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Project 567
F1Tenth Autonomous Training Platform, Courseware and Community Activities

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Final Report – July 2025

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16. Abstract

ROBORACER (formerly known as F1Tenth), is an open-source autonomous driving software stack with associated scaled vehicle platforms for systematic development and validation of high-performance and safe autonomous machines. The ROBORACER stack provides a versatile framework for modeling AI-CPS in the form of multi-agent dynamic games, the interactive environments they operate in, with a well-defined simulation-to-reality pipeline that permits rapid autonomous system algorithm prototyping, testing and deployment. The same code can be deployed across multiple vehicles scales from 1/10th, 1/5th, 1/2 to full-scale vehicles with a suite of sensors, actuators and controllers for self driving. We have had considerable success in deploying RoboRacer in industry, academia, and government – over 90 universities are using RoboRacer for research, for teaching as part of their curriculum and for student engagement in international competitions. ROBORACER is used extensively by the US Department of Transportation as part of the FHWA's CDA 1Tenth program for connected driving automation. ROBORACER is used by several top R&D companies such as Toyota Research Institute, Honda Research Institute, Tier IV (Japan), HUMDA Mobility (Hungary), etc. and has resulted in over 68 academic publications and 4 workshops in robotics, transportation and CPS conferences]. Over 24 ROBORACER international autonomous racing competitions have been hosted averaging 150-200 participants who compete in the battle of autonomous system algorithms using the same reference vehicle design [54-64]. From 2025 onwards, ROBORACER competitions will be sponsored by the Robotics and Automation Society (RAS) for races in top robotics conferences such as ICRA and IROS; it is sponsored by the Intelligent Transportation Society (ITS) and IEEE for races in top transportation conferences such as IEEE Intelligent Vehicles, IEEE Intelligent Transportation Systems Conference, IEEE CDC and CPSWeek. ROBORACER's Slack communities connect 2406+ active users and support a systematic methodology for the design, testing, & deployment of AI-CPS.

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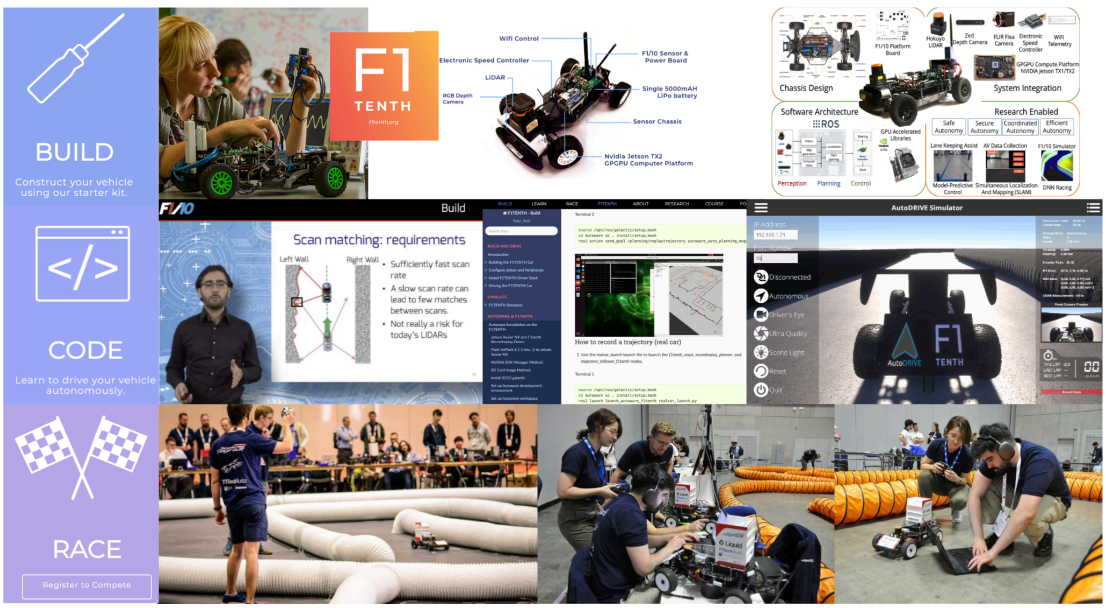
1. Project Abstract

