THE UNIVERSITY OF TEXAS AT AUSTIN

Human Centered Robotics

Design and Control Considerations for High-Performance Series Elastic Actuators

Actuators Workshop IROS 2014

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Some observations

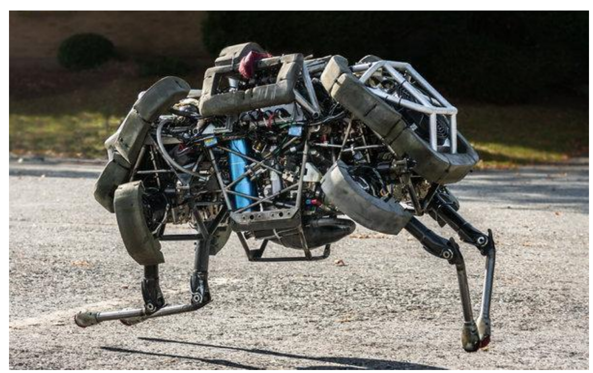
- **Performance** – Nature outperforms man-made machines (locomoting, dynamic maneuvers, catching, efficiency)
- **Versatility** – A single animal can (usually) outperform the each of the most specialized man-made machines

Fundamental improvements are needed in the physical ability of robots

In this talk…

1) We seek to improve performance of robotic actuators for legged robot applications
2) Establish a common metric which may be used to compare to other work

A few performance metrics

Metric	Torque/Weight	Power/weight	Efficiency
Optimized human	 Arnold	 Usain Bolt	 Wilson Kipsang
Optimized robot	 NASA-JPL ATHELETE	 Boston Dynamics Wildcat	 Cornell Ranger

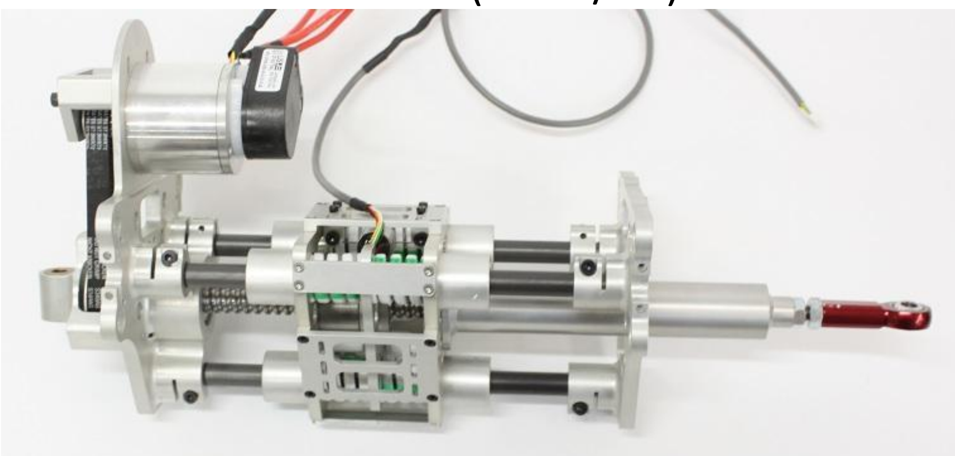
High-performance electric SEA design

Prismatic series elastic actuators

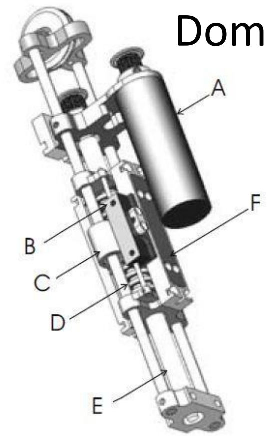
Ballscrews excel in **power output** and **efficiency**

A **ballscrew** speed reduction and **series elasticity** combine together to define a class of prismatic series elastic actuators

