PAL

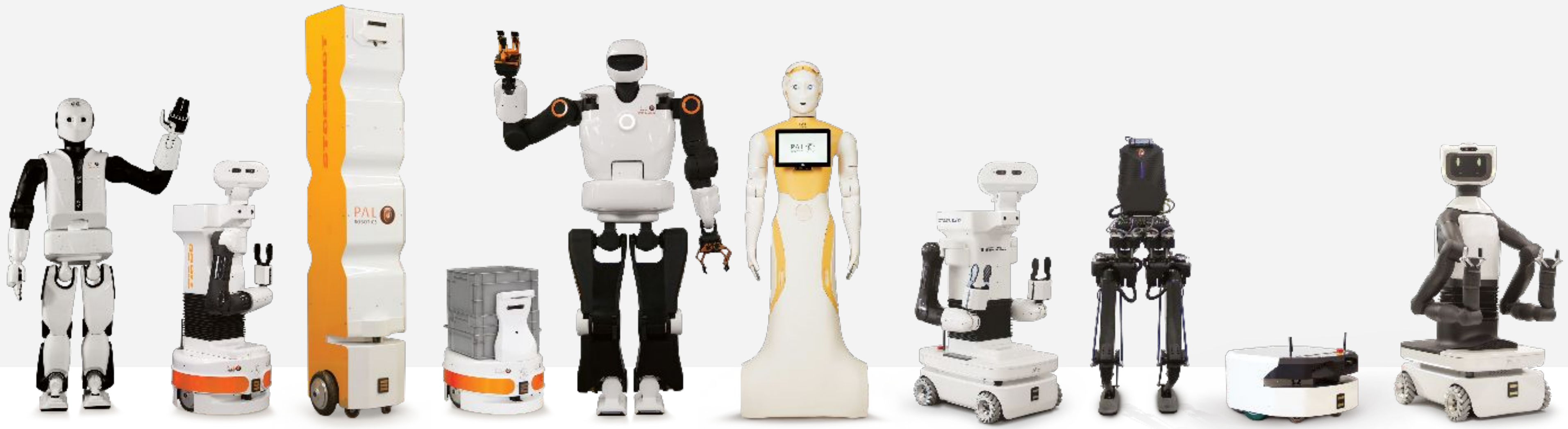
IEEE RTSI 2024

Advancements in high performance humanoid robot functionalities

Luca Marchionni, CTO

LECCO, ITALY | SEPTEMBER 2024

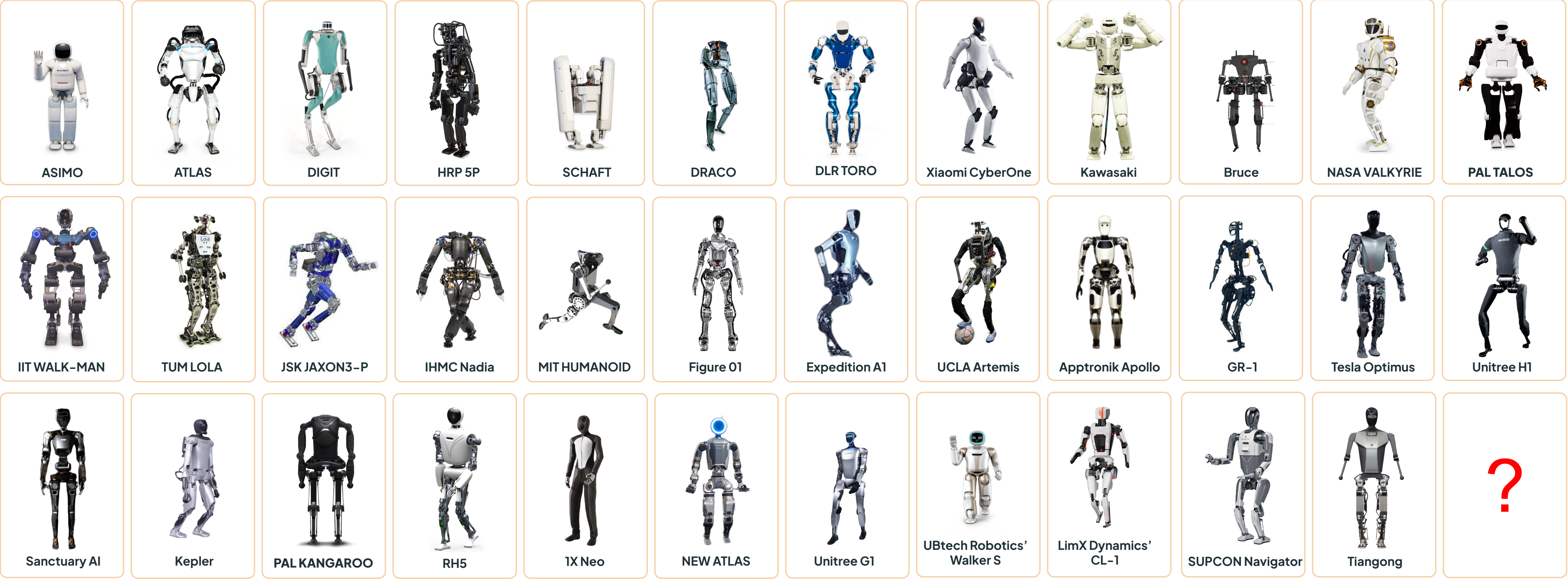
Who we are



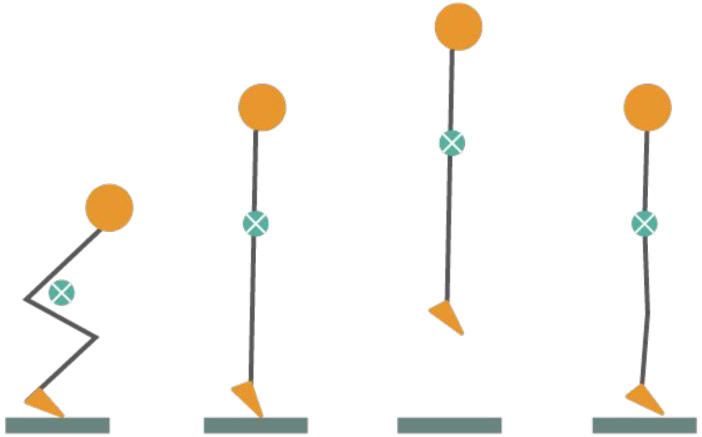
Associations we are part of

euROBOTICS	5G PPP	Adra – The AI Data Robotics Association	Hispa Rob	A35R	IFR International Federation of Robotics
Francesco Ferro **Industry Director**		Francesco Ferro **Industry Robotics Director**	Francesco Ferro **Board Director**		Francesco Ferro **Chair IFR Service Robot Group**

The Legged robots family is growing



Motivation and inspiration for KANGAROO platform

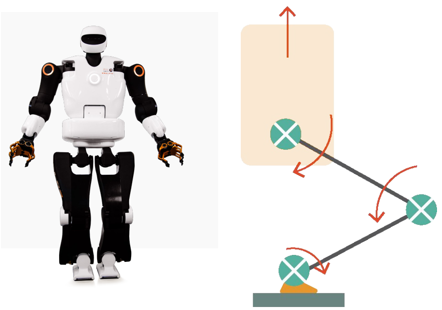


Mass of robot **40 kg**	Height to jump **300 mm** with straight legs
Velocity required **2.4 m/s** at take off	Power required **360 W** per leg

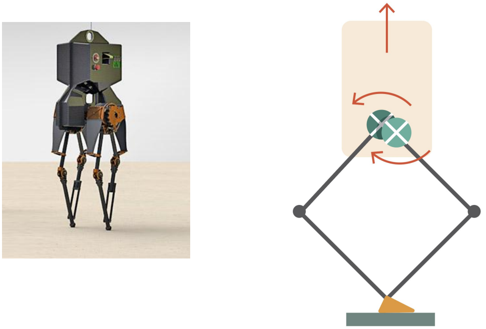
Can we build a jumping robot?

