The Mechanics and Control of Leaning to Lift Heavy Objects with a Dynamically Stable Mobile Robots

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Overview

To be truly useful, mobile robots need to be able to lift and transport objects to collaborate with humans in work and home environments. Humans performing repetitive heavy lifting tasks may suffer injuries and problems such as low back pain [1]. Previous work has successfully demonstrated two-wheeled dynamically stable mobile manipulator robots transporting heavy objects. We report here the first ballbot to reliably achieve such a task. A successful semi-autonomous lift and transport of a heavy box of unknown mass (up to 15 kg) was achieved using a combination of feedforward and feedback control laws based on a quasi-static center of mass computation.

A control algorithm was developed to enable dynamically stable spherical-wheel robots (ballbots) with arms to semi-autonomously:

1) detect a heavy payload of unknown mass
2) navigate to it
3) lift and transport it
4) place it at a desired location

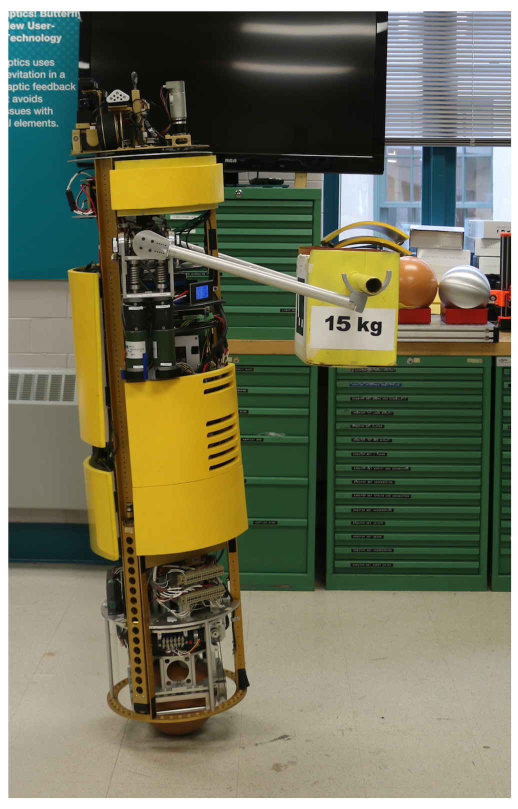


Figure 1: The CMU ballbot lifting a 15 kg payload using its 2-DOF arms while maintaining a fixed location on the floor.

Lean Angle Compensation

The overall lean angle compensation consists of four separate blocks. The payload localization, the mass estimation, the center of mass calculation, and the lean angle control.

Payload localization

Payload's 3D pose estimation was performed through the ArUco [2] framework to detect AprilTags on the payload box.

ASUS Xtion Pro RGB-D camera mounted on the ballbot's pan/tilt turret was used for detection.

The box could be detected anywhere inside a circle of radius 3.5 m centered at the ballbot.

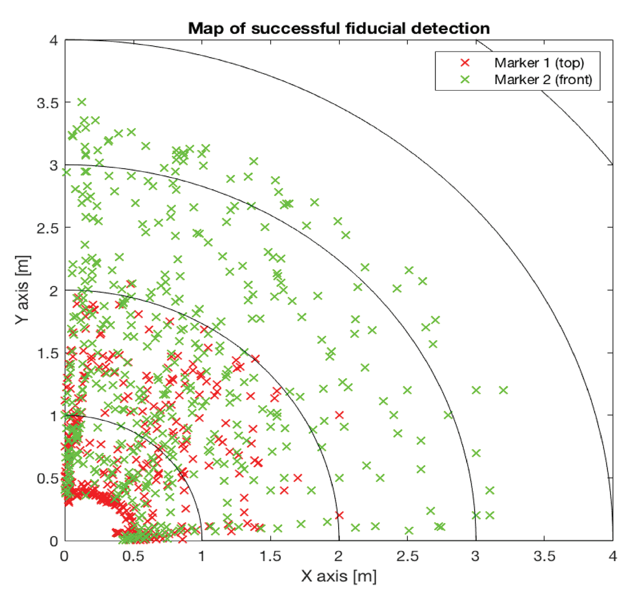


Figure 2: Turret RGB-D camera object detection and localization range using the ArUco framework.

Online payload mass estimation

Mass estimated from elastic element deflection in the arm's SEAs.

Characterized the elastic element of the arms' SEAs with respect to different payload mass to find polynomial relation between SEA deflection and payload mass.

We estimate mass at same rate of the controller, 500Hz.

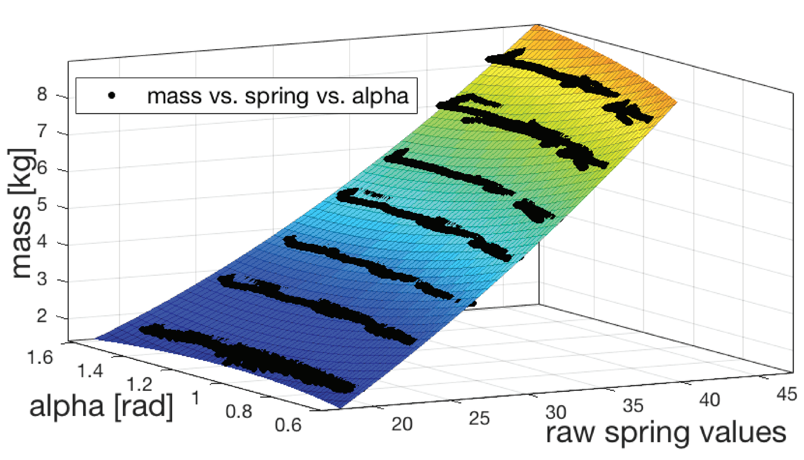


Figure 3: Plot of recorded deflection angles due to different payload masses (black). Fitted polynomial surface is overlayed data points.

Lean angle compensation

Center-of-Mass COM axis angle with respect to the vertical will change as arm angle α and payload mass m_{arm} change.

System COM position:

$$COM_{sys} = \frac{COM_{body} \cdot m_{body} + COM_{arm} \cdot m_{arm}}{m_{body} + m_{arm}}$$

COM angle offset w.r.t. gravity:

$$\phi_a = \operatorname{atan}\left(\frac{COM_{sys,x}}{COM_{sys,y}}\right)$$

Closed form solution:

$$\phi_a = \operatorname{acot}\frac{m_{body} \cdot L_b + m_{arm} \cdot (L_{armjoint} - L_a \cdot \cos(\alpha))}{L_a \cdot m_{arm} \cdot \sin(\alpha)}$$

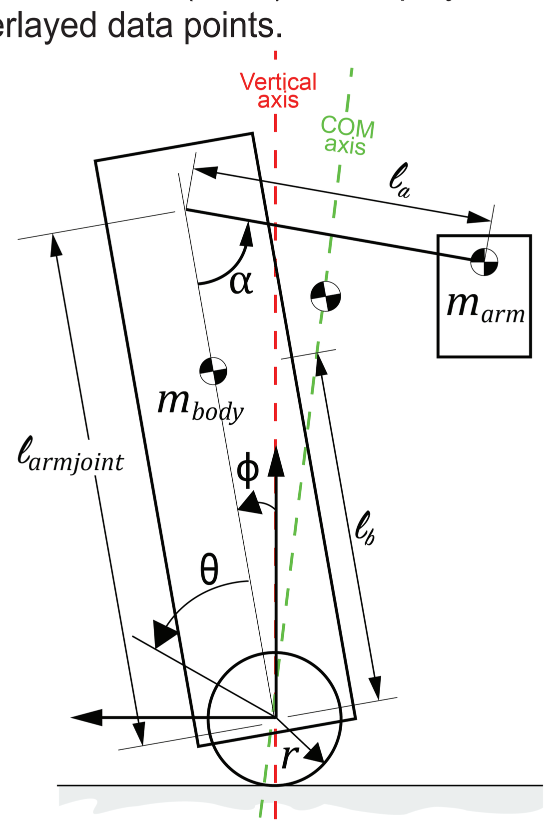


Figure 4: Planar ballbot model with arms and external payload.

Controller

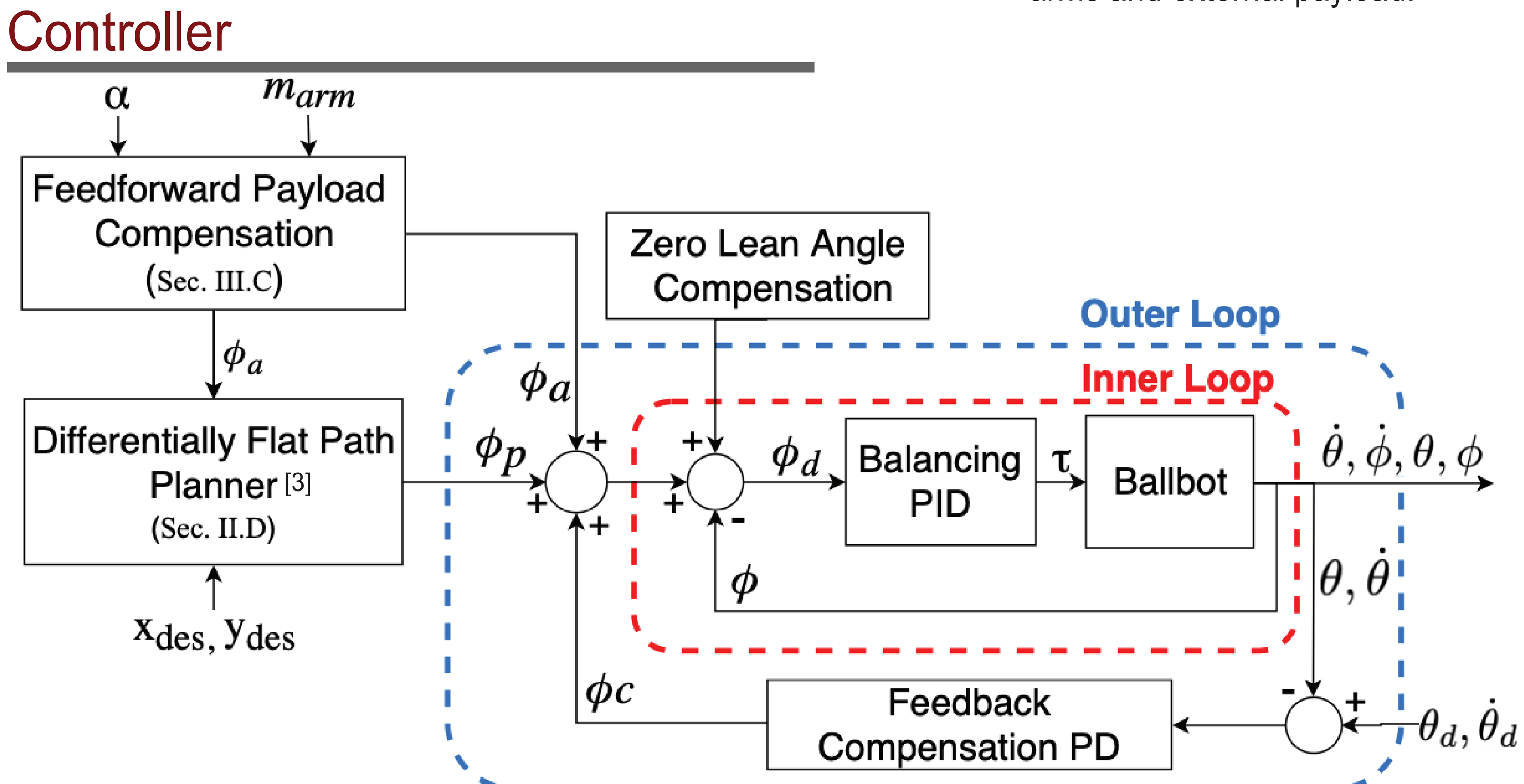


Figure 4: Overview of the implemented cascading control loops with feedforward compesation terms

Experimental Results

Lifting heavy payload + station keeping

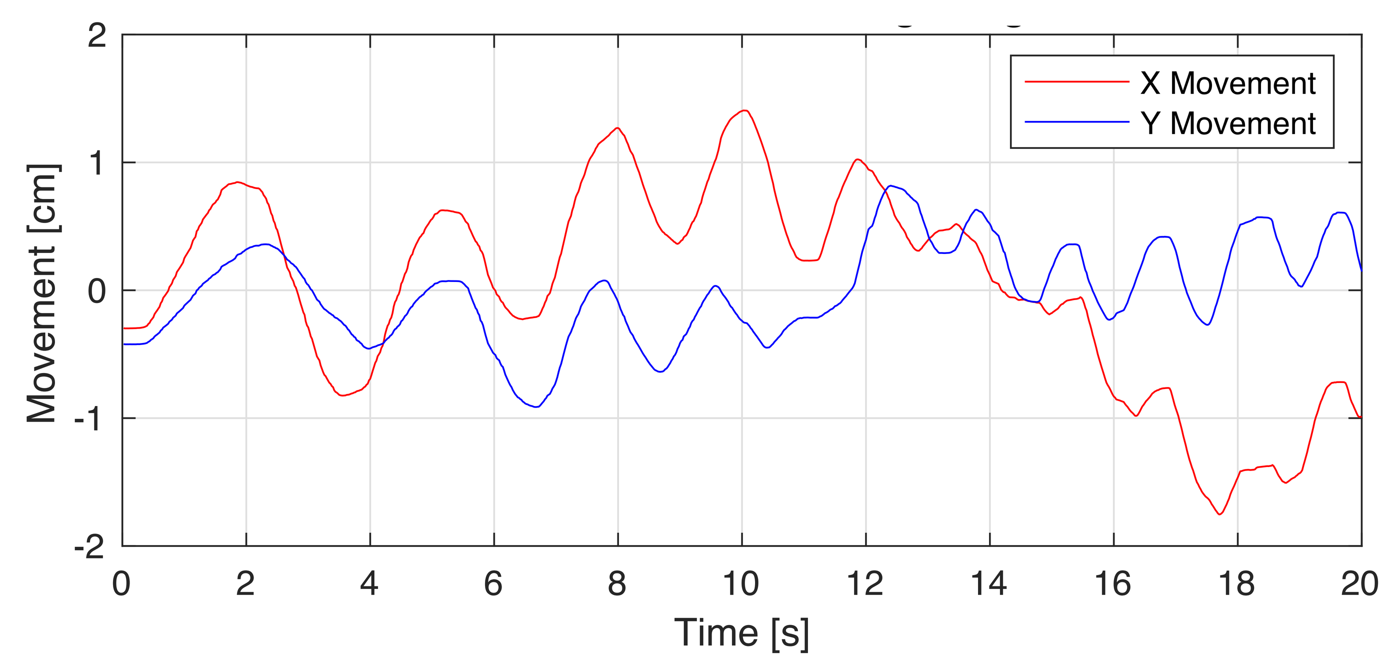
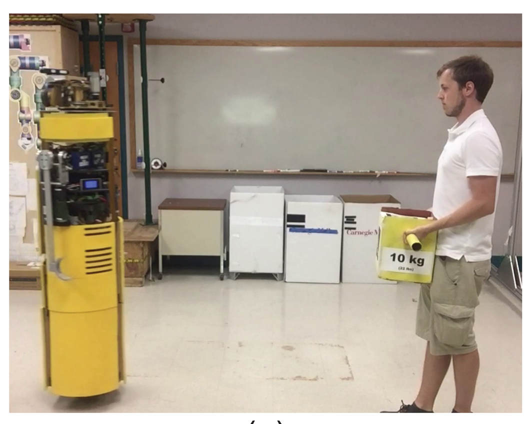


Figure 5: The ballbot ground position movement while lifting a 10 kg payload.

Human-to-ballbot transfer & transport



(a)
Navigating to payload in human arms

(b)
Recieving payload from human and actively estimating its mass (10 kg)

(c)
Navigating away from human with the payload

Lifting, yawing, and setting down a heavy payload

(a)
Detecting box on table

(b)
Lifting box from table

(c)
Yawing 90° in place

(d)
Setting payload down

Conclusion

- Showed the first ballbot to reliably achieve semi-autonomous lift and transport a payload of a unknown mass of up to 15 kg.
- Described a feedforward and feedback control law to balance and navigate while carrying a heavy payload.
- Online payload mass estimation through the characterization of the arm's SEAs.
- Sucessfully performed ballbot-to-human and human-to-ballbot exchanges of a 10 kg heavy object while dynamically balancing.

Future Work

- Heavy payloads require a large lean angle. In turn, the body mounted 2D LiDAR pitch view angle will change and hinder localization. Mounting the LiDAR in a gimbal would solve this issue.
- Replace simple 2-DOF arms with more powerful and dexterous 7-DOF arms and hands.
- Develop a unified locomotion and manipulation planning framework to improve the end-effector and ground position tracking precision.

[1] S. M. Hsiang, G. E. Brogmus, and T. K. Courtney, "Low back pain (LBP) and lifting technique - A review," International Journal of Industrial Ergonomics, vol. 19, no. 1, pp. 59–74, 1997.

[2] S. Garrido-Jurado, R. Mun oz-Salinas, F. Madrid-Cuevas, and M. Mar ın-Jime nez, "Automatic generation and detection of highly reliable fiducial markers under occlusion," Pattern Recognition, vol. 47, no. 6, pp. 2280–2292, 2014.

[3] M. Shomin and R. Hollis, "Differentially flat trajectory generation for a dynamically stable mobile robot," Proceedings - IEEE International Conference on Robotics and Automation,

Watch video

BALLBOT

Microdynamic Systems Laboratory