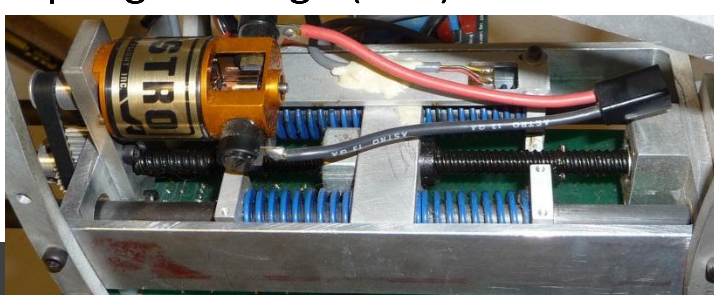
Hume (Meka/UT) SEA

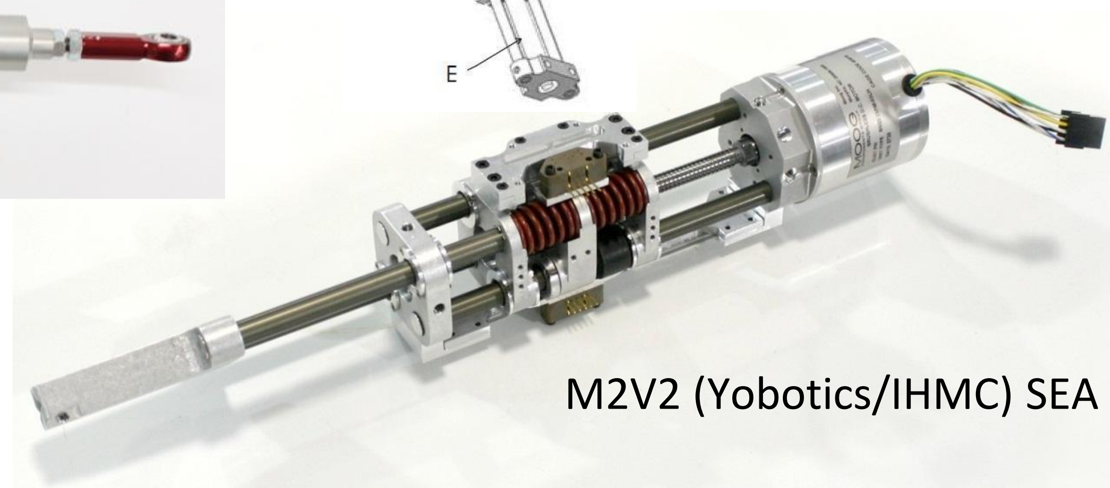


Domo (MIT) SEA



Spring Flamingo (MIT) SEA

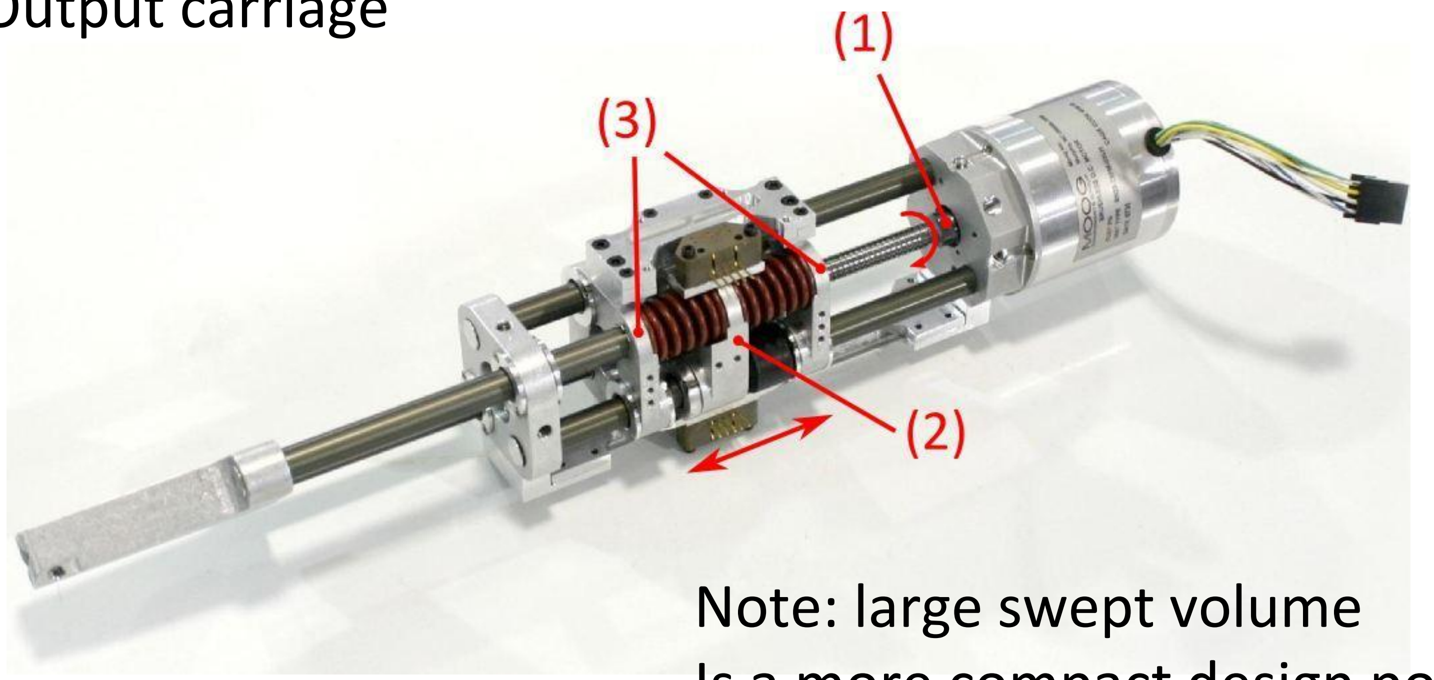




M2V2 (Yobotics/IHMC) SEA

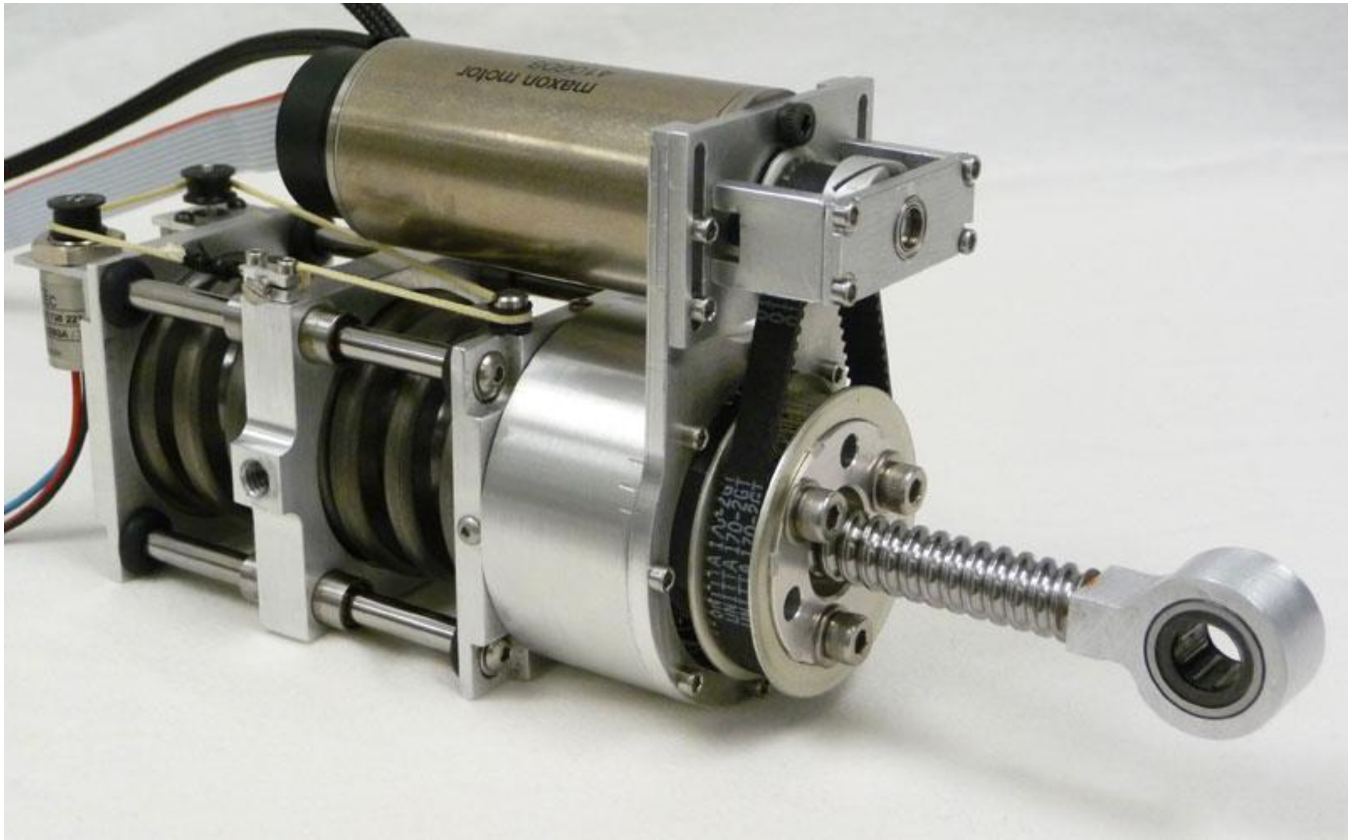
Basics of operation for previous SEAs

(1) Ball screw rotation
(2) Ball nut translation
(3) Output carriage



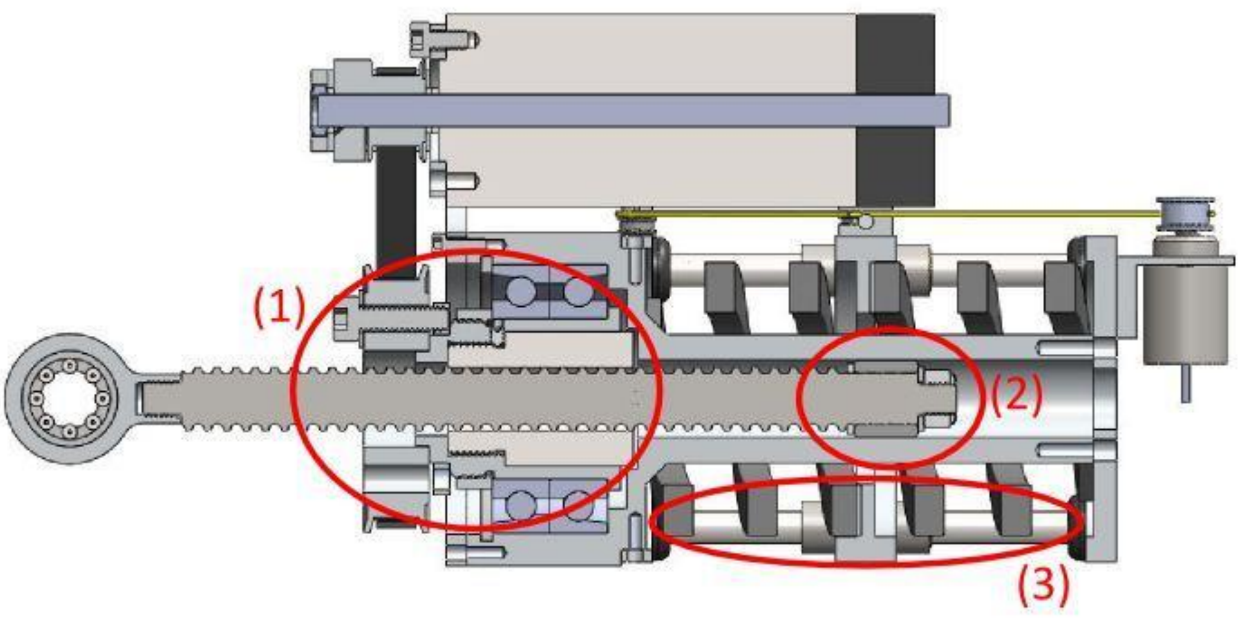
Note: large swept volume
Is a more compact design possible?

Our design: the UT-SEA



Unique features

Our actuator differs from other prismatic SEAs by: (1) driving the ball nut, (2) piston style ball screw support, (3) springs concentric with drive shaft.

