Feedback Control of Bipedal Locomotion

University of Michigan

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Acknowledgements

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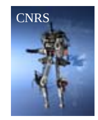


RABBIT
ROBEA Project
France

Videos and Papers

- http://www.youtube.com/user/DynamicLegLocomotion
- http://web.eecs.umich.edu/~grizzle/papers/robotics.html

2011 RAS Pioneer Award to Mark Spong

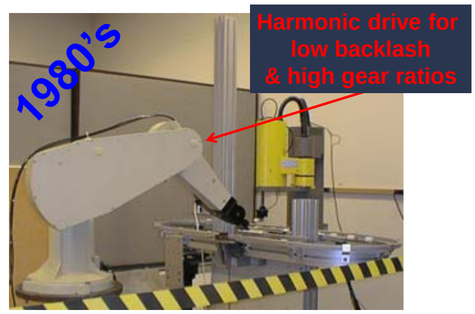
To recognize individuals who, by virtue of initiating new areas of research, […] have had a significant impact on development of the robotics and/or automation fields.

- **Joint elasticity in robot manipulators**
- **Bilateral teleoperation**
- **Normal forms for underactuated mechanical systems**
- **Bipedal locomotion (Passivity and energy shaping, controlled symmetries)**

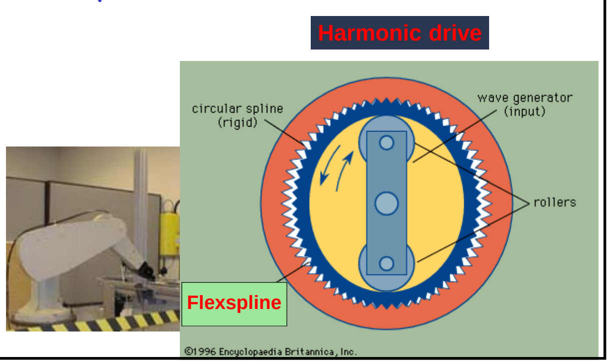
Outline

- Springs in Robots
  - Mark's problem and approach
  - Jessy's problem
    - approach 1
    - approach 2
    - application to MABEL
- Introduction of the ATRIAS Series of Robots and MARLO (time permitting)

Manipulators: Designed to be Rigid

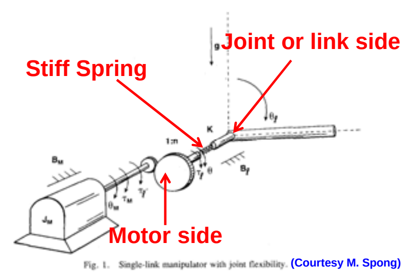


Manipulators with Flexible Joints



Manipulators with Flexible Joints

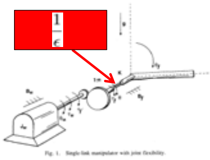
- Poor tracking?
- Vibrations in closed loop?



Manipulators with Flexible Joints

$$
\begin{aligned}
D(q_1)\ddot{q}_1 + C(q_1,\dot{q}_1)\dot{q}_1 + G(q_1) + \underline{K(q_1 - q_2)} &= 0 \\
J\ddot{q}_2 - \underline{K(q_1 - q_2)} - u &= 0.
\end{aligned}
$$

$\frac{1}{\epsilon}$

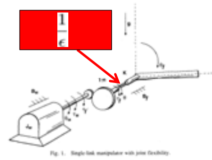


$$K = \frac{1}{\epsilon} I_{n\times n}$$

$$\boxed{z = \frac{1}{\epsilon}(q_1 - q_2)}$$

Manipulators with Flexible Joints

$\frac{1}{\epsilon}$



$$
\begin{aligned}
\ddot{q}_1 &= -A(q_1)z - H(q_1,\dot{q}_1) \\
\epsilon\ddot{z} &= -(A(q_1)z + B)\,z - H(q_1,\dot{q}_1) - Bu.
\end{aligned}
$$

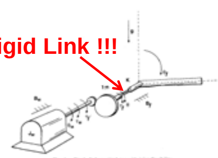
Composite Control

$$\boxed{u = u_s(q_1,\dot{q}_1) + u_f(z,\dot{z})}$$

"Rigid Model" **"Corrective Term"**

Manipulators with Flexible Joints

Rigid Link !!!



