GIRAF - Greatly Increased Reach for Adaptive Fieldwork

Stanley Wang*, Long Yin Chung, Venny Kojouharov, Lukas Klostermair, Dan Morton, and Mark Cutkosky

***Abstract*— We present GIRAF (Greatly Increased Reach for Adaptive Fieldwork), a mobile manipulation platform integrating an ANYmal D quadruped with a long-reach deployable manipulator arm. Compared to conventional architectures, incorporating a deployable joint enables greater reach while preserving useful payload capacity. This is well suited to construction, inspection, and maintenance tasks in field and space environments, where robots operate across large structures and extended workspaces. On the lunar surface, for example, infrastructure tasks can require access across multiple meters. Tasks such as cable routing, large-surface cleaning, and servicing distributed infrastructure benefit from extended reach (>3 m), enabling access to otherwise inaccessible locations and improving task efficiency. We present the GIRAF system design, an optimization-based formulation for robust mobile manipulation, and initial hardware deployments.**

***Index Terms*— Space robotics, field robotics, manipulation, deployable, in-space manufacturing and assembly**

I. INTRODUCTION

Large-scale construction, inspection, and maintenance in field and space environments require robots to operate across workspaces far larger than themselves. On the lunar surface, future infrastructure [1] [2], including large vertical solar arrays [3], launch/landing sites, and habitats constructed via in-situ resources [4] [5], demands extensive construction, inspection, and maintenance. In these settings, robots must reach individual task locations while working efficiently across large structures and partially built environments. Tasks such as routing cable harnesses through partially built structures [6], cleaning dust off solar array panels [7], or fixturing and installing sensors [1] therefore require operation across regions spanning multiple meters.

As shown in Fig. 1, GIRAF addresses this challenge with a legged mobile manipulation platform that combines an ANYmal D quadruped [8] with a long-reach deployable arm. The mobile base provides rough-terrain mobility and coarse repositioning, while the deployable manipulator enables access to a large workspace, supporting task execution across large, partially structured environments. We coordinate them through an optimization-based planning formulation that jointly reasons over base placement and arm reachability for obstacle-aware task execution.

II. RELATED WORK

Conventional mobile manipulators tend to tackle the challenge of large workspace access poorly. Robots such as the GITAI Inchworm [9] or NASA ARMADAS [10] rely on self-locomotion with small manipulators to operate within a modularized structure, achieving simple and reliable traversal but at low speeds and only across such structured environments. Conversely, the NASA LSMS (Lightweight Surface Manipulation System) [11] performs well across fixed work areas but is far more difficult to reposition.

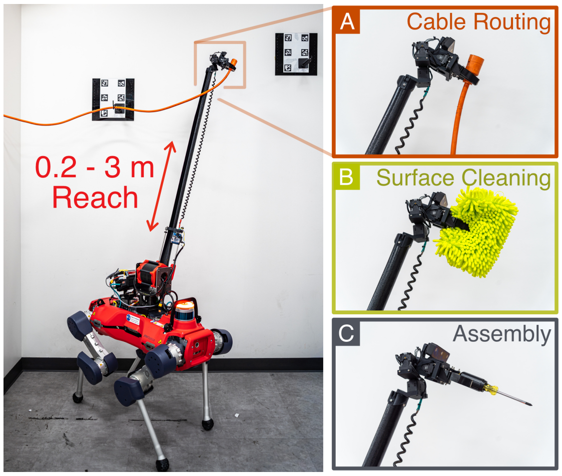

Fig. 1. The GIRAF system (left) consists of an ANYmal D legged quadruped with a lightweight deployable manipulator arm. This enables large workspace tasks for lunar construction, such as (a) cable outfitting, (b) cleaning and inspection, and (c) fixturing and assembly

Deployable structures offer a promising solution by bridging the gap between transportability and workspace access for large-scale construction and maintenance tasks. Deployable booms are well established in space applications requiring compact stowage and large deployed length, including CTM, STEM, and TRAC architectures [12]–[14]. Related mechanisms have also been explored in robotics for lightweight long-reach manipulation [15]–[17]. In the lunar domain, recent work has begun adapting these ideas to tasks such as cable routing and surface cleaning, while also highlighting practical challenges arising from boom compliance, vibration, and deployment uncertainty [6], [7].