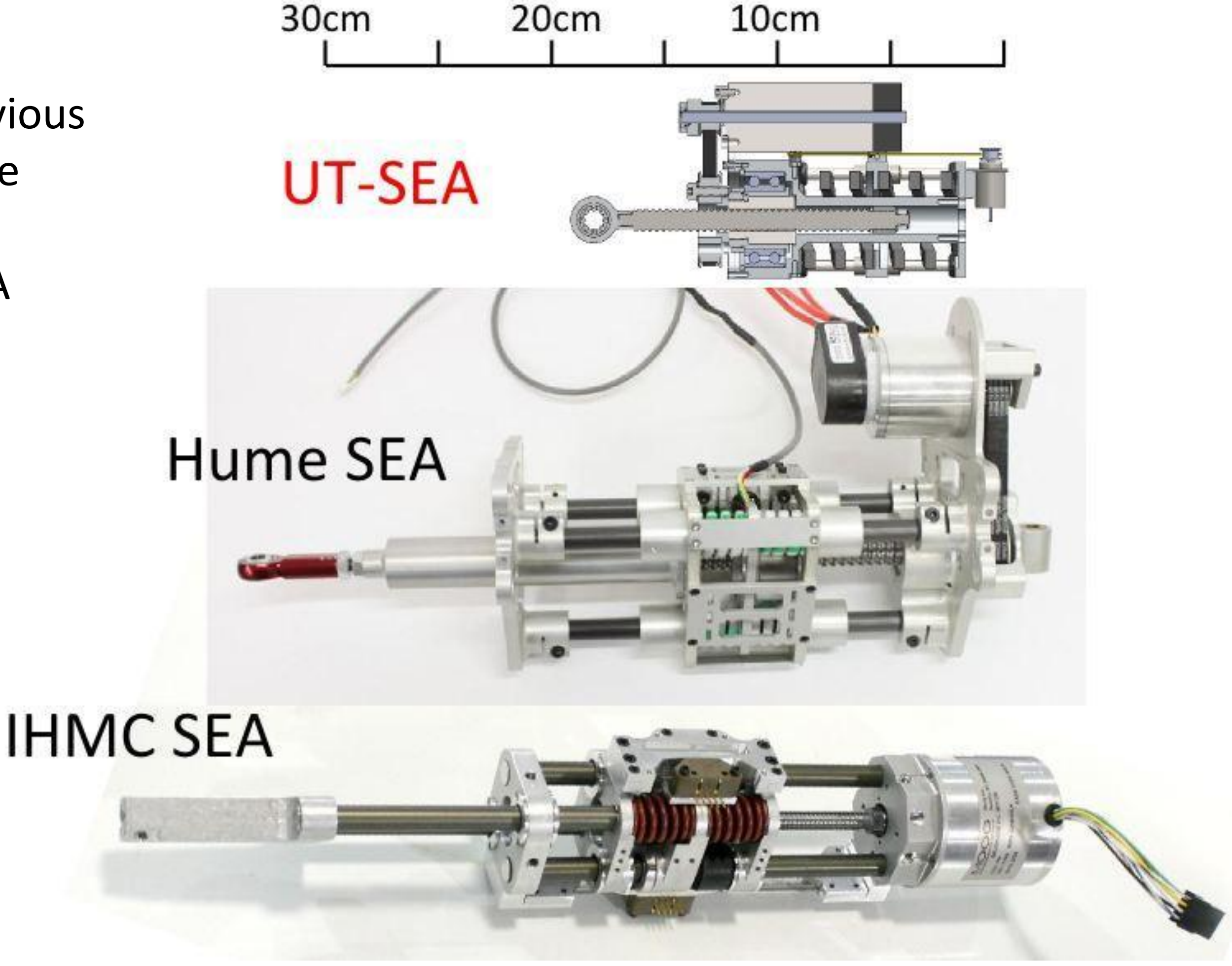


N. PAINE, S. Oh and L. Sentis. "Design and Control Considerations for High-Performance Series Elastic Actuators," *Mechatronics, IEEE/ASME Transactions on*, vol.19, no.3, pp.1080,1091, June 2014.

To-scale comparison

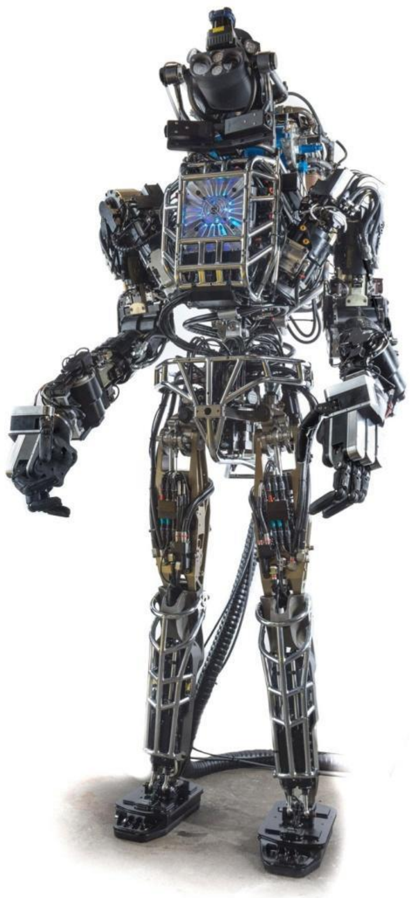
Significantly smaller than previous designs of similar performance

2.2X less mass than Hume SEA



Importance of small actuator size

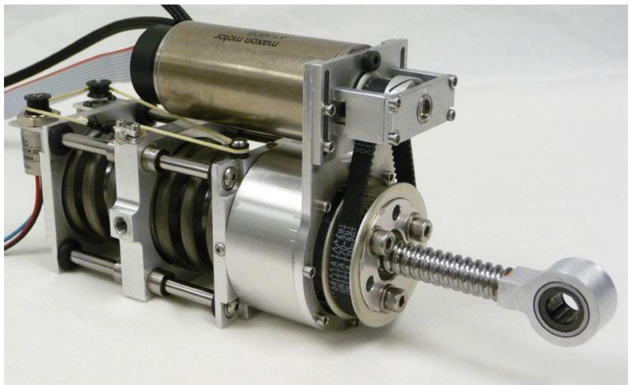
a) Atlas robot
28 hydraulic actuators



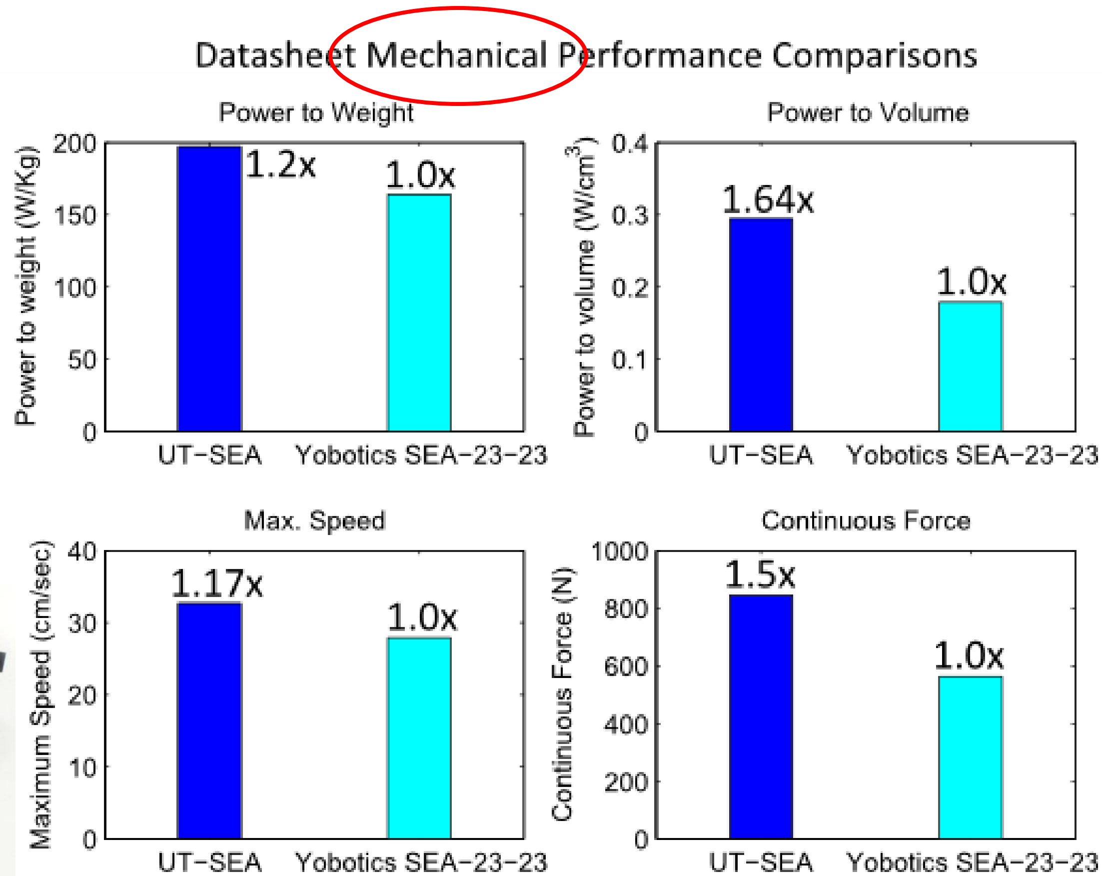
b) Valkyrie robot
25 SEAs

Datasheet performance comparison

UT-SEA



Yobotics SEA-23-23



Knowing mechanical capability alone is not good enough

Limits of datasheet performance

Knowing mechanical performance alone is not good enough

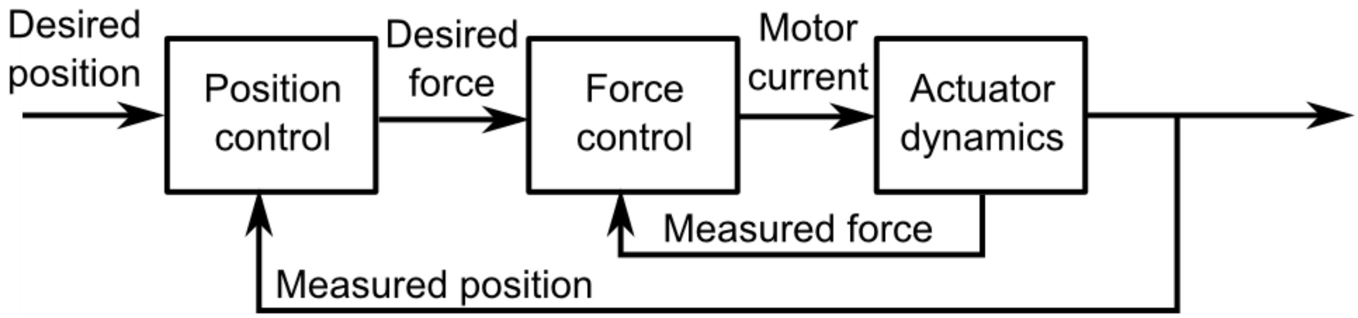
1) It depends on motor manufacturer's "rated values", which are non-standardized metrics
2) It does not take into account other system limitations, most notably due to control issues

- Empirical (measured) performance is a more useful metric

High-performance SEA control

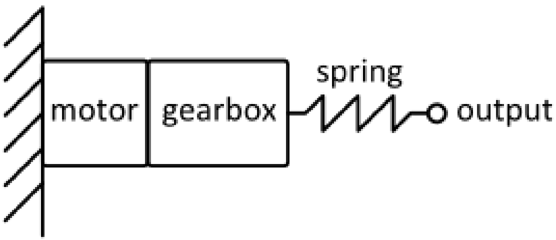
Taking control into account – our control approach

