

RB5: A Low-Cost Wheeled Robot for Real-Time Autonomous Large-Scale Exploration

Adam Seewald¹, Marvin Chancán¹, Connor M. McCann², Seonghoon Noh¹, Omeed Fallahi¹, Hector Castillo¹, Ian Abraham¹, and Aaron M. Dollar¹

Abstract—

Index Terms—Article submission, IEEE, IEEEtran, journal, L^AT_EX, paper, template, typesetting.

I. INTRODUCTION

WIDELY used in cluttered environments [1]–[4], mobile robots can both substitute [5] and outperform humans in, e.g., areas that are too far or too dangerous to navigate [6]–[9]. In these areas, robots are often required to identify their surroundings by sensing the environment [10] and planning and executing complex trajectories [11], [12]. With little or no human intervention [13], this problem is known in the literature as autonomous exploration [11]. While successful in challenging indoor and outdoor environments [14], [15], autonomous exploration is especially useful in dynamic environments with no prior knowledge of the space to be covered [5], [16]. Despite recent advancements, autonomy is limited and costly in such environments. Many approaches that tackle autonomous exploration integrate commercial robots with sensing equipment that is both prohibitively expensive and difficult to maintain [8], [9], [14], [15], [17]–[20]. There is a wide range of methodologies for autonomous exploration at present [15], [21] nonetheless, which span from algorithmic foundations [15], [19], [22] to system-of-systems frameworks where, e.g., a multitude of robots integrate existing algorithms with sensors for large-scale exploration [3], [7]–[9], [18]. Recent efforts in this direction include low-cost robots for exploration [17], [23], [24] but lack terrain adaptability [17] and computational capabilities [23], [24] often required to navigate outdoors in the real-world [2], [5].

Furthermore, in areas that are ambiguous or challenging to traverse—albeit autonomous—state-of-the-art approaches rely on humans for supervision and high-level decision-making [3], [7], [8]. As a result, robots often operate close to humans or require expensive network equipment, such as a mesh of communication devices [2], [3], [9], or existing network

infrastructure [25]–[27], thereby restricting autonomous exploration to indoor settings only [12], [28]–[31]. Conversely, our methodology exploits LoRa—an inexpensive long-range and low-power communication technology [32] from the internet-of-things domain—with a customized communication protocol for human intervention in, e.g., the eventuality of the robot being unable to move with the local sensory information.

Starting from the cost advantages of LoRa communication, we develop here RB5—a novel rocker-bogie-like mobile robot capable of exploring autonomously dynamic indoor and outdoor environments—and an open-source robot operating system (ROS)-based [33] exploration framework. Rocker-bogie mobile robots comprise a multi-body system with a moving base [24], [34], [35] (see Figure ??) and provide rough terrain static adaptability [36]. They are cheaper than, e.g., legged robots in terms of cost per unit and operation, as they are able to overcome obstacles without costly computations for gait adaptation and planning [17]. Hardware-wise, RB5 maintains a lower sensory footprint with low-cost components, whereas software-wise, it integrates multiple modules into the exploration framework. Being able to operate in both unknown and GPS-denied environments, RB5 derives its position using a state-of-the-art simultaneous localization and mapping (SLAM) algorithm [37], [38], and the trajectory with a novel methodology that extends exploration literature with a path following vector field [39] from the aerial robotics domain [40]–[42]. This allows RB5 to explore its surroundings at lower frequencies, utilizing cheaper computing hardware compared to state-of-the-art approaches [8], [9], [15], [19].

The remainder of the letter is structured as follows. In Section VI data show improved “coverage per cost” over the baseline of existing autonomous exploration system-of-systems with indoor and outdoor “in the field” experiments. Sec. IV–V describe RB5 from the hardware and software standpoints. Sec. II summarizes and compares existing literature, Sec. III formalizes the problem of autonomous exploration, and Sec. VII drafts conclusions and future directions.

II. RELATED WORK

III. PROBLEM FORMULATION

The problem considered in this work to showcase RB5 for large-scale exploration is that of exploring a bounded volume $\mathcal{Q} \subseteq \mathbb{R}^3$ with respect to an inertial navigation frame \mathcal{O}_W . If the notation $[n]$ denotes a set with positive naturals up to n and $[n]_{>0}$ with strictly positive naturals, we are

Manuscript received: Month, Day, Year; Revised Month, Day, Year; Accepted Month, Day, Year.

This paper was recommended for publication by Editor Editor A. Name upon evaluation of the Associate Editor and Reviewers’ comments.