This report summarizes the F1TENTH project, an innovative educational initiative designed to improve autonomous systems instruction through hands-on experiences and competitive challenges. Recognizing the limitations of purely theoretical curricula in higher education, F1TENTH introduces a novel university course built around a modular, small-scale autonomous vehicle platform. The project outlines the comprehensive course design, its pedagogical principles, the structure of its individual teaching modules, and the architecture of the F1TENTH hardware and software. An evaluation, based on surveys from five universities that adopted these modules, conclusively demonstrates that the practical hardware platform and integrated learning components significantly boost student engagement, deepen their understanding of practical techniques, and enhance overall learning outcomes in the complex field of autonomous systems.



2. Project Overview

The rapid advancement of autonomous and intelligent transportation systems has created an urgent demand for a new generation of engineers and researchers equipped with both theoretical knowledge and practical expertise. Traditional academic approaches often prioritize theoretical concepts, leaving a gap in students' hands-on experience and their ability to apply classroom learning to real-world engineering problems. The F1TENTH project was initiated to bridge this critical gap by developing and implementing an active, experiential, and competition-driven educational framework. The fundamental premise of F1TENTH is to provide students with a tangible, scaled-down autonomous vehicle. This platform allows them to directly implement theoretical algorithms, conduct experiments, and observe the practical consequences of their designs. This immersive approach aims to cultivate a profound understanding of autonomous systems, develop robust problem-solving abilities, and effectively prepare students for the multifaceted challenges inherent in autonomous engineering.

3. Main Contributions

The F1TENTH project makes several pivotal contributions to the pedagogy of autonomous systems education:

- 3.1. Addressing Gaps in Autonomous Systems Education:
  The project directly tackles the pervasive issue in autonomous systems education where an overemphasis on theoretical instruction often results in graduates lacking crucial practical experience. F1TENTH remedies this by providing a hands-on environment, ensuring students gain direct exposure to the engineering complexities and practical techniques essential for developing real-world autonomous solutions.
- 3.2. F1TENTH Course Design and Educational Philosophy:
  A unique university course structure has been developed, centered around the F1TENTH platform. The core educational philosophy promotes active learning, problem-based assignments, and an iterative design process. This pedagogical shift moves beyond conventional lecture formats by incorporating practical exercises and mini-projects, all culminating in a competitive environment that profoundly enhances student engagement with the course material.

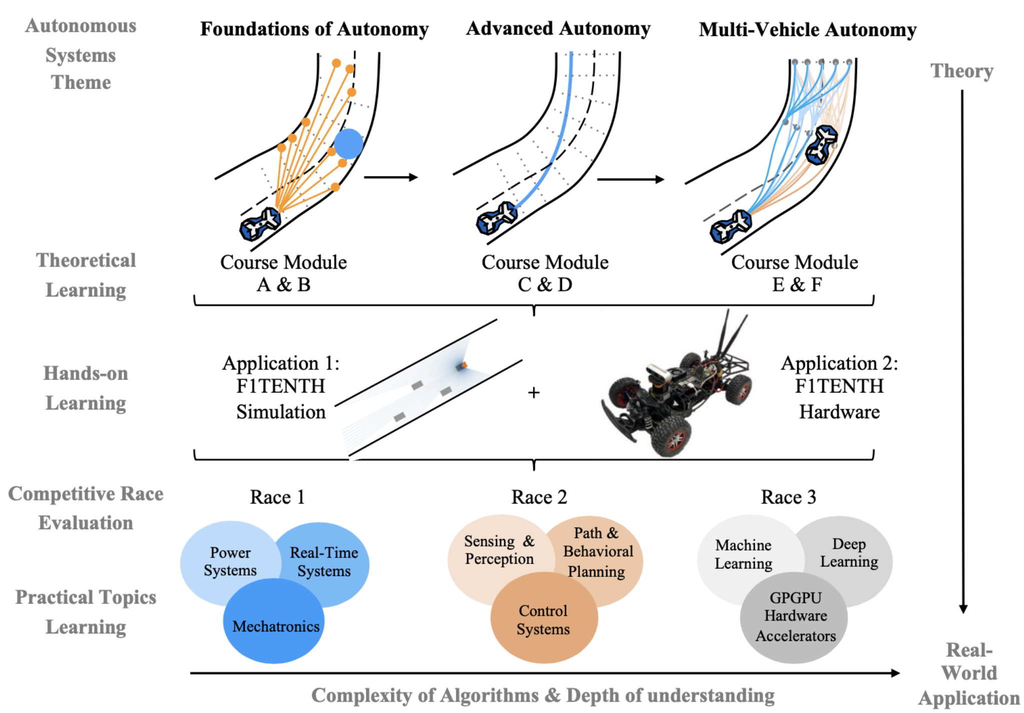
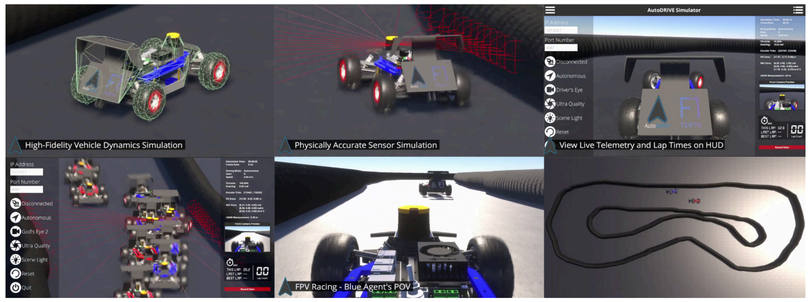