- Inner force control loop
  - PD force feedback (shaped to be critically damped)
  - Disturbance observer to improve tracking accuracy and disturbance rejection
- Outer position control loop
  - Inverse dynamics based (assumes a model of the load is known)
  - Feedback achieved through a disturbance observer

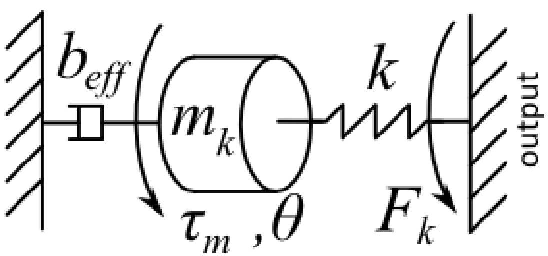


SEA force control

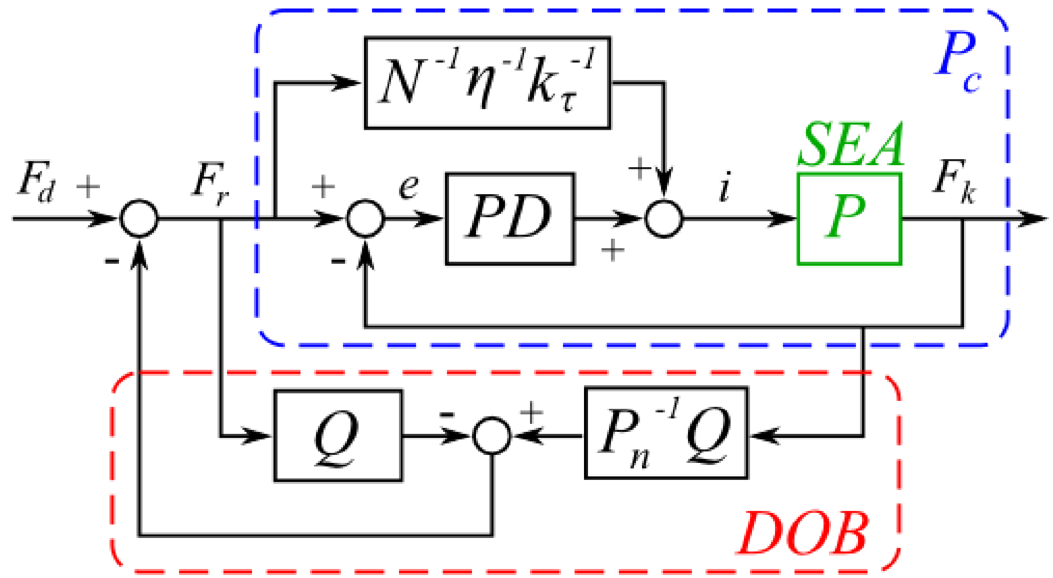
a) Series Elastic Actuator (SEA)



b) Locked output SEA model (plant)



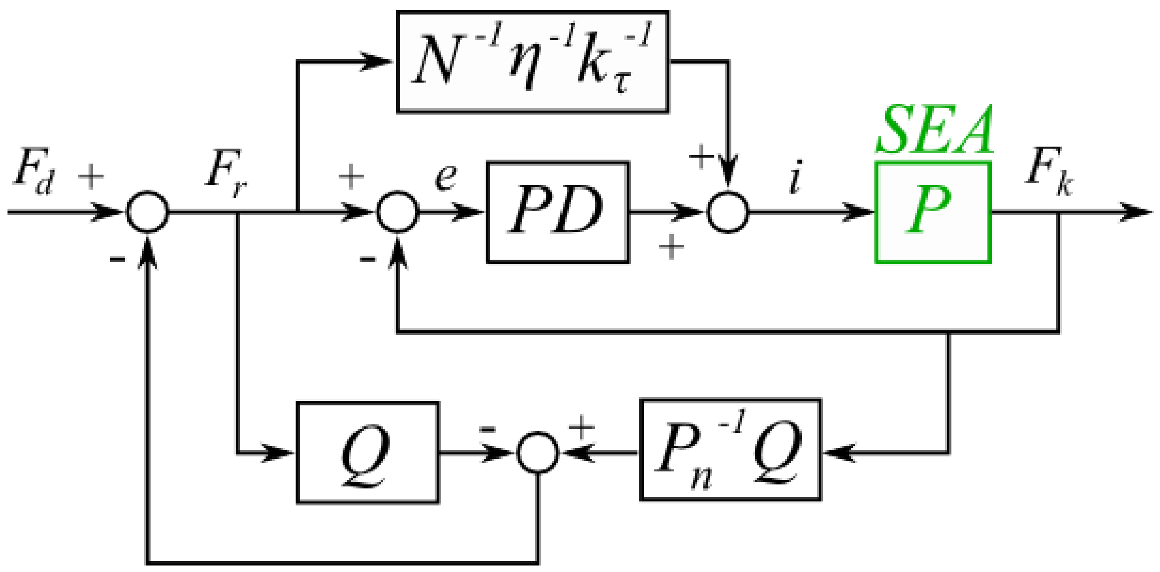
c) Torque control diagram



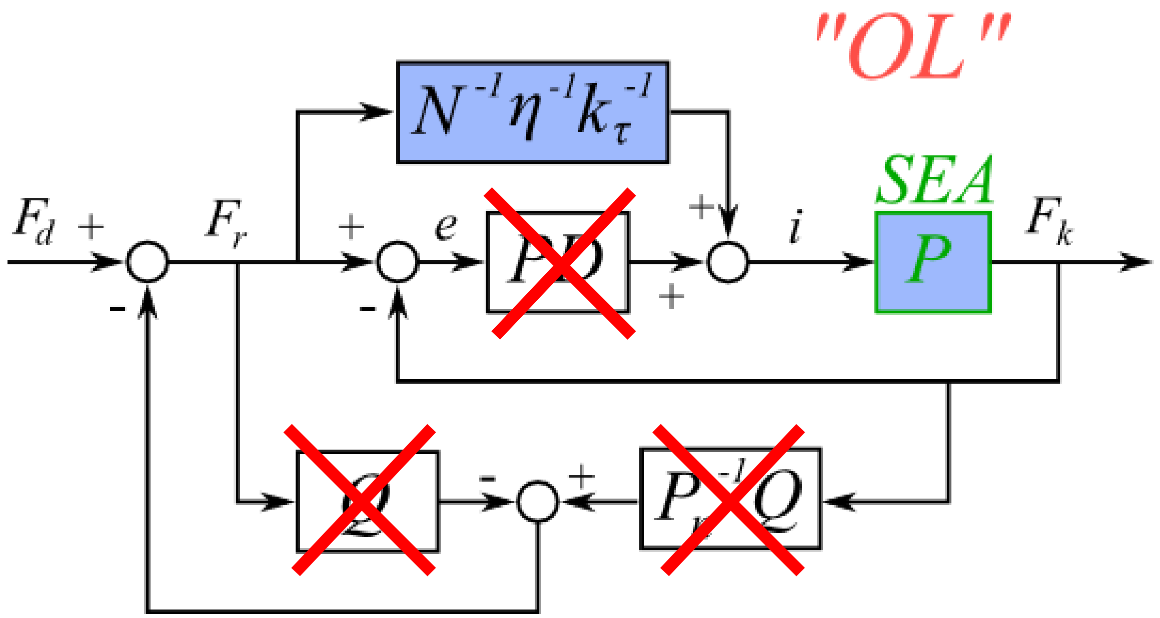
Closed-loop transfer function:

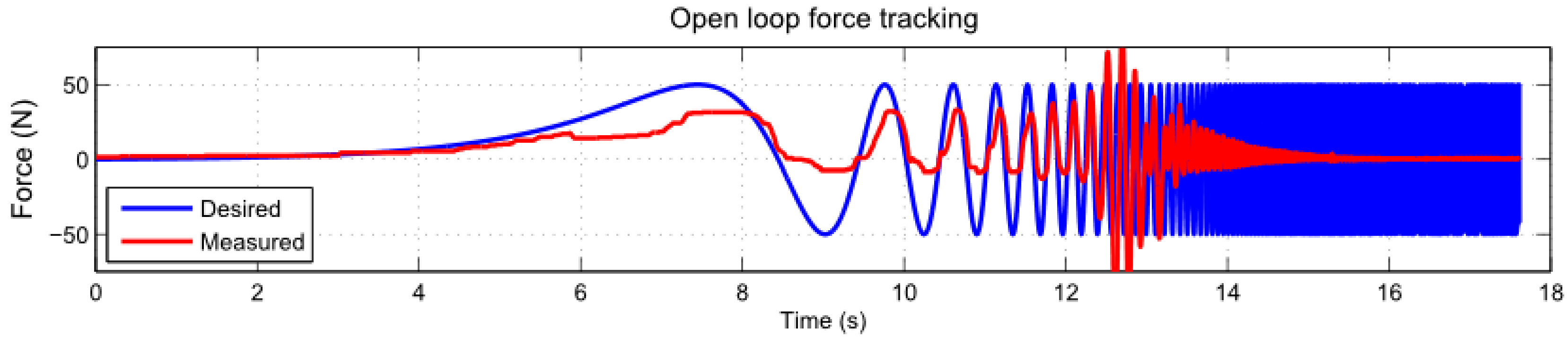
$$P_c(s) = \frac{F_k(s)}{F_r(s)} = \frac{(k\beta k_d)s + k(1+\beta k_p)}{m_k s^2 + (b_{eff} + k\beta k_d)s + k(1+\beta k_p)}$$