¹A. S., C. M., S. N., O. F., H. C., I. A., and A. M. D. are with the Department of Mechanical Engineering and Materials Science, Yale University, CT, USA. Email: adam.seewald@yale.edu;

C. M. C. is with the School of Engineering and Applied Sciences, Harvard University, MA, USA.

Digital Object Identifier (DOI): see top of this page.

interested in collision-free trajectories that explore \mathcal{Q} and avoid $i \in [n]_{>0}, n \in \mathbb{N}_{\geq 0}$ obstacles $\mathcal{Q}^{O_i} \subset \mathbb{R}^3$. We can approximate the space that delimits \mathcal{Q} and \mathcal{Q}^{O_i} for each i with a set of vertices within which the two sets are contained.

Problem (Exploration). Consider sets of vertices $V := \{\mathbf{v}_1, \mathbf{v}_2, \dots\}$, $O_i := \{\mathbf{o}_{i,1}, \mathbf{o}_{i,2}, \dots\}$ with $i \in [n]$, $\mathbf{v}_j, \mathbf{o}_{i,k} \in \mathbb{R}^2$, $\forall j \in [|v|], k \in [|o_i|]$ a point w.r.t. \mathcal{O}_W . Let V enclose \mathcal{Q} , $O_i \subset \mathcal{Q}^{O_i}$ per each i . The *exploration problem* is the problem of finding the coverage that visits each point $\mathbf{p} \in \mathcal{Q} \cap \mathcal{Q}^{O_1} \cap \mathcal{Q}^{O_2} \cap \dots \cap \mathcal{Q}^{O_n} := \mathcal{Q}^V$.

Here the notation $|\cdot|$ denotes the cardinality and \mathbb{R}, \mathbb{Z} are reals and integers. Bold notation is used for vectors.

Let ϕ be a path function, i.e., a function RB5 tracks as it explores its surroundings in \mathcal{Q}^V , avoiding the obstacles \mathcal{Q}^{O_i} .

Definition III.1 (Path function). $\phi : \mathbb{R}^2 \rightarrow \mathbb{R}$ is a two-dimensional continuous and differentiable *path function* of the x, y components of \mathbf{p} .

Definition III.2 (Coverage). Given a tuple with a path function and its time component, $\langle \phi, t \rangle$, the *coverage* is the collection of multiple tuples.

The large-scale exploration framework (see Sec. V) derives ϕ at each sampling step and adds it to the global “coverage stack”. The process ends once \mathcal{Q}^V is covered.

IV. RB5 MECHANICAL DESIGN

V. LARGE-SCALE EXPLORATION

There is a large body of work for robot exploration [15], [19], [21], [22], [43]. While the majority exploits the concept of frontiers [44], i.e., boundaries between known and unknown space, mixed approaches are emerging [15], [45], [46]. Especially useful in the presence of diverse sensing modalities, e.g., involving raw sensory data, topologies, semantics, etc., they have multiple advantages for real-world environments [15], [47]. We propose a mixed approach for RB5 large-scale exploration framework, combining frontier- and sampling-based methods, similar to some recent approaches [44], [45], [19].

The framework evaluates local frontiers at each step, samples the environment, and determines feasible candidate path functions ϕ that intersect \mathcal{Q}^V (Definition III.1). The next ϕ is selected so that the frontier is largest, but other costs are also possible (see Sec. VII). The framework then derives a path-following vector field that points to ϕ at any point, and guides the robot utilizing the gradient descent algorithm. This allows RB5 to, e.g., follow the covering path longer than approaches that utilize frontiers only, decreasing computational and cost requirements (see Sec. VI).