Fig. 2. The F1TENTH course structure: Each autonomy theme provides both the theoretical content and practical learning units with simulations and real hardware. Over the different course modules, the complexity of algorithms is increasing while the depth of understanding also increases.

- 3.3. Development of a Modular Hardware/Software Platform:

A foundational contribution is the F1TENTH modular autonomous small-scale vehicle platform itself. This platform is meticulously designed for accessibility, scalability, and robustness, enabling students to experiment with core autonomous driving components, including various sensors (e.g., LiDAR, cameras), actuators, and embedded computing systems. Its inherent modularity facilitates the effortless integration of new technologies and customization for diverse educational objectives.



- 3.4. Creation of Individual Teaching Modules:
  The project has developed a comprehensive suite of individual teaching modules. These modules systematically cover fundamental concepts in autonomous systems, such as perception, localization, mapping, motion planning, and control. Each module is structured to deliver essential theoretical background followed by practical implementation exercises directly on the F1TENTH platform, thereby ensuring a direct and immediate application of learned concepts.

- 3.5. Integration of Competition-Based Learning:
  A cornerstone and powerful motivator within the F1TENTH project is the incorporation of a competitive element. Students are challenged to apply their accumulated knowledge and implemented algorithms in races against other teams. This fosters a highly dynamic, engaging, and collaborative learning environment. The competitive aspect actively encourages innovation, cultivates effective teamwork, and promotes continuous improvement, closely mimicking the demands and pressures of real-world engineering projects.

4. Results

The efficacy of the F1TENTH project's educational approach has been thoroughly evaluated, yielding overwhelmingly positive results.

- 4.1. Student Engagement and Feedback:
  Surveys conducted across five universities that implemented the F1TENTH teaching

modules consistently showed exceptionally positive student feedback. Approximately 80% of all participating students strongly affirmed that the hands-on hardware platform and integrated modules significantly increased their understanding of and engagement with autonomous systems concepts. This high level of consensus underscores the success of the practical, experiential learning model in captivating student interest and fostering deeper comprehension.

- 4.2. Impact on Practical Skills and Conceptual Understanding:
  The evaluation clearly demonstrated a marked improvement in students' practical skills and their grasp of real-world autonomous systems techniques. Students reported an enhanced capability to effectively implement complex algorithms, efficiently debug system issues, and critically understand the intricate interplay between hardware and software components. These are crucial skills often underdeveloped in solely theoretical curricula.
- 4.3. Scalability and Broad Adoption:
  The successful integration and adoption of the F1TENTH course design and platform by multiple academic institutions highlights its robust scalability and significant potential for widespread impact. This demonstrates that the F1TENTH framework is not only effective in a single educational setting but can be successfully adapted and deployed across diverse academic environments, thereby globally enhancing the quality of autonomous systems education.