Force control performance

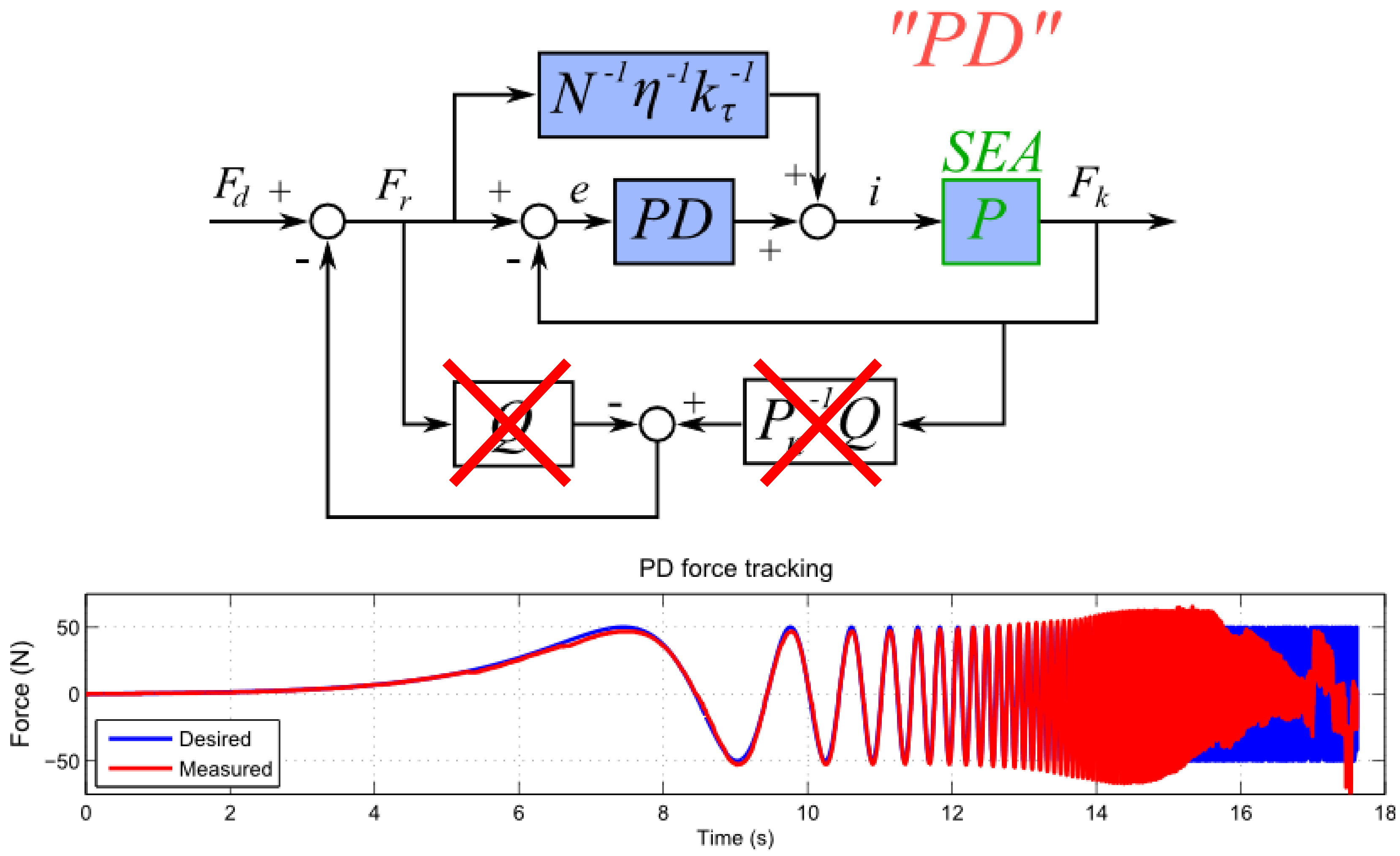


“Open loop” force control

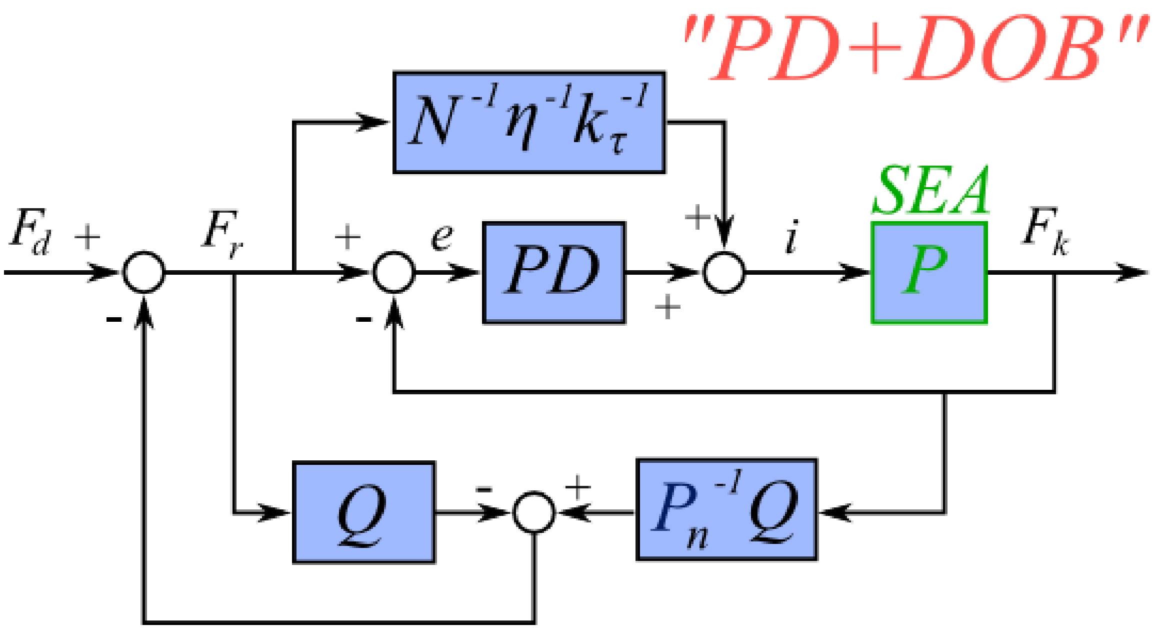


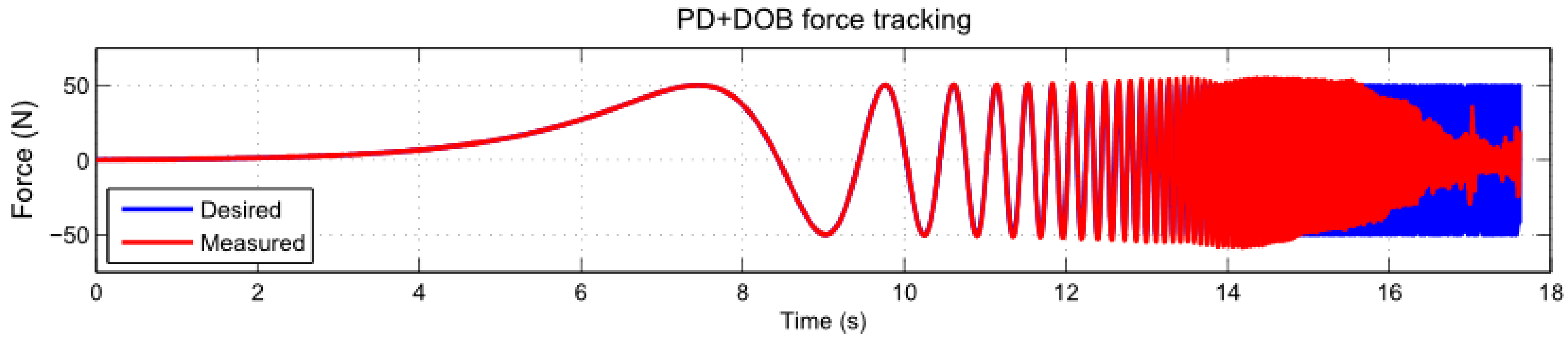


Adding the PD compensator

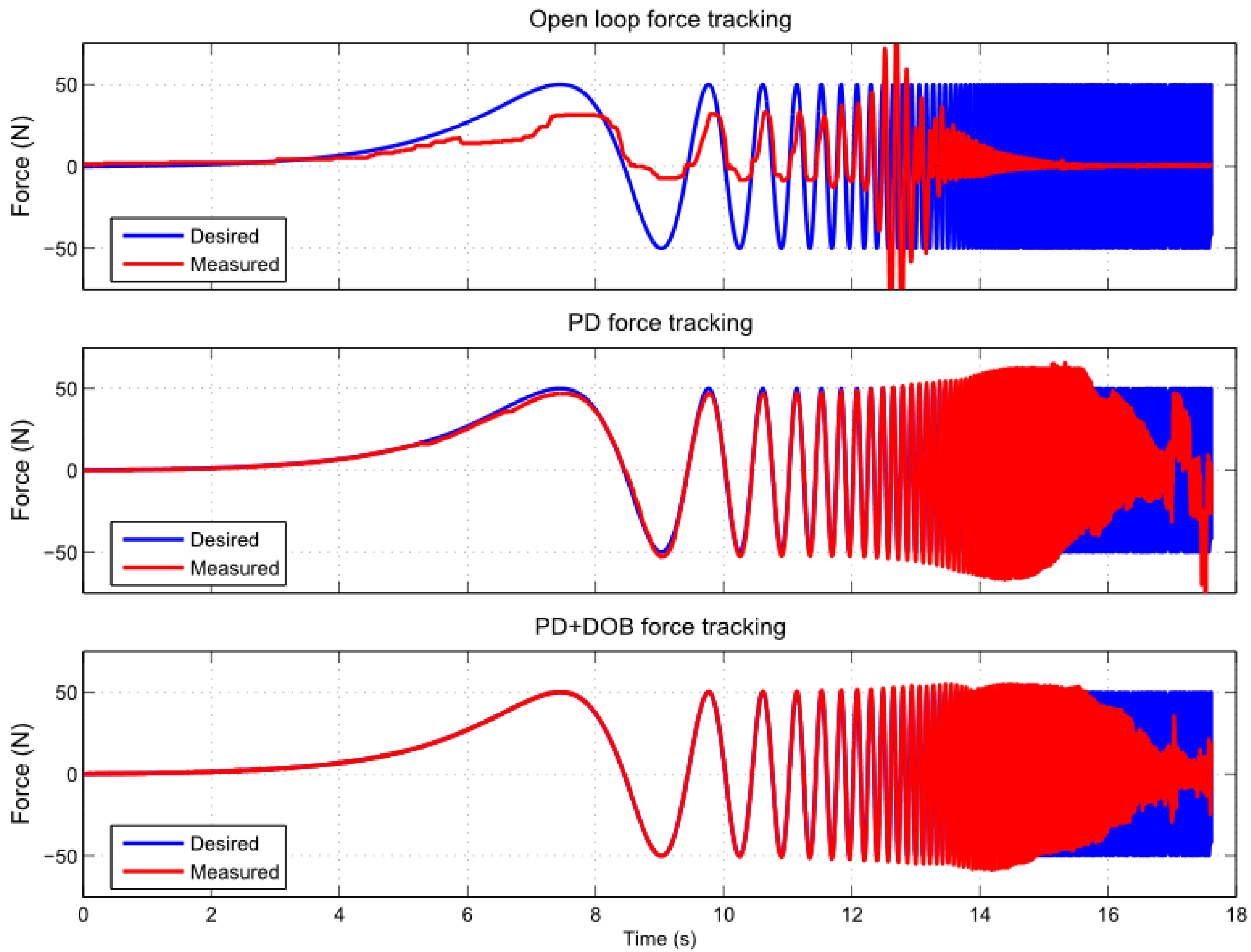


Adding the DOB (full controller)

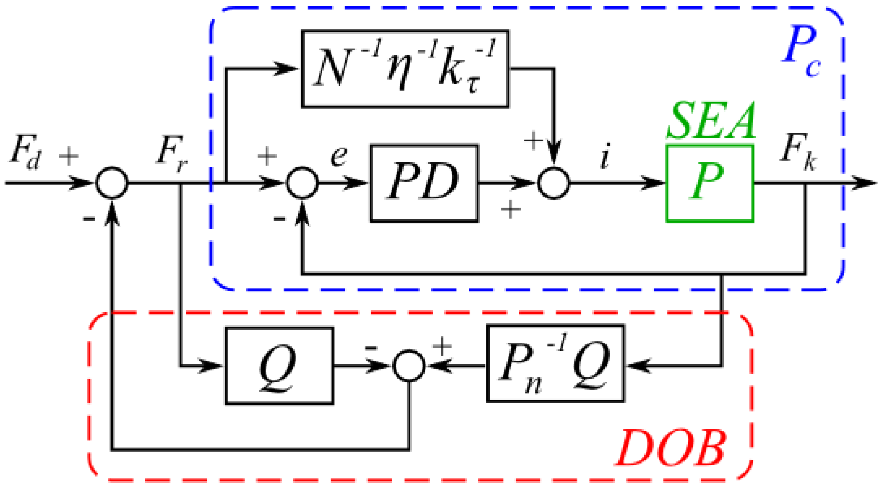




Force tracking comparison

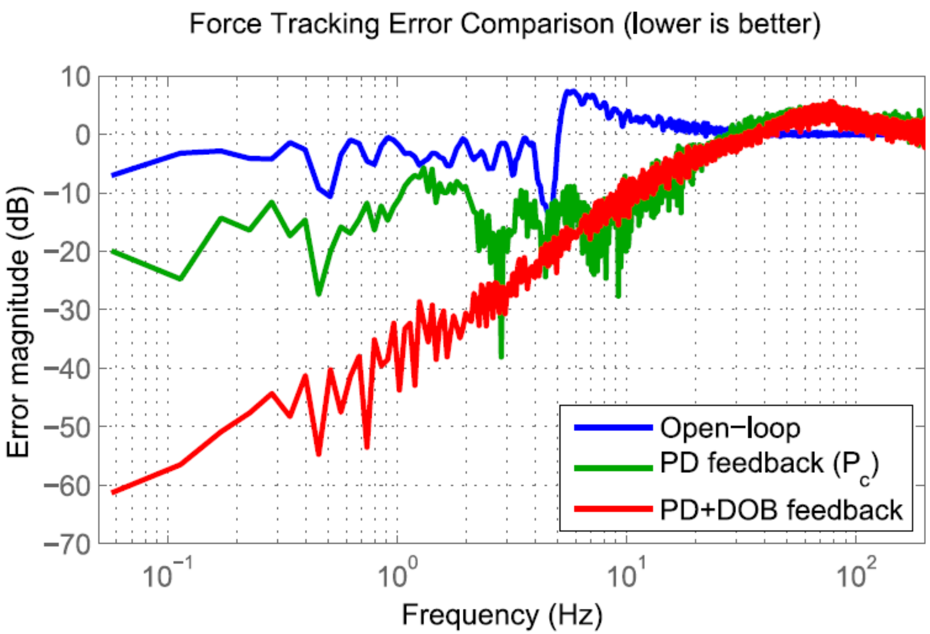


Tracking Error Comparison



