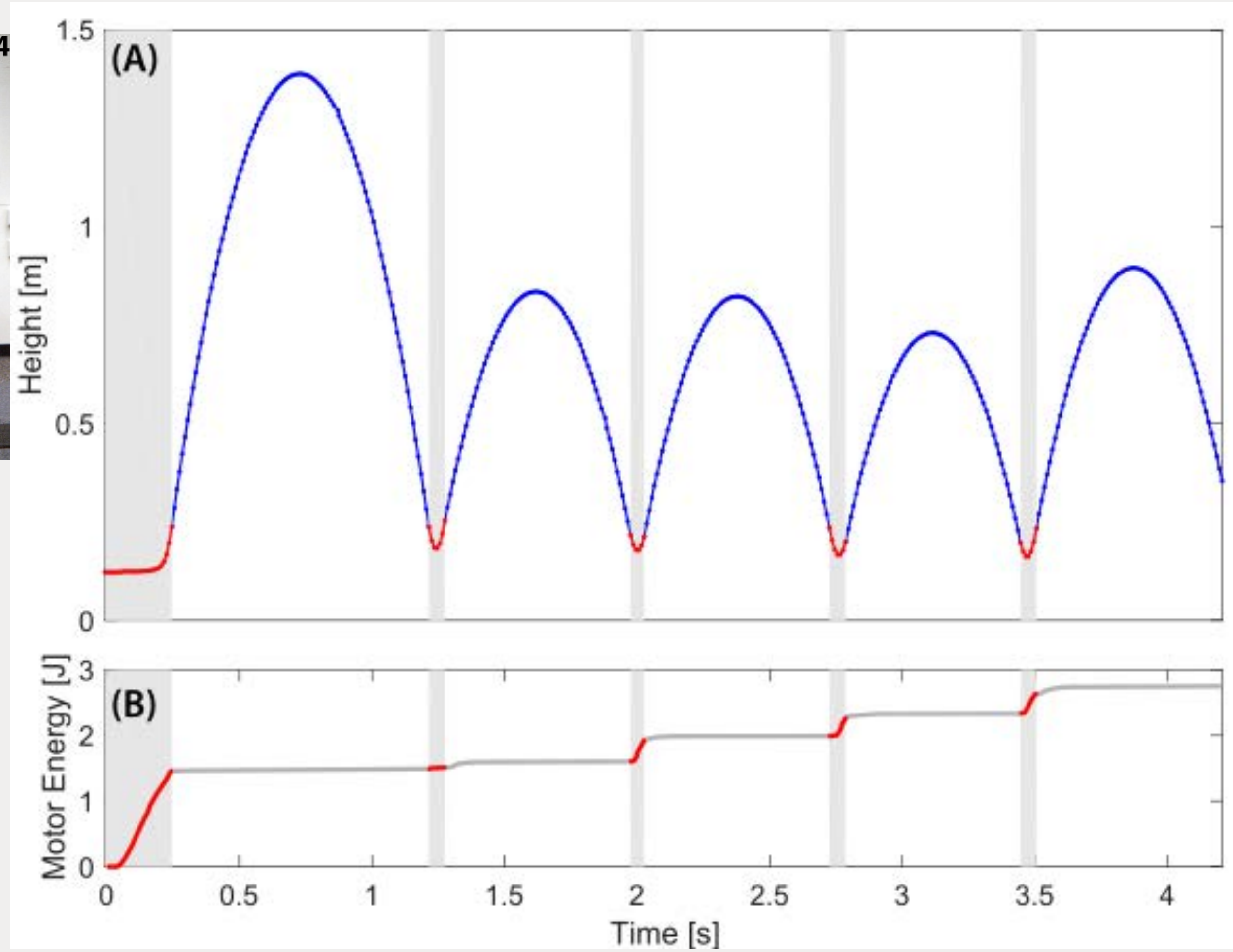



(a) Horizontal position of Salto-1P's center of mass.