However, effective operation in these environments depends on more than workspace access, since the robot must also traverse unstructured terrain reliably. This motivates a mobile base that can reposition efficiently over rough terrain while supporting precise manipulation. Quadrupeds have shown promise for lunar and planetary navigation [18], [19], and prior work has studied base–manipulator coordination for planetary field tasks [20], while more recent systems demonstrate whole-body end-effector tracking with rigid arms [21]. GIRAF builds on these directions by pairing a quadrupedal base with a deployable long-reach arm and jointly reasoning over base placement and arm configuration, enabling a single system to balance terrain mobility, workspace access, and manipulation performance.

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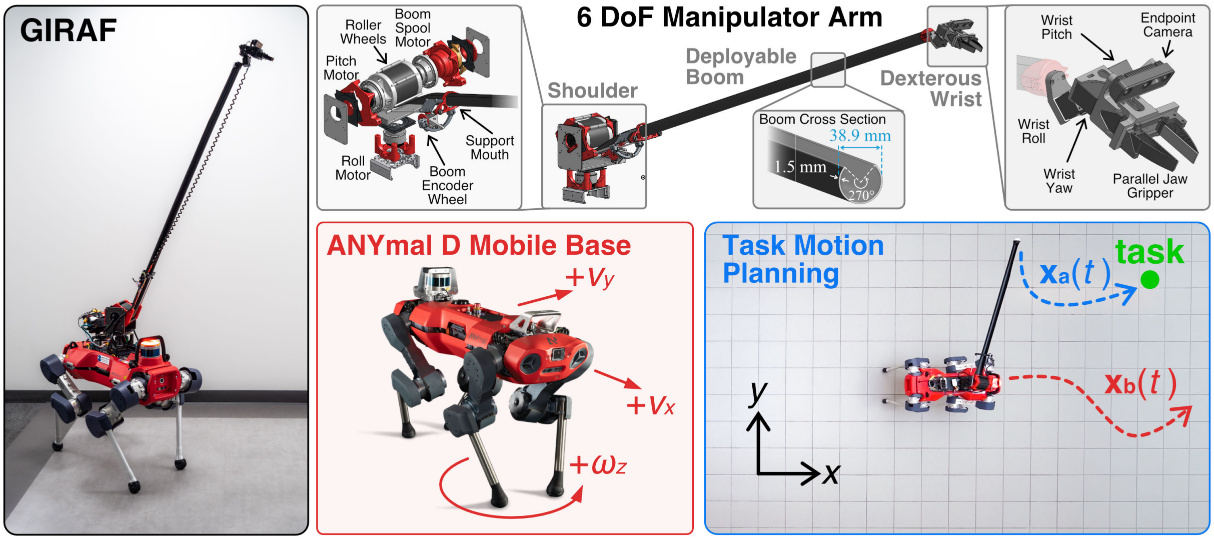

Fig. 2. System overview of the GIRAF (Greatly Increased Reach for Adaptive Fieldwork) robot. The ANYmal D legged mobile base is controlled with planar locomotion velocities (v_x, v_y, ω_z), with a 6 DoF deployable manipulator arm mounted on top and controlled with a resolved rate task motion controller. Motion planning of both mobile base and manipulator trajectories are designed to avoid obstacles while reaching task locations.

III. SYSTEM OVERVIEW

Fig. 2 shows an overview of the GIRAF system. The mobile base is an ANYmal D legged quadruped [8] capable of traversing complex surface terrains with a maximum speed of 1 m/s. We mount our deployable manipulator arm on top of this mobile base.