5. Authors

The research, development, and pedagogical innovation presented in this report were conducted by the following individuals:

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6. Bibliography

[1] M. O'Kelly, H. Zheng, D. Karthik, and R. Mangharam, "F1tenth: An open-source evaluation environment for continuous control and reinforcement learning," in Proceedings of the NeurIPS 2019 Competition and Demonstration Track, ser. Proceedings of Machine Learning Research, H. J. Escalante and R. Hadsell, Eds., vol. 123. PMLR, 08-14 Dec 2020, pp. 77–89.

[2] J. Betz, H. Zheng, A. Liniger, U. Rosolia, P. Karle, M. Behl, V. Krovi, and R. Mangharam,

"Autonomous Vehicles on the Edge: A Survey on Autonomous Vehicle Racing." IEEE Open Journal of Intelligent Transportation Systems, vol. 3, pp. 458–488, 2022.

[3] A. Dosovitskiy, G. Ros, F. Codevilla, A. Lopez, and V. Koltun, "Carla: An open urban driving simulator," in Conference on robot learning. PMLR, 20...

[4] S. R. Batta, A. M. H. Adib, P. R. Murali, K. P. Shivakumar, A. D. Jain, A. Gupta, B. Singh, C. Gupta, K. Gupta, N. Mittal, P. A. Sharma, R. Kaushik, R. Singh, S. M. P. Adithya, and V. Gupta, "Rccar: A novel low cost and open source autonomous robot platform for educational purposes," in 2019 International Conference on Robotics and Automation (ICRA). IEEE, 2019, pp. 10452–10457.

[5] S. Thrun, "Robotic education: A new paradigm for learning," in Proceedings 2004 IEEE International Conference on Robotics and Automation, vol. 1. IEEE, 2004, pp. 48–53.

[6] J. Kolter and J. Goldberg, "Autonomous driving in the classroom: A pedagogical approach," in Proceedings of the 2019 ACM Conference on Innovation and Technology in Computer Science Education. ACM, 2019, pp. 320–326.

[7] F. Codevilla, A. López, and V. Koltun, "Learning to drive in a day," in Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018, pp. 3174–3180.

[8] D. H. Wolpert and J. F. Macready, "No free lunch theorems for optimization," IEEE transactions on evolutionary computation, vol. 1, no. 1, pp. 67–82, 1997.

[9] L. P. Kaelbling, "Learning to act by observing," in Proceedings of the Twelfth National Conference on Artificial Intelligence. AAAI Press, 1994, pp. 1162–1168.

[10] S. Russell and P. Norvig, Artificial Intelligence: A Modern Approach, 3rd ed. Pearson Education, 2010.

[11] S. Thrun, W. Burgard, and D. Fox, Probabilistic Robotics. MIT press, 2005.

[12] R. E. Kalman, "A new approach to linear filtering and prediction problems," Journal of basic Engineering, vol. 82, no. 1, pp. 35–45, 1960.

[13] S. J. Julier and J. K. Uhlmann, "A new extension of the kalman filter to nonlinear systems," in Aerospace/Defense Sensing, Simulation, and Controls. International Society for Optics and Photonics, 1997, pp. 182–193.

[14] M. W. Spong, S. Hutchinson, and M. Vidyasagar, Robot Modeling and Control. John Wiley & Sons, 2006.

[15] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, Introduction to Autonomous Mobile Robots. MIT press, 2011.

[16] F. Dellaert, D. Fox, W. Burgard, and S. Thrun, "Monte carlo localization for mobile robots," in Proceedings 1999 IEEE international conference on robotics and automation. IEEE, 1999, pp. 1322–1328.

[17] S. B. Sukhatme, G. S. Sukhatme, and M. J. Mataric, An Introduction to Robotics: Concepts, Systems, and Applications. MIT press, 2008.

[18] S. Russell, D. Koller, and R. Stuart, Artificial Intelligence: A Modern Approach. Prentice Hall, 1995.

[19] C. S. H. K. P. Singh, G. N. Ramadas, and R. S. K. Singh, "Real-time odometry using a camera and imu," in 2019 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2019, pp. 4872–4879.

[20] A. Geiger, P. Lenz, and R. Urtasun, "Are we there yet? The kitti vision benchmark suite," in 2012 IEEE conference on computer vision and pattern recognition. IEEE, 2012, pp. 3360–3367.