Novel wall-jump beha

# AGILE | ENERGETICS OF REPEATED JUMPING




**First jump establishes energy**

**63% average energy recovery by series elastic element**

Novel wall-jump behavior

# 3: SPATIAL AGILE LOCOMOTION

## EXPANDING LOCOMOTORY CAPACITY WITHOUT COMPROMISING POWER DENSITY

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Approach

Result

Stride kinematics

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Prototype & results

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Attitude control

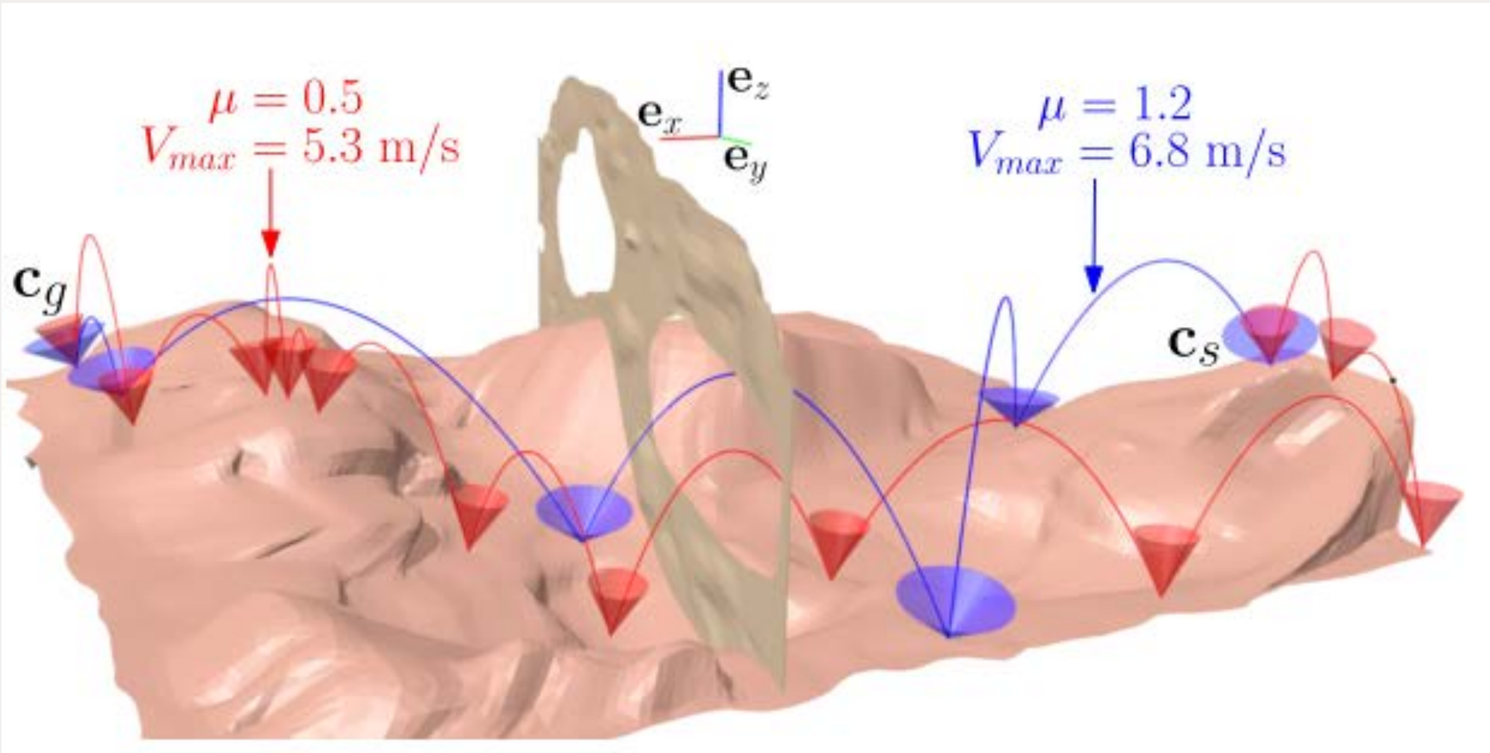
Spatial controller

In-place jumping

Forwards-backwards

Jump exploration

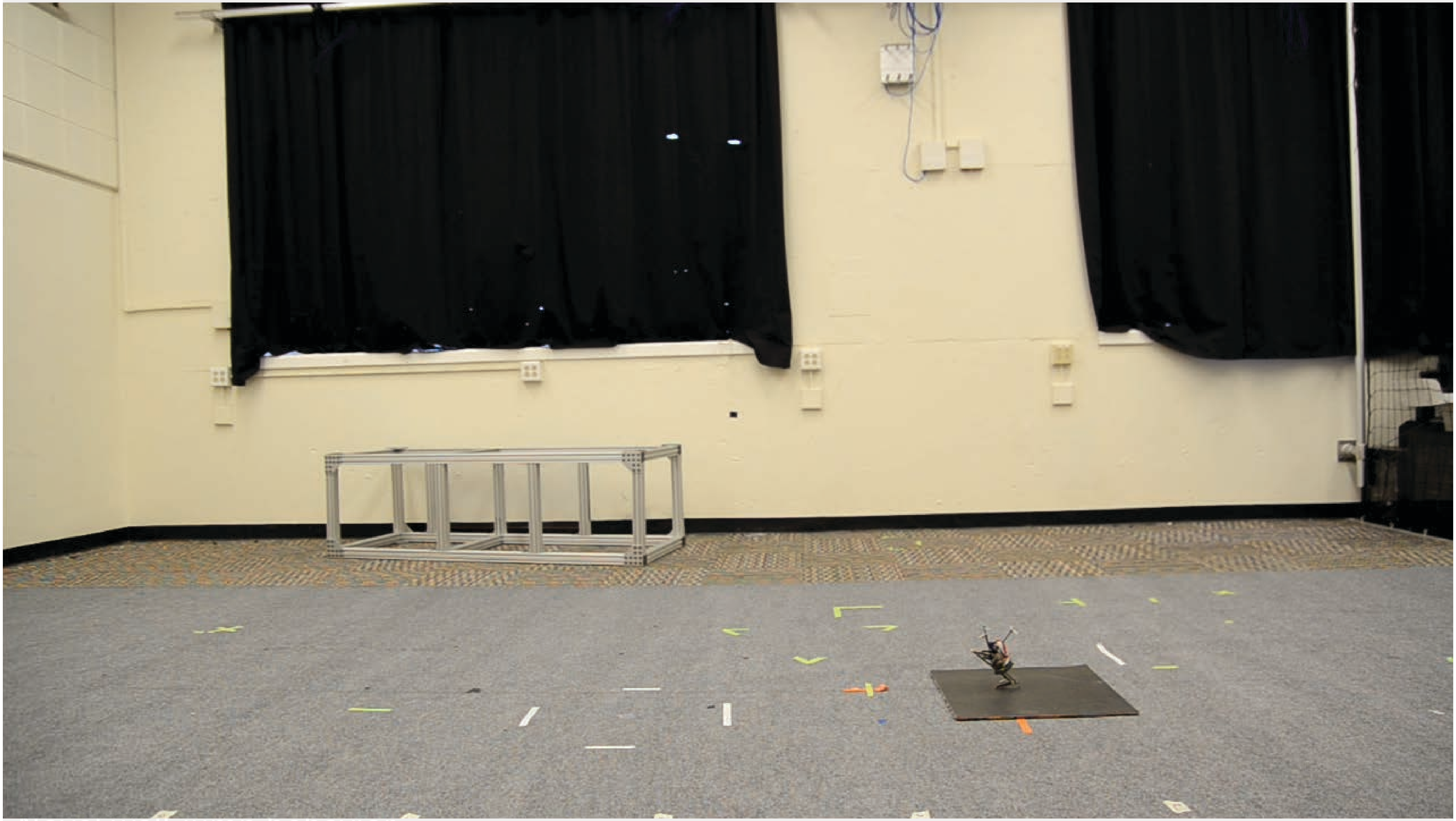
# AGILE | JUMP EXPLORATION




M. Campana and J.-P. Laumond, “Ballistic motion planning,” in *IEEE Int. Conf. Intell. Robots. Syst.*, 2016, pp. 1410–1416.

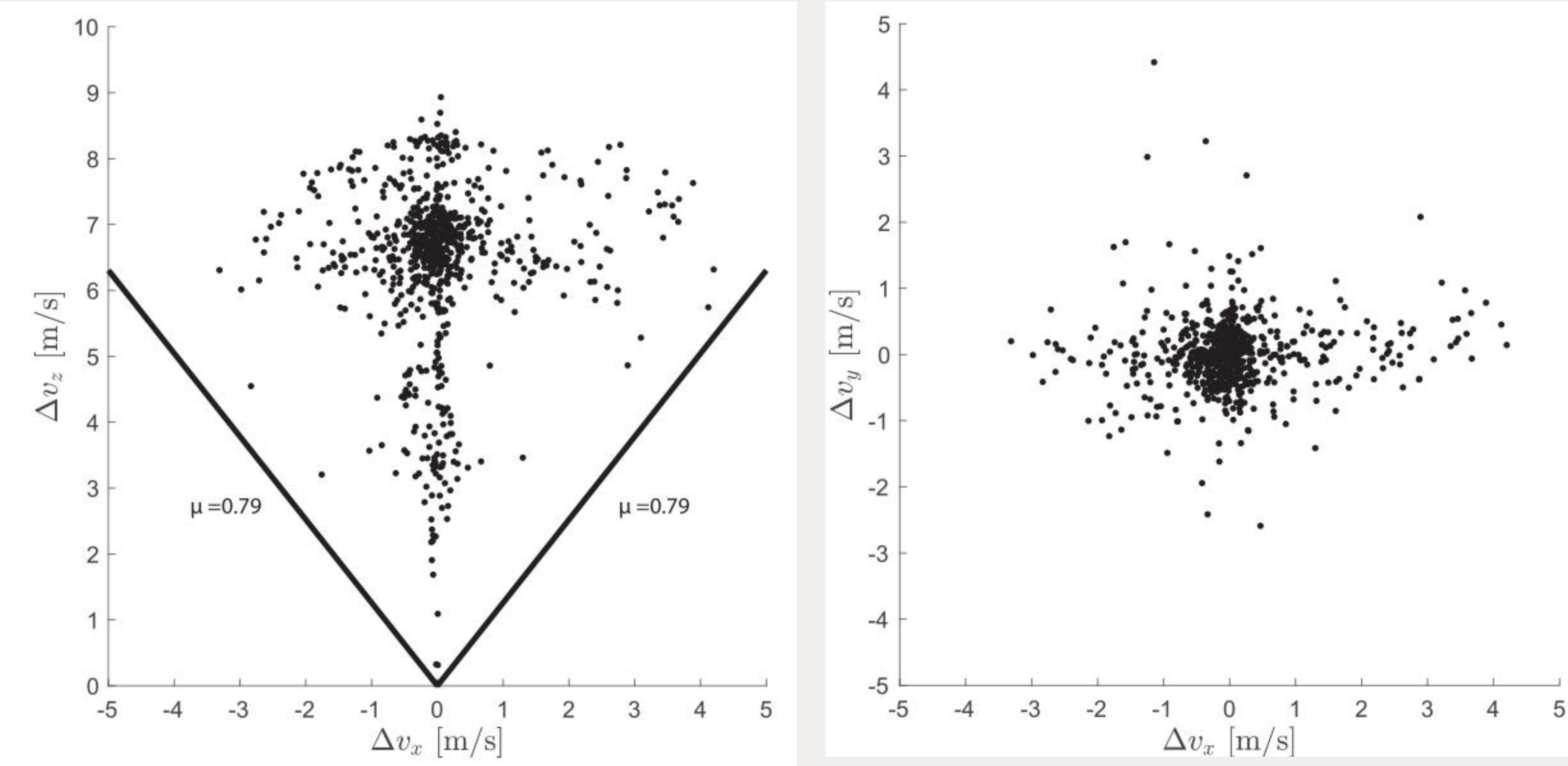
Novel wall-jump behavior

# AGILE | JUMP EXPLORATION



Novel wall-jump behavior

# AGILE | JUMP EXPLORATION




Novel wall-jump behavior

**8.93 m/s maximum Δv**

# AGILE | GRANULAR MEDIA

# AGILE | CONCLUSIONS

Power-density maintained using small actuators to get spatial control authority

Early work to simplify mechanism dynamics allowed use of simple Raibert controller