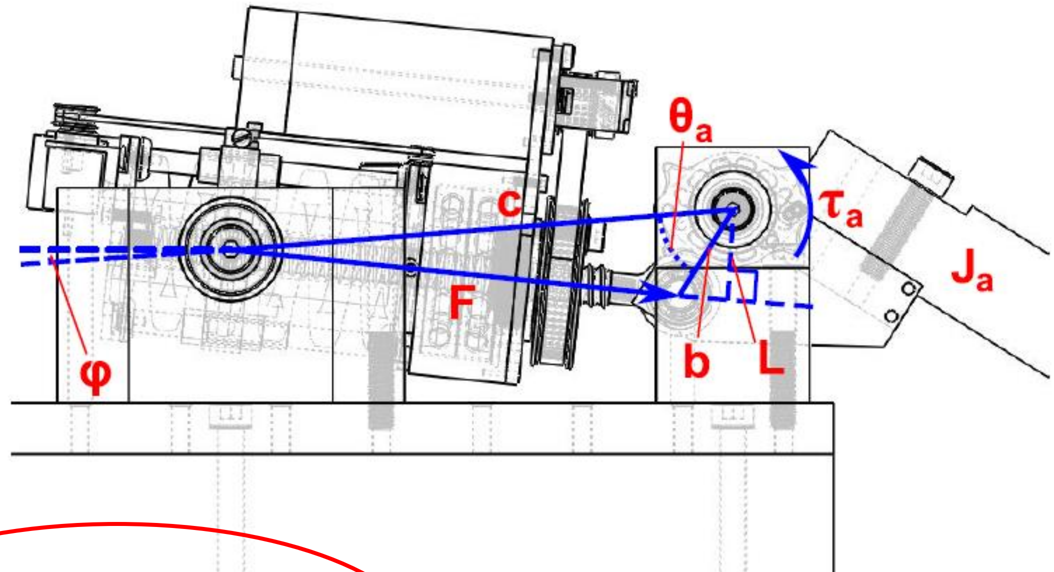
Parameter	Value	Units
k_p	0.05	A/N
f_{kd}	100	Hz
ζ_d	0.9	n/a
f_q	40	Hz
β	219	N/A
m_k	360	kg
b_{eff}	2200	Ns/m
k	350000	N/m

Ferr/Fdes



N. PAINE, J. Mehling, J. Holley, N. Radford, G. Johnson, C. Fok, and L. Sentis. "Actuator Control for the NASA-JSC Valkyrie Humanoid Robot: A Decoupled Dynamics Approach for Torque Control of Series Elastic Robots," *Journal of Field Robotics*, 2014, **Under revision**.