This manipulator uses a 3m rollable fiberglass boom (Metolius Climbing) [22] as a lightweight, low-cost deployable actuator that provides long reach while maintaining enough stiffness and durability for manipulation. Deployment is driven by a motorized spool with support rollers, while an encoder wheel mounted directly against the boom provides accurate deployed-length and velocity feedback to mitigate blossoming effects that would otherwise degrade extension control. The overall arm has 6 degrees of freedom (DoF), with two high-torque base joints for large-scale boom reorientation (θ_1, θ_2), a deployable boom for long-range extension (d_3), and a compact 3-DoF wrist at the endpoint for fine manipulation $(\theta_4, \theta_5, \theta_6)$. A parallel-jaw gripper with compliant fingers is utilized for general-purpose grasping.

All control stacks are implemented in Dockerized ROS 1 Noetic and run onboard an ASUS NUC 14 Pro+.

IV. TRAJECTORY PLANNING

A. Overview

To operate effectively across large workspaces, we balance the kinematic tradeoffs between the mobile base (ANYmal D quadruped) and long-reach manipulator arm. For instance, precise deliberate motions at the deployable arm's endpoint are well suited for fine manipulation tasks, while movement of the quadruped base is important for large-scale navigation and substantial pose reorientation.

We formulate this coordination between the mobile base and the manipulator as an optimal trajectory planning problem. Here, we consider the quadruped base as a point robot with planar degrees of freedom, position $\mathbf{x}_b = (x_b, y_b)$ and yaw θ_b, while the long-reach arm has a full 3D workspace with endpoint position $\mathbf{x}_a = (x_a, y_a, z_a)$. We thus define the position of the system as:

$$\mathbf{x} = \begin{bmatrix}\mathbf{x}_b & \mathbf{x}_a\end{bmatrix}^T = \begin{bmatrix}x_b & y_b & x_a & y_a & z_a\end{bmatrix}^T$$

We consider planning with trajectories defined by N discrete waypoints, used to define a polyline or smoothed cubic path:

$$X = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\}$$

The trajectory must navigate towards target task locations, while avoiding any workspace obstacles.

B. Task Reachability

Due to the compliant nature of the deployable long-reach arm, task accuracy and stability tend to scale inversely with deployed boom length (d_3). Thus, for given predefined task requirements, we can impose a maximum allowable limit on boom length. Projecting the task point to planar coordinates $\mathbf{x}_t = (x_t, y_t)$ consistent with the mobile base, we define a 2D reachability constraint as:

$$\|\mathbf{x}_b - \mathbf{x}_t\|_2 \leq r_t$$

The metric r_t captures task limitations on boom length and the vertical height (z_t) of the task point. This represents a "safe radius" within which the mobile base $\mathbf{x}_b$ must be positioned such that the long-reach arm can fully execute the task below a given boom length limit.

We additionally consider workspace obstacles in a similar manner. For example, for a circular keep-out region with center and radius $(\mathbf{x}_o, r_o)$ within which the mobile base cannot traverse (but the long-reach arm can pass through/over), we define the constraint:

$$\|\mathbf{x}_b - \mathbf{x}_o\| \geq r_o$$

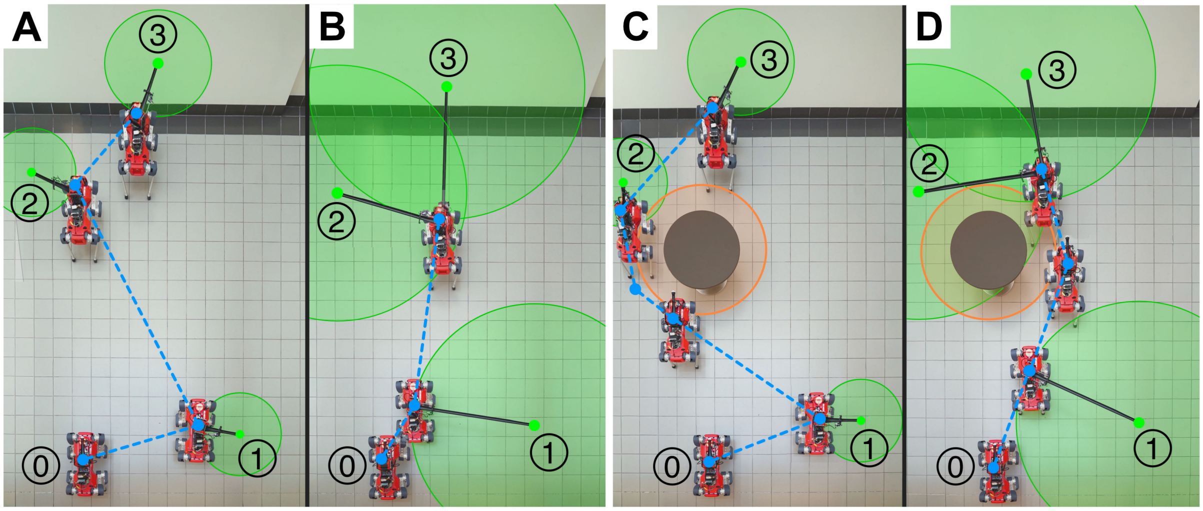

Fig. 3. Snapshots from motion planning experiments on GIRAF hardware. The robot begins at (0), then follows the dashed blue polyline trajectory to three task locations (1-3). At each task, the green radii represent the safe regions imposed by boom reachability limits. We consider planning with both long (2m) and short (0.5m) reach limits in both free space (A, B) and around a circular obstacle (C, D)

Experiment	Reach Limit	Obstacle	Distance	Time
A	0.5 m	no	6.5 m	48 sec
B	2.0 m	no	3.3 m	67 sec
C	0.5 m	yes	7.5 m	60 sec
D	2.0 m	yes	4.2 m	73 sec

TABLE I

C. *Problem Definition*

Consider a representative scenario consisting of three tasks

$$\{(\mathbf{x}_{t1}, r_{t1}),\ (\mathbf{x}_{t2}, r_{t2}),\ (\mathbf{x}_{t3}, r_{t3})\}$$

and a single obstacle $(\mathbf{x}_o, r_o)$. The planning problem is thus to generate a safe and viable trajectory passing through all task regions $(\mathbf{x}_{ti}, r_{ti})$ while avoiding the obstacle.

For initial experiments, we utilize a minimum-distance approach desirable for efficiency and robustness. We consider a trajectory X with N waypoints, where specific points $\{\mathbf{x}_{b1}, \mathbf{x}_{b2}, \mathbf{x}_{b3}\} \in X$ correspond to locations where the robot is positioned within the respective safe regions to perform each task. We define this as the optimization problem:

$$\begin{aligned} \min_{X} \quad & \sum_{i=1}^{N-1} \|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2 \\ \text{s.t.} \quad & \|\mathbf{x}_{b1} - \mathbf{x}_{t1}\|_2 \leq r_{t1} \\ & \|\mathbf{x}_{b2} - \mathbf{x}_{t2}\|_2 \leq r_{t2} \\ & \|\mathbf{x}_{b3} - \mathbf{x}_{t3}\|_2 \leq r_{t3} \\ & \|\mathbf{x}_i - \mathbf{x}_o\|_2 \geq r_o \quad i = 1, \dots, N \end{aligned}$$

While we enforce obstacle-avoidance for waypoints, there is no guarantee that paths in between are collision-free. This is done by ensuring sufficiently dense intermediate waypoints with maximum separation smaller than obstacle scale ($\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2 \leq r_o$). The obstacle also introduces non-convexity, which is handled with DCCP (Convex-Concave Programming) [23]. We solve in CVXPY [24] with average solve times around 0.3 sec.