SE+MA mechanism able to passively recover 63% of jumping energy

Jumping power translates to wide range of $\Delta v$

Novel wall-jump behavior

# OVERVIEW

## RAPID AND AGILE LOCOMOTION WITH POWER-DENSE MILLIROBOTS

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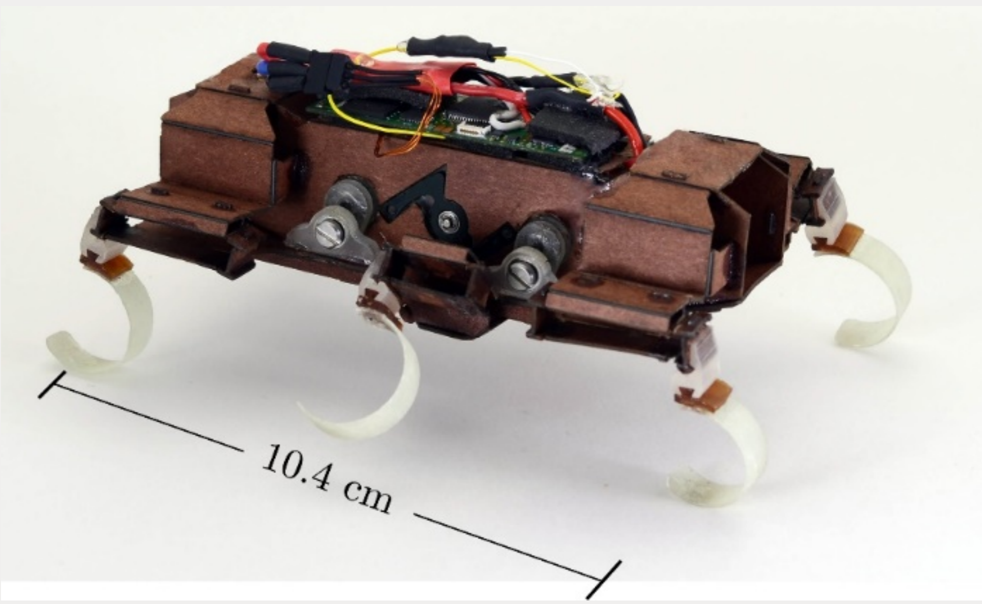
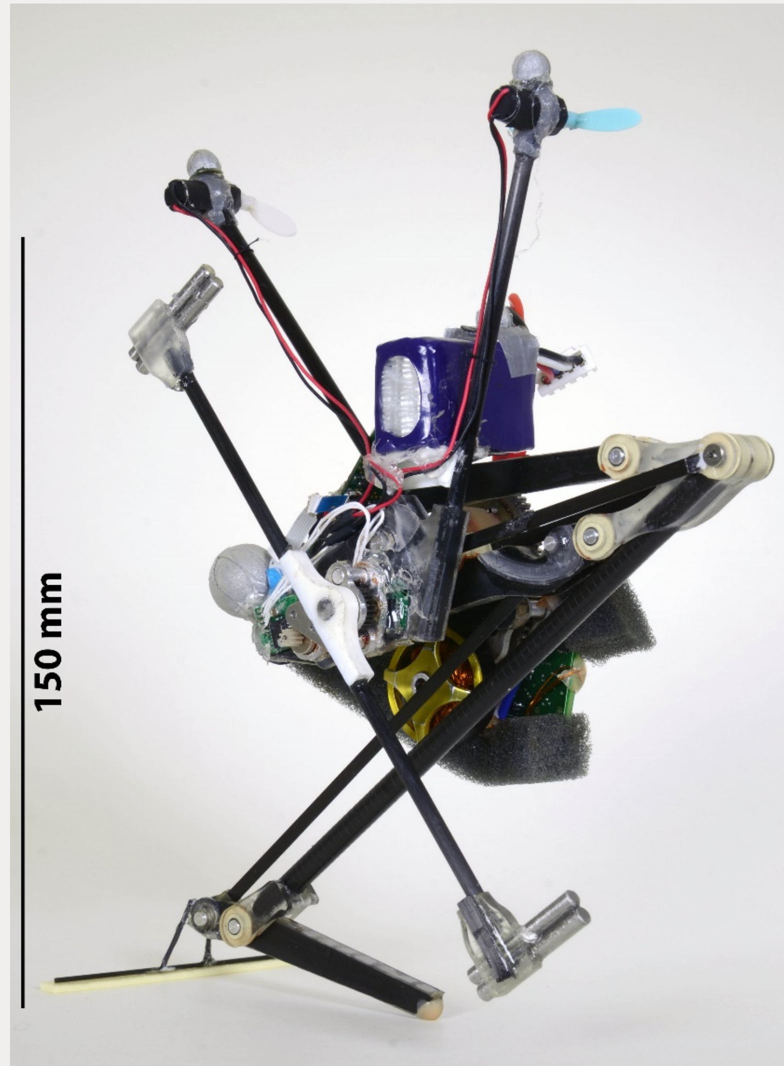
# CONCLUSION | DESIGN FOR POWER-DENSITY

Tested power density first design with running robot and jumping robot.