Position control -> inverse dynamics



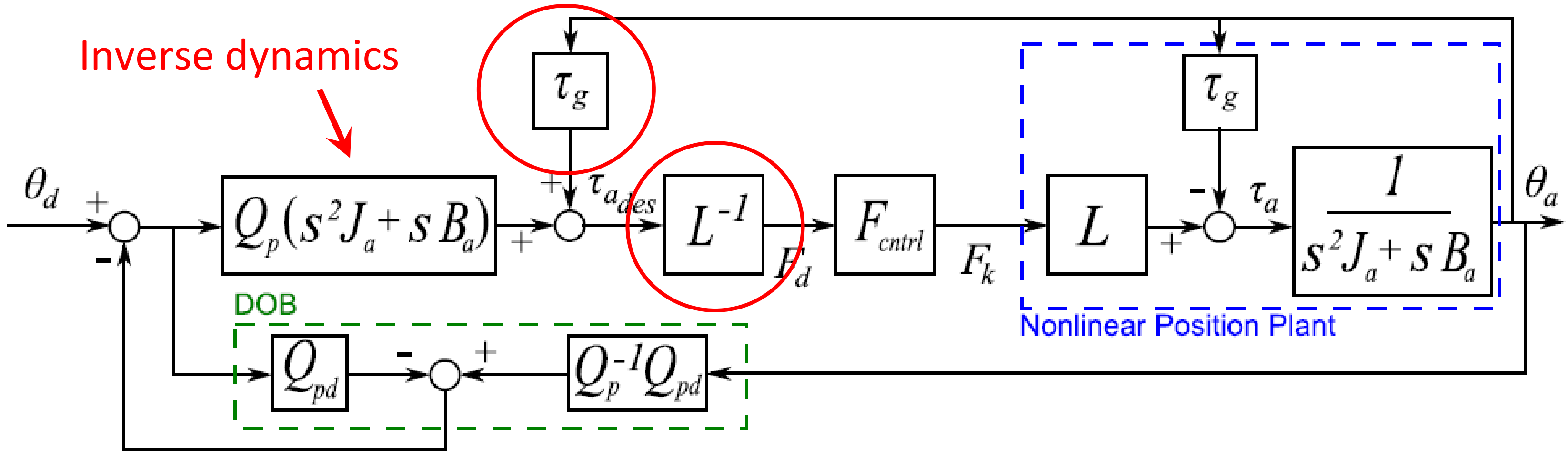
"L"

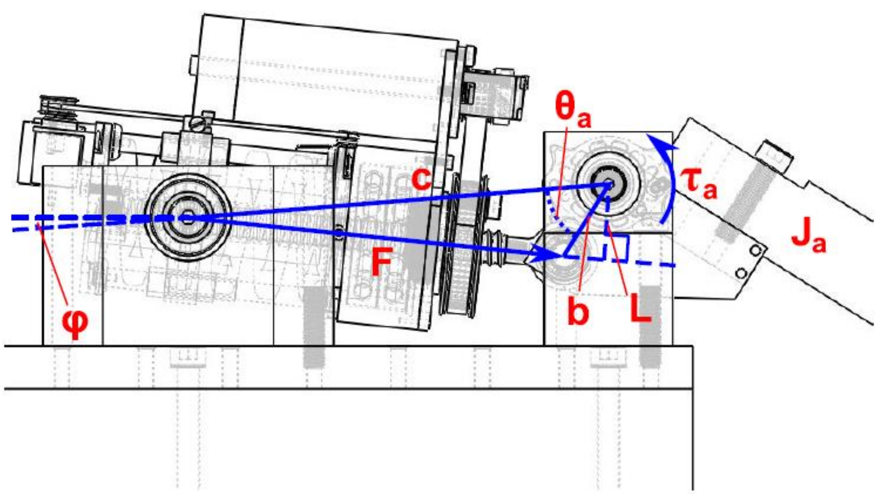
"τ_g"

$$F = \frac{\sqrt{b^2 + c^2 - 2bc\cos\theta_a}}{cb\sin\theta_a}\left[J_a\ddot{\theta}_a + B_a\dot{\theta}_a - m_a g l_m \cos\left(\theta_a + \phi\right)\right]$$

Solve for F given θ_a

Our high performance position control approach



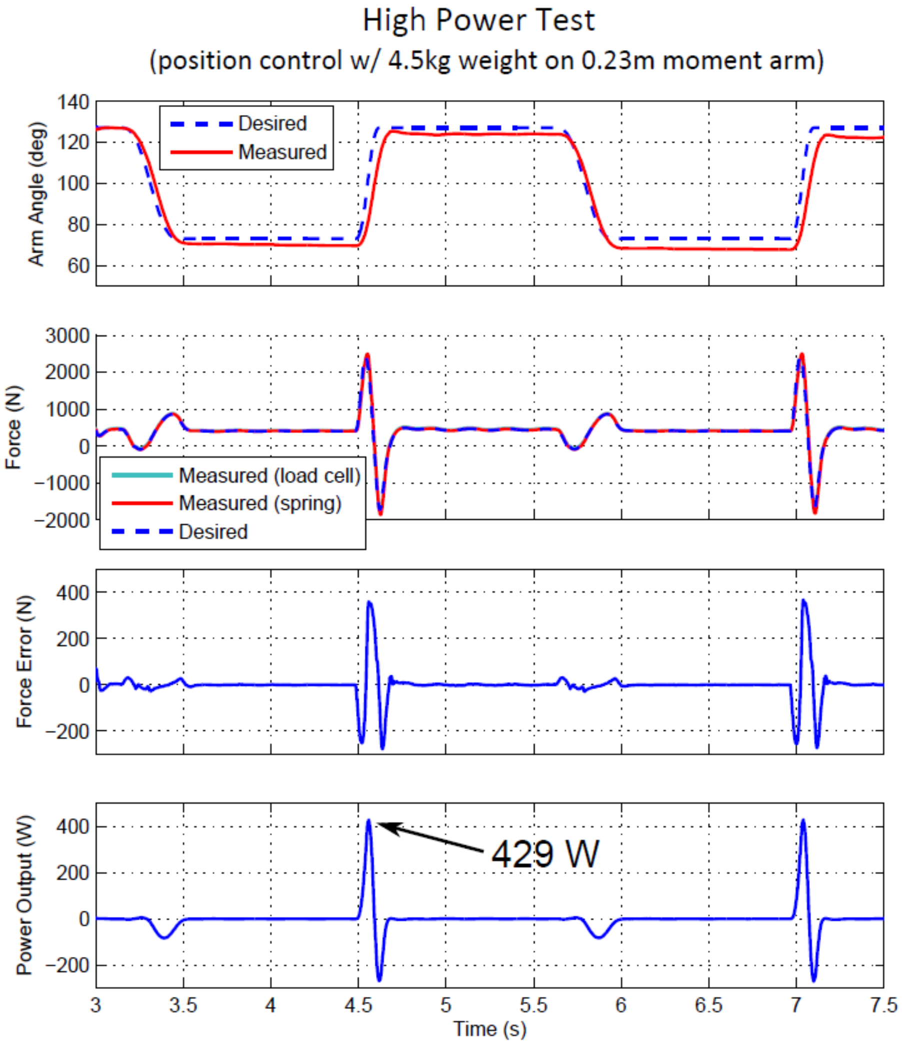


Control plant reduced to:

$$\frac{\theta_a(s)}{\tau_a(s)} = \frac{1}{s^2 J_a + s B_a}$$

Controlled using inverse dynamics and DOB

Data from high power test



more useful than "datasheet" performance

Empirical power-to-weight ratio of **423 W/kg**

4.5x improvement over our previous work (UT-SEA version 1) due to mechanical and control improvements