V. EXPERIMENTS

For deployment of our trajectory optimization with hardware, we consider three task locations and a circular obstacle:

$$\mathbf{x}_{t1} = [0.5, -2.0] \text{ m} \qquad \mathbf{x}_{t2} = [3.5, 1.0] \text{ m}$$
$$\mathbf{x}_{t3} = [5.0, -0.5] \text{ m} \qquad \mathbf{x}_{o} = [3.0, 0.0] \text{ m}$$

The robot begins in the same position $\mathbf{x}_0$ for all experiments. PD controllers with velocity limits steer the ANYmal's linear velocities (v_x, v_y) towards each of the trajectory waypoints and the angular velocity ω_z to maintain constant yaw heading θ_b. When the mobile base arrives within each task region, the deployable arm is extended to the exact task coordinate. Table 1 and Fig. 3 show four experiments (A-D) where we vary the reach limit (r_{ti}) and introduce an obstacle.

VI. DISCUSSION AND FUTURE WORK

Our current work presents a preliminary framework for the design and control of a coordinated mobile manipulation platform utilizing a deployable arm with extensive reach. As shown by experiments, long reach offers significant advantages in path planning. Comparing trajectories utilizing long reach (B, D) to those with short reach (A, C), we see an almost 50% reduction in travel distance. Execution times are slower in the long-reach trajectories due to boom velocity limits imposed to mitigate instability.

These results lay initial groundwork for performing large-workspace tasks, where mobile base and arm motions must be coordinated to trade off stability and performance. Ongoing work examines demonstrating full hardware proficiency with fine-manipulation control (e.g. vision-informed grasping or assembly tasks), and refined planning to better capture tradeoffs at longer reach, especially with full-body kinematics and dynamic effects. Planning in complex environments (i.e. more obstacles or risk-aware contexts) will require more sophisticated strategies such as GCS (Graphs of Convex Sets) [25] or sampling-based methods like RRT* [26].

ACKNOWLEDGMENT

Special Thanks: The Stanford Robotics Center (SRC), including Matt Van Cleave, Eiko Rutherford, Zen Yaskawa, Steve Cousins, and Oussama Khatib.

Funding: Stanley Wang and Daniel Morton were supported by the NASA Space Technology Graduate Research Opportunity (NSTGRO). Venny Kojouharov was supported by the NSF Graduate Research Fellowship, with additional support from Knight-Hennessy Scholars.

REFERENCES

[1] D. Arney, J. Mulvaney, C. Williams, W. A. R. Hernandez, J. Friz, C. Stockdale, J. Nelson, and R. R. Vargas, "In-space servicing, assembly, and manufacturing (isam) state of play-2024 edition," 2024.

[2] W. K. Belvin, W. R. Doggett, J. J. Watson, J. T. Dorsey, J. E. Warren, T. C. Jones, E. E. Komendera, T. Mann, and L. M. Bowman, "In-space structural assembly: Applications and technology," in *3rd AIAA Spacecraft Structures Conference*, 2016, p. 2163.

[3] Blue Origin. (2024, Sep.) Honeybee robotics deploys lamps at nasa johnson space center. Blue Origin. [Online]. Available: https://www.blueorigin.com/news/honeybee-robotics-deploys-lamps-at-nasa-johnson-space-center

[4] H. Benaroya, "Lunar habitats: A brief overview of issues and concepts," *Reach*, vol. 7, pp. 14–33, 2017.

[5] A. Ellery, "Sustainable in-situ resource utilization on the moon," *Planetary and Space Science*, vol. 184, p. 104870, 2020.

[6] S. Wang, V. Kojouharov, L. Y. Chung, D. Morton, and M. Cutkosky, "Long-reach robotic manipulation for assembly and outfitting of lunar structures," 2026. [Online]. Available: https://arxiv.org/abs/2603.29226

[7] ——, "Long-reach robotic cleaning for lunar solar arrays," 2026. [Online]. Available: https://arxiv.org/abs/2603.29240

[8] M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, K. Bodie, P. Fankhauser, M. Bloesch *et al.*, "Anymal-a highly mobile and dynamic quadrupedal robot," in *2016 IEEE/RSJ international conference on intelligent robots and systems (IROS)*. IEEE, 2016, pp. 38–44.

[9] GITAI. Inchworm robot. GITAI. [Online]. Available: https://gitai.tech/inchworm-robot/

[10] C. E. Gregg, D. Catanoso, O. I. B. Formoso, I. Kostitsyna, M. E. Ochalek, T. J. Olatunde, I. W. Park, F. M. Sebastianelli, E. M. Taylor, G. T. Trinh *et al.*, "Ultralight, strong, and self-reprogrammable mechanical metamaterials," *Science robotics*, vol. 9, no. 86, p. eadi2746, 2024.

[11] J. Dorsey, T. Jones, W. Doggett, B. King, C. Mercer, J. Brady, F. Berry, E. Anderson, and G. Ganoe, "Recent developments in the design, capabilities and autonomous operations of a lightweight surface manipulation system and test-bed," in *AIAA SPACE 2011 Conference & Exposition*, 2011, p. 7266.

[12] J. M. Fernandez and A. J. Lee, "Bistable collapsible tubular mast booms," in *International Conference on Advanced Lightweight Structures and Reflector Antennas*, no. NF1676L-30217, 2018.

[13] M. Thomson, "Deployable and retractable telescoping tubular structure development," 1993. [Online]. Available: https://api.semanticscholar.org/CorpusID:109203948

[14] T. W. Murphey, D. Turse, and L. Adams, "Trac boom structural mechanics," in *4th AIAA spacecraft structures conference*, 2017, p. 0171.

[15] F. Collins and M. Yim, "Design of a spherical robot arm with the spiral zipper prismatic joint," in *2016 IEEE international conference on robotics and automation (ICRA)*. IEEE, 2016, pp. 2137–2143.

[16] L. H. Blumenschein, M. M. Coad, D. A. Haggerty, A. M. Okamura, and E. W. Hawkes, "Design, modeling, control, and application of everting vine robots," *Frontiers in Robotics and AI*, vol. 7, p. 548266, 2020.

[17] T. G. Chen, S. Newdick, J. Di, C. Bosio, N. Ongole, M. Lapôtre, M. Pavone, and M. R. Cutkosky, "Locomotion as manipulation with reachbot," *Science Robotics*, vol. 9, no. 89, p. eadi9762, 2024.

[18] J. Richter, H. Kolvenbach, G. Valsecchi, and M. Hutter, "Multi-objective global path planning for lunar exploration with a quadruped robot," in *2024 International Conference on Space Robotics (iSpaRo)*. IEEE, 2024, pp. 48–55.

[19] H. Kolvenbach, "Quadrupedal robots for planetary exploration," *Thesis, ETH Zurich*, 2021.

[20] P. Lehner, S. Brunner, A. Dömel, H. Gmeiner, S. Riedel, B. Vodermayer, and A. Wedler, "Mobile manipulation for planetary exploration," in *2018 IEEE aerospace conference*. IEEE, 2018, pp. 1–11.

[21] T. Portela, A. Cramariuc, M. Mittal, and M. Hutter, "Whole-body end-effector pose tracking," 2025. [Online]. Available: https://arxiv.org/abs/2409.16048

[22] Metolius Climbing, "Roll up stick clip kit," https://www.metoliusclimbing.com/roll-up-stick-clip-kit.html, 2025, accessed: 1 August 2025.

[23] X. Shen, S. Diamond, Y. Gu, and S. Boyd, "Disciplined convex-concave programming," in *2016 IEEE 55th conference on decision and control (CDC)*. IEEE, 2016, pp. 1009–1014.

[24] S. Diamond and S. Boyd, "Cvxpy: A python-embedded modeling language for convex optimization," *Journal of Machine Learning Research*, vol. 17, no. 83, pp. 1–5, 2016.

[25] T. Marcucci, "Graphs of convex sets with applications to optimal control and motion planning," Ph.D. dissertation, Massachusetts Institute of Technology, 2024.

[26] I. Noreen, A. Khan, Z. Habib *et al.*, "Optimal path planning using rrt* based approaches: a survey and future directions," *International Journal of Advanced Computer Science and Applications*, vol. 7, no. 11, pp. 97–107, 2016.