Both were best in class




X2-VelociRoACH




Salto-1P

# QUESTIONS?

## RAPID AND AGILE LOCOMOTION WITH POWER-DENSE MILLIROBOTS

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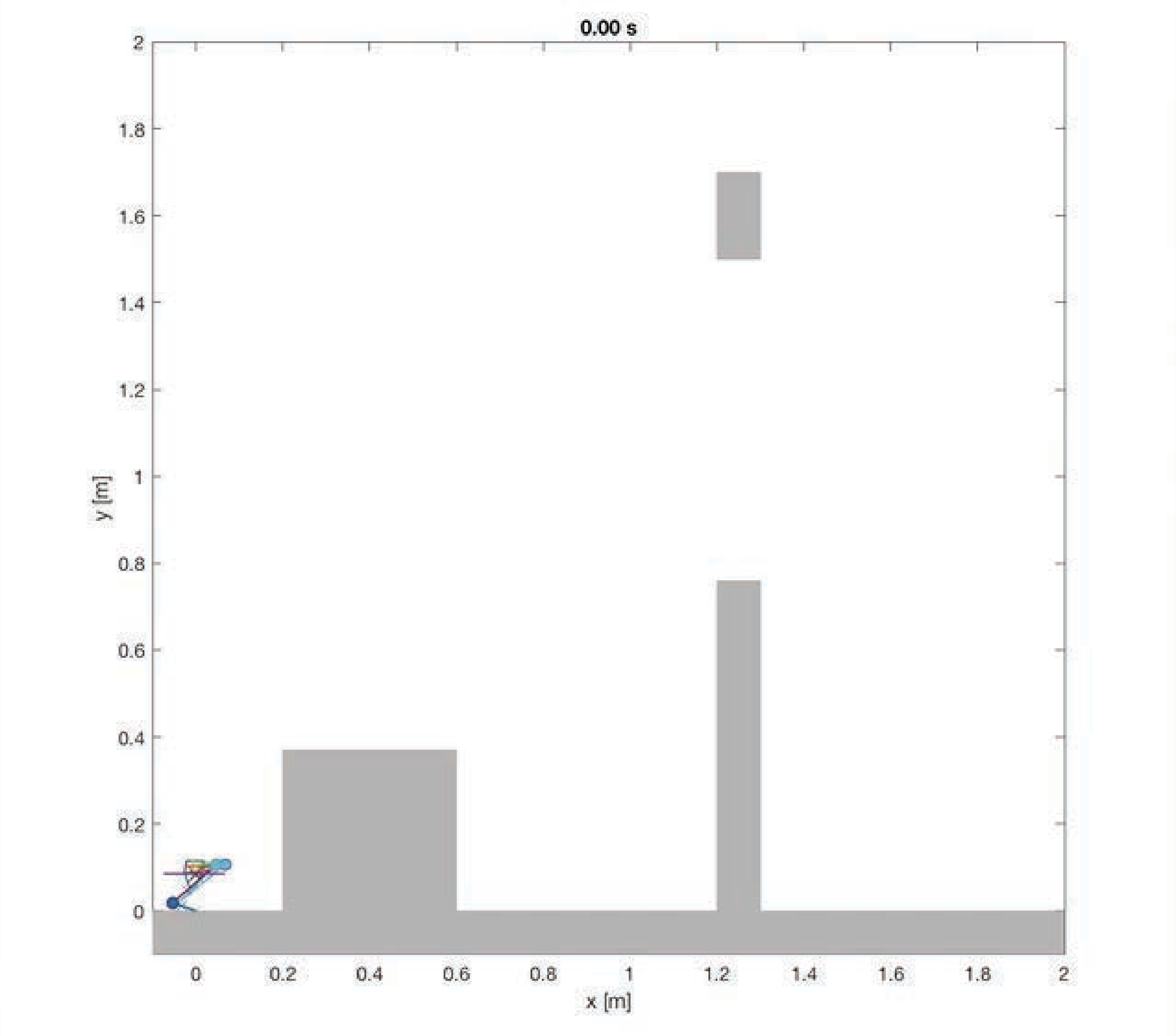
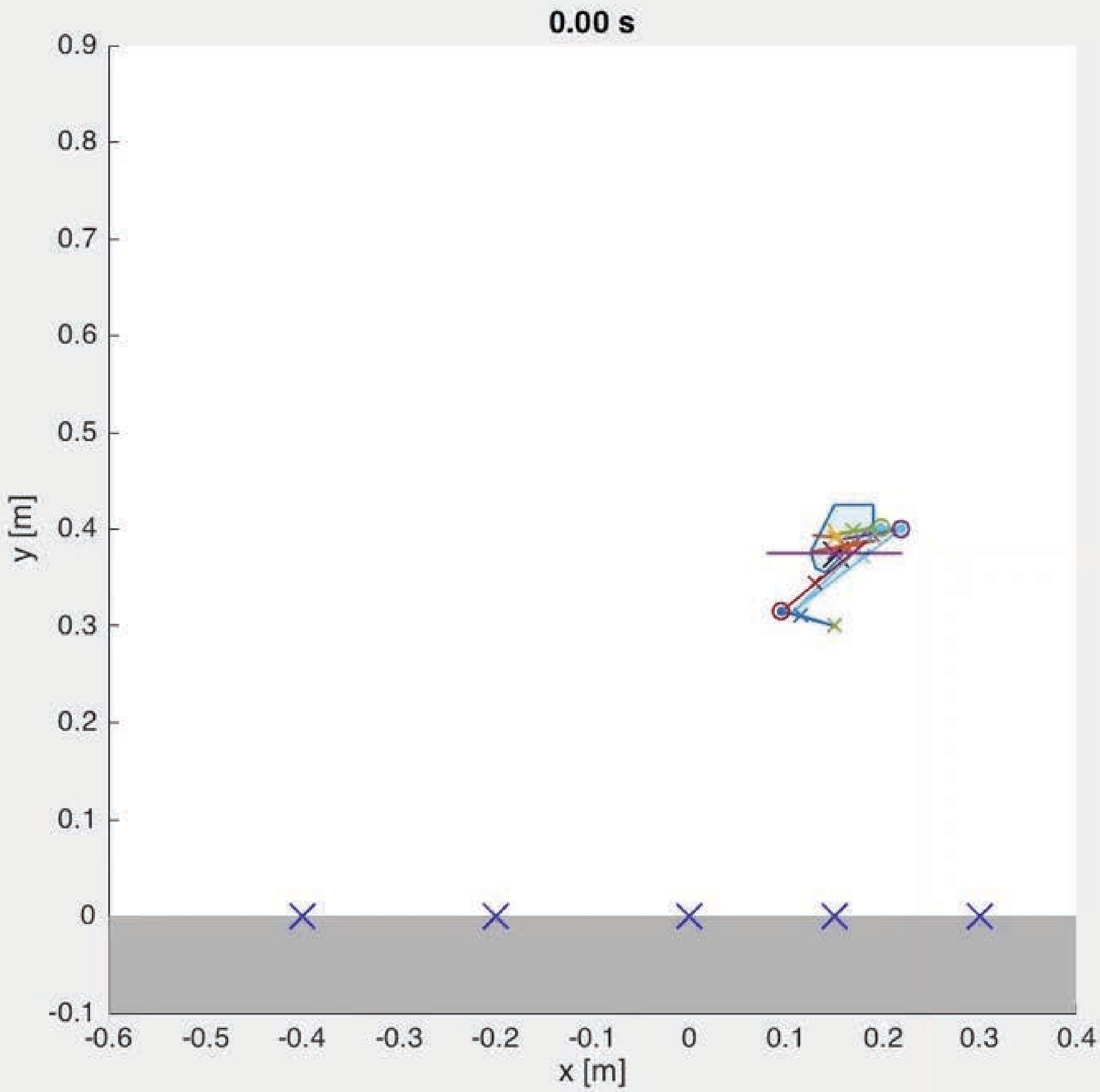
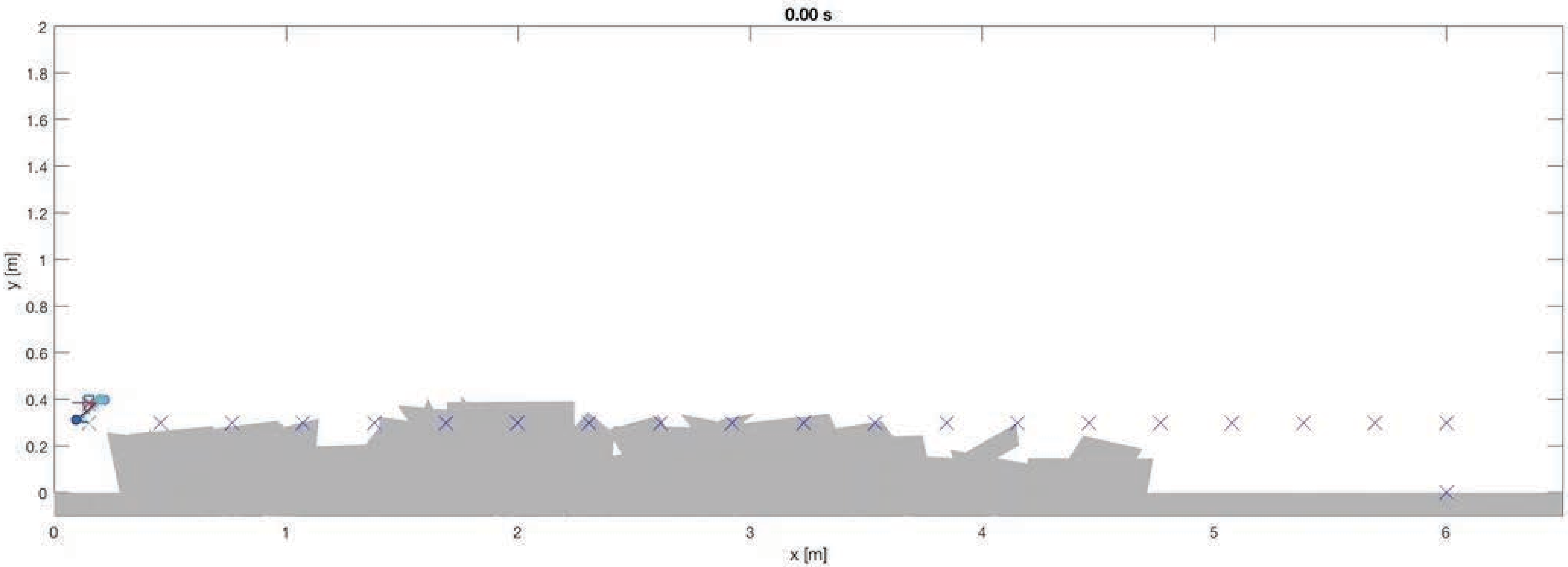
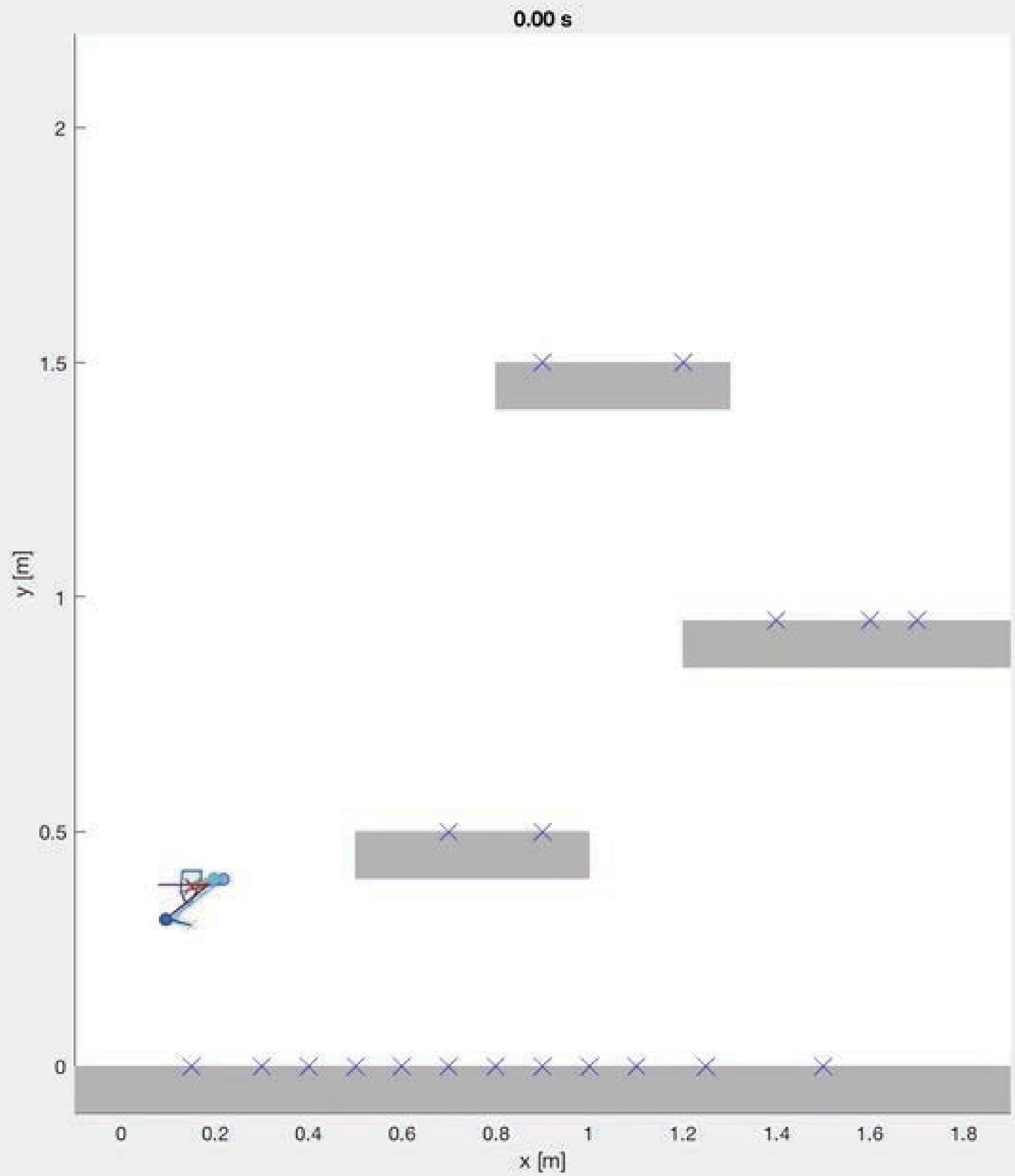



Novel wall-jump


0.00 s
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
y [m]
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
x [m]