Leg architecture analysis

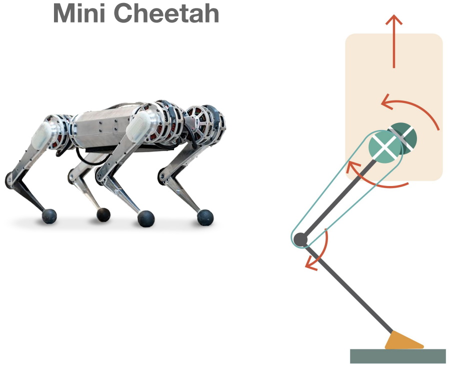
TALOS



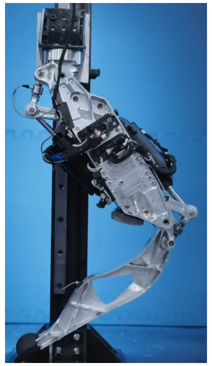
Atrias



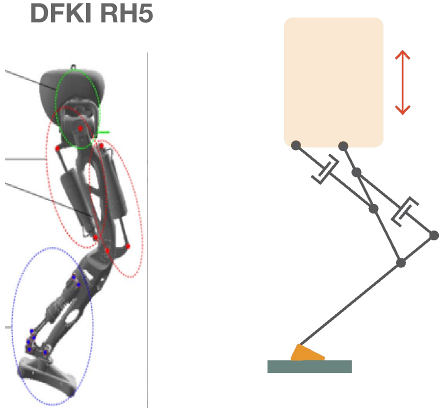
Mini Cheetah



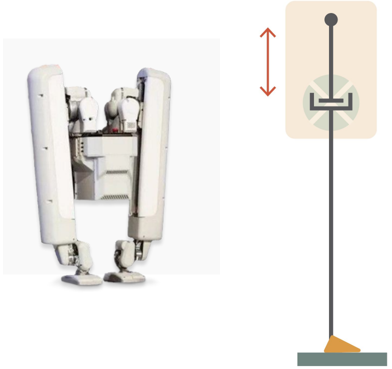
Tesla Optimus



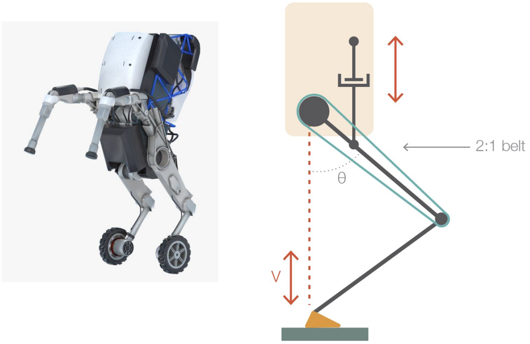
DFKI RH5



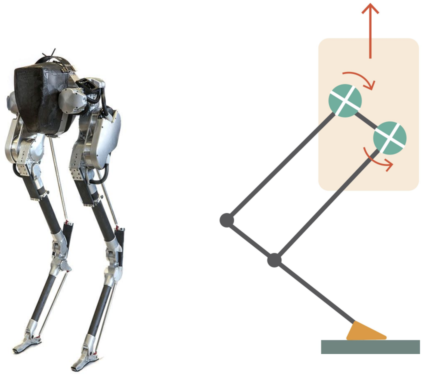
Schaft Biped



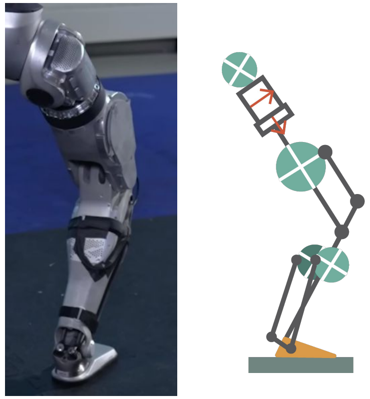
BD Handle



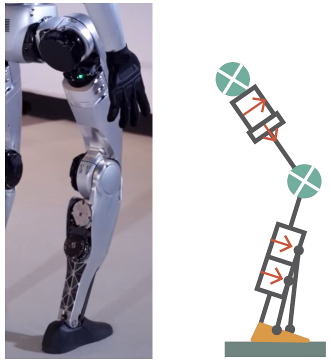
Cassie



New Atlas

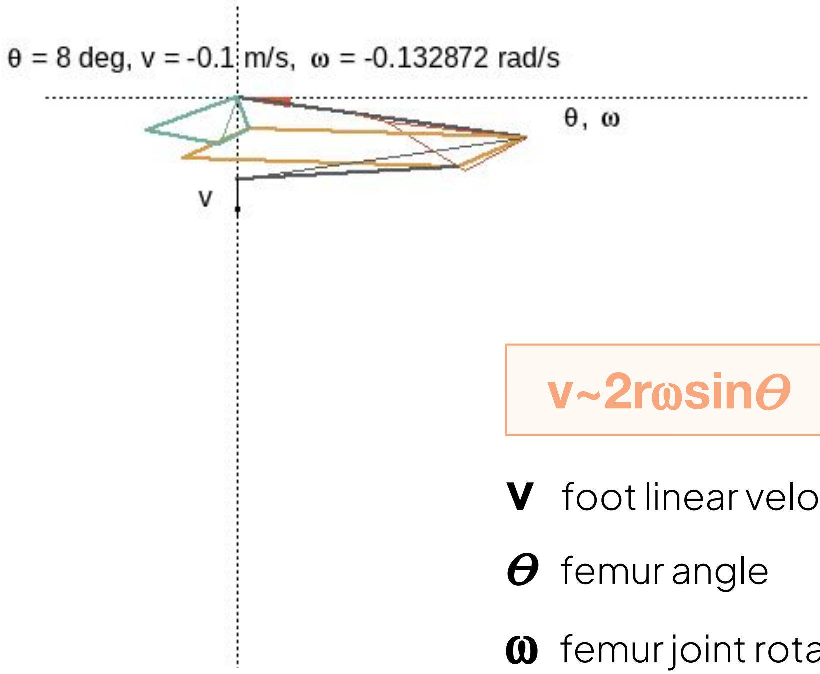


Unitree G1



KANGAROO leg length actuator concept

- Single linear actuator and 2 four bar linkages
- Foot moves along a straight line
- Leg length and swing motions are decoupled
- Gear ratio changes depending on leg angle



v~2rωsinθ

v foot linear velocity

θ femur angle

ω femur joint rotational velocity

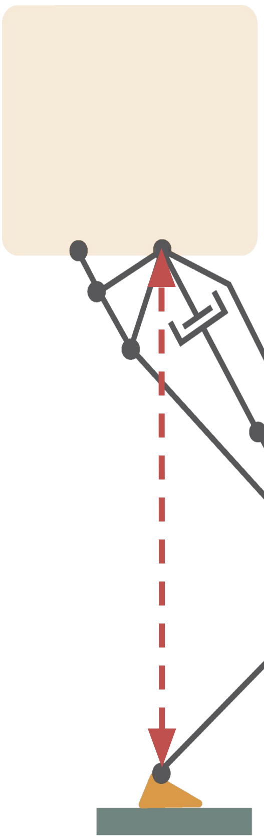
Mass
25 kg
robot + payload

Jump Height
300 mm

Velocity
2.4 m/s
at take off

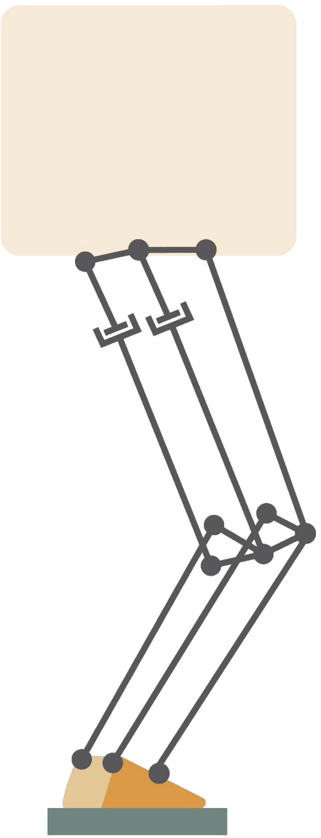
KANGAROO leg architecture highligths

Leg length



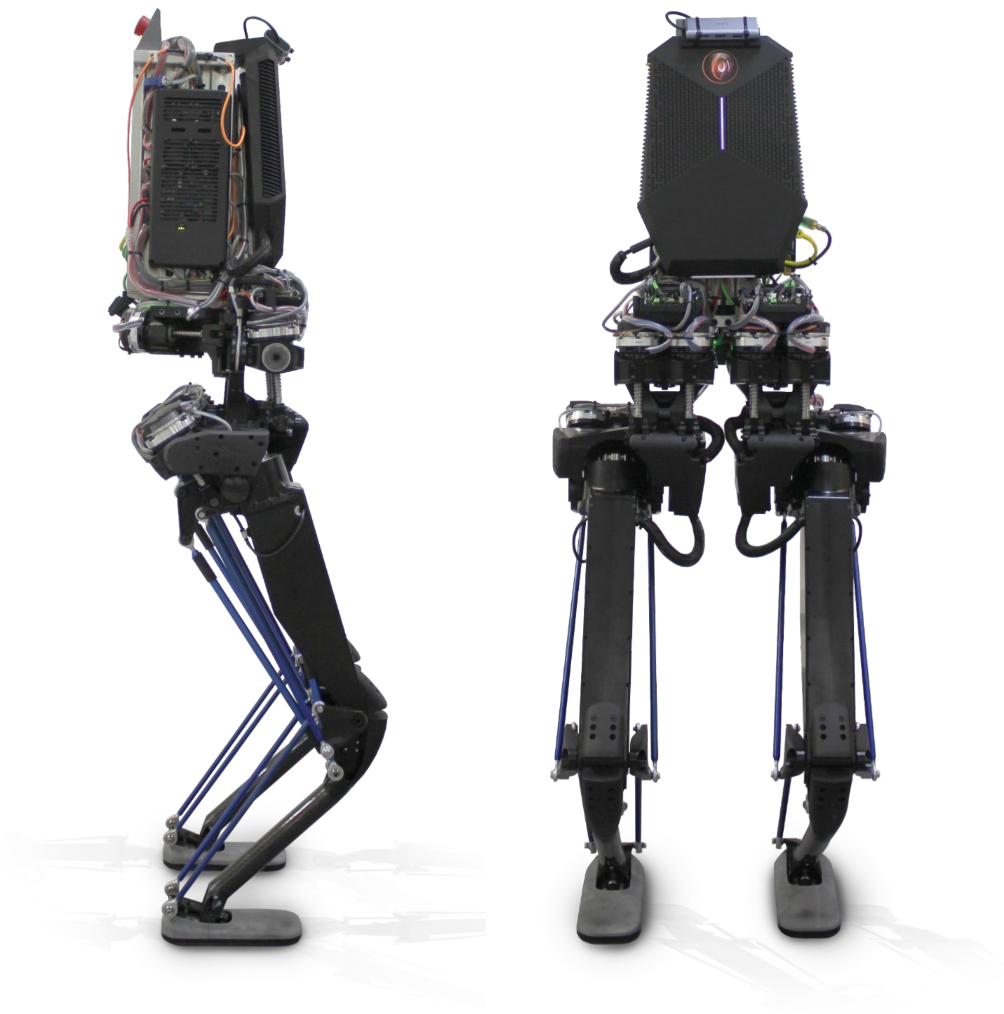
- Foot is kept planar when leg length moves

Ankle



- Ankle actuators are on the thigh

KANGAROO prototype



KANGAROO 2024

Commercial product for R&D

KANGAROO

Research platform for agile locomotion

- 2 x 6 DoF legs
- 2 on board computers with Intel i7 CPU
- 3h autonomy
- AHRS/IMU in the torso
- EtherCAT communication bus
- 4x RGB-D camera
- WiFi 6 802.11a/n/ac/ax 5 GHz and 2.4 GHz
- Remote Wireless emergency stop
- Premium Transportation Crate
- Joystick