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\begin{aligned}
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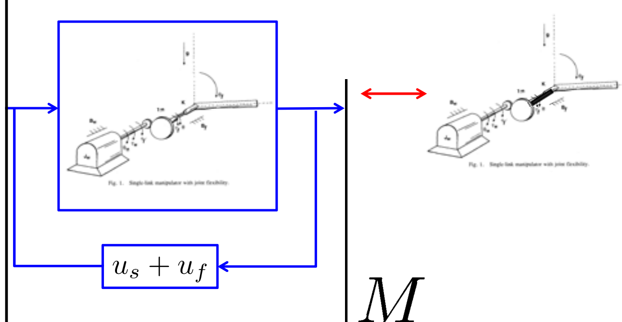
Manipulators with Flexible Joints

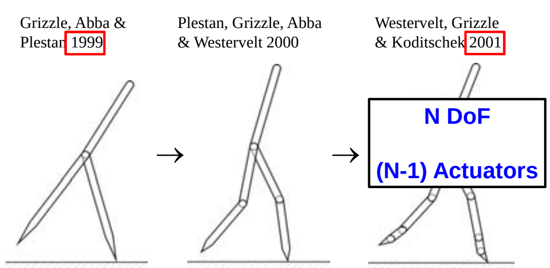


Key Papers

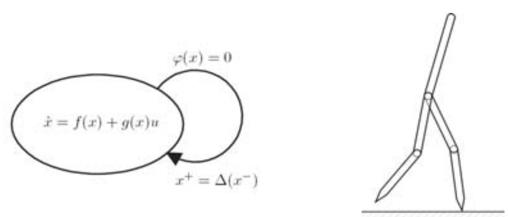
- Spong, Khorasani, Kokotovic, "A Slow Manifold Approach to Feedback Control of Nonlinear Flexible Systems," *ACC*,1985
- **(718 citations)** MW Spong, "Modeling and control of elastic joint robots," *Journal of Dynamic Systems, Measurement, and Control*, 1987. **Implemented worldwide**
- Spong, Khorasani, Kokotovic, "An integral manifold approach to the feedback control of flexible joint robots," *IEEE Trans. Rob. and Automation*, 1987 ,