0.00 s
y [m]
x [m]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4
5
6



0.00 s
y [m]
x [m]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0.5
1.5
2

# Kinematic Design of Salto's Leg

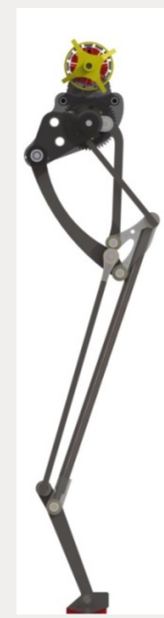
Functions

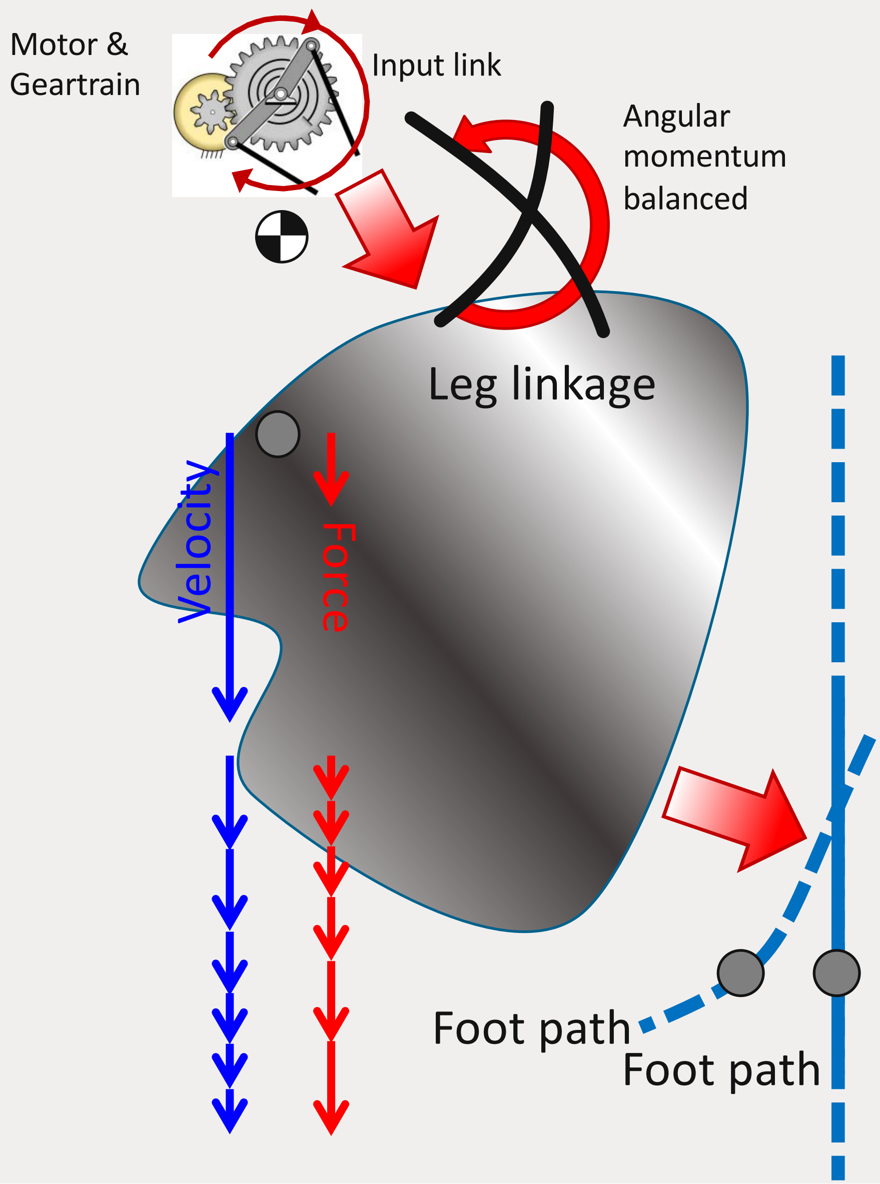
- Transform motor torque into vertical jumping force
- Reduce required motor/gear train torque
- Minimize peak forces
- Jump without rotation
- Power modulate a series-elastic actuator

Requirements

1. Traces a straight line
2. Long stroke
3. CM near line-of-action
4. Compact dimensions
5. Input link rotates over large range
6. Low mech. adv. at top of stroke
7. Constant ground reaction force
8. Angular momentum balanced

Single structure






<u>Requirements</u>

- ✓1. Traces a straight line
- ✓2. Long stroke
- ✓3. CM near line-of-action
- ✓4. Compact dimensions
- ✓5. Input link rotates over large range
- ✓6. Low mech. adv. at top of stroke
- ✓7. Constant ground reaction force
- ✓8. Angular momentum balanced

# Starting from Scratch


Requirements

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2. Long stroke
3. CM near line-of-action
4. Compact dimensions
5. Input link rotates over large range
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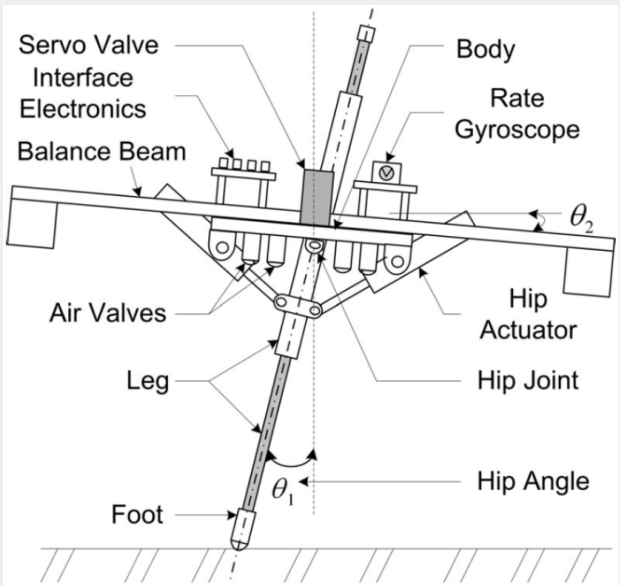
We have no clue what this mechanism might look like.

# A Prismatic Joint




A single spring-loaded prismatic joint

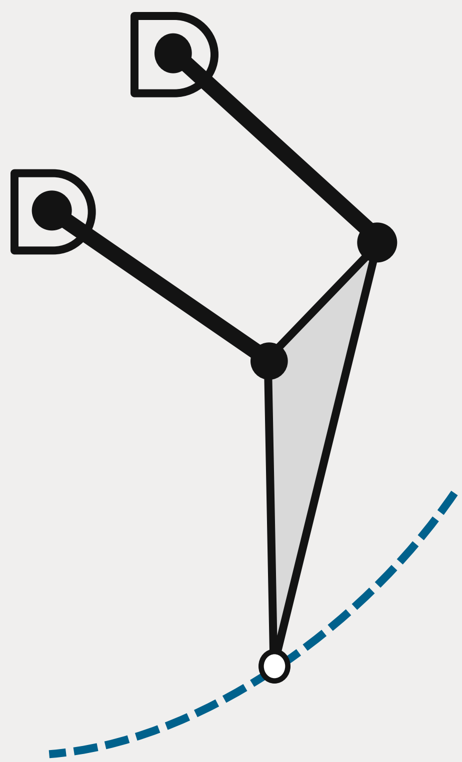
Sliders are heavy and not great with lateral loads.

<u>Requirements</u>

✓1. Traces a straight line
✓2. Long stroke
✓3. CM near line-of-action
✓4. Compact dimensions
5. Input link rotates over large range
6. Low mech. adv. at top of stroke
7. Constant ground reaction force
✓8. Angular momentum balanced

# Pick a four-bar

Use incredible visualization skills to design a four-bar:

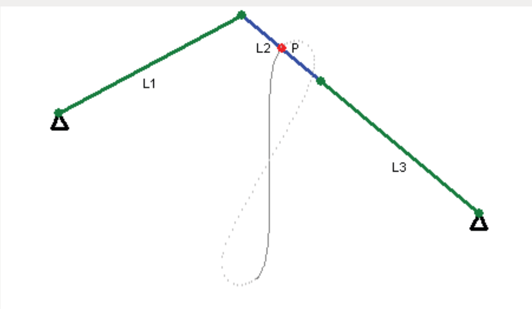


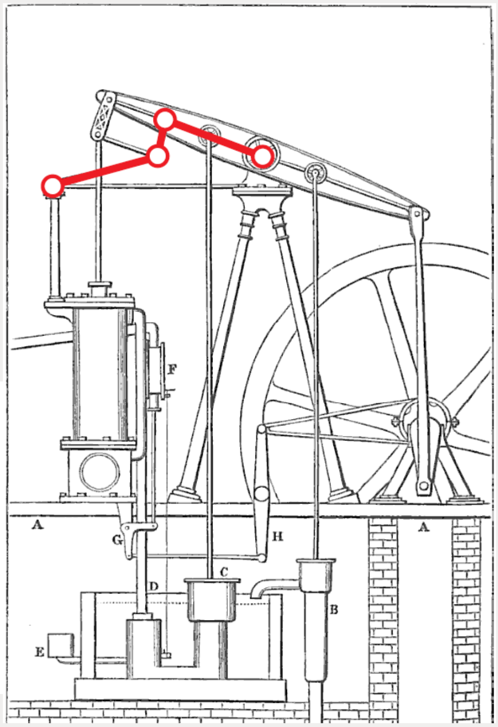
Requirements

1. Traces a straight line
2. ✓ Long stroke
3. CM near line-of-action
4. ✓ Compact dimensions
5. Input link rotates over large range
6. Low mech. adv. at top of stroke
7. Constant ground reaction force
8. Angular momentum balanced

# Straight-line Linkages

James Watt designed this linkage over 230 years ago:




<u>Requirements</u>

✓1. Traces a straight line
✓2. Long stroke
3. CM near line-of-action
✓4. Compact dimensions
5. Input link rotates over large range
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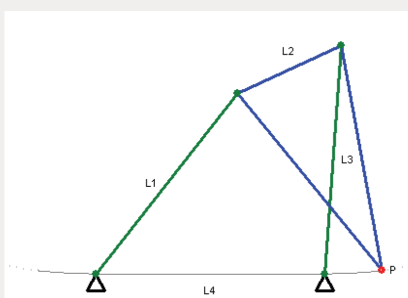
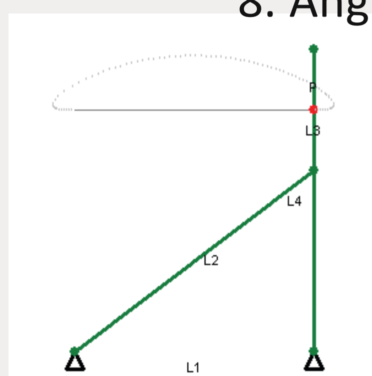
8. Angular momentum balanced

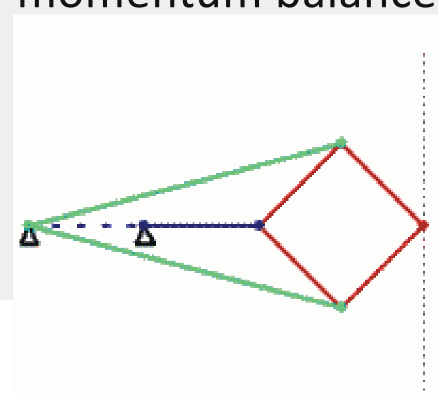
Other straight-line mechanisms:




Roberts linkage



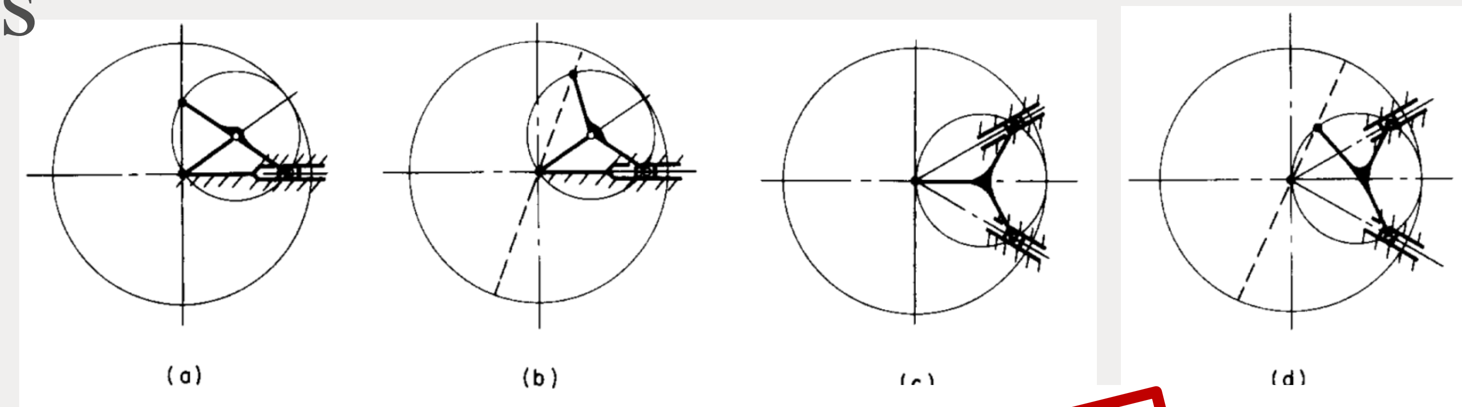

Chebyshev linkage



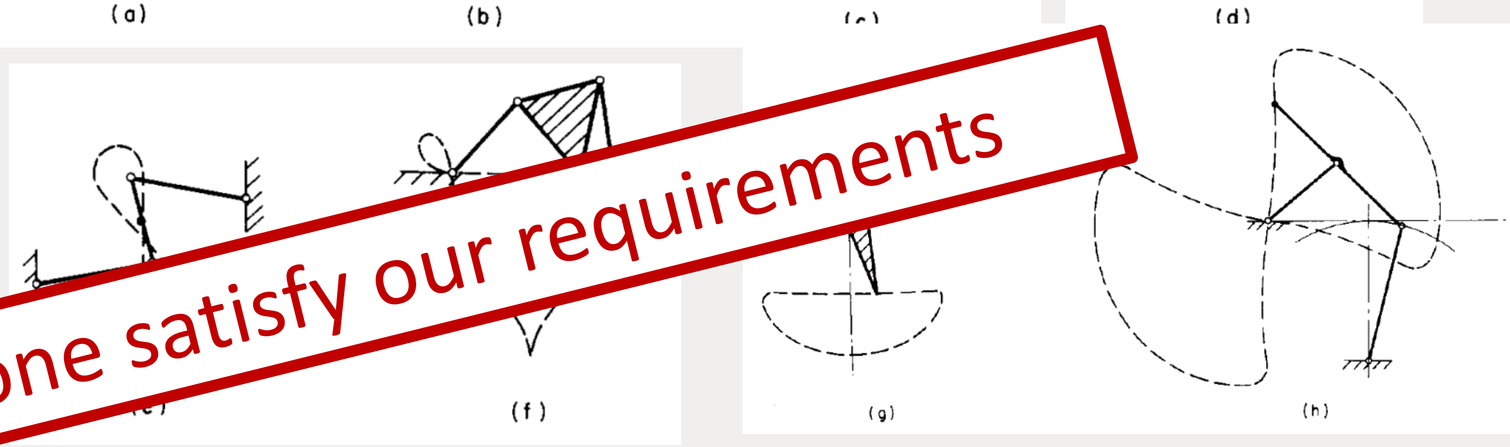
Peaucellier linkage

# An Atlas Of All Known Straight-Line Four-Bars

Four-bars w/ sliders: exact straight lines

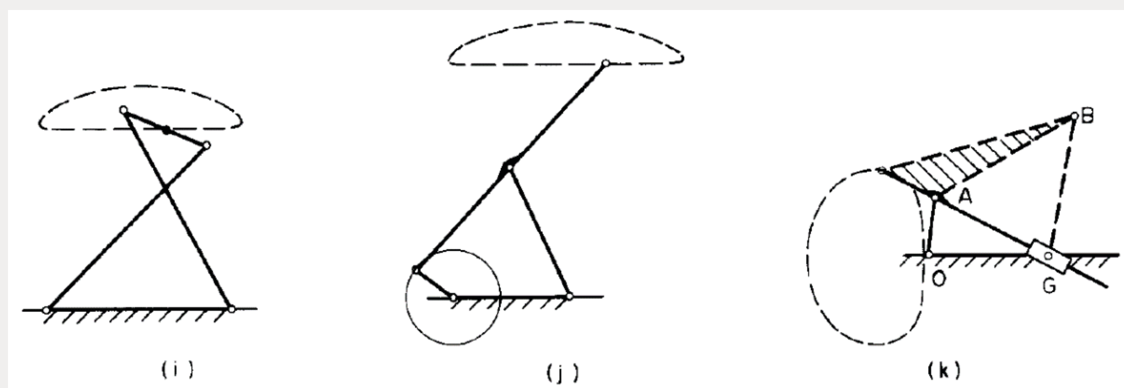



Approx. straight line four-bars



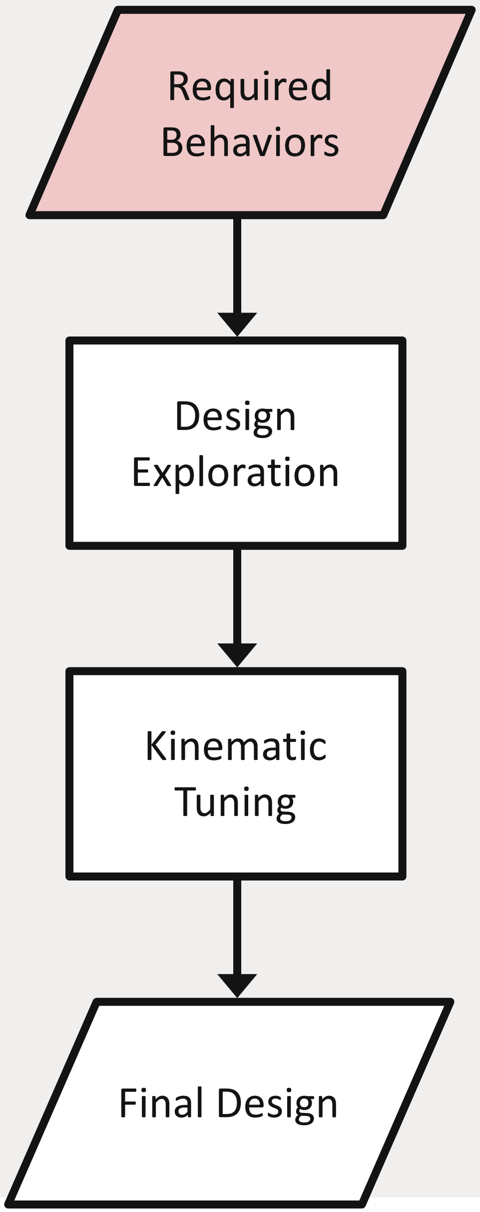

None satisfy our requirements

- None of these have ground pivots in suitable locations




Nolle, H. "Linkage coupler curve synthesis: a historical review—I. Developments up to 1875." Mechanism and Machine Theory 9.2 (1974): 147-168.