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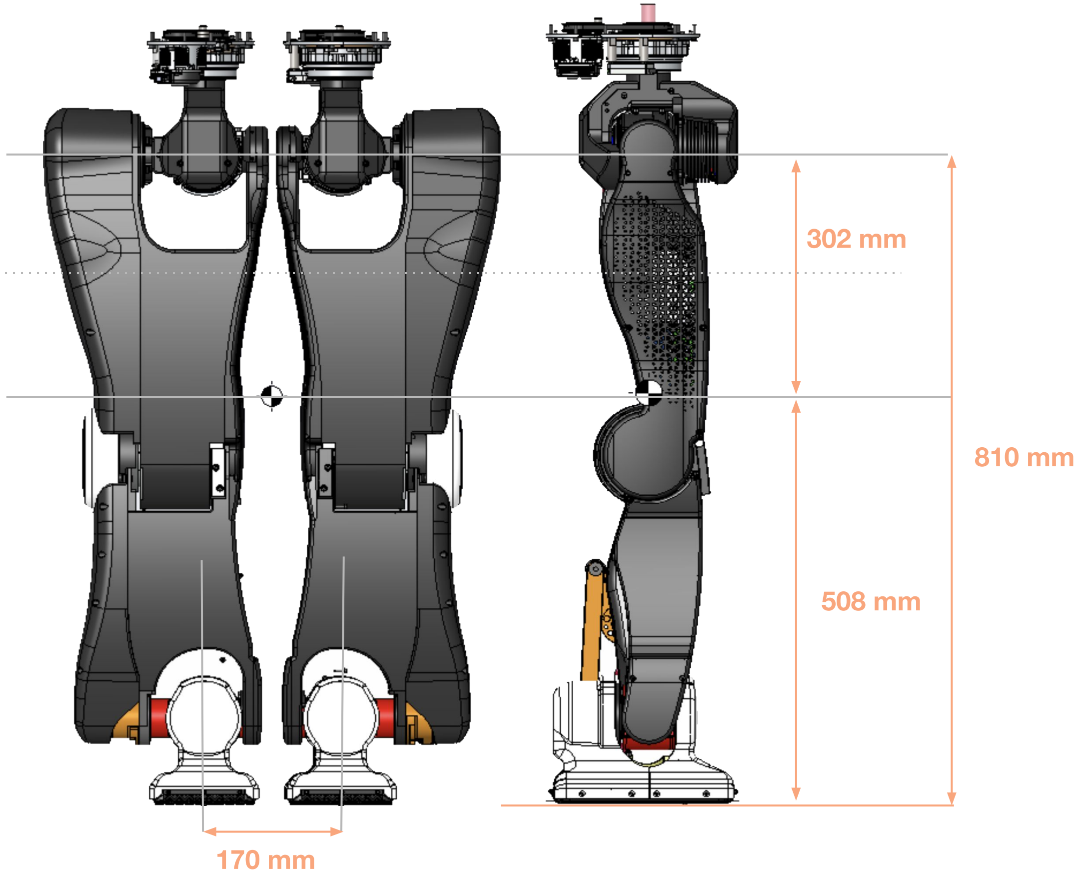
KANGAROO

Research platform for agile locomotion

- Ubuntu LTS (RT Preempt kernel) + ROS LTS
- Web-based control and diagnosis interface
- Available actuators control modes:
  Impedance, Position, Velocity, Force and Current
- Kinematic and dynamic robot model
- Gazebo, MuJoCo, Isaac Sim simulation
- **Kinematic/Dynamic Whole Body Control**
- **Robot State Estimation**
- **Kinematic/Dynamic Walking Controller (MPC, DCM)**

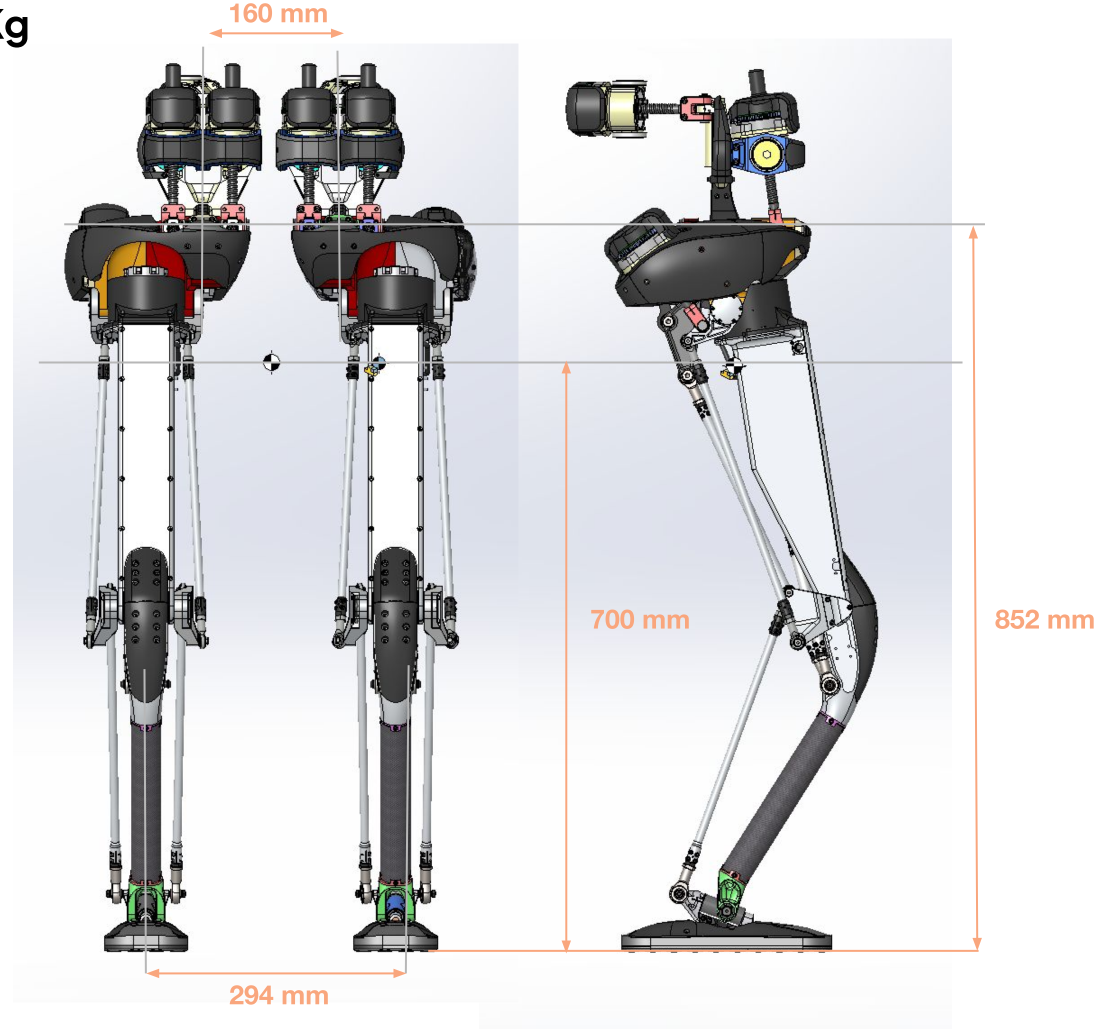
TALOS

Total Leg Mass
18 Kg



KANGAROO

Total Leg Mass
13 Kg



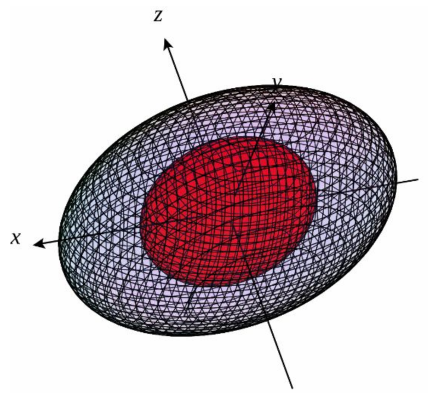
CoM and Inertia of the leg as seen from hip swing joint

	Center of Mass			Mass	Inertia Matrix					
	X	Y	Z		Ixx	Ixy	Ixz	Iyy	Iyz	Izz
KANGAROO	0.01602	0.059887	-0.23678	9.22	0.016053	0.00020982	0.0020098	0.019208	1,5813E-05	0.0082247
TALOS	0.001683	0.043672	-0.39978	13.398	0.061394	-0.00036979	0.0016425	0.063444	-0.00034857	0.018615

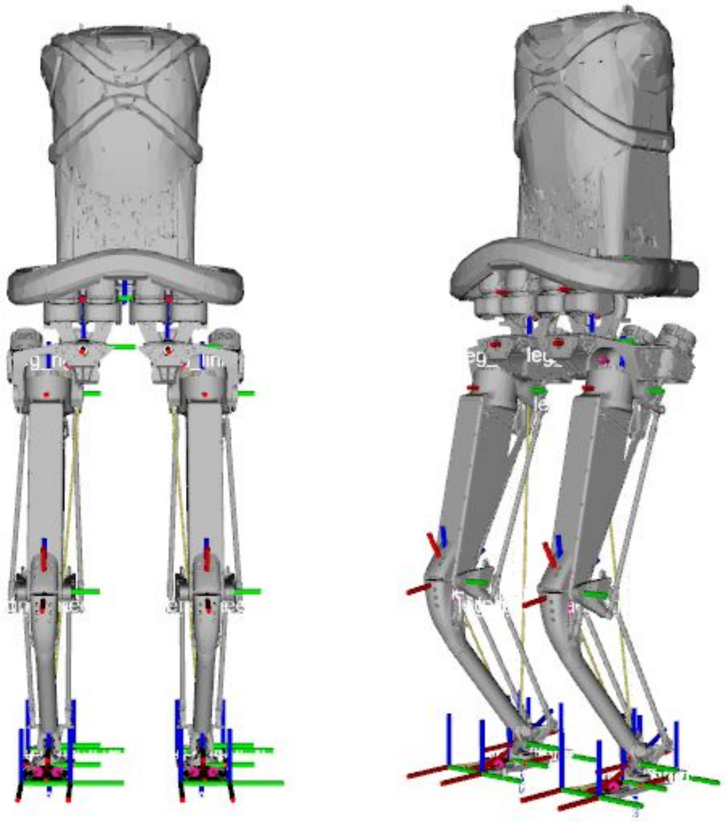
- **Leg mass reduction and smaller intertia**
  - reduce energy cost for walking [Browning et al., 2007]
  - shorten swing time [Royer and Martin, 2005]
  - reduce non-linear effects of swing leg

Comparative
Moment Ixx / Iyy / Izz

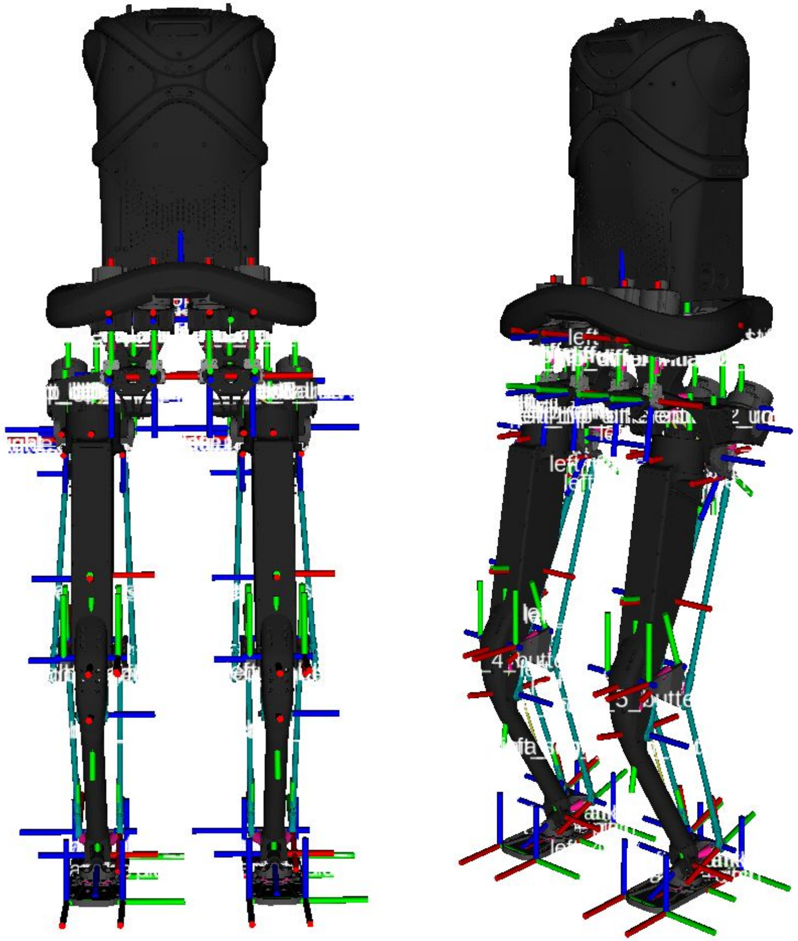
KANGAROO
TALOS



KANGAROO robot model



Simplified URDF (12 active + 4 passive DoF)



Full model URDF (12 active + 64 passive DoF)

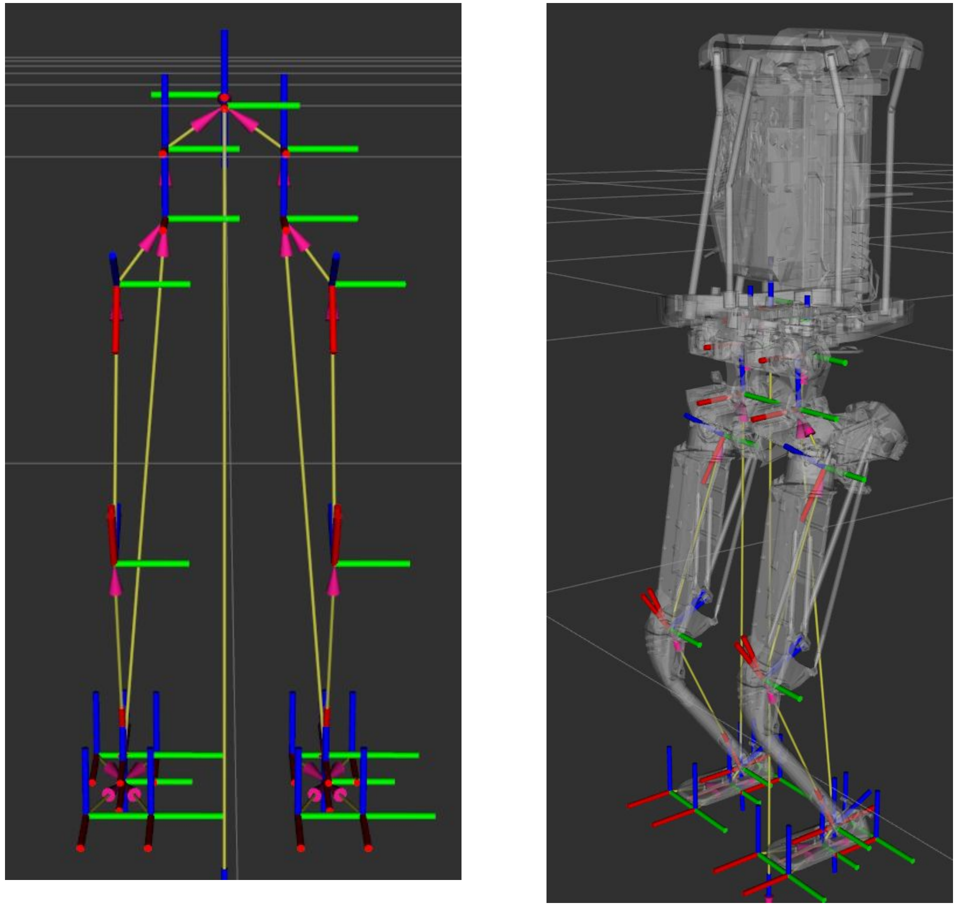
KANGAROO transmissions

The control of kangaroo's legs requires 4 custom transmissions:

- **Leg length**: ball screw <-> Leg length (1 dof)
- **Hip roll and pitch**: 2 ball screws <-> Leg roll and pitch (2 dof)
- **Hip yaw**: ball screw <-> Leg yaw rotation (1 dof)
- **Ankle**: 2 ball screws <-> Foot roll and pitch (2 dof)

Relation between ball screw lengths and corresponding joint states is **nonlinear**.

Dedicated class to solve nonlinearities → ros_control transmission plugin



Simplified URDF


PAL
ROBOTICS

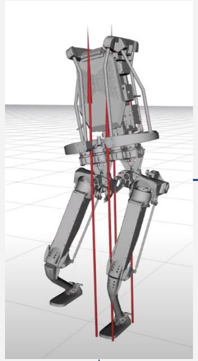
Trajectory Optimisation

The simple model represents a convenient interface for trajectory optimisation, having less DOFs and complexity. Results can be mapped consecutively to the full model to take into account all closed-linkages.

Simple model

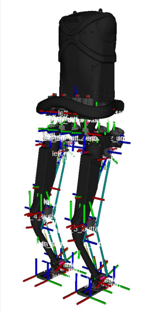
TRO with CasADi and **Pinocchio**

- Multiple-Shooting
- Variable time



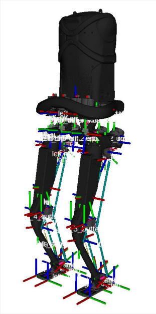
$\ddot{\mathbf{q}}\ \mathbf{F}_c$

Full-model ID



$\boldsymbol{\tau}$

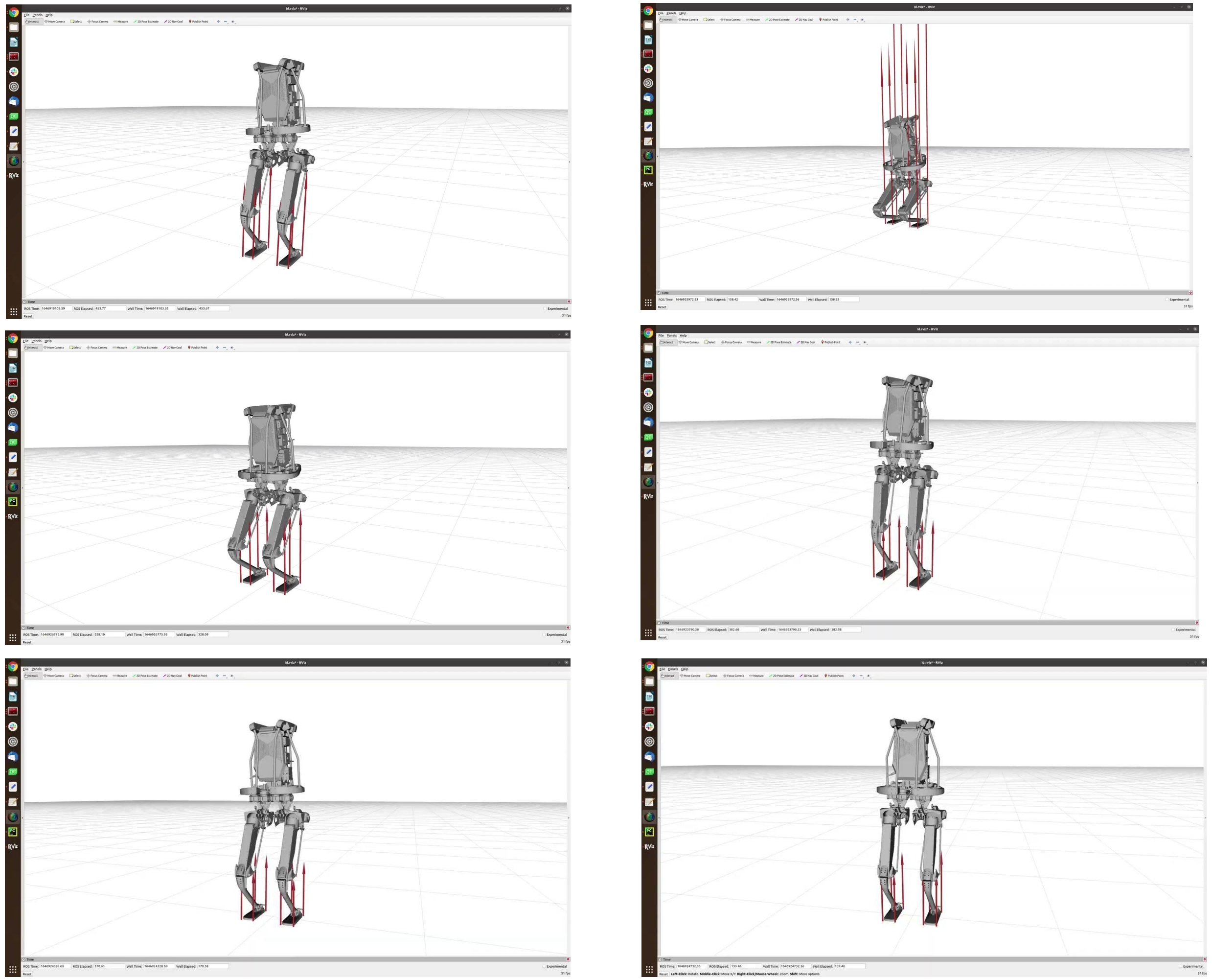
Full-model FK



$\boldsymbol{\theta}_a$

$\dot{\boldsymbol{\theta}}_a$

$\mathbf{q}\ \dot{\mathbf{q}}$



RTO + MPC + WBID using reduced model *coming soon on the real robot ...*

Robot Trajectory Optimisation (RTO)

↓

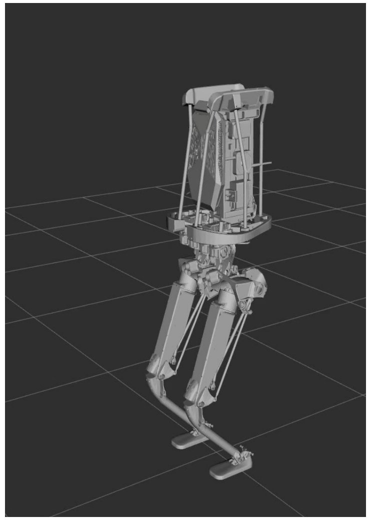
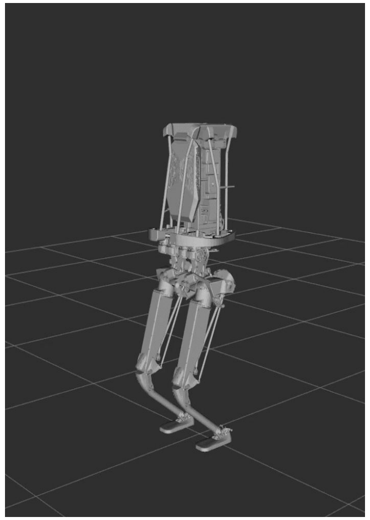
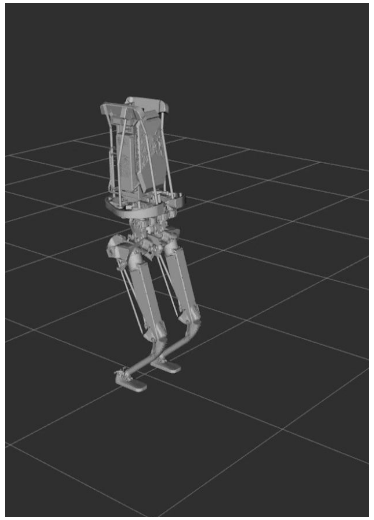
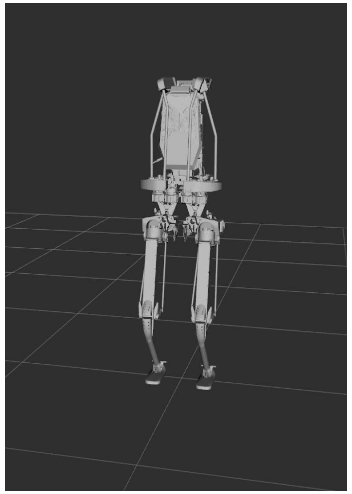
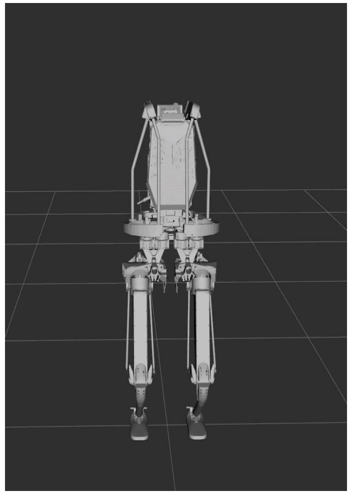
Model Predictive Control (MPC)

↓

Whole Body Inverse Dynamics (WBID)

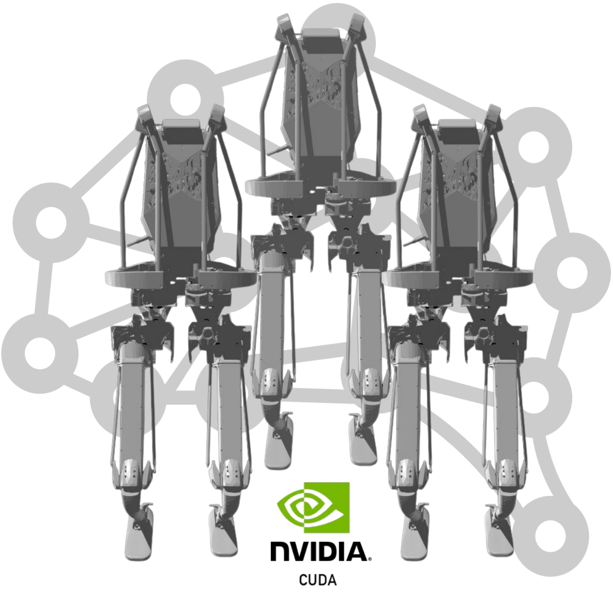
↓

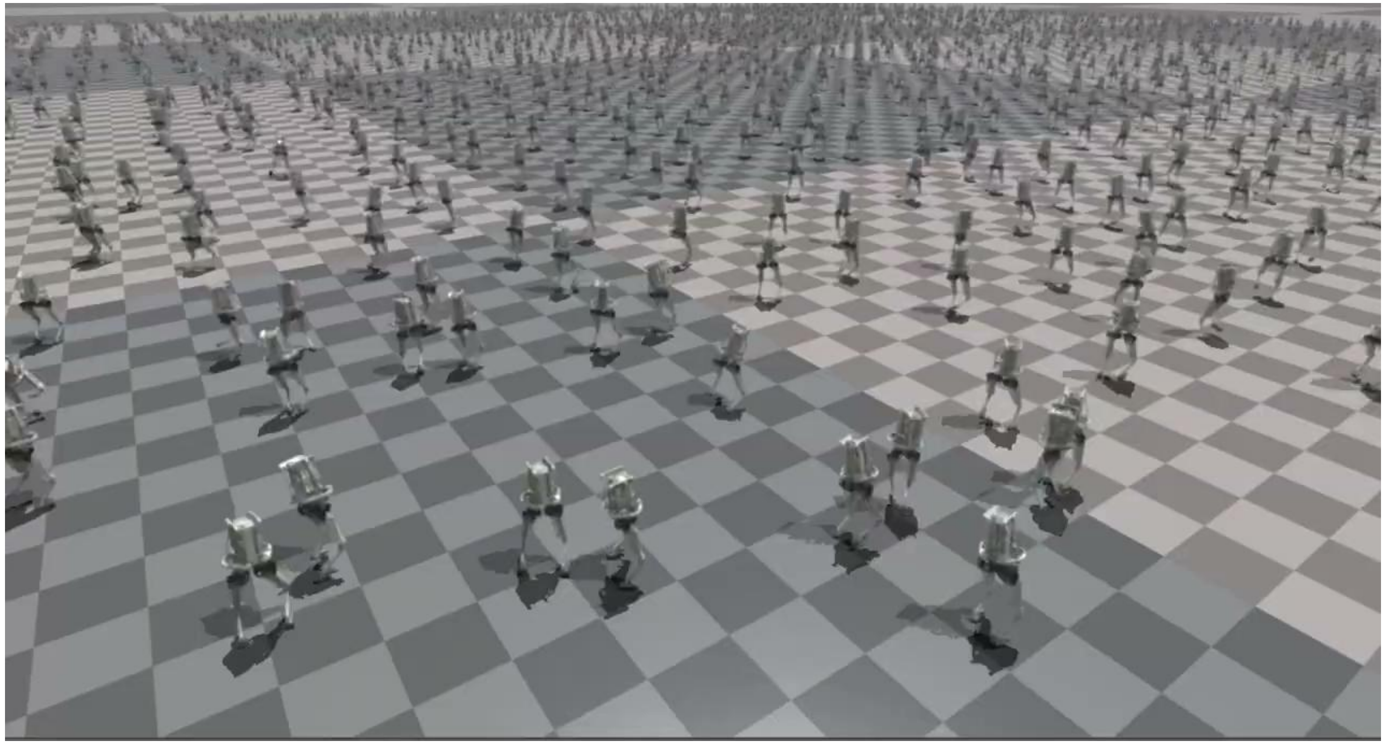
Force Control

Reinforcement Learning

- Isaac Gym walking learning framework
- Simplified and accurate simulation
- Over 4000 models in parallel
- Fully hardware accelerated
- Trained policies in ~20 min.
- Public access with ready-to-use examples





Our goal is to provide the full ecosystem for using RL with Kangaroo:

- support for multiple frameworks: Isaac Sim, MuJoCo, …
- Kangaroo Full Model open source
- Easy deployment on real robot

KANGAROO

Future

PRIMI

ONGOING PROJECT

Performance in Robots Interaction via Mental Imagery

- Research project in neuromorphic engineering, machine intelligence, cognitive mechatronics
- Involve Humanoid robots to build higher-cognition abilities – mental imagery, boosted by energy-efficient event-driven computing
- Validate prototypes of neuromorphic humanoid robots in clinical pilot studies of robot-led physical rehabilitation of stroke survivors.

FUNDING
€ 5M

MONTHS
48

ROBOT
KANGAROO

PARTNERS
6

AREA
R&D

COUNTRIES
4

PARTNERS

Funded by the European Union

PAL

KANGAROO Pro design roadmap

KANGAROO

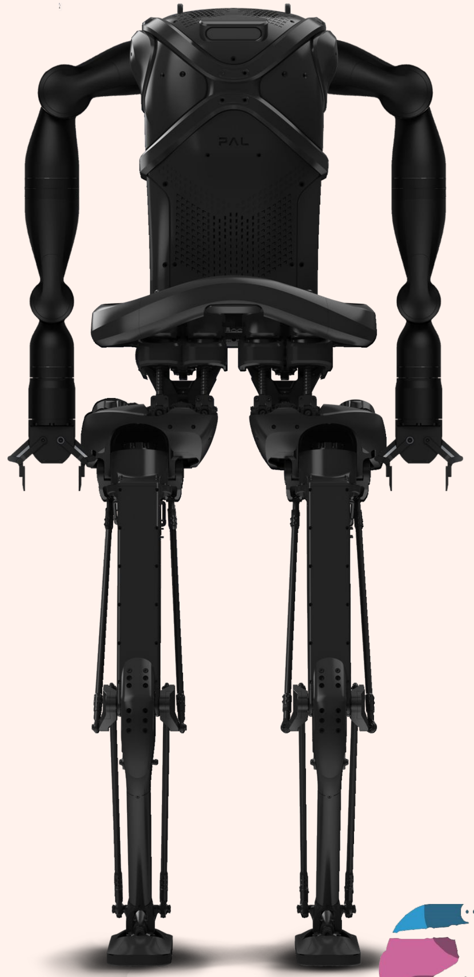
Force controllable linear actuators
Closed kinematic chains
Low inertia legs
Low weight

+

TIAGo Pro

Series Elastic Rotary actuators
7 DoF arms
Optimised for manipulation workspace
Lightweight arm design

=



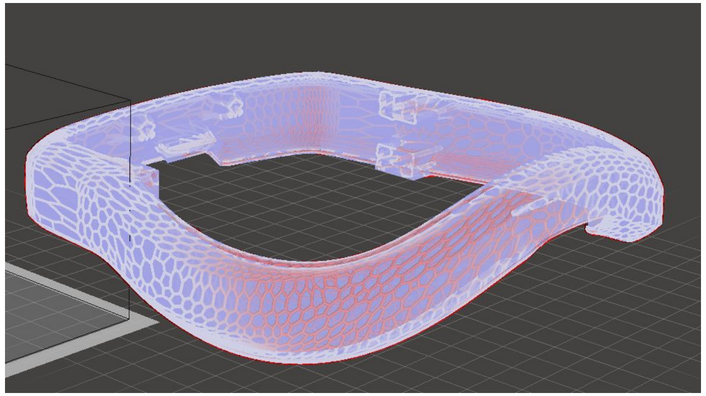
KANGAROO Pro 2025

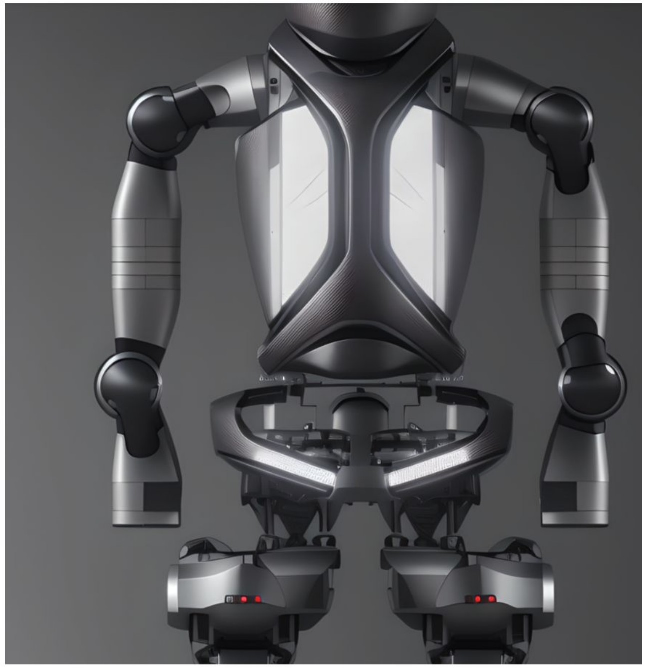
PRIMI

Industrial design proposals

Design requirements:

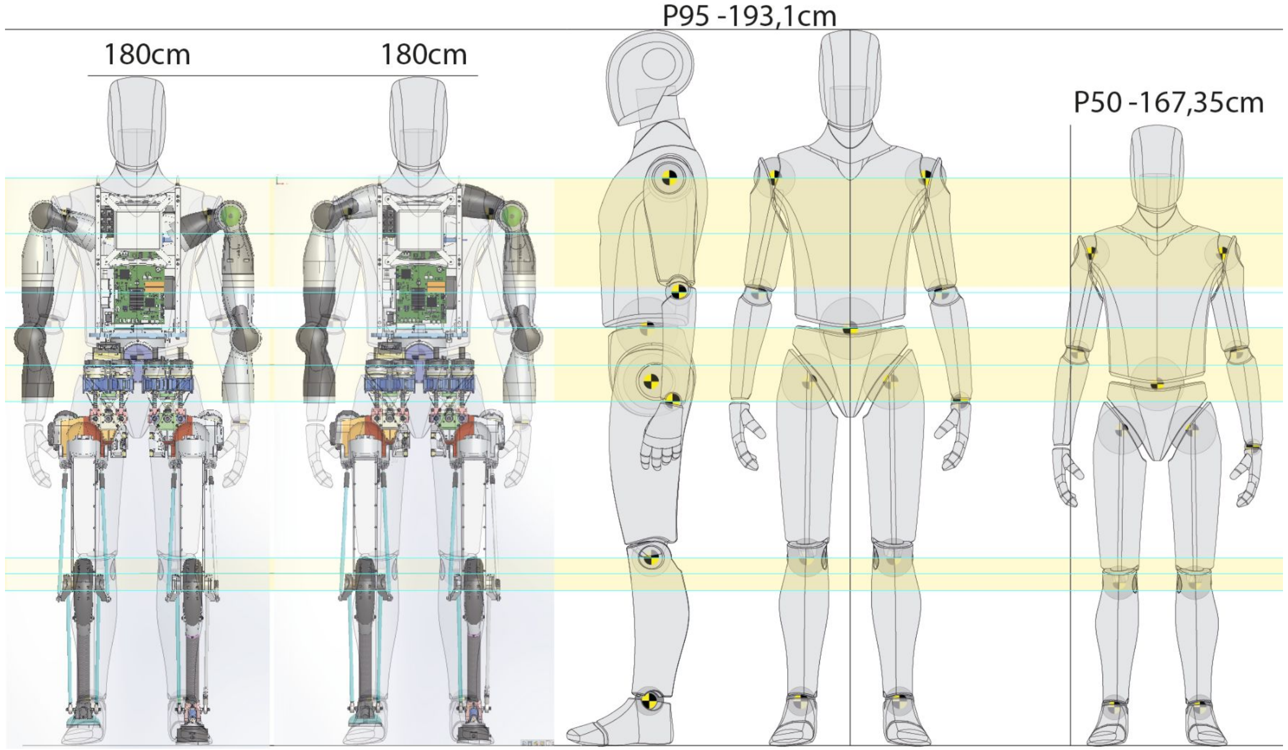
- Lightweight and minimal design
- Shock absorption materials
- Easy to assemble and to access





KANGAROO Pro

Joint	DoF	Axis
Arm	7	Y-X-Z-Y-Z-Y-X
Torso	2	X-Z
Hip	3	Z-Y-X
Leg length	1	Z (prismatic)
Ankle	2	Y-X
Total	**28**	



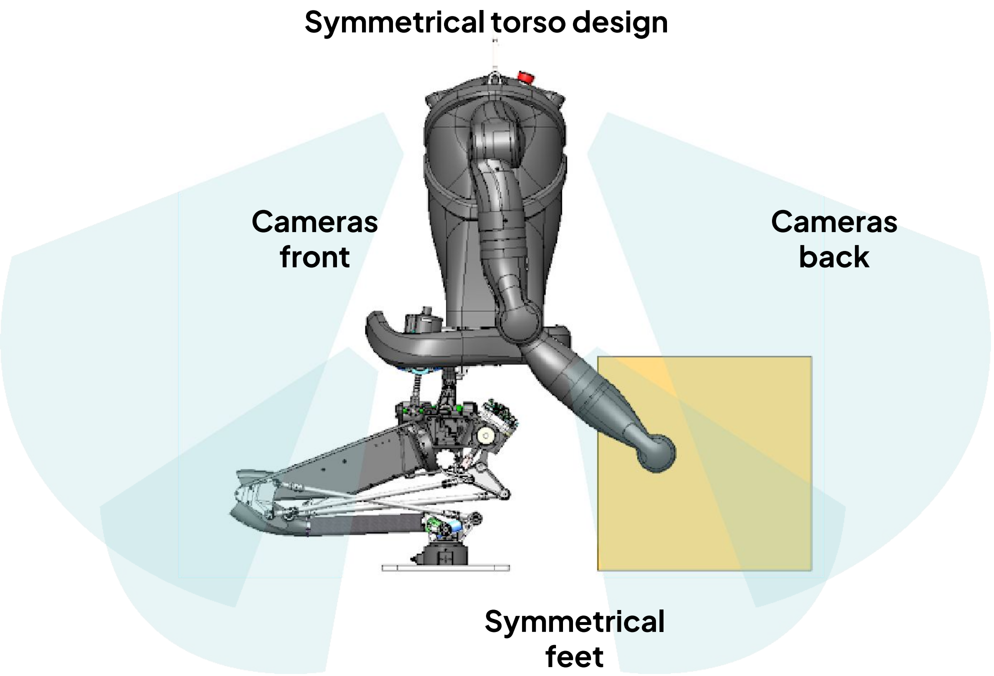
- Proportion of **torso** and **arms** will be defined using human proportion* of a male 1.8m tall.
- **Co-design** for arm kinematics to maximise workspace and range of motion.

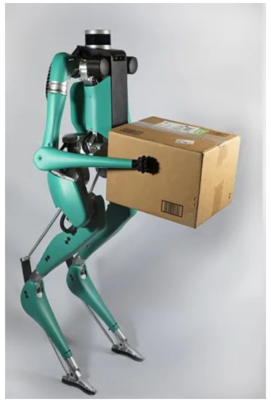
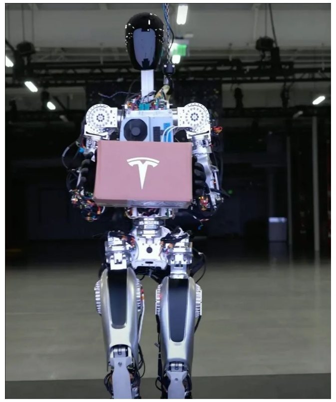
* ISO 7250-1:2017 Basic human body measurements for technological design — Part 1: Body measurement definitions and landmarks
CONTINI R, DRILLIS RJ, BLUESTEIN M. DETERMINATION OF BODY SEGMENT PARAMETERS. Hum Factors. 1963 Oct;5:493-504. doi: 10.1177/001872086300500508. PMID: 14101572.

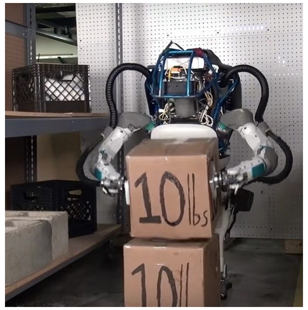
General Purpuse Robots

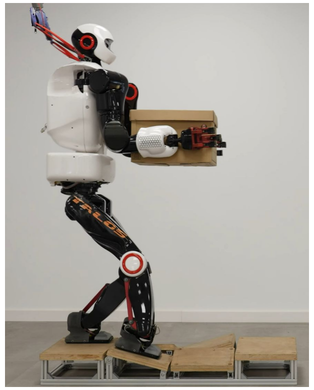
Large **manipulation workspace** both in the front as in the back, useful for object manipulation or multicontact behaviors.

Wide **field of view of RGBD** cameras for 3D perception during locomotion or manipulation tasks.





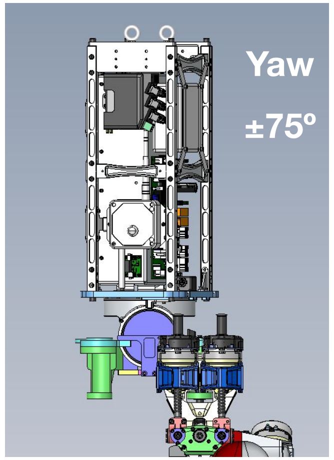



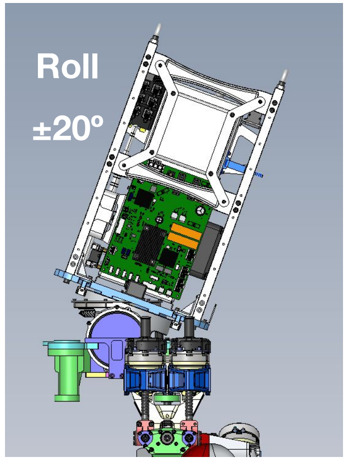

Do we need torso pitch?

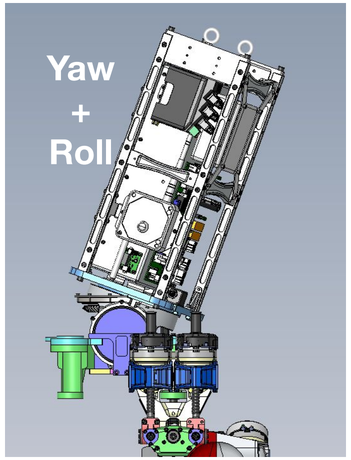
- Torso pitch is barely used in walking and running motions
- Arms are more effective at regulating angular momentum
- Roll and yaw joints are useful for keeping the upper body straight.

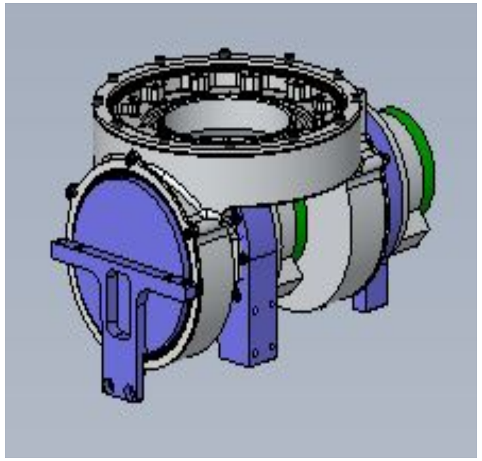
Design proposal

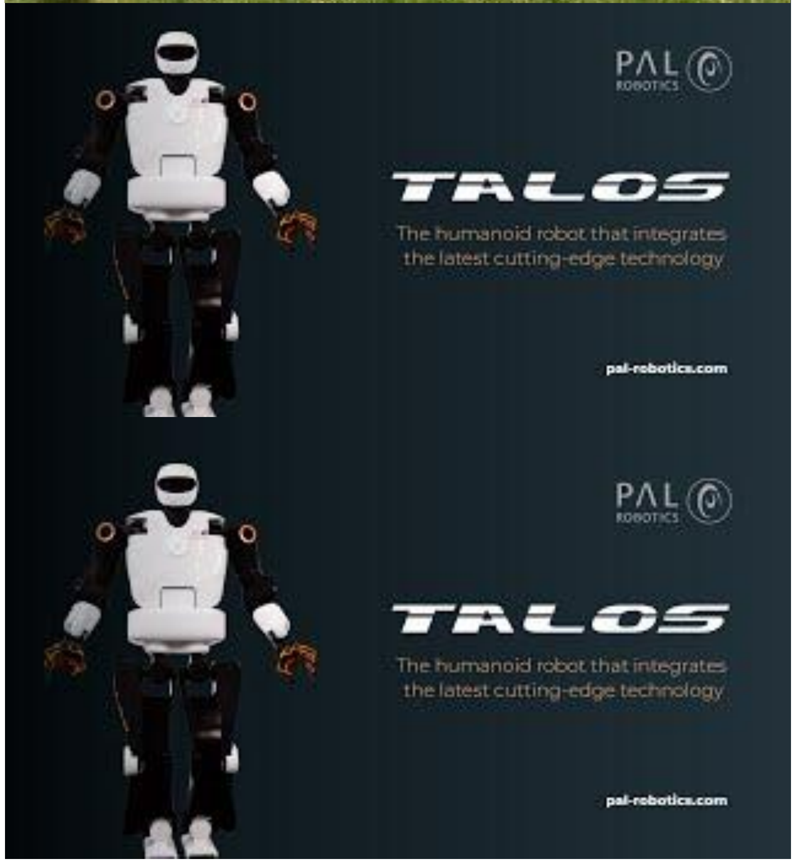
- Modular differential mechanism
- 2 Rotary Series Elastic Actuators
- Peak torque 140Nm, Peak speed 6 rad/s









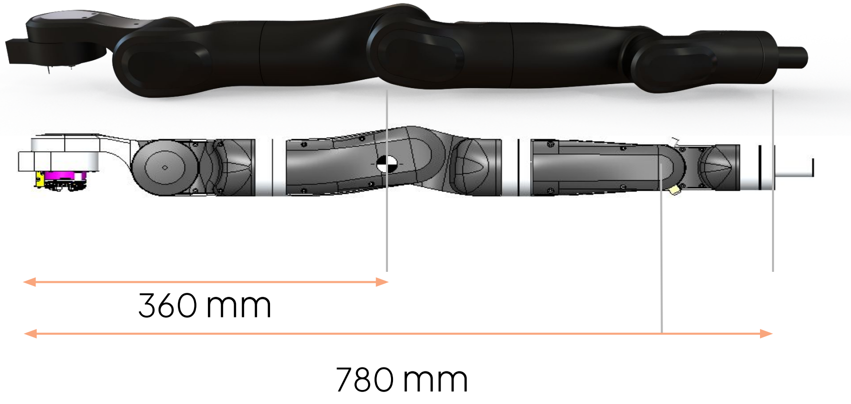


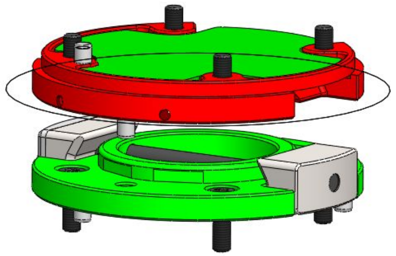
KANGAROO arm design

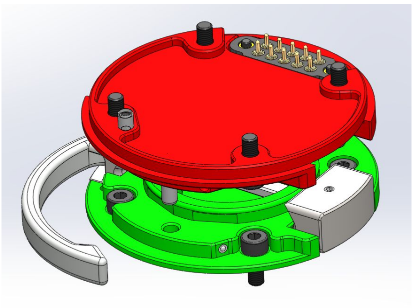
- 7 Degrees of Freedom arm
- 3 sizes of rotary actuators
- Integrated joint motor drive
- Series Elastic Actuators
- EtherCAT communication
- Safety brakes (optional)
- Structural shells
- ISO 9409-1 flange and quick tool changer

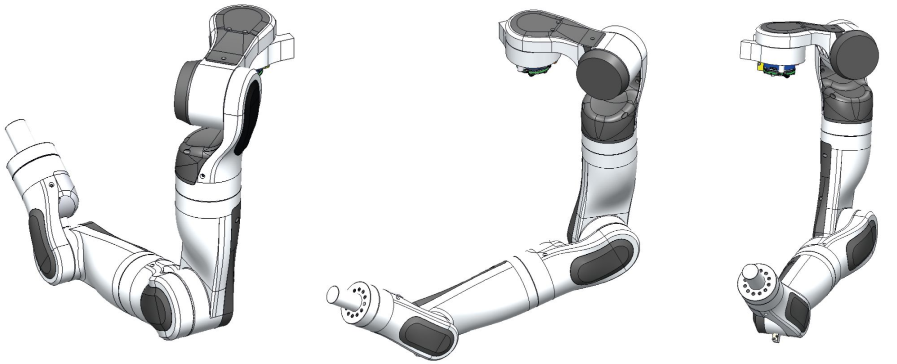
Total Arm Mass
6 Kg

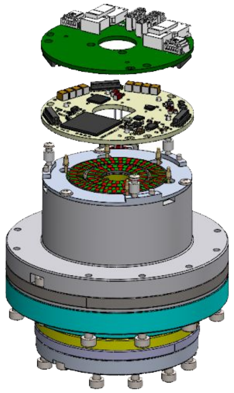
Payload
3.5 Kg







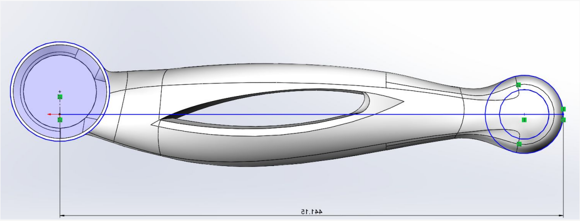




Actuators	XS	S-	S+
Continuous torque (N)	20	26	45
Peak speed (rad/s)	6	6	3
Peak torque (N)	35	45	70
Weight (g)	460	650	700

KANGAROO end effectors

Phase 1



- Fake forearm for balancing
- Box picking and lifting

Phase 2

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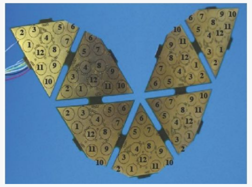

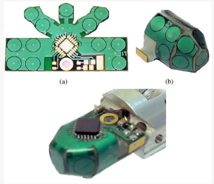

- Parallel gripper (1 DoF)
- HW/SW integration of Tactile Skin on gripper’s fingers

Phase 3

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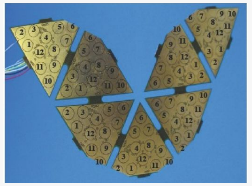
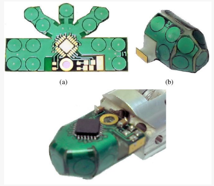




- Humanoid hand integration
- Tactile sensors in fingers and forearms

KANGAROO Pro in PRIMI project

Phase 1

- 4 RGB-D cameras for navigation
- Expansion panel for testing additional sensors

Phase 2

- Head for HRI
- HW integration event camera
- HW integration SpiNNaker2 board

Phase 3

- Ubuntu 22.04 LTS (Ubuntu 24.04 LTS from Q4 2025)
- ROS2 Humble (ROS2 Jazzy from Q4 2025)
- PAL Alum (PAL Beryl from Q4 2025)
- Gazebo classic (Gazebo Harmonic Q4 2025)
- Mujoco v3

- Neuromorphic models
- Cognitive architecture
- ROS4HRI
- Demonstrators and pilots

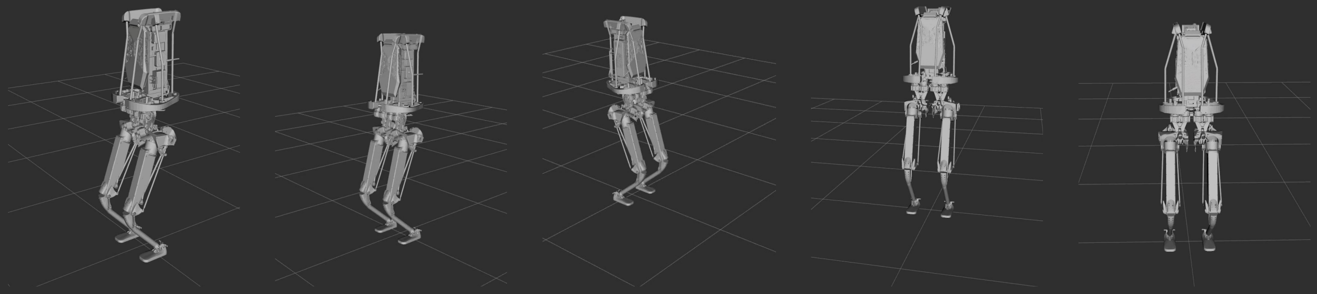
Conclusion

- Kangaroo's design can be suitable for agile locomotion
- Robot model is close to traditional template models used in research (LIPM, SLIP, etc)
- Preliminary results with robot hardware
- Ongoing design of the upper body
- Humanoids are creating a lot of interest recently but there is still a lot of work to do in order to deploy them in industrial applications

Roadmap
KANGAROO as platform for research
Software development and experiments to showcase hardware capabilities
Kangaroo Pro prototype (Q4 2024)
Use cases and pilots demonstrators (2025)
Kangaroo Pro commercialization (2026)

PAL

20 YEARS OF ROBOTICS



thank you

Luca Marchionni

luca.marchionni@pal-robotics.com

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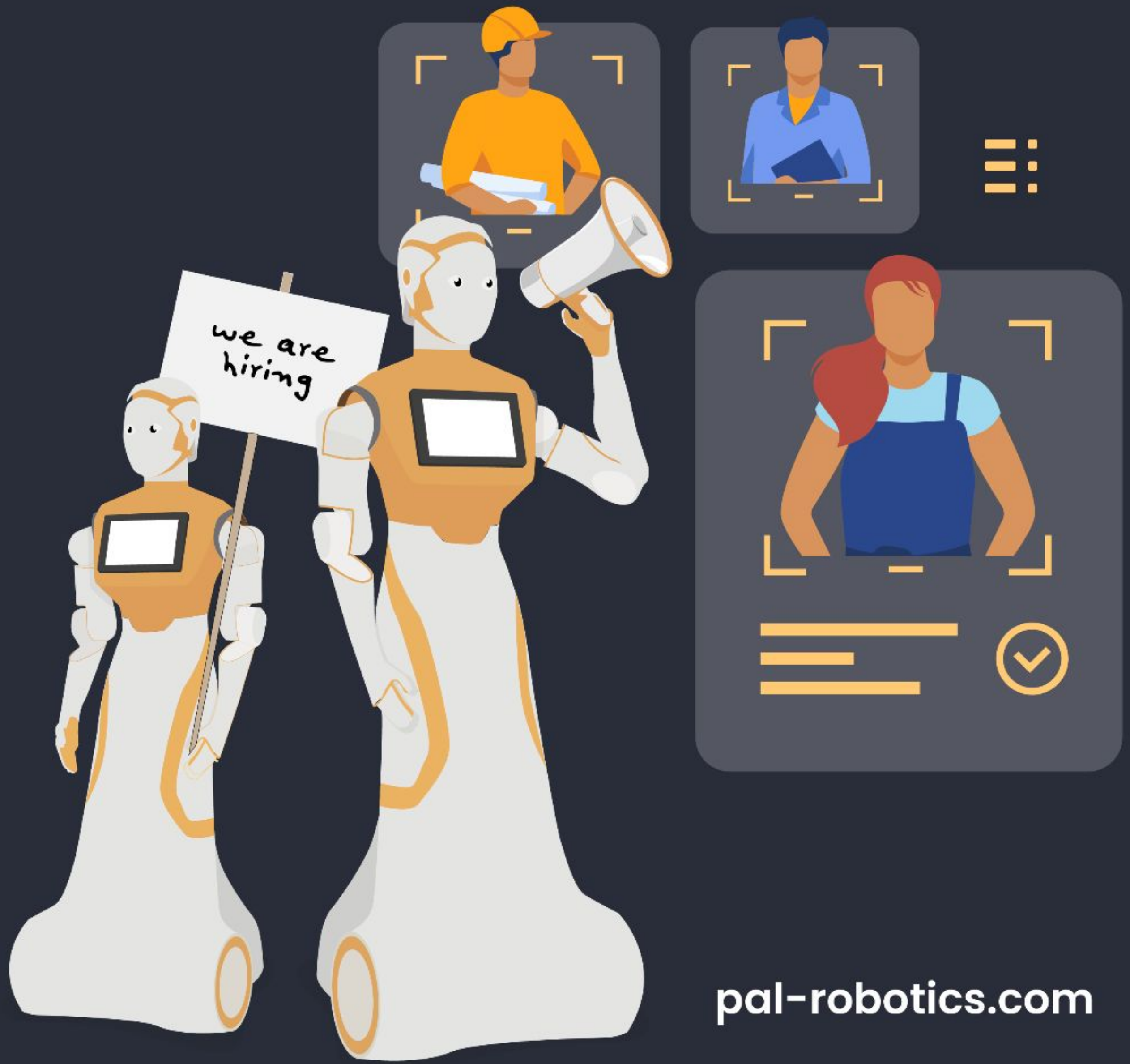

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