Bipedal Robots and Springs

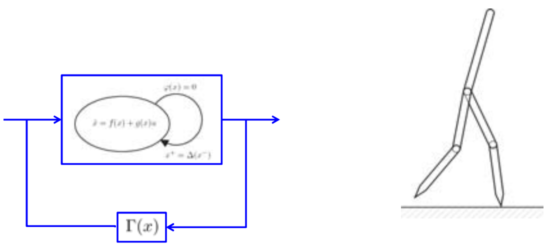
Natural Progression



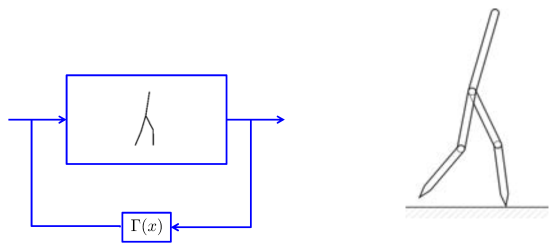
Geometric Control



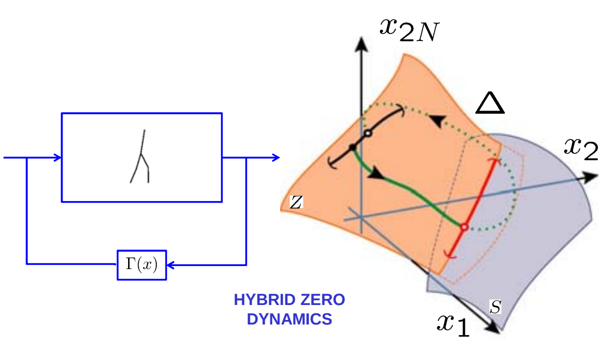
Geometric Control



Geometric Control

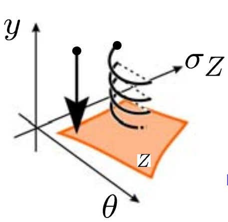


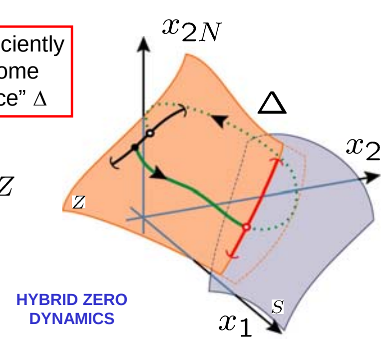
Geometric Control



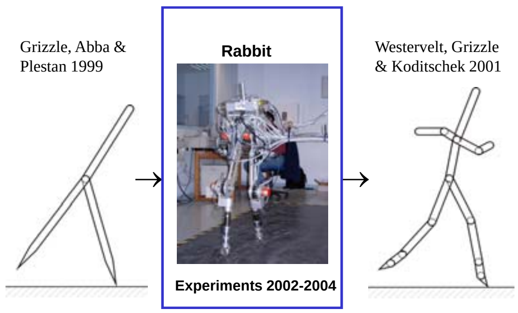
Geometric Control

Render surface sufficiently attractive to overcome impulse "disturbance" Δ





Natural Progression



Natural Progression

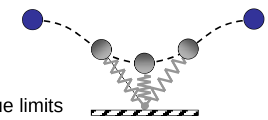
- Successful walking experiments
  - Model → controller design → simulation → experiment, with minimal trial and error.
  - Various speeds
  - Gait transitions (continuous & discrete)
  - Robustness to unknown loads
  - Robustness to shoves

2004 with Rabbit

7 Years of hard labor later …

7 Years of Work to Get Here

Why Did Rabbit Not Run Well?



- ***Actuator saturation***
  - Workspace limitations
  - Lossy powertrain
  - Nominal gait at 95% of torque limits
- **Motors were asked to emulate a compliant (spring-like), high-bandwidth restoring force**
  - Negative work
  - Bandwidth issues at impact
  - Ground reaction forces

Teamed up with CMU to Build a Robot with Compliance

Springs

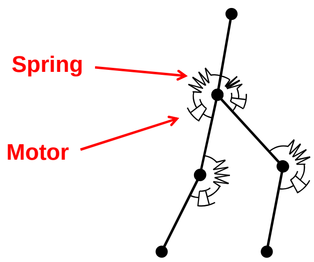
Torsional Compliance

Planning started in late 2004

Michigan-CMU Robot

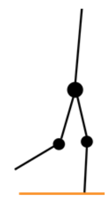
Springs, Take 1

Started Analyzing Models + Series Elastic Actuators



Nominal Robot Without Compliance

N DoF
&
(N-1) Actuators

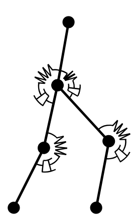


$$q = \begin{bmatrix} q_a \\ \theta \end{bmatrix} = \begin{cases} \text{actuated} \\ \text{body} \end{cases}$$

$$D(q_a)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = Bu,$$

Robot + SEA

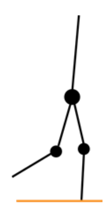
(2N-1) DoF
&
(N-1) Actuators



Highly Underactuated

$$\begin{aligned} D(q_a)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) - \underline{BK(q_m - q_a)} &= 0 \\ \underline{J\ddot{q}_m + K(q_m - q_a)} &= u_c. \end{aligned}$$

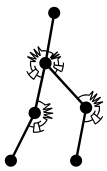
Robot Without SEA



Feedback Equivalent (Spong, 1994)

$$\begin{aligned} \dot{\sigma} &= -\frac{\partial V}{\partial \theta}(q) \\ \dot{\theta} &= \frac{\sigma}{d_{NN}(q_a)} + R(q_a)\dot{q}_a \\ \underline{\ddot{q}_a} &\underline{= w,} \end{aligned}$$

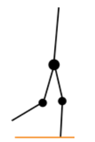
Robot + SEA



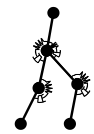
Feedback Equivalent **(Isidori + Spong)**

$$
\begin{aligned}
\dot{\sigma} &= -\frac{\partial V}{\partial \theta}(q) \\
\dot{\theta} &= \frac{\sigma}{d_{NN}(q_a)} + R(q_a)\dot{q}_a \\
q_a^{(4)} &= w
\end{aligned}
$$

