Development of a Humanoid Dual Arm System for a Single-Wheeled Balancing Mobile Robot

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Overview

This work presents a new 14-DoF dual manipulation system for the CMU ballbot [1]. The result is a new type of robot that combines smooth omnidirectional motion with the capability to interact with objects and the environment through manipulation.

The integration of the arms with the CMU ballbot is demonstrated through heavy payload lifting and balancing experiments.

Related Work

The are many collaborative robotic manipulation platform. Unfortunately, they suffer from one or more:

- Low mass-to-payload ratio
- Low payload capacity
- Large external control box
- Non-anthropomorphic kinematics
- Bulky and heavy

Research has been conducted to mitigate these issues [3][4].

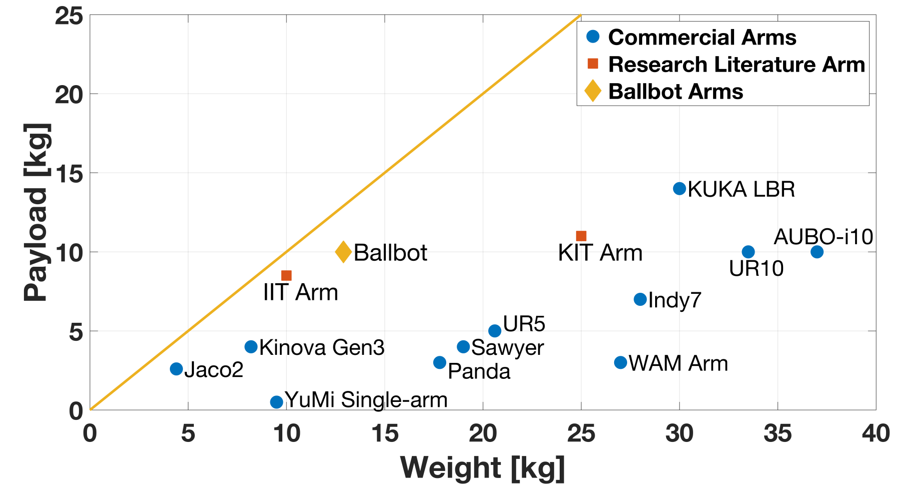


Figure 2: Plot of arm weight vs. payload capacity for different robotic arms. Commercial and research literature arms are shown.

Arm Mechanical Design

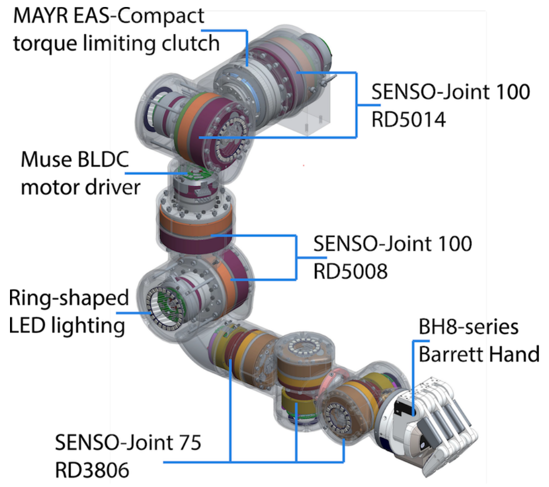


Figure 3: CMU ballbot dual arm system with BH-282 grippers (CAD rendering).

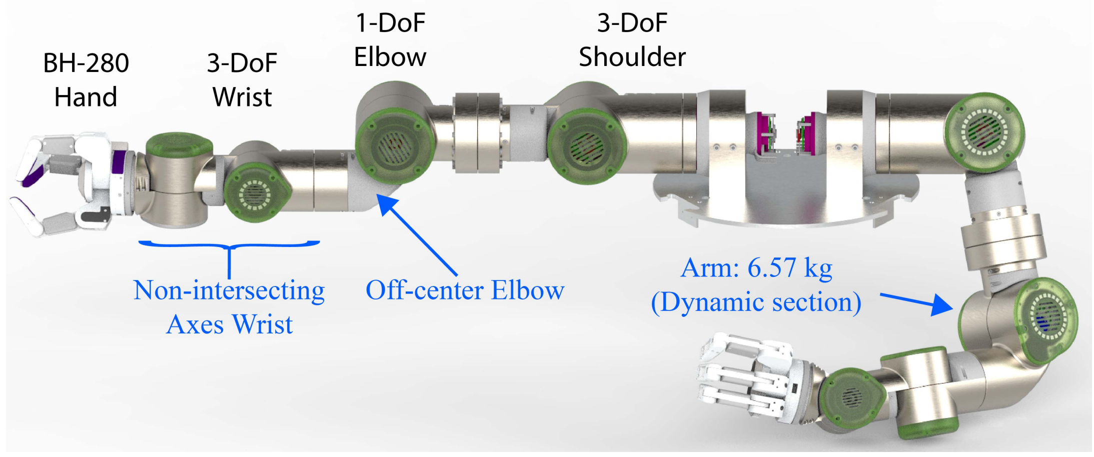


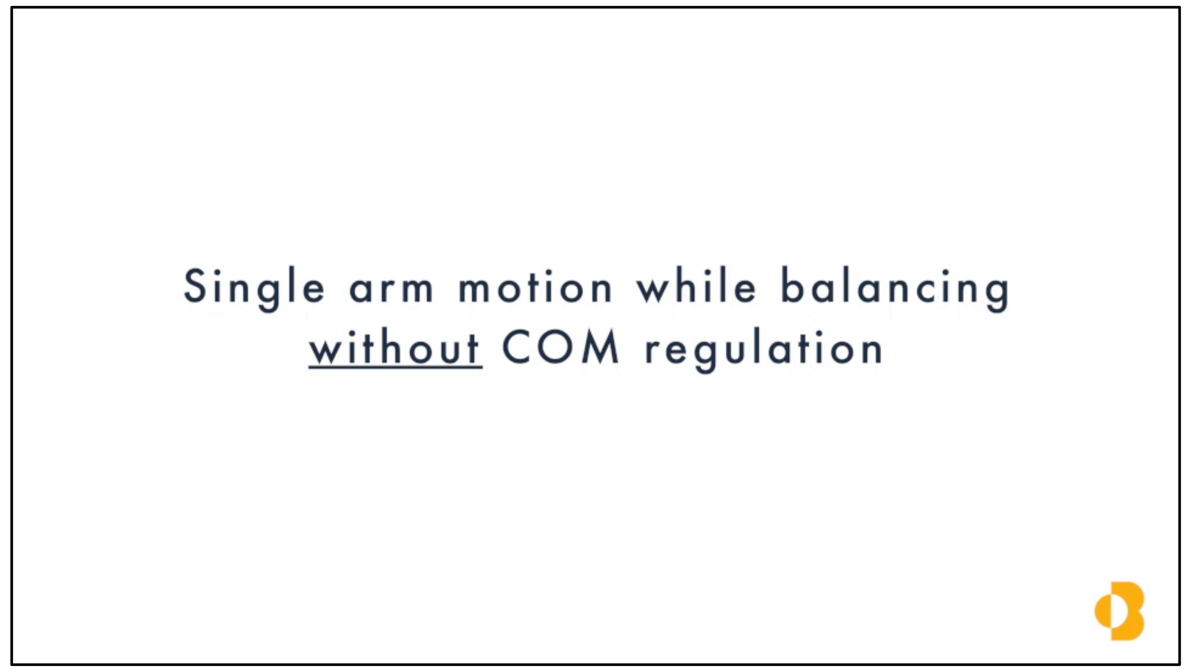
Figure 4: CMU ballbot dual arm system with BH-282 grippers (CAD

Property	Functional Requirement	Specification
Size	High power and strength density	***mass-to-payload ratio:* 0.78**
	Lightweight to be compatible with ballbot	***Mass:* 12.9 kg**
	Arm dimensions comparable to those of human	***Shoulder - Wrist distance:* 615.5 mm**
Sensing	High proprioception	***Sensors:* Absolute + Incremental Encoder, IMU, Joint Torque, Temperature.**
Usefulness	Lift and carry large payloads	***Max. Payload @ Full Extension:* 10 kg**
	Large bi-manual workspace; similar to that of a human	***Bi-manual workspace:* 0.46 m²**
Robustness & Safety	Physical robustness against perturbations and impacts	**Joint Torque Limiter**
	React compliantly to unanticipated disturbances	**Active Compliance**

Table I: Mechanical Properties of the 7-DoF Arm

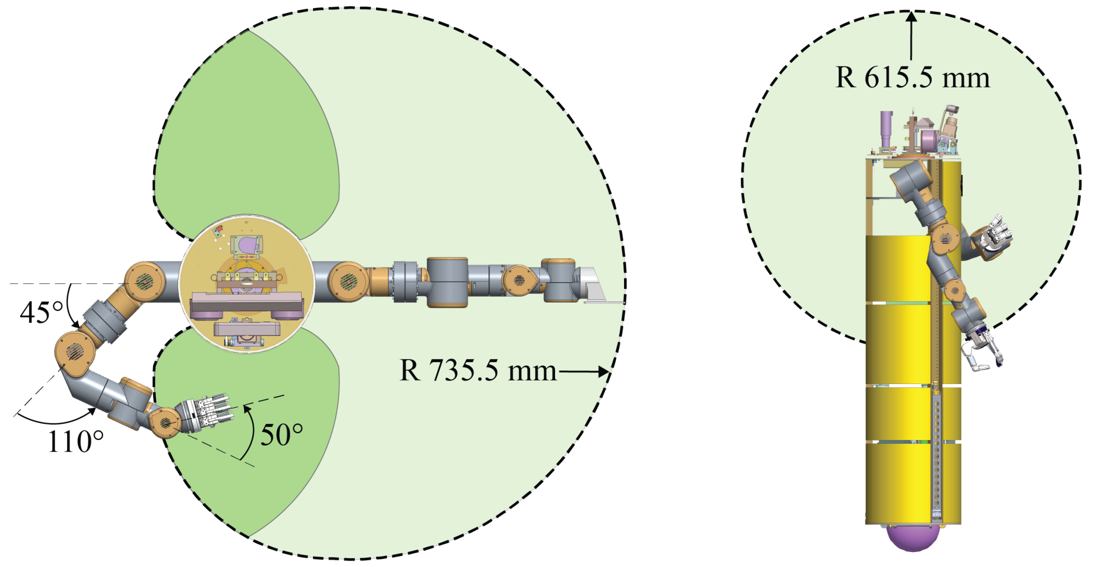
Experimental Validation

Video: Balancing while arm movement



Video: Lifting 6.8 kg [statically stable]

Workspace



(a) (b)

Figure 5: Workspace of the ballbot arms: (a) top view (b) side view. Dark green represent bi-manual workspace area.

Conclusion

- Developed pair of 7-DoF arms of comparable size and weight to that of an average adult human.
- Introduced a new type of agile and dexterous mobile manipulator by adding a pair of 7-DoF arms and hands to enhance the CMU ballbot research platform.
- Demonstrated lifting a 6.8 kg payload with Barrett Hand
- Demonstrated successful control of the arms while balancing.

Future Work

- Developing more intelligent controls that combine manipulation and locomotion - whole body control
- Incorporate vision to improve end-effector position
- Realize assistive tasks such as maneuvering a manual wheelchair, leading elderly or sight impaired individuals from place to place

[1] U. Nagarajan, G. Kantor, and R. Hollis, “The ballbot: An omnidirec- tional balancing mobile robot,” *The International Journal of Robotics Research*, vol. 33, no. 6, pp. 917–930, 2014.

[2] F.Sonnleitner,R.Shu,andR.L.Hollis,“Themechanicsandcontrolof leaning to lift heavy objects with a dynamically stable mobile robot,” in *RoboticsandAutomation,(ICRA)InternationalConferenceon*. IEEE, 2019, pp. 9264–9270.

[3] S. Rader, L. Kaul, H. Fischbach, N. Vahrenkamp, and T. Asfour, “Design of a high-performance humanoid dual arm system with inner shoulder joints,” in *Humanoid Robots (Humanoids), International Conference on*. IEEE, 2016, pp. 523–529.

[4] L. Baccelliere, N. Kashiri, L. Muratore, *et al.*, “Development of a human size and strength compliant bi-manual platform for realistic heavy manipulation tasks,” in *Intelligent Robots and Systems, (IROS) International Conference on*. IEEE, 2017, pp. 5594–5601.

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Arm Dimensions

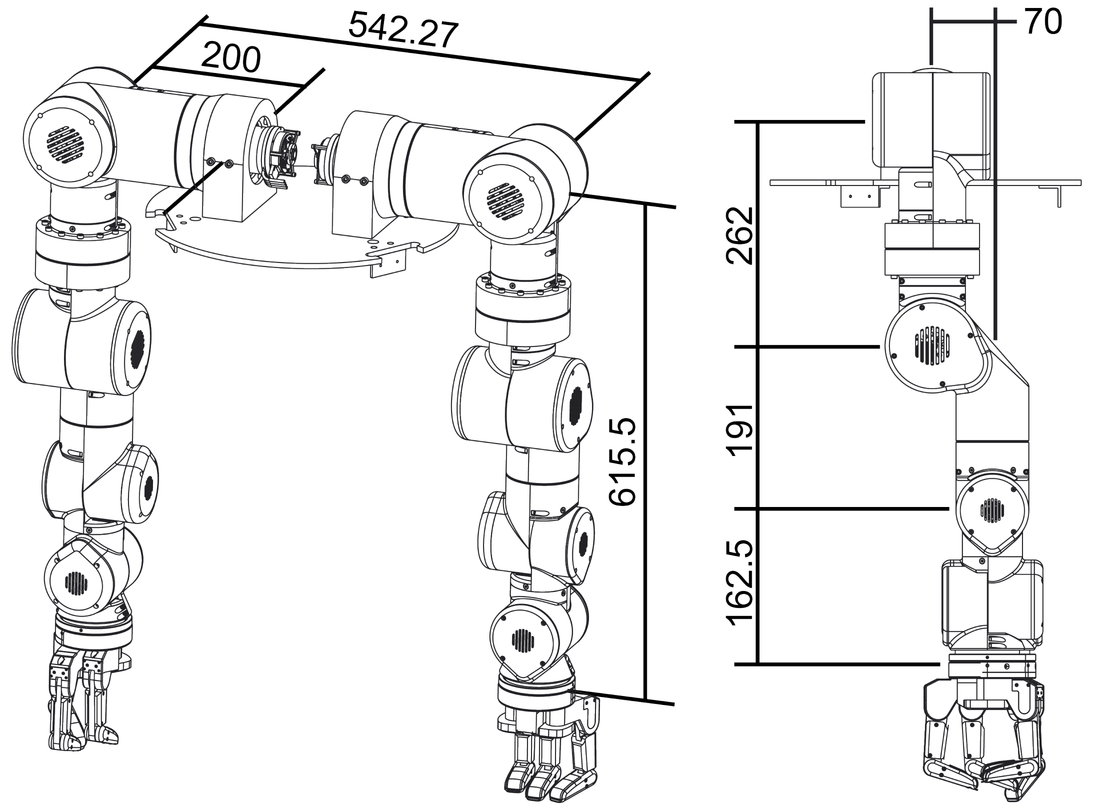


Figure 6: Size specification for pair of arms, all dimensions in mm.

Robot vs Human Workspace

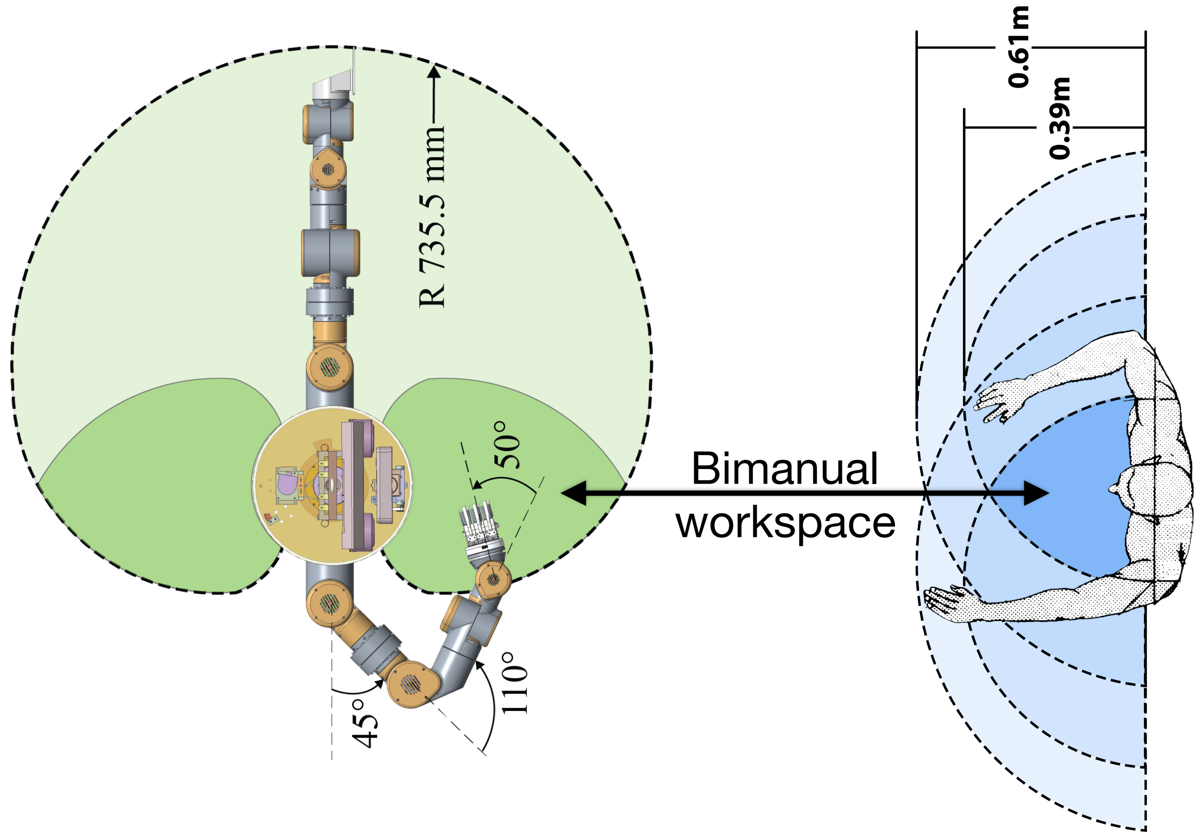
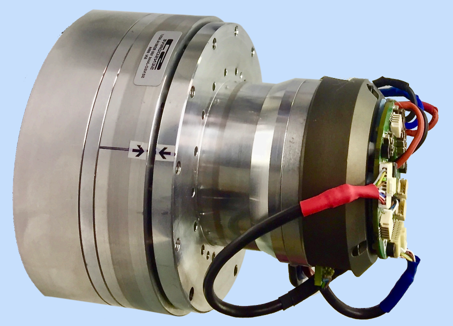


Figure 7: Workspace of the ballbot arms: (a) top view (b) side view. Dark green represent bi-manual workspace area.

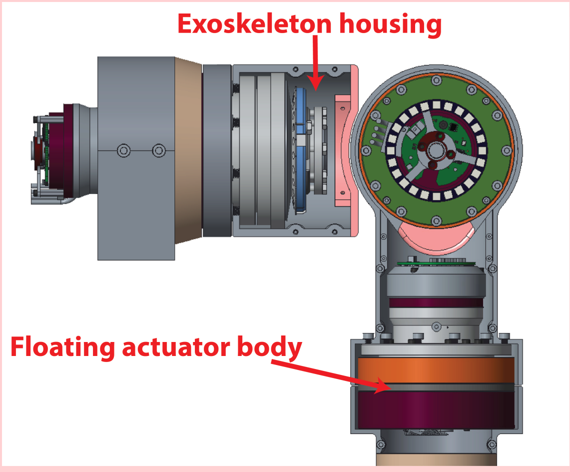
Key Design Features

Compact Sensor-Actuator-Control Units



- High density BLDC motors + High ratio gear box
- Torque sensor + IMU
- Integrated motor controller
- Daisy Chain
- Hollow Shaft
- Multi-turn

Load-bearing exoskeleton construction

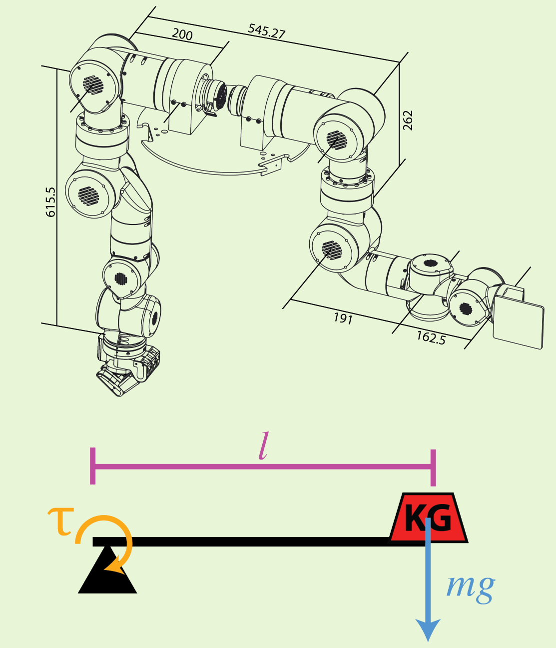


- Low-weight design; hollow 3mm shell structure
- The links weigh between 0.242 kg - 0.454 kg

Link bending stiffness: K = 3EI/L .

- Can increase link stiffness; thus increase precision

Short moment arm



$$\tau = l \cdot m \cdot g$$

- Arm reach: **0.615 m**

7-DoF Arm Joint Specs

Joint No.	Articulation	Range [deg.]	Actuator Type [SENSO-Joint]	Gear Ratio	Torque [N/m] peak - nominal	Max. Velocity [rpm]	Mass [kg]
1	Shoulder flexion/extension	[-720, 720]	100 RD5014 AEST	160	120 - 56	21	1.45
2	Shoulder abduction/adduction	[-10,190]	100 RD5014 AEST	160	120 - 56	21	1.45
3	Shoulder rotation int./ext.	[-720, 720]	100 RD5008 AEST	160	100.8 - 30	34	1.35
4	Elbow flexion/extension	[-30,110]	100 RD5008 AEST	160	100.8 - 30	34	1.35
5	Wrist rotation	[-720,720]	75 RD3806 AEST	100	19 - 5.4	85	0.7
6	Wrist flexion/extension	[-90,90]	75 RD3806 AEST	100	19 - 5.4	85	0.7
7	Wrist abduction/adduction	[-90,90]	75 RD3806 AEST	100	19 - 5.4	85	0.7

Ballbot Evolution

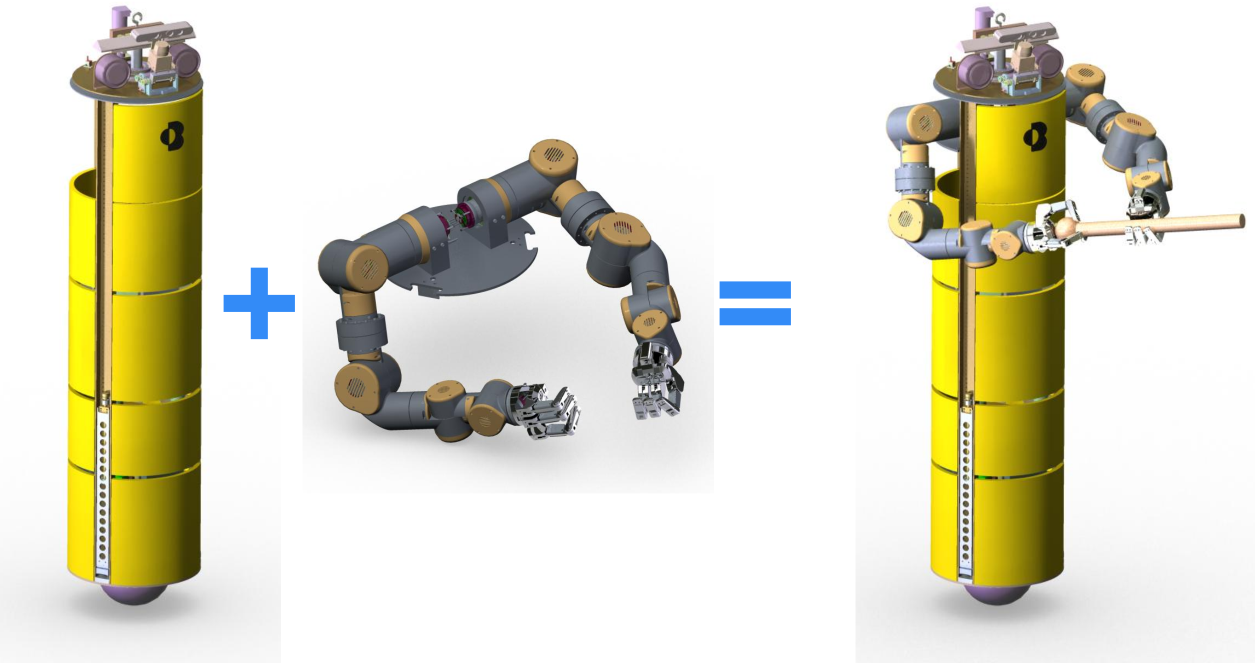


Figure 8: System integration performed in this work

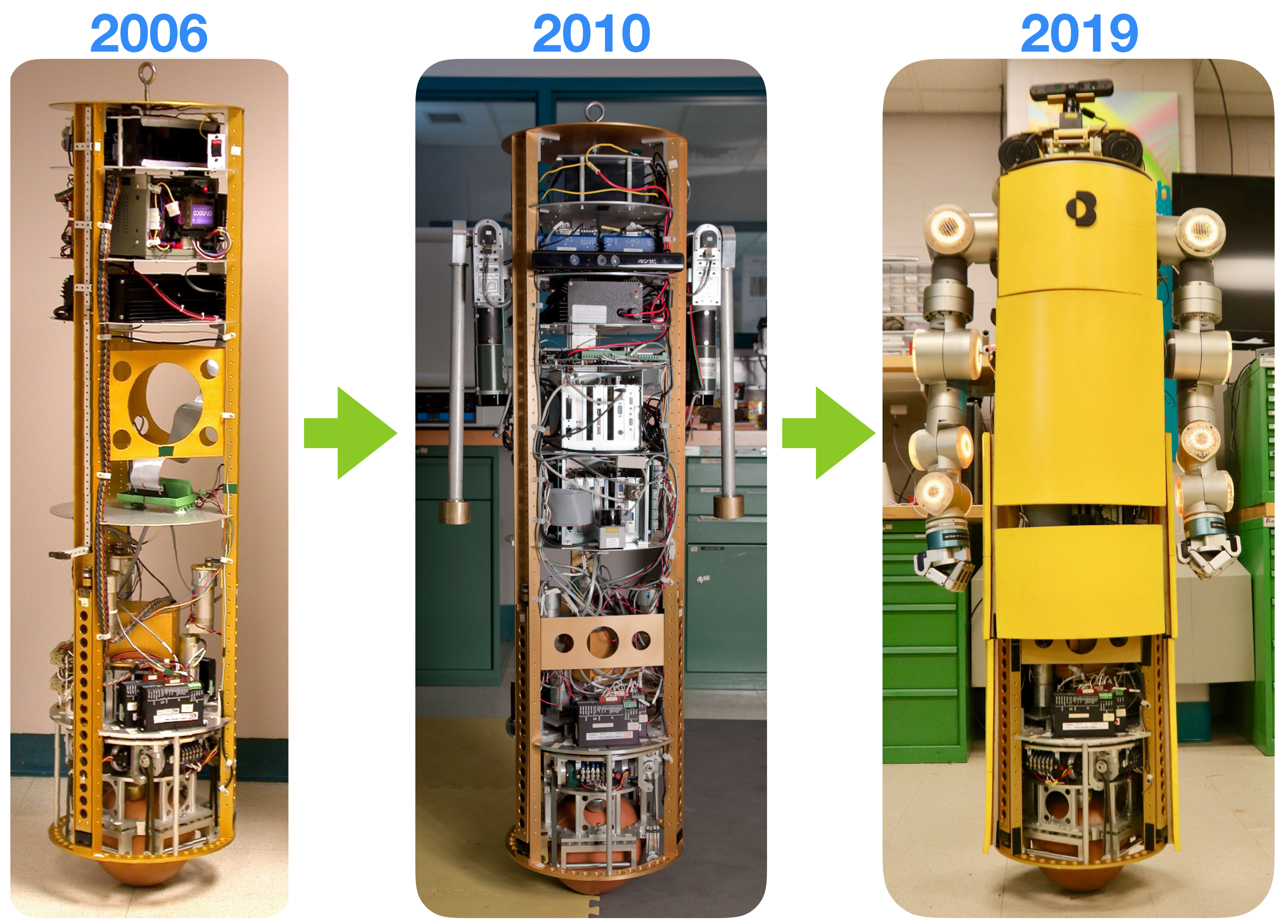


Figure 9: Evolution of the CMU ballbot research platform. In all images the ballbot is dynamically balancing.

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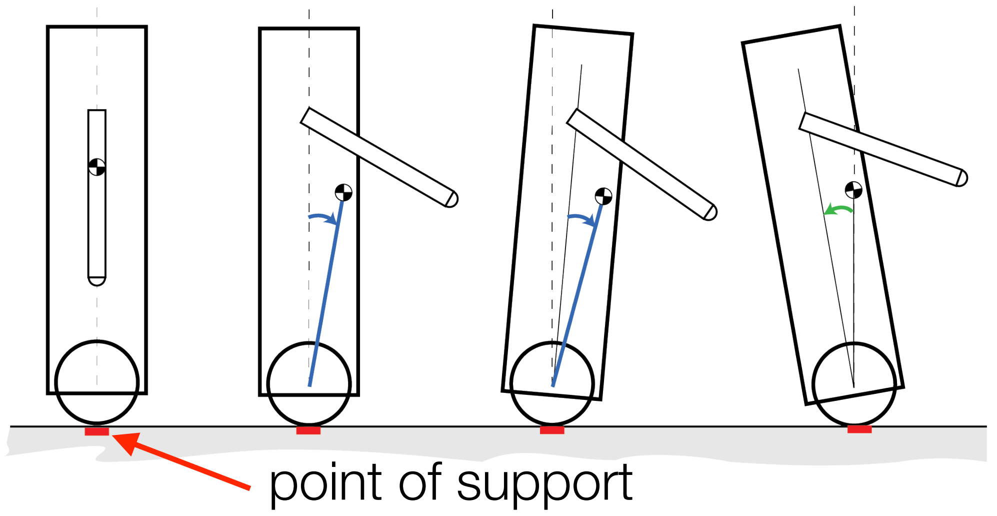
Balancing controller

Challenges:

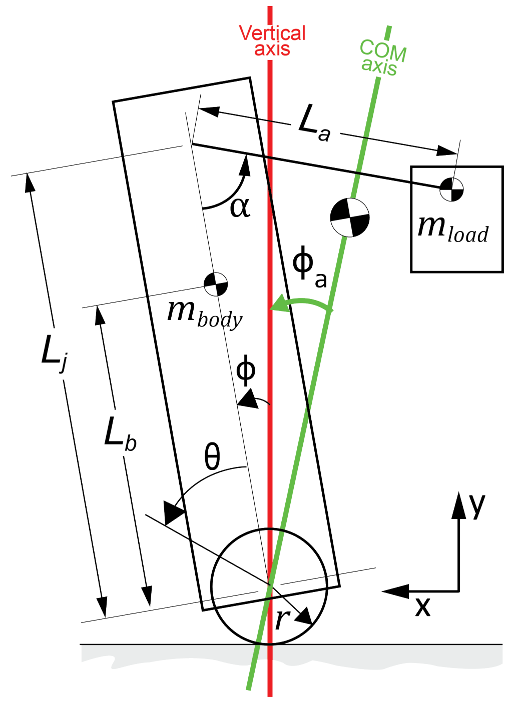
Ballbot is a shape accelerating robot:

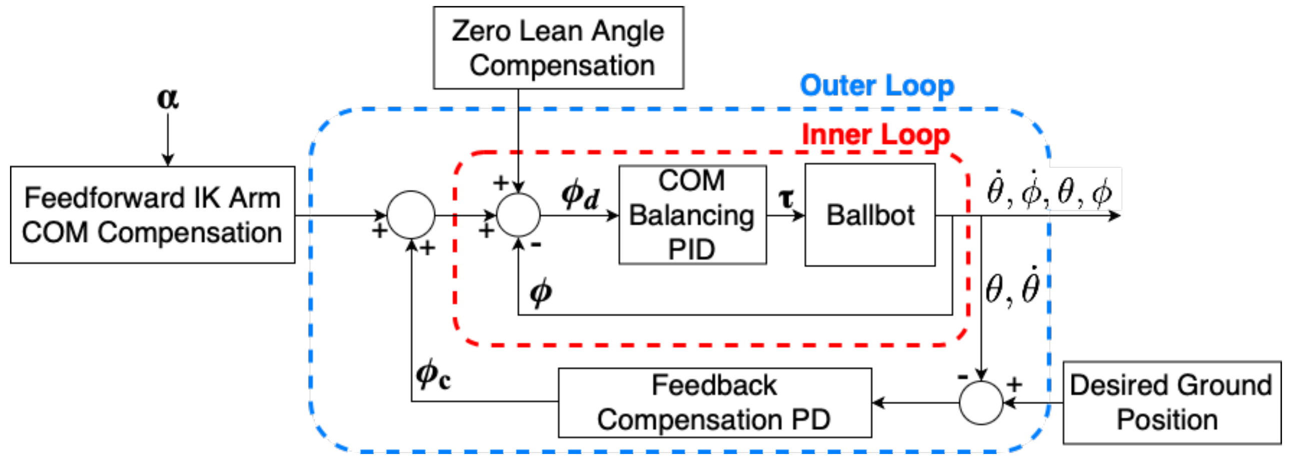
- Point instead of polygon of support
- Changes in the shape of the robot will cause it to accelerate



Cascading PD-PID with feedforward COM regulation

- 3D Forward Kinematics and CAD model properties used to estimate the COM position
- The FF compensation lean angle trajectory is calculated through a forward kinematics analysis of the desired joint trajectory to determine the resulting COM angle offset
- The balancing controller runs real-time at 500 Hz on a second Intel Core2 Duo @ 2.4GHz onboard computer running QNX RTOS.





Zero Lean Angle Compensation

Outer Loop

Inner Loop

α

Feedforward IK Arm COM Compensation

ϕ_d

COM Balancing PID

τ

Ballbot

$\dot{\theta}, \dot{\phi}, \theta, \phi$

ϕ

$\theta, \dot{\theta}$

ϕ_c

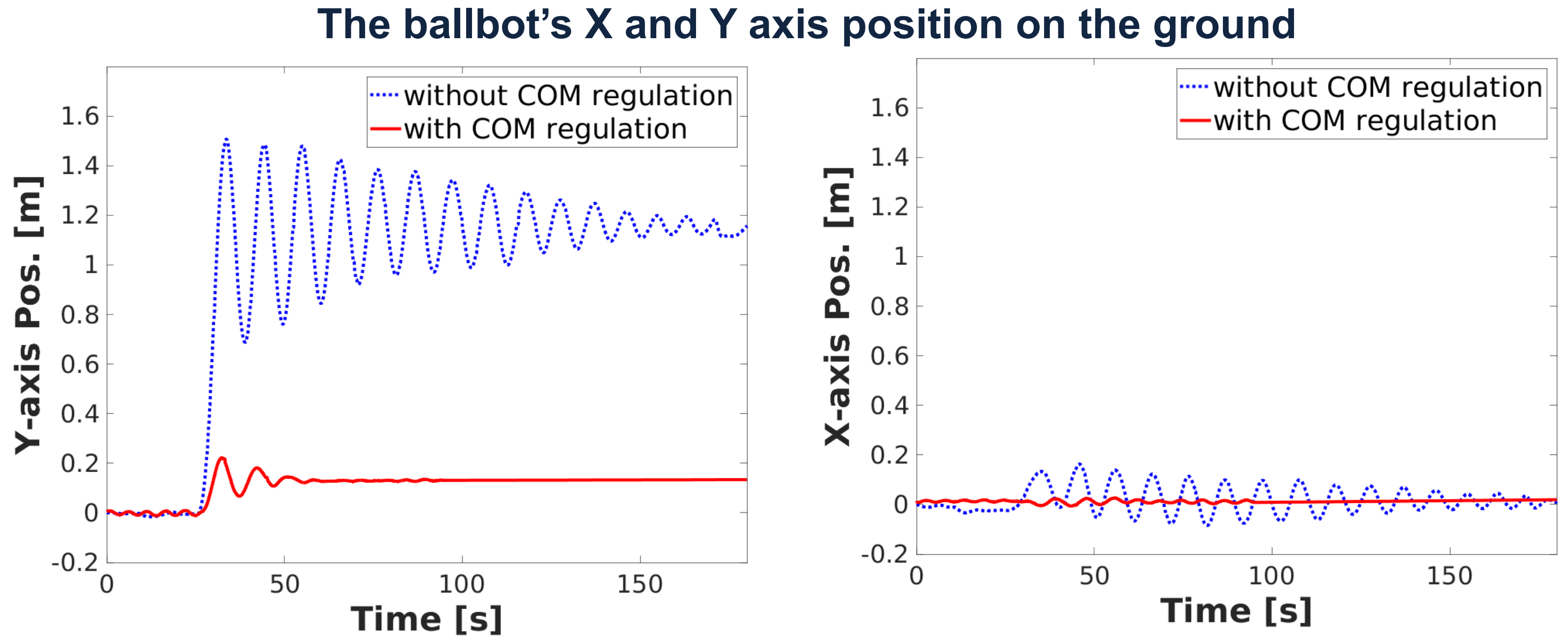
Feedback Compensation PD

Desired Ground Position

Figure 11: Overview of the balancing cascading control loops with feedforward lean angle compensation term

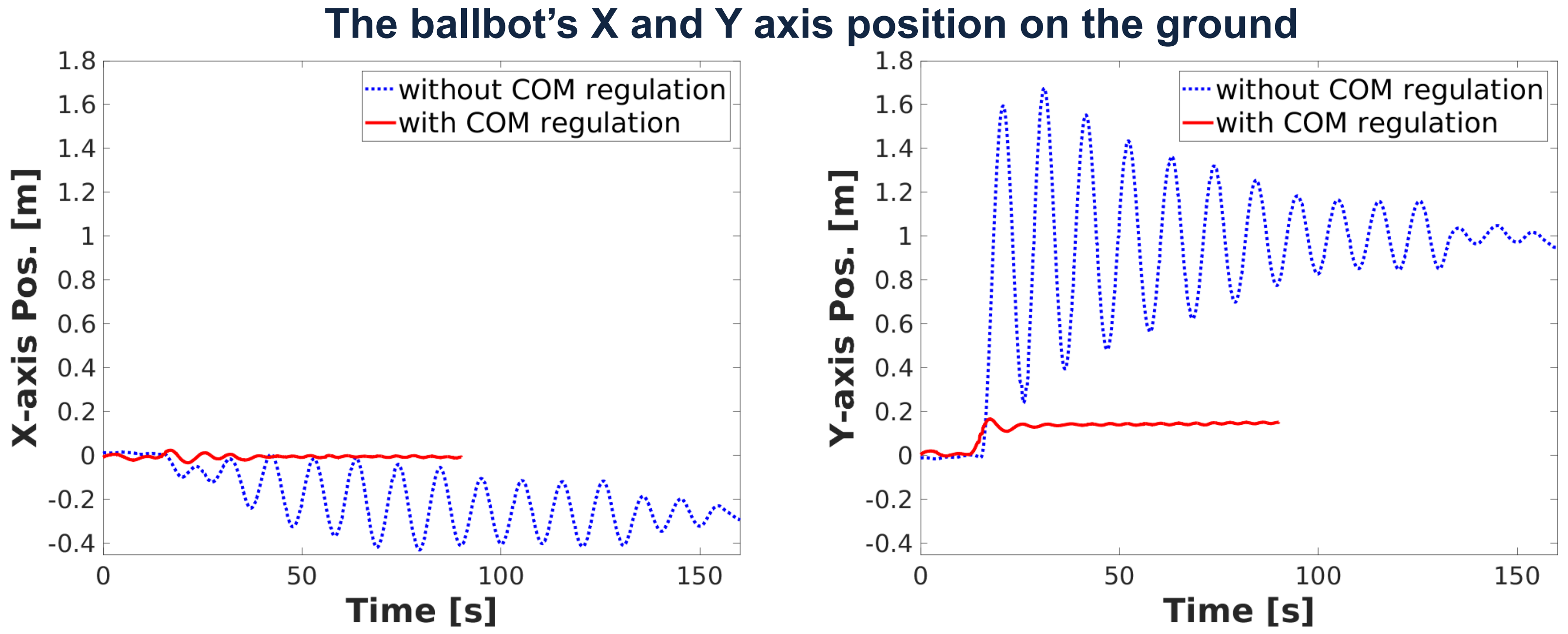
Balancing Evaluation

Single Arm Motion



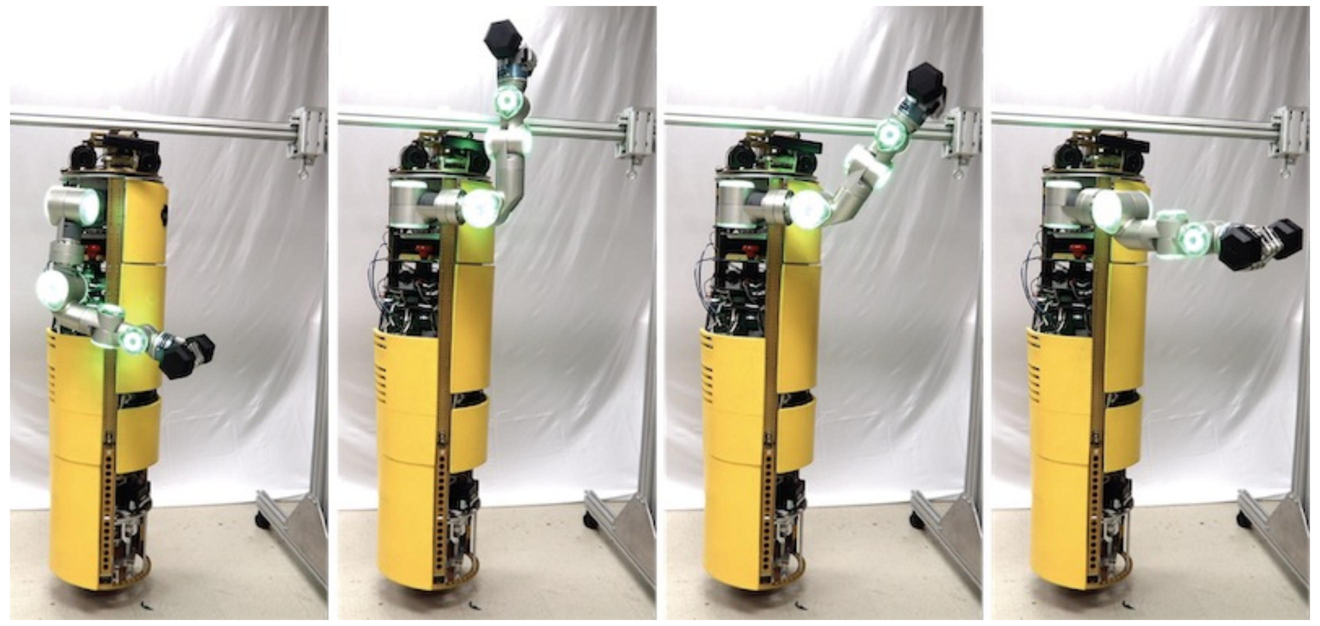
The ballbot's X and Y axis position on the ground

Double Arm Motion



The ballbot's X and Y axis position on the ground

Lifting 6.8 kg Payload



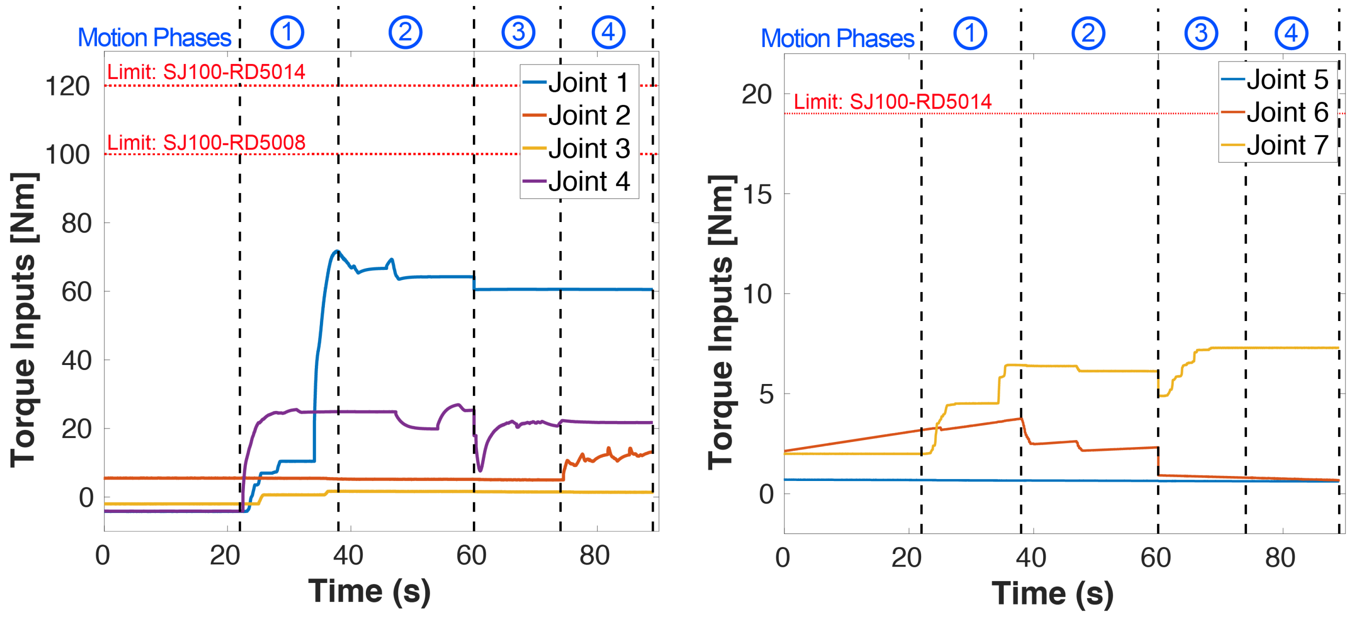
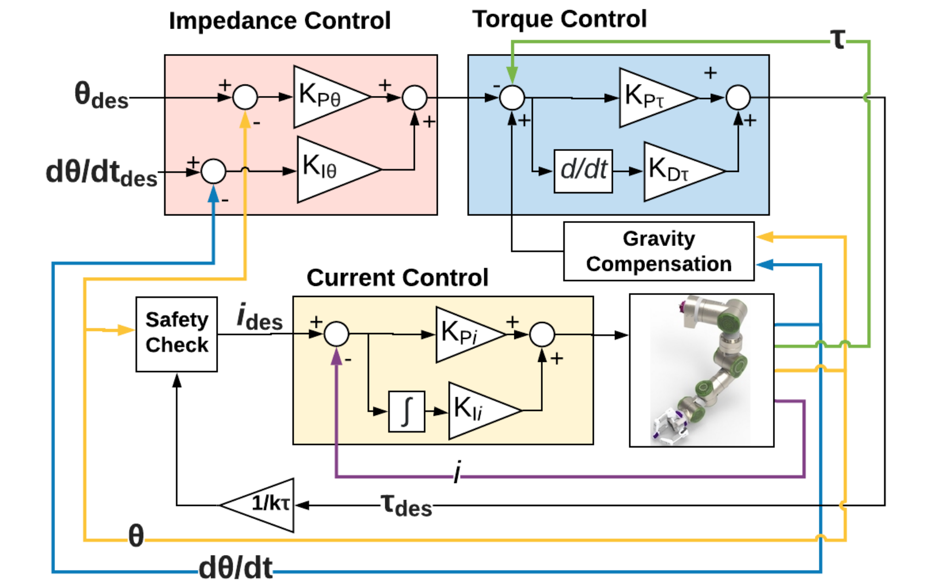


Figure 1: Joint torque command evolution to lift a 6.7 kg payload at the end of the arm.

Arm Controller



Impedance Control

Torque Control

Current Control

θ_{des}

$d\theta/dt_{des}$

$K_{P\theta}$

$K_{I\theta}$

$K_{P\tau}$

d/dt

$K_{D\tau}$

τ

Gravity Compensation

Safety Check

i_{des}

K_{Pi}

$\int$

K_{Ii}

i

$1/k_\tau$

τ_{des}

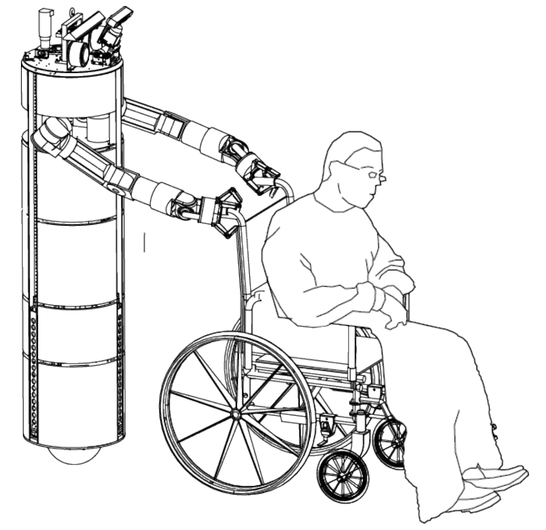
θ

$d\theta/dt$

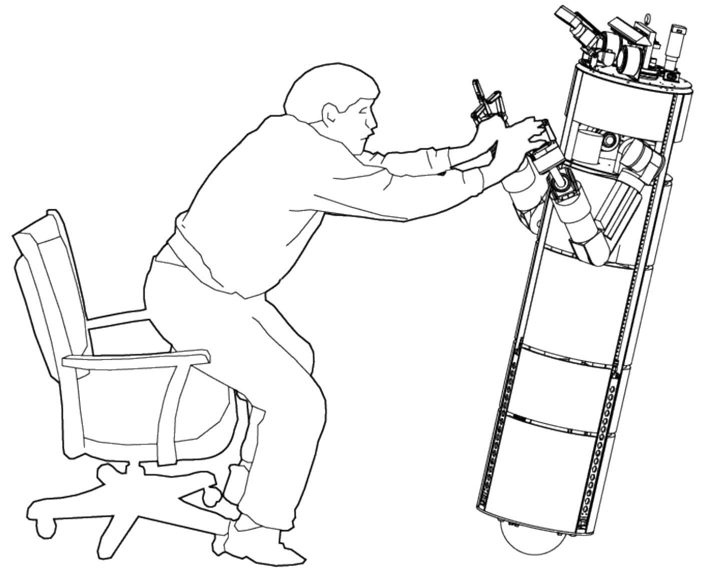
Figure 10: Block diagram of the impedance joint controller with gravity compensation.

Future Work and Applications

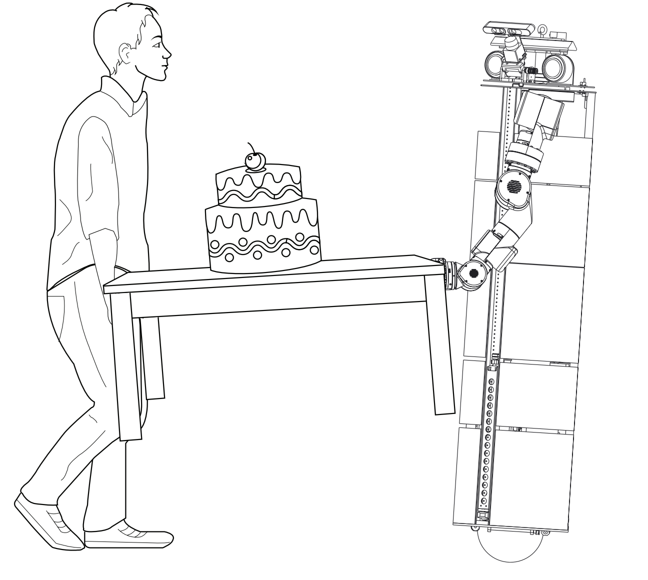
Maneuvering a manual wheelchair



Sit-to-stand maneuvers



Cooperative carrying



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