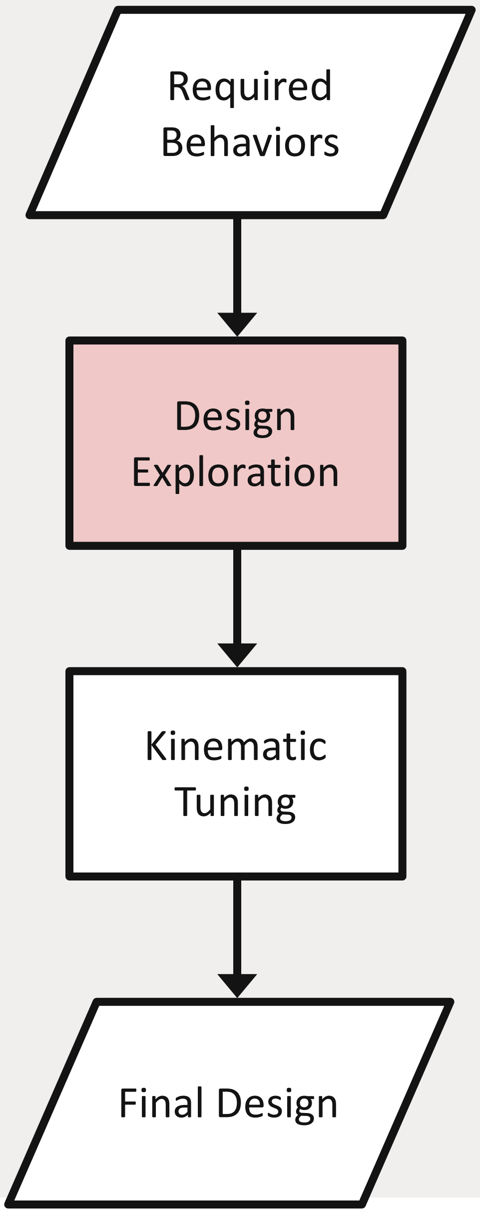
# Design Approach



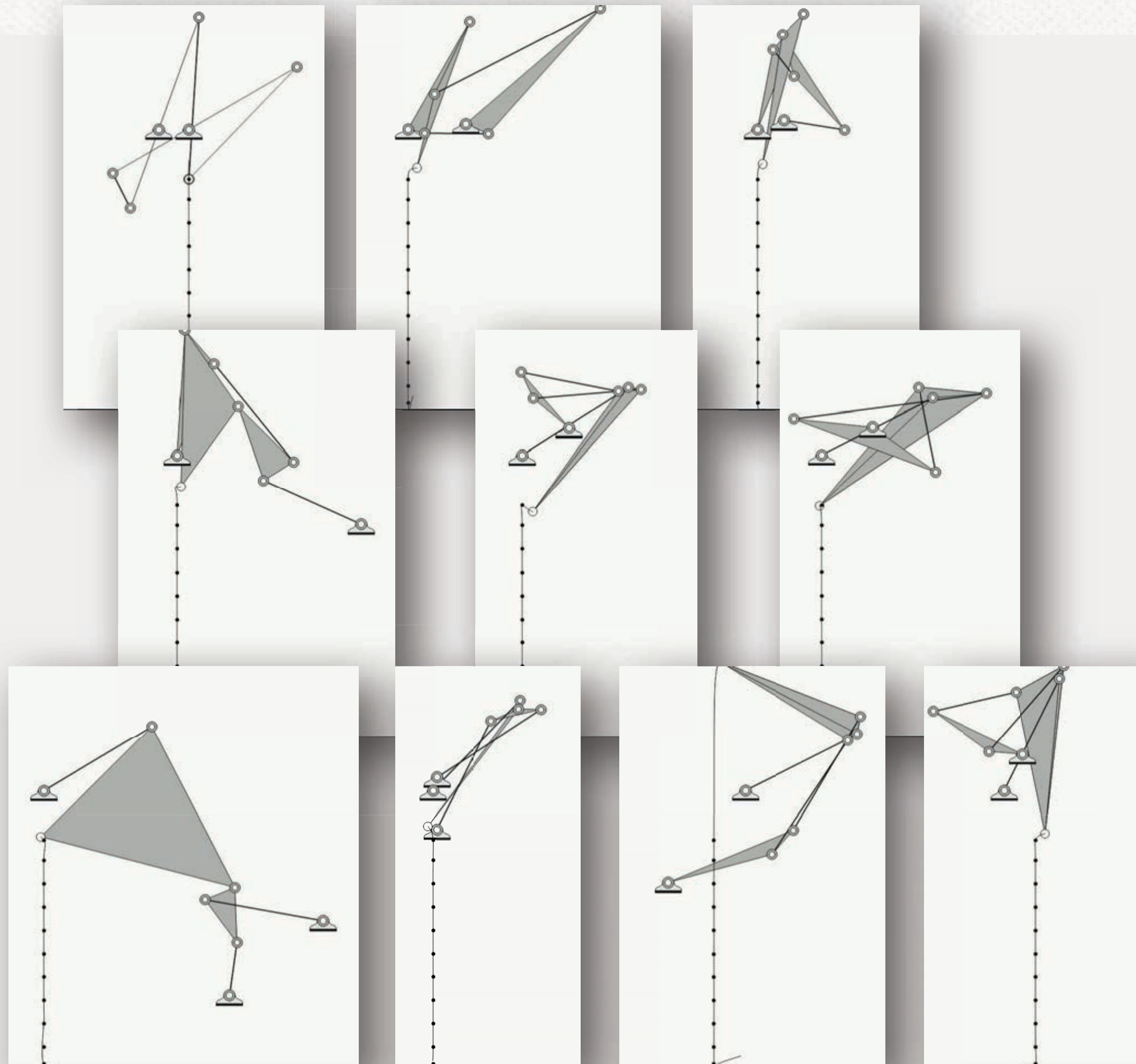

<u>Requirements</u>

1. Traces a straight line
2. Long stroke
3. CM near line-of-action
4. Compact dimensions
5. Input link rotates over large range
6. Low mech. adv. at top of stroke
7. Constant ground reaction force
8. Angular momentum balanced

# Design Approach

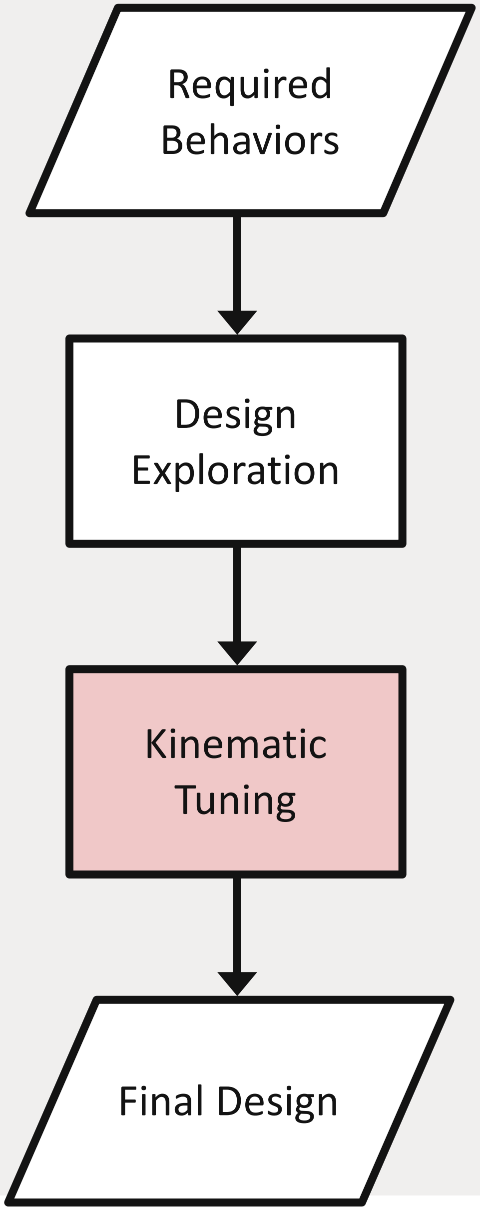



## Generate An Atlas Of Designs



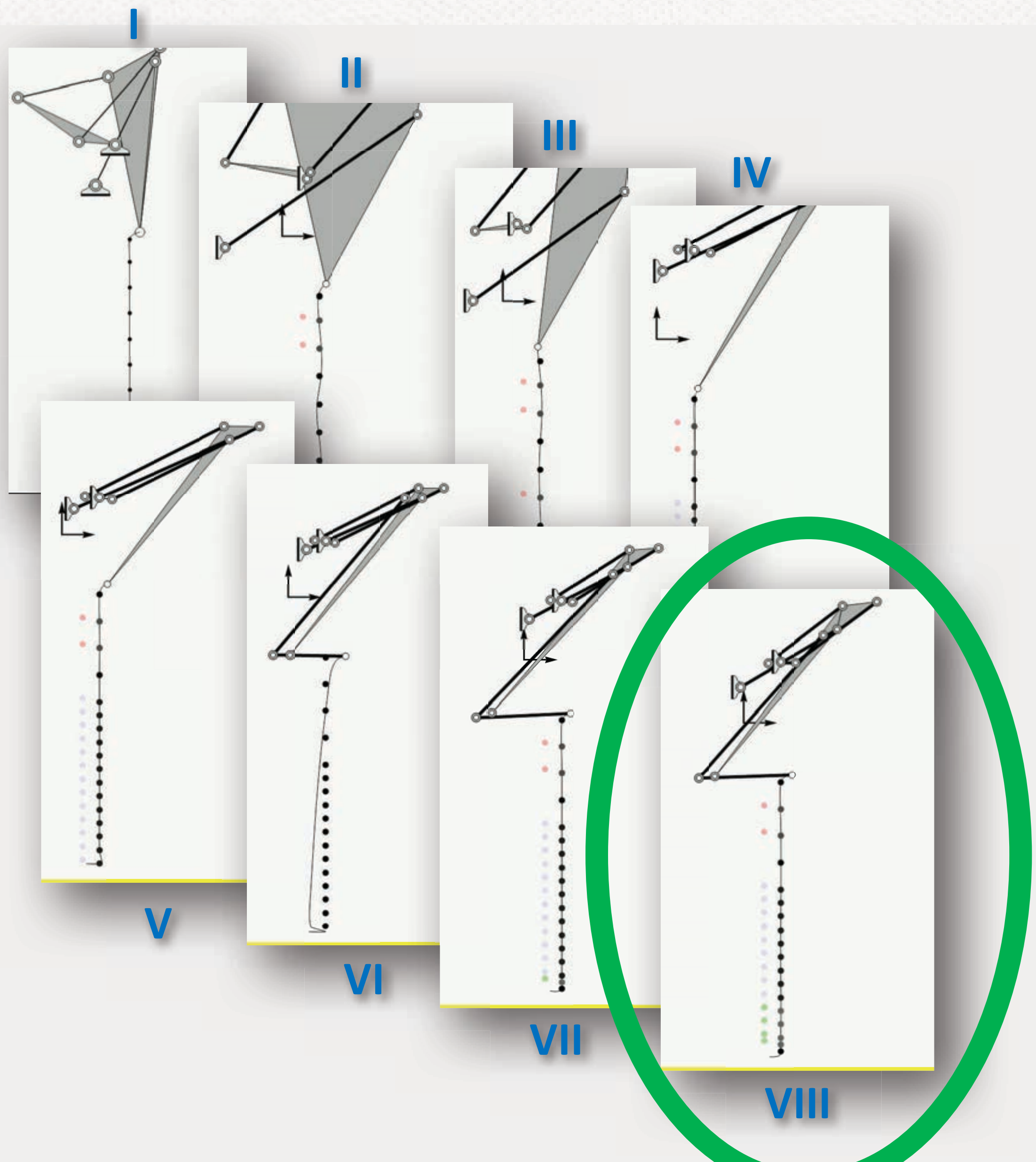
M. M. Plecnik, D. W. Haldane, J. K. Yim and R. S. Fearing, 2016. "Design Exploration and Kinematic Tuning of a Power Modulating Jumping Monopod," *Journal of Mechanisms and Robotics*, 9(1):011009.