Consequences



$\boxed{y = h(q_a, \theta)}$

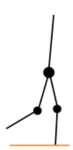


Vector Rel. Degree 2 $\Leftrightarrow$ **Vector Rel. Degree 4**

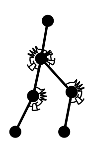
Identical Zero Dynamics

(Morris + JG TAC 2009)

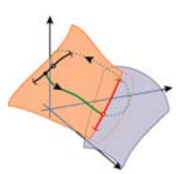
Consequences



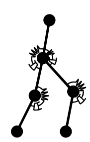
$\boxed{y = h(q_a, \theta)}$



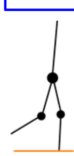
Learned how to create invariant manifolds in hybrid models with many degrees of underactuation (TAC 2009)



Consequences

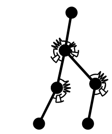


$\boxed{y = h(q_a, \theta)}$

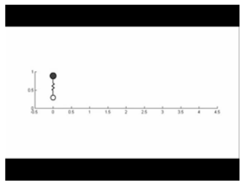


Design periodic orbit taking advantage of springs

Consequences



$$\boxed{y = h(q_a, \theta)}$$



Stability analysis
for a 1 DOF hybrid model

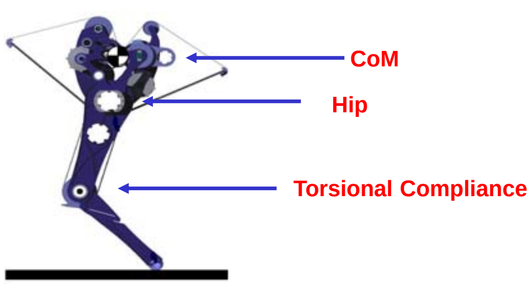
(TAC 2009)