6.41x improvement over empirical Yobotics SEA performance

2.1x improvement over the most power-dense human muscle

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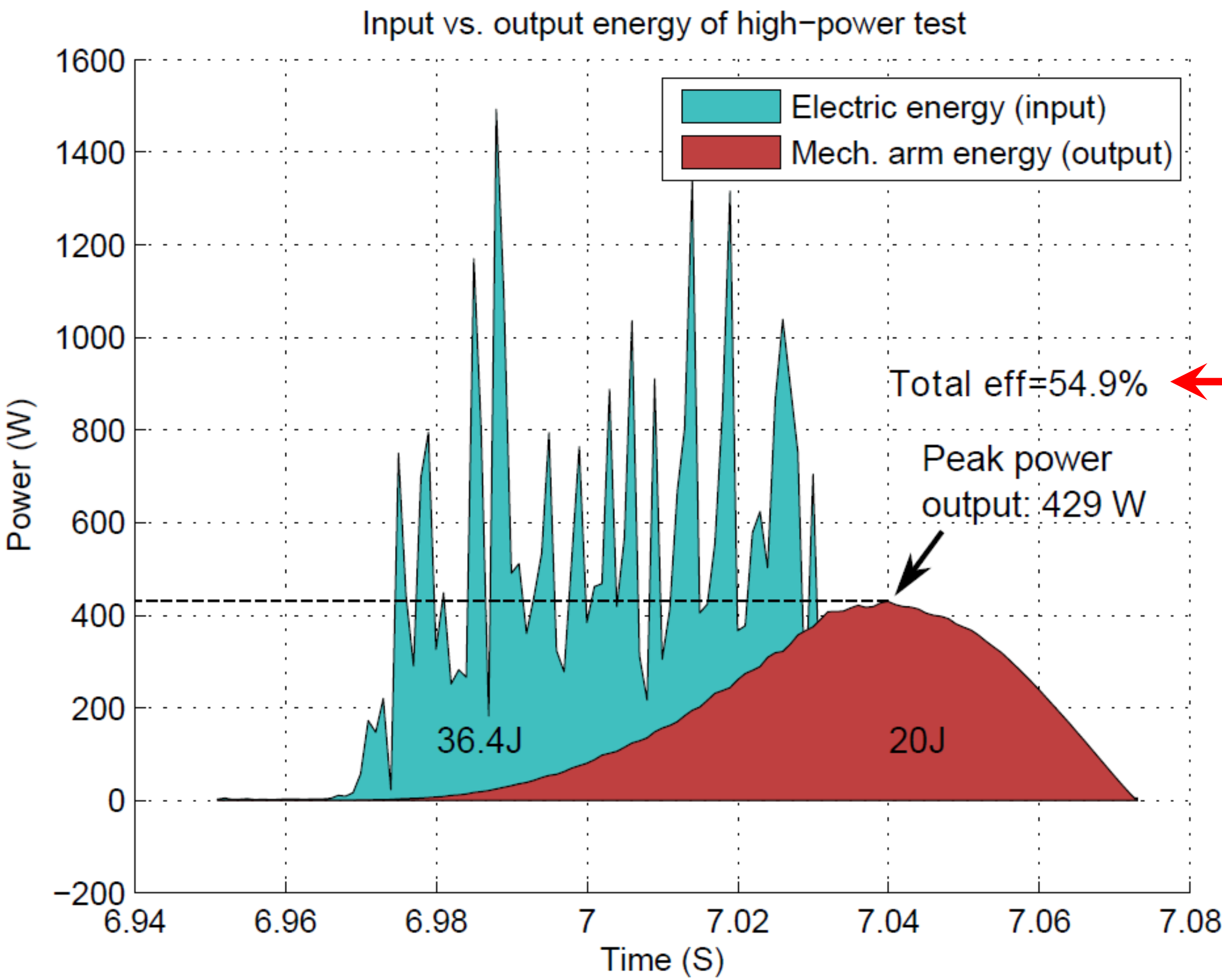
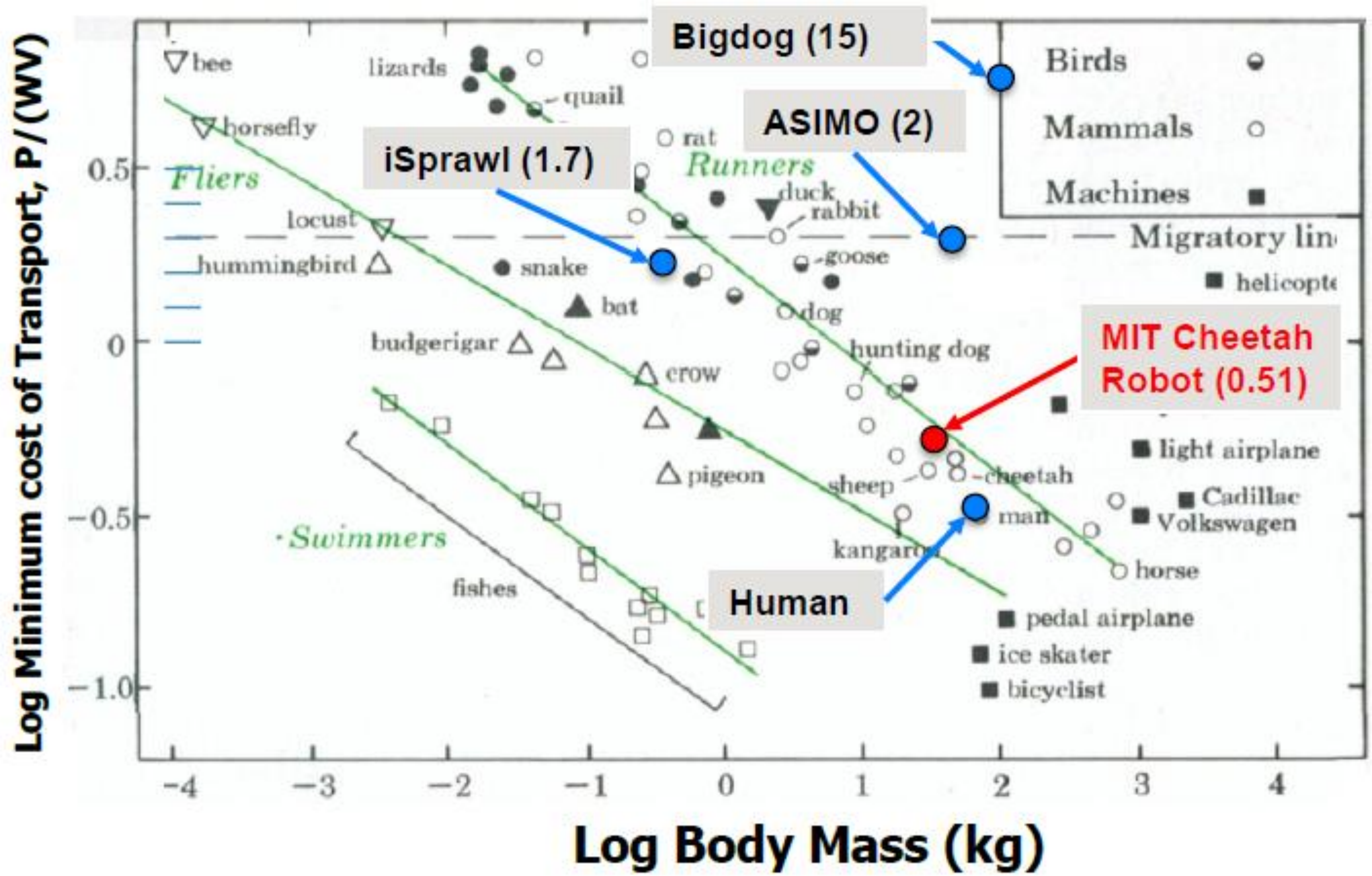
Energy efficiency of high power test



Near-worst-case value

Hydraulics nominal efficiency < 50%

Visualization of CoT efficiency metric



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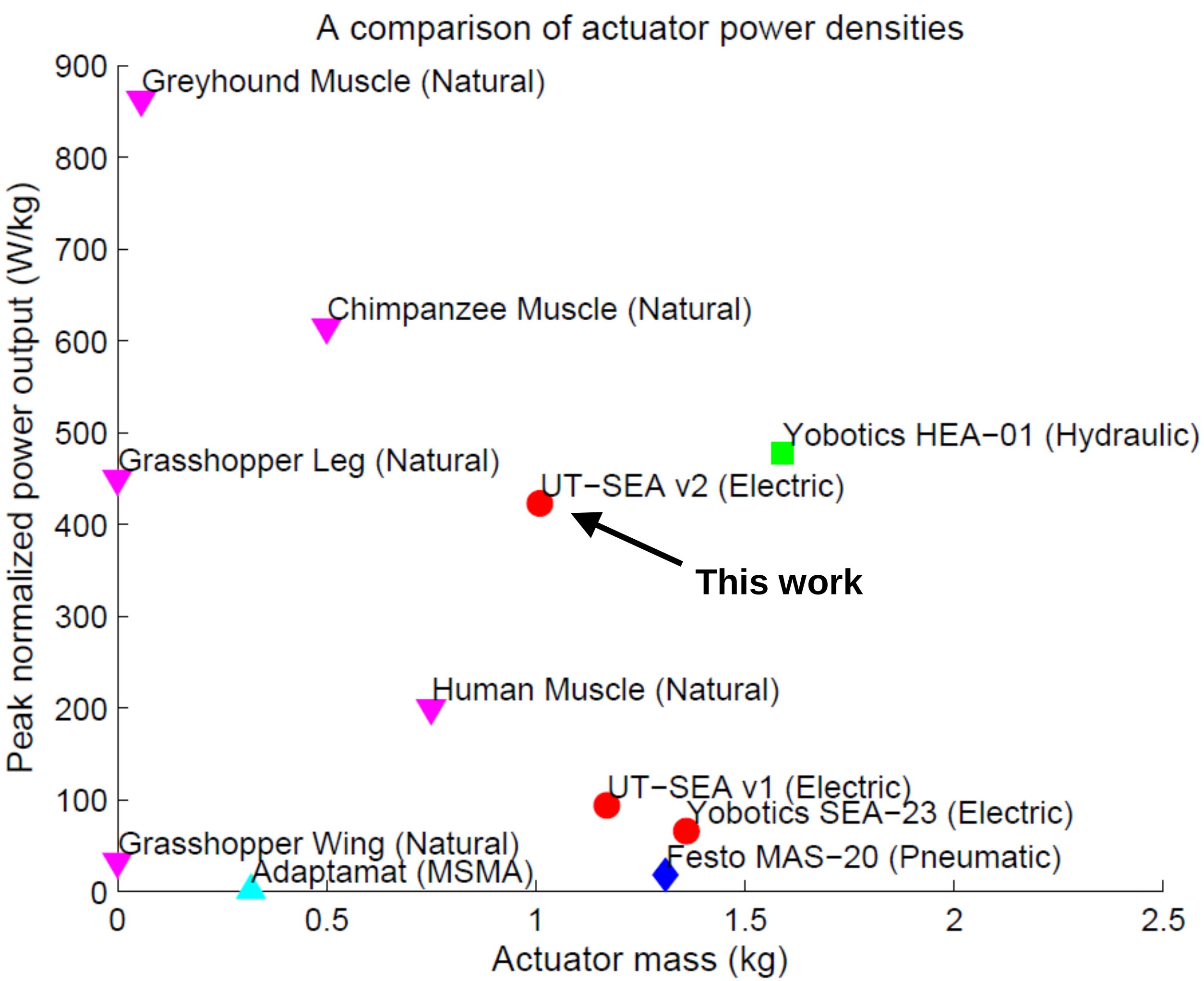
Visualization of power/weight metric



Thank you

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