# Design Approach




# Iterative Design Optimization

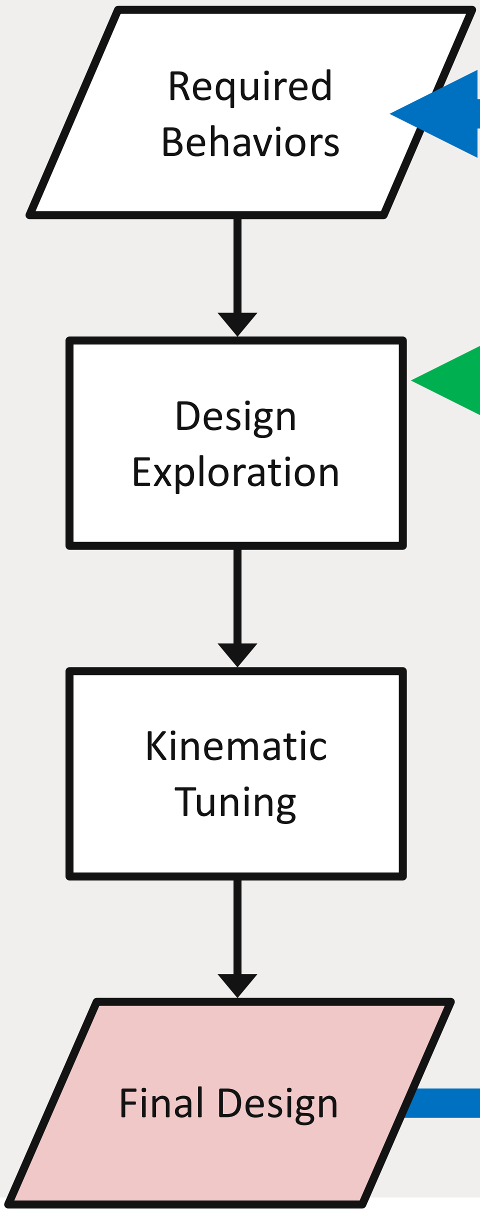
# Final Design




M. M. Plecnik, D. W. Haldane, J. K. Yim and R. S. Fearing, 2016. "Design Exploration and Kinematic Tuning of a Power Modulating Jumping Monopod," *Journal of Mechanisms and Robotics*, 9(1):011009.

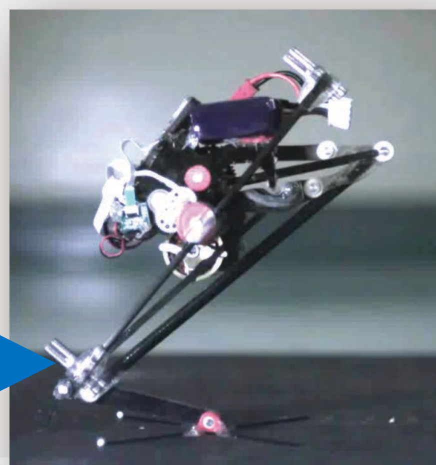
# Design Approach

## Key Design Phase




Key design phase

- Pre-existing designs not used for optimization starting points
- Does not depend on geometric intuition or “mechanical genius”
- Challenged by the curse of dimensionality



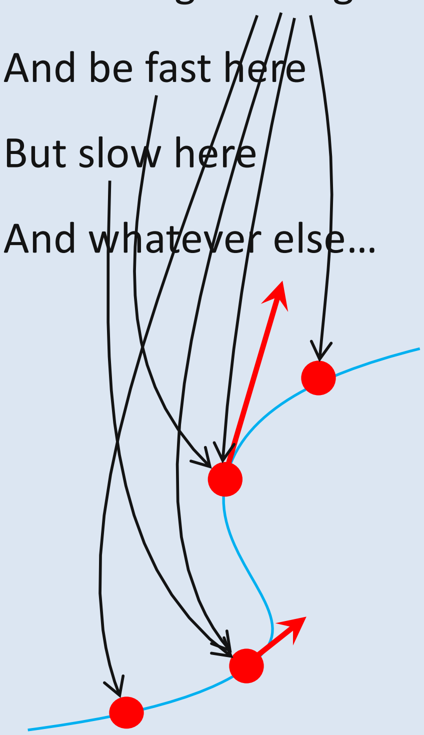
# Design Exploration

Solving Massive Polynomial Systems

## 1. Motion requirements

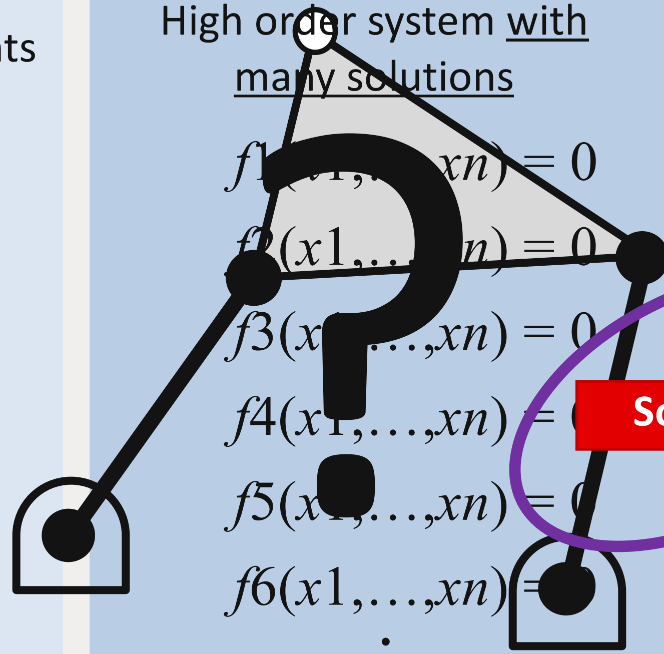
Example

- It should go through these points
- And be fast here
- But slow here
- And whatever else…



## 2. Polynomial system

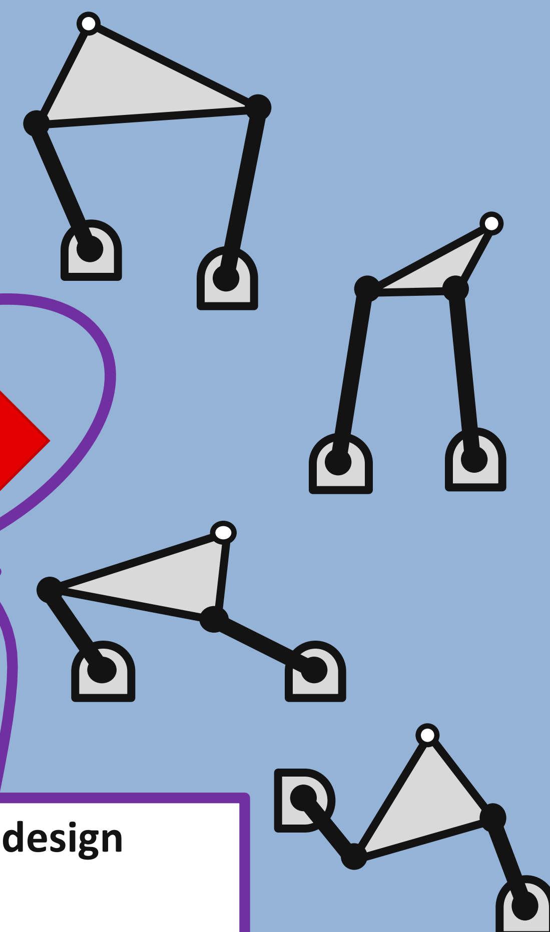
High order system with <u>many solutions</u>



$$f1(x1,\ldots,xn) = 0$$
$$f2(x1,\ldots,xn) = 0$$
$$f3(x1,\ldots,xn) = 0$$
$$f4(x1,\ldots,xn) = 0$$
$$f5(x1,\ldots,xn) = 0$$
$$f6(x1,\ldots,xn) = 0$$
$$\vdots$$
$$fn(x1,\ldots,xn) = 0$$

Solve

## 3. Polynomial solutions



**Key process of design exploration:**
Polynomial homotopy continuation