Springs, Take 2

Ioannis Poulakakis

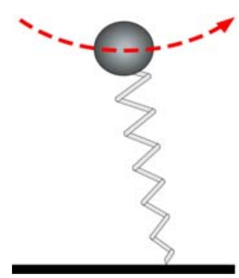
TAC 2009
IROS 2007, ICRA 2008

Modeling Hierarchy



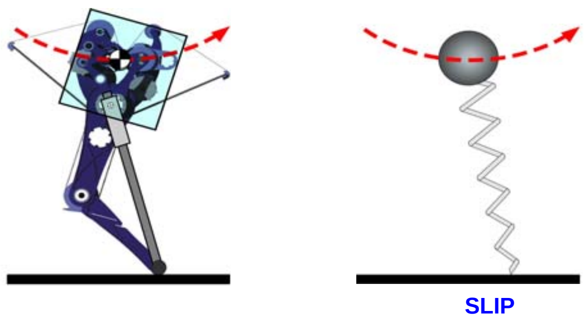
Michigan-CMU Robot

Modeling Hierarchy

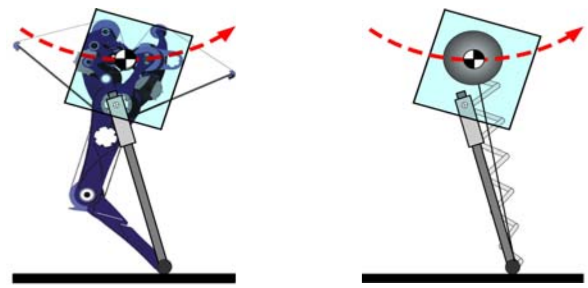


SLIP=Spring Loaded Inverted Pendulum

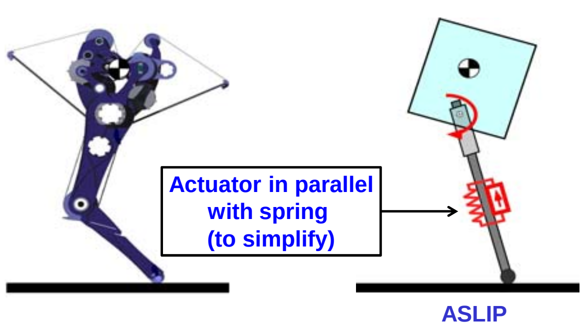
Modeling Hierarchy



Modeling Hierarchy



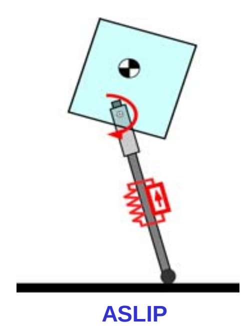
Modeling Hierarchy



Modeling Hierarchy

3 DoF

2 Actuators



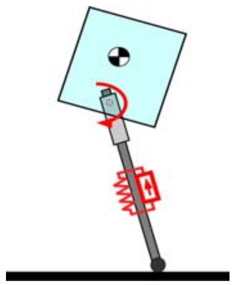
Modeling Hierarchy

Key Differences with Literature

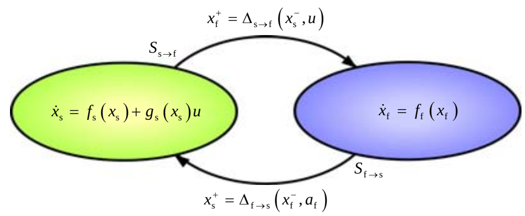
Massive Torso

Hip offset from CoM

Could not be handled by Raibert, Koditschek, Beuhler, Francois, Samson …



ASLIP Hybrid Dynamics: Stance + Flight



Formal Embedding of the SLIP into an ASLIP Model

Theorem [IROS'07, **TAC 2009**] There exist:

1. A continuous feedback controller Γ_c active in the stance of the ASLIP, and an invariant surface Z (embedded) in the stance state space, such that
   - $f_s(x_s) + g_s(x_s)\Gamma_c(x_s)\big|_Z$ = SLIP stance phase model
   - Z is exponentially attractive
2. A discrete feedback controller Γ_f active in transitions from flight to stance, such that
   - $\Delta\left(x_s^-, \Gamma_c(x_s^-), \Gamma_f(x_s^-)\right)\big|_Z$ = SLIP reset map
   - $S_{s\to f} \cap Z$ is hybrid invariant

Formal Embedding of the SLIP into an ASLIP Model

Moreover,

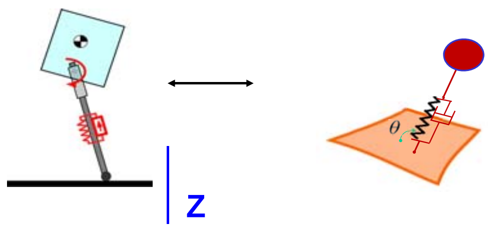
If a controller is designed to render a particular orbit of the SLIP exponentially stable the same controller will create an exponentially stable orbit in the ASLIP closed-loop system!

Controller results available for the SLIP can be directly used in the ASLIP!

Caveat: Embedding is local due to unilateral constraints

Theorem in a Picture

There exists a hybrid zero dynamics such that



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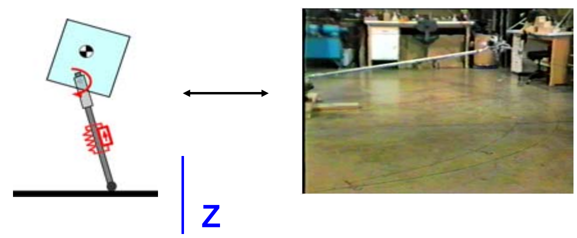


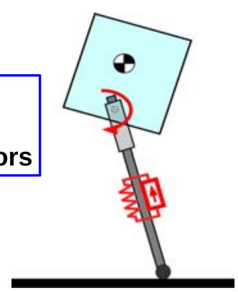
ASLIP

Can be controlled via two approaches:

- 1 DOF HZD
- 2 DOF HZD

3 DoF

2 Actuators

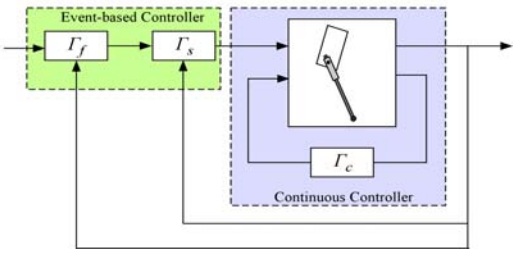


ASLIP

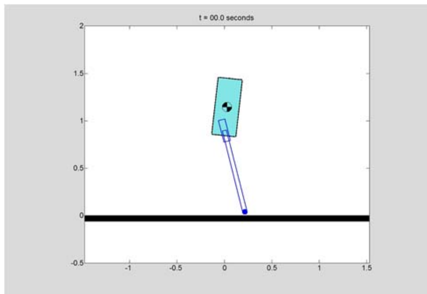
Comparison of the Two Control Approaches

Identical Hybrid Controller Structure

- The SLIP embedding and the 1-DOF rigid HZD controller have the same structure, same stability proofs, though different objectives.

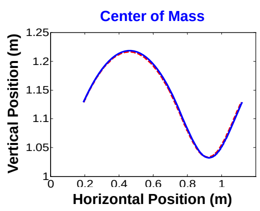


Identical Periodic Orbit



Comparison: **Steady State**

- **1-DOF HZD controller**
- **SLIP embedding controller**
- **Same leg actuator force on the nominal orbit.** **(<0.5% difference)**

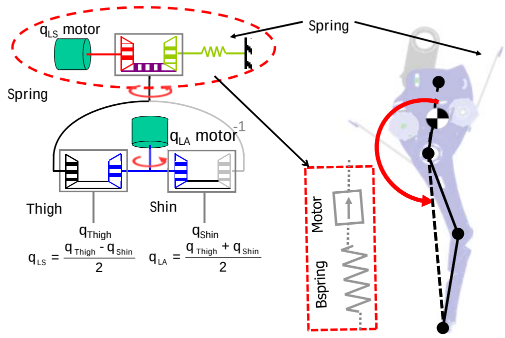


Comparison: **Transients**

Perturbation	Control	Stride	$(u_1^a, u_2)^{max}$	$(W_1, W_2)^{total}$
$\delta\theta = +3^o$	1 DOF	4	$(447,15)$	$(60,18)$
	SLIP	3	$(36,16)$	$(18,18)$
$\delta\theta = -4^o$	1 DOF	13	$(493,13)$	$\boxed{(125,53)}$
	SLIP	4	$(69,16)$	$\boxed{(21,20)}$
$\delta \dot{x}_c = +0.9\, m/s$	1 DOF	12	$(448,21)$	$(241,76)$
	SLIP	6	$(418,16)$	$(110,40)$
$\delta \dot{x}_c = -0.4\, m/s^2$	1 DOF	3	$(73,13)$	$(40,10)$
	SLIP	3	$(53,23)$	$(29,13)$

Compliant HZD➔ **Larger Domain of Attraction, Less Work by Actuator**

MABEL - Actuation



Long Path to Running on MABEL

- ***Series Elastic Actuation***
- ***Mass in Legs***
- ***Cable Stretch***
- ***Springs too Stiff***
- ***Rotor Inertias +***
  +Torque Limits, …

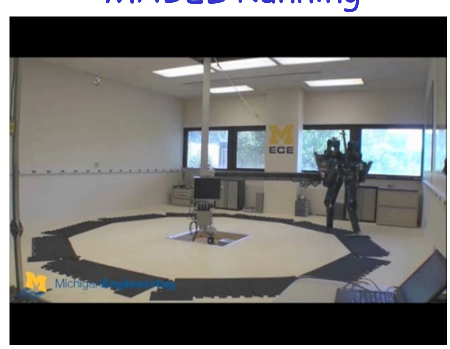
Koushil Sreenath

Long Path to Running on MABEL

Koushil Sreenath, Hae-Won Park, Ioannis Poulakakis, and Jessy W. Grizzle, A Compliant Hybrid Zero Dynamics Controller for Stable, Efficient and Fast Bipedal Walking on MABEL, Int. J. Robotics Research (IJRR), 30(9):1170-1193, August 2011.

Koushil Sreenath, Hae-Won Park, and Jessy W. Grizzle, Embedding Active Force Control within the Compliant Hybrid Zero Dynamics to Achieve Stable, Fast Running on MABEL, *in review.*

MABEL Running



ATRIAS Robots & MARLO

The End