2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

Educational Applications of the Cyber-Physical Mobility Lab: A Summary

Simon Schäfer[1], Jianye Xu[1], David Klüner[1], Armin Mokhtarian[1],
Patrick Scheffe[1], *Student Members, IEEE*, and Bassam Alrifaee, *Senior Member, IEEE*

***Abstract*— In the domain of Connected and Automated Vehicles (CAVs), small-scale testbeds bridge expensive testing in the real world and computer simulations. Meanwhile, they offer educational opportunities for students to acquire hands-on experience in areas like control, vehicle dynamics, trajectory planning, and real-time software. At RWTH Aachen University, we, the Cyber-Physical Mobility Group, built a small-scale testbed, the open-source and remotely accessible Cyber-Physical Mobility Lab (CPM Lab). We use it for one undergraduate course, one graduate course, and an international competition. Our literature research indicates that no similar publicly available testbed offers continuous educational applications for all academic levels, including postgraduate students.**

This paper presents (i) an educational umbrella concept designed to create a course portfolio suitable for undergraduate, graduate, and postgraduate needs, (ii) updates to the course concepts with an emphasis on previous publications, and (iii) lessons learned to develop an education portfolio based on small-scale testbeds. We base our results on evaluations conducted over four years involving over 370 students participating in our courses. Our findings indicate that small-scale testbeds can help students become more invested in the topic and may motivate them beyond course requirements.

***Index Terms*— Cyber-Physical Systems, Mobility, Small-scale Testbeds, Education, Competition**

OPEN MATERIAL

CPM Academy	cpm-remote.de/academy
Networked Control of Vehicles	cpm.embedded.rwth-aachen.de/course
CPM Olympics	cpm-remote.de/olympics

I. INTRODUCTION

A. Motivation

Small-scale testbeds bridge the gap between expensive real-world testing and computer simulations. They offer a more cost-effective solution for rapid prototyping applications for Connected and Automated Vehicles (CAVs) compared to real-world test vehicles while producing a more realistic testing environment than simulations. Additionally, small-scale testbeds offer opportunities for practice-driven bottom-up education, enabling students to gain hands-on experience in topics like control, vehicle dynamics, trajectory planning, and real-time software. Our yearly evaluation shows that, on average, around 90 % (see Fig. 1) of students who take our courses are interested or highly interested in these topics. However, designing courses that cater to undergraduate and graduate students' diverse skill levels and needs can be challenging. Furthermore, conducting CAV simulations demands high-performance computer hardware, which can pose a financial obstacle for many students.

Within the Cyber-Physical Mobility (CPM) Group at RWTH Aachen University, we built the CPM Lab [1], a small-scale testbed focusing on CAVs and their applications in education. For instance, our small-scale vehicles (μCars) feature replaceable controllers, empowering students to explore control of vehicle dynamics. We launched our courses in 2019 and published our original concepts two years later [2]. Since then, the courses evolved, guided by feedback collection over the past four years. In 2023, we have integrated our testbed into three educational applications: one undergraduate-level course, a graduate-level course, and an international competition. Our literature research indicates that no similar publicly available testbed offers continuous educational applications for all academic levels, including postgraduate students.

In this paper, we present an umbrella concept that unifies our courses, and we present updates to the course concepts based on the feedback gathered over four years. Additionally, we provide lessons learned for implementing similar testbeds in educational settings derived from feedback from over 370 students participating in our courses. Our results show that the students appreciate the courses' practice-driven focus, which often motivates them to extend their efforts beyond the course requirements.

B. Related Work

Literature research reveals several examples exploring the educational uses of other small-scale testbeds comparable to the CPM Lab. F1TENTH, for instance, offers a comprehensive, open-access course with materials and grading criteria on its website [3]. This course accommodates an individual track and material for educators, although hardware must be purchased separately. Additionally, they describe an undergraduate-level course in [4]. A preprint study involving F1TENTH reports increased student engagement and improved comprehension of relevant topics [5]. The Robotarium states in the original paper [6] that many submissions are for educational use, but the authors do not provide specific references or open-access course materials. Duckietown, on the other hand, offers online videos and lecture materials with solutions linking to multiple university courses where it has been integrated [7]. The IDS Scaled Smart City also serves educational purposes, although the

[1] The authors are with the Chair of Embedded Software, RWTH Aachen University, {lastname}@embedded.rwth-aachen.de

B. Alrifaee is with the Department of Aerospace Engineering, University of the Bundeswehr Munich, Germany, bassam.alrifaee@unibw.de

authors refrain from outlining specific course details in the available publications [8]. While comparable to the CPM Lab, some testbeds like the MiniCity [9] do not mention any education uses in publicly available information.

There are many more examples of robots or car-like robots used in education, like the small-scale racing platforms MIT RACECAR [10] and Amazon DeepRacer [11] or the educational concepts presented in [12], where the authors present three different use cases for the education of Advanced Driver Assistance Systems (ADAS) applications. However, most literature focuses on single-agent applications. In contrast, the abovementioned tesbeds concentrate on multi-agent robot systems.

Moving beyond testbeds for car-like robot systems, we also find various applications in other domains. For instance, a systematic review focuses on using Unmanned Aerial Vehicles (UAVs) in education [13]. This study surveys 43 papers, revealing that integrating UAVs into educational contexts increases students' learning interest and fosters a stronger sense of responsibility among learners. Another source provides a detailed account of five distinct courses, each supported by a remote learning platform [14]. Notably, only one of these courses utilizes a physical robot, while the others rely on simulations. All the described courses employ gamification techniques to engage students and enhance their interest in the subject matter. Feedback is collected through final questionnaires to assess the effectiveness of the lectures. Furthermore, in [15], the authors present a comprehensive simulation-based course, emphasizing the teaching of common tasks related to UAVs.

All these applications illustrate the growing diversity of educational technologies and approaches used to increase students' engagement in various domains. Some testbeds comparable to the CPM Lab provide educational resources catering to undergraduate and graduate students. We further extend these educational provisions to postgraduate students, offering continuous learning opportunities across all academic levels. Additionally, the prevailing literature often focuses on the course concepts without incorporating updates or lessons learned from the supervision of the courses.

C. *Cyber-Physical Mobility Lab*

In [1], we introduced the Cyber-Physical Mobility Lab (CPM Lab) as an open-source, small-scale testbed for rapid prototyping of CAV applications. It features 20 car-like robots called µCars [16] with Ackermann steering and onboard sensors. We provide one external computation unit for each vehicle, allowing for distributed computation with up to 20 participants. The Indoor Positioning System [17] handles environmental perception with a camera-based detection system that localizes LEDs mounted on vehicles.

The vehicles send and receive messages using the Data Distribution Service (DDS), supporting all programming languages with a DDS implementation, including but not limited to MATLAB, Python, and C++. We support three different modes of sending commands to our µCars: (i) the direct command mode, in which the planner provides the control inputs for the actuators, (ii) the planner provides a path and the vehicle's current speed in the path-tracking mode, and (iii) in trajectory mode, the planner provides trajectories composed of a path and the speed along the path.

D. *CPM Remote*

We launched the Cyber-Physical Mobility Lab Remote Access (CPM Remote) [18], a web-based platform that provides remote access to the CPM Lab and server-side simulations, to overcome the limitations imposed by physical testbeds. The server-side simulations eliminate the need for users to invest in expensive hardware. Besides, it provides a library named *CPM Routing*, which acts as an interface between users and the CPM Lab. The library encompasses essential functions such as obstacle detection, vehicle state retrieval, and navigation on a map. With all these features, CPM Remote enables two of our educational applications, namely CPM Academy and CPM Olympics, which will be elaborated in Sections II-B and II-D, respectively.

E. *Contribution of this Paper*

This paper introduces an educational umbrella concept outlining the differences in teaching undergraduate and graduate students with our CPM Lab. We explore use cases for small-scale testbeds, including project-based and competition-based approaches, as well as using gamification. Our evaluation highlights the strengths and weaknesses of our educational approach and demonstrates how our course portfolio improved over time based on student feedback. Furthermore, we provide lessons learned for educators interested in creating their own testbed-based courses.

F. *Paper Structure*

We present the umbrella concept that creates a common thