Designing for Unconventional Mobility and Manipulation in Space Robotics

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Introduction

When designing robots for space, we encounter challenges that conventional robots typically cannot overcome: for instance, payload limitations (minimizing stowed size and weight to fit onboard launch services), compute limitations (rad-hardened low-power processors), and requiring robustness at all costs (inaccessibility of the robot post-launch). This motivates rethinking the robot morphology to something less conventional, but better suited to these challenges. ReachBot, an extendable-boom-driven robot for advanced mobility and manipulation in space, addresses the challenge of maximizing the workspace volume, while still retaining a small stowed volume [1], [2], [3], [4], [5], [6]. Recently, a new hardware prototype, ReachBot-Lite (Fig. 1 A/B), demonstrates the key concepts behind the original idea (microspine grasping and boom-driven actuation), while significantly reducing the hardware requirements by incorporating cables into the design. Development of both the hardware and control systems of this robot has explored three key tenets of unconventional robot design: hardware design for efficient control, using strategies from conventional analogs, and hardware/simulation co-validation.

I. Hardware design for efficient control

Co-design of hardware and control systems is critical to ensure efficient operation with guarantees on optimality and robustness. Wherever possible, we use convex optimization in the planning and control methods, and ensure that the hardware lends itself to the use of these methods. For instance, with ReachBot-Lite, careful design of the interaction between the booms and cables is critical, so that we maintain a convex cone assumption for the domain of each cable. Without this, even if the total reachable area is greater for a non-convex design, we lose any guarantees on optimality and must resort to less-efficient planning methods. In general, if an unconventional robot adds new hardware capabilities over a conventional counterpart, it must employ efficient and guaranteeable control methods to fully take advantage of these capabilities.

II. Using strategies from conventional analogs

With unconventional platforms, not everything needs to be discovered from the ground-up: if the kinematics are similar to existing platforms, we can employ established control design methods, with some tweaks. ReachBot's manipulation and mobility planners (Fig. 1 C) build upon methods for cable-driven parallel robots (CDPRs) [7], [8] and dexterous hands [9], with modifications to include (1) reconfigurability, and (2) the stochasticity of microspine grasping. When all booms/cables are attached to the environment, ReachBot behaves as a parallel robot, relying primarily on tensile forces (like a CDPR). Additionally, these forces on the ReachBot body mimic those of a dexterous grasp – except, trading compression (fingers) for tension (booms/cables). Given this, we extend upon typical PD-based control methods for CDPRs by running convex-optimization-based tension planning methods in the loop to minimize the chance of stochastic failure. Additionally, we use techniques from dexterous

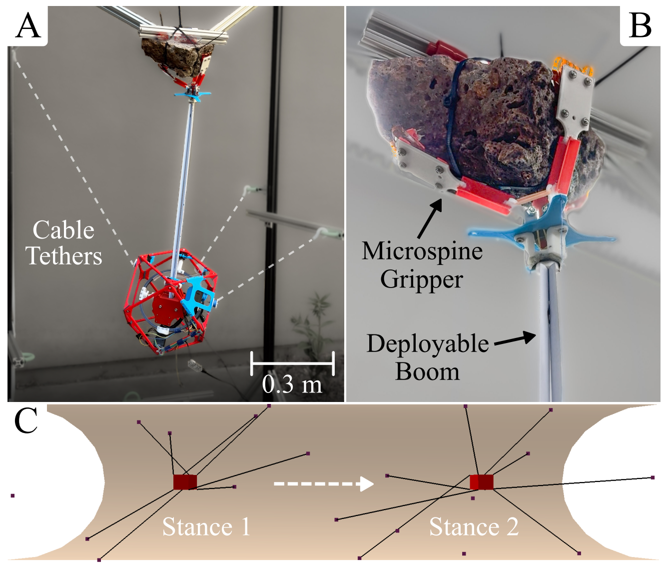

Fig. 1. (A) ReachBot-Lite hardware prototype, with combined cable/boom mobility and anchoring system. (B) Microspine grasping for anchoring to features in martian caves. (C) Simulated cave environment for motion planning between optimal stances.

grasping to select the positioning of the ReachBot booms/cables based on classical robustness metrics [10], [11], [12].

III. Hardware/simulation co-validation

Iterative validation of an unconventional concept in both hardware and software is critical to the design process. Simulation has helped validate the ReachBot kinematics and ensure that mobility methods are still feasible, even with a constrained hardware setup. We also used simulation to compare our planning methods across various embodiments of ReachBot – especially to visualize the tradeoff between using booms or cables. For ReachBot-Lite, our simulation showed that smart planning of the gripper placements can mitigate the downsides of the cable-driven version, particularly with respect to vibrational modes and workspace size [6].

Also, the relationship between hardware and simulation validation is bidirectional: hardware can help guide the software and simulation development as well. Repeated prototyping of the hardware encourages designing control methods that are agnostic to the exact hardware configuration, and this process also helps understand what is feasible to develop. It is easy to design an unconventional system in simulation which is impossible to build on real hardware, and this hardware/software interaction serves as a check and balance on the development process.

Conclusion

Every conventional robot was once a far-fetched concept: with these design tenets, we aim to bring unconventional ideas into reality for new space robotics missions.

REFERENCES

[1] S. Schneider, A. Bylard, T. G. Chen, P. Wang, M. Cutkosky, and M. Pavone, "Reachbot: A small robot for large mobile manipulation tasks," in *2022 IEEE Aerospace Conference*, IEEE, 2022.

[2] S. Newdick, T. G. Chen, B. Hockman, E. Schmerling, M. R. Cutkosky, and M. Pavone, "Designing reachbot: System design process with a case study of a martian lava tube mission," in *2023 IEEE Aerospace Conference*, pp. 1–9, 2023.

[3] T. G. Chen, B. Miller, C. Winston, S. Schneider, A. Bylard, M. Pavone, and M. R. Cutkosky, "Reachbot: A small robot with exceptional reach for rough terrain," in *IEEE ICRA 2022*, pp. 4517–4523, 2022.

[4] S. Newdick, N. Ongole, T. G. Chen, E. Schmerling, M. R. Cutkosky, and M. Pavone, "Motion planning for a climbing robot with stochastic grasps," in *IEEE ICRA 2023*, pp. 11838–11844, 2023.

[5] T. G. Chen, S. Newdick, J. Di, C. Bosio, N. Ongole, M. Lapôtre, M. Pavone, and M. Cutkosky, "Locomotion as manipulation: Grasp analysis for ReachBot," *Science Robotics*, 2024. Accepted.

[6] D. Morton, M. Cutkosky, and M. Pavone, "Task-driven manipulation with reconfigurable parallel robots," *arXiv preprint arXiv:2403.10768*, 2024. Submitted to 2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).

[7] S. Qian, B. Zi, W.-W. Shang, and Q.-S. Xu, "A review on cable-driven parallel robots," *Chinese Journal of Mechanical Engineering*, vol. 31, p. 66, Aug 2018.

[8] D. Q. Nguyen, *On the Study of Large-Dimension Reconfigurable Cable-Driven Parallel Robots*. Theses, Université Montpellier 2, Dec. 2014.

[9] A. Okamura, N. Smaby, and M. Cutkosky, "An overview of dexterous manipulation," in *IEEE ICRA 2000*, vol. 1, pp. 255–262 vol.1, 2000.

[10] C. Ferrari and J. Canny, "Planning optimal grasps," in *IEEE ICRA 1992*, pp. 2290–2295 vol.3, 1992.

[11] R. Haschke, J. Steil, I. Steuwer, and H. Ritter, "Task-oriented quality measures for dextrous grasping," in *IEEE CIRA 2005*, pp. 689–694, 2005.

[12] Z. Li and S. Sastry, "Task-oriented optimal grasping by multifingered robot hands," *IEEE Journal on Robotics and Automation*, vol. 4, no. 1, pp. 32–44, 1988.