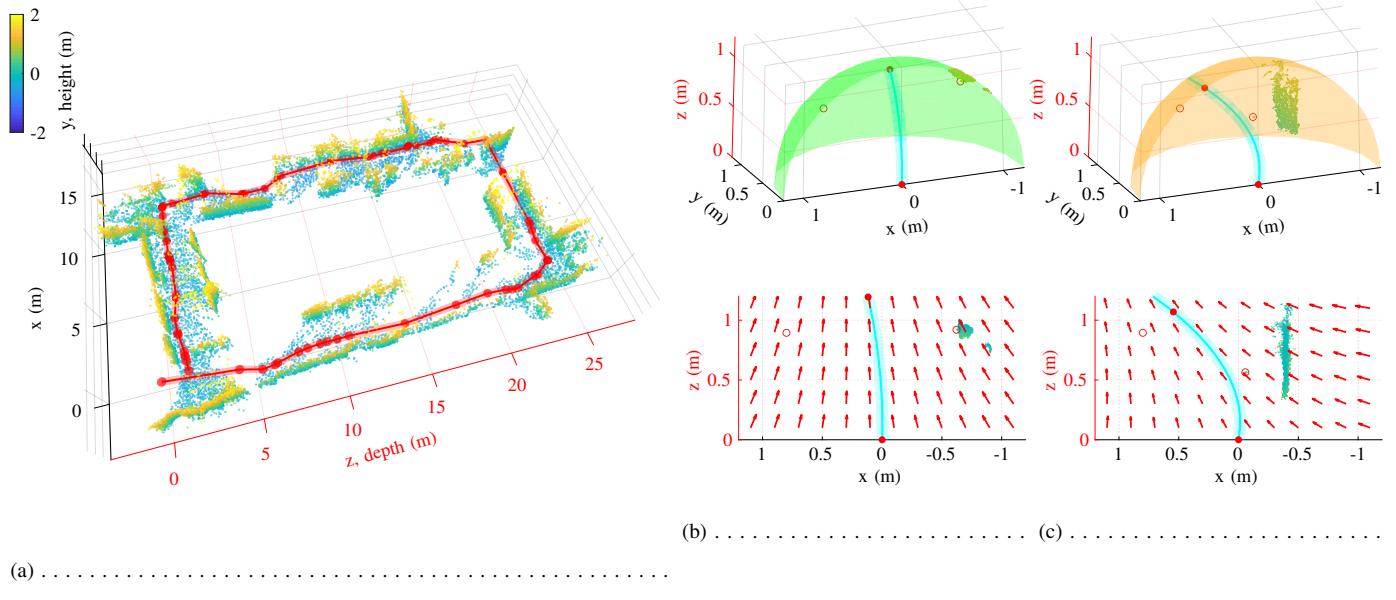
Let the gradient of ϕ be defined

$$\nabla \phi := \begin{bmatrix} \partial \phi(\mathbf{p}) / \mathbf{p}_x \\ \partial \phi(\mathbf{p}) / \mathbf{p}_y \end{bmatrix}, \quad (1)$$

where $\partial \phi / \mathbf{p}$ is the differential and $\mathbf{p}_x, \mathbf{p}_y$ are the x and y components of \mathbf{p} .

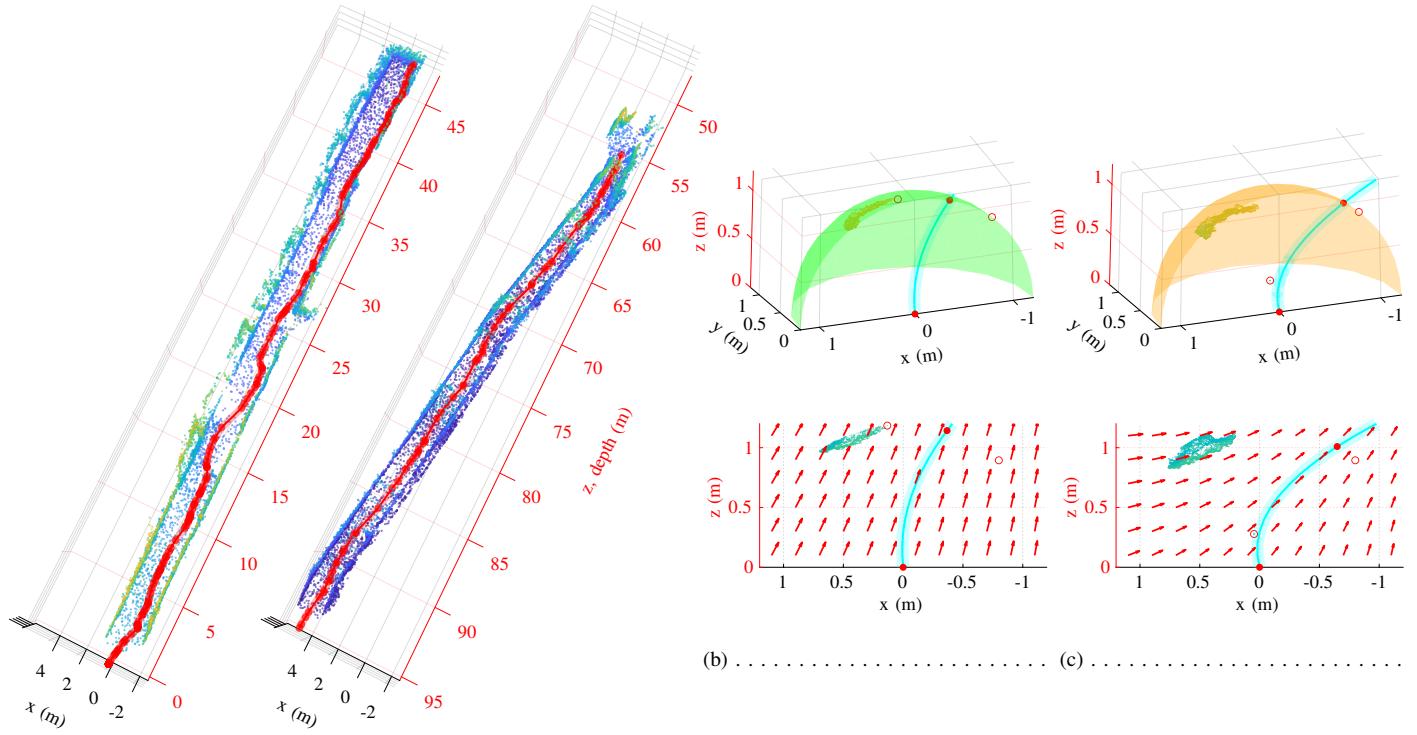
VI. FIELD EXPERIMENTS

VII. CONCLUSION AND FUTURE DIRECTIONS



(a)

Fig. 1:



(a)

Fig. 2:

REFERENCES

- [1] S. Kohlbrecher, J. Meyer, T. Gruber *et al.*, “Hector open source modules for autonomous mapping and navigation with rescue robots,” in *RoboCup 2013: Robot World Cup XVII*. Springer, pp. 624–631. [1](#)
- [2] M. Kulkarni, M. Dharmadhikari, M. Tranzatto *et al.*, “Autonomous teamed exploration of subterranean environments using legged and aerial robots,” in *International Conference on Robotics and Automation (ICRA’22)*. IEEE, 2022, pp. 3306–3313. [1](#)
- [3] M. Tranzatto, F. Mascarich, L. Berreiter *et al.*, “CERBERUS: Autonomous legged and aerial robotic exploration in the tunnel and urban circuits of the DARPA Subterranean Challenge,” *Field Robotics*, vol. 2, pp. 274–324, 2022. [1](#)
- [4] H. Kim, H. Kim, S. Lee *et al.*, “Autonomous exploration in a cluttered environment for a mobile robot with 2d-map segmentation and object detection,” *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 6343–6350, 2022. [1](#)
- [5] F. Rubio, F. Valero, and C. Llopis-Albert, “A review of mobile robots: Concepts, methods, theoretical framework, and applications,” *International Journal of Advanced Robotic Systems*, vol. 16, no. 2, p. 22, 2019. [1](#)
- [6] T. Miki, J. Lee, J. Hwangbo *et al.*, “Learning robust perceptive locomotion for quadrupedal robots in the wild,” *Science Robotics*, vol. 7, no. 62, p. 14, 2022. [1](#)
- [7] T. Rouček, M. Pecka, P. Čížek *et al.*, “DARPA subterranean challenge: Multi-robotic exploration of underground environments,” in *Modelling and Simulation for Autonomous Systems*. Springer, 2020, pp. 274–290. [1](#)
- [8] W. Tabib, K. Goel, J. Yao *et al.*, “Autonomous cave surveying with an aerial robot,” *IEEE Transactions on Robotics*, vol. 38, no. 2, pp. 1016–1032, 2022. [1](#)
- [9] K. Ebadi, Y. Chang, M. Palieri *et al.*, “LAMP: Large-scale autonomous mapping and positioning for exploration of perceptually-degraded subterranean environments,” in *International Conference on Robotics and Automation (ICRA’20)*. IEEE, 2020, pp. 80–86. [1](#)
- [10] Y. Mei, Y.-H. Lu, C. Lee *et al.*, “Energy-efficient mobile robot exploration,” in *International Conference on Robotics and Automation (ICRA’06)*. IEEE, 2006, pp. 505–511. [1](#)
- [11] R. Shrestha, F.-P. Tian, W. Feng *et al.*, “Learned map prediction for enhanced mobile robot exploration,” in *International Conference on Robotics and Automation (ICRA’19)*. IEEE, 2019, pp. 1197–1204. [1](#)
- [12] A. Eldemiry, Y. Zou, Y. Li *et al.*, “Autonomous exploration of unknown indoor environments for high-quality mapping using feature-based RGB-D SLAM,” *Sensors*, vol. 22, no. 14, p. 16, 2022. [1](#)
- [13] M. B. Alatise and G. P. Hancke, “A review on challenges of autonomous mobile robot and sensor fusion methods,” *IEEE Access*, vol. 8, pp. 39 830–39 846, 2020. [1](#)
- [14] I. Lluvia, E. Lazcano, and A. Ansustegui, “Active mapping and robot exploration: A survey,” *Sensors*, vol. 21, no. 7, 2021. [1](#)
- [15] J. A. Placed, J. Strader, H. Carrillo *et al.*, “A survey on active simultaneous localization and mapping: State of the art and new frontiers,” *IEEE Transactions on Robotics*, p. 20, 2023, doi.org/10.48550/arXiv.2207.00254. [1, 2](#)
- [16] A. Bircher, M. Kamel, K. Alexis *et al.*, “Receding horizon “next-best-view” planner for 3D exploration,” in *International Conference on Robotics and Automation (ICRA’16)*. IEEE, 2016, pp. 1462–1468. [1](#)
- [17] M. Müller and V. Koltun, “OpenBot: Turning smartphones into robots,” in *International Conference on Robotics and Automation (ICRA’21)*. IEEE, 2021, pp. 9305–9311. [1](#)
- [18] D. Tardioli, L. Riazuelo, D. Sicignano *et al.*, “Ground robotics in tunnels: Keys and lessons learned after 10 years of research and experiments,” *Journal of Field Robotics*, vol. 36, no. 6, pp. 1074–1101, 2019. [1](#)
- [19] T. Dang, F. Mascarich, S. Khattak *et al.*, “Graph-based path planning for autonomous robotic exploration in subterranean environments,” in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2019, pp. 3105–3112. [1, 2](#)
- [20] H. Surmann, A. Nüchter, and J. Hertzberg, “An autonomous mobile robot with a 3D laser range finder for 3D exploration and digitalization of indoor environments,” *Robotics and Autonomous Systems*, vol. 45, no. 3, pp. 181–198, 2003. [1](#)
- [21] M. Juliá, A. Gil, and O. Reinoso, “A comparison of path planning strategies for autonomous exploration and mapping of unknown environments,” *Autonomous Robots*, vol. 33, pp. 427–444, 2012. [1, 2](#)
- [22] B. Yamauchi, “A frontier-based approach for autonomous exploration,” in *Proceedings 1997 IEEE International Symposium on Computational Intelligence in Robotics and Automation CIRA’97. Towards New Com-*
putational Principles for Robotics and Automation’, 1997, pp. 146–151. [1, 2](#)
- [23] B. Zhou, Z. Wu, and X. Liu, “Smartphone-based robot indoor localization using unertial sensors, encoder and map matching,” in *International Conference on Automation, Control and Robots (ICACR’21)*. IEEE, 2021, pp. 145–149. [1](#)
- [24] S. M. F. Faisal, T. Rahman, and M. A. Kabir, “A low-cost rough terrain explorer robot fabrication using rocker bogie mechanism,” in *International Conference on Computer, Communication, Chemical, Materials and Electronic Engineering (IC4ME2’21)*, 2021, pp. 1–4. [1](#)
- [25] K. Ismail, R. Liu, J. Zheng *et al.*, “Mobile robot localization based on low-cost LTE and odometry in GPS-denied outdoor environment,” in *International Conference on Robotics and Biomimetics (ROBIO’19)*. IEEE, 2019, pp. 2338–2343. [1](#)
- [26] “ROS-based unmanned mobile robot platform for agriculture,” *Applied Sciences*, vol. 12, no. 9, p. 13, 2022. [1](#)
- [27] F. Voigtlander, A. Ramadan, J. Eichinger *et al.*, “5G for robotics: Ultra-low latency control of distributed robotic systems,” in *International Symposium on Computer Science and Intelligent Controls (ISCSIC’17)*. IEEE, 2017, pp. 69–72. [1](#)
- [28] C. Delgado, L. Zanzi, X. Li *et al.*, “OROS: Orchestrating ROS-driven collaborative connected robots in mission-critical operations,” in *International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM’22)*. IEEE, 2022, pp. 147–156. [1](#)
- [29] C. Cadena, L. Carlone, H. Carrillo *et al.*, “Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age,” *IEEE Transactions on Robotics*, vol. 32, no. 6, pp. 1309–1332, 2016. [1](#)
- [30] M. Corah, C. O’Meadhra, K. Goel *et al.*, “Communication-efficient planning and mapping for multi-robot exploration in large environments,” *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 1715–1721, 2019. [1](#)
- [31] C. Papachristos, S. Khattak, and K. Alexis, “Uncertainty-aware receding horizon exploration and mapping using aerial robots,” in *International Conference on Robotics and Automation (ICRA’17)*. IEEE, 2017, pp. 4568–4575. [1](#)
- [32] J. P. Shanmuga Sundaram, W. Du, and Z. Zhao, “A survey on LoRa networking: Research problems, current solutions, and open issues,” *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 371–388, 2020. [1](#)
- [33] M. Quigley, K. Conley, B. Gerkey *et al.*, “ROS: An open-source robot operating system,” in *ICRA Workshop on Open Source Software*, vol. 3, no. 3.2, 2009, p. 5. [1](#)
- [34] T. P. Setterfield and A. Ellery, “Terrain response estimation using an instrumented rocker-bogie mobility system,” *IEEE Transactions on Robotics*, vol. 29, no. 1, pp. 172–188, 2013. [1](#)
- [35] M. Mann and Z. Shiller, “Dynamic stability of a rocker bogie vehicle: Longitudinal motion,” in *International Conference on Robotics and Automation (ICRA’05)*, 2005, pp. 861–866. [1](#)
- [36] D. Kim, H. Hong, H. S. Kim *et al.*, “Optimal design and kinetic analysis of a stair-climbing mobile robot with rocker-bogie mechanism,” *Mechanism and Machine Theory*, vol. 50, pp. 90–108, 2012. [1](#)
- [37] M. Labbé and F. Michaud, “RTAB-Map as an open-source lidar and visual simultaneous localization and mapping library for large-scale and long-term online operation,” *Journal of Field Robotics*, vol. 36, no. 2, pp. 416–446, 2019. [1](#)
- [38] C. Campos, R. Elvira, J. J. G. Rodríguez *et al.*, “ORB-SLAM3: An accurate open-source library for visual, visual-inertial, and multimap SLAM,” *IEEE Transactions on Robotics*, vol. 37, no. 6, pp. 1874–1890, 2021. [1](#)
- [39] V. M. Goncalves, L. C. A. Pimenta, C. A. Maia *et al.*, “Vector fields for robot navigation along time-varying curves in n -dimensions,” *IEEE Transactions on Robotics*, vol. 26, no. 4, pp. 647–659, 2010. [1](#)
- [40] A. Seewald, H. García de Marina, H. S. Midtiby *et al.*, “Energy-aware planning-scheduling for autonomous aerial robots,” in *International Conference on Intelligent Robots and Systems (IROS’22)*. IEEE, 2022, pp. 2946–2953. [1](#)
- [41] H. García de Marina, Y. A. Kapitanyuk, M. Bronz *et al.*, “Guidance algorithm for smooth trajectory tracking of a fixed wing UAV flying in wind flows,” in *International Conference on Robotics and Automation (ICRA’17)*. IEEE, 2017, pp. 5740–5745. [1](#)
- [42] A. Seewald, “Energy-aware coverage planning and scheduling for autonomous aerial robots,” Ph.D. thesis, Syddansk Universitet, 2021, doi.org/10.21996/7ka6-r457. [1](#)
- [43] S. M. LaValle, *Planning algorithms*. Cambridge Univ. Press, 2006. [2](#)

- [44] W. Qiao, Z. Fang, and B. Si, "A sampling-based multi-tree fusion algorithm for frontier detection," *International Journal of Advanced Robotic Systems*, vol. 16, no. 4, p. 14, 2019. [2](#)
- [45] A. Dai, S. Papatheodorou, N. Funk *et al.*, "Fast frontier-based information-driven autonomous exploration with an MAV," in *International Conference on Robotics and Automation (ICRA'20)*. IEEE, 2020, pp. 9570–9576. [2](#)
- [46] L. Schmid, M. Pantic, R. Khanna *et al.*, "An efficient sampling-based method for online informative path planning in unknown environments," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 1500–1507, 2020. [2](#)
- [47] A. Batinovic, T. Petrovic, A. Ivanovic *et al.*, "A multi-resolution frontier-based planner for autonomous 3d exploration," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 4528–4535, 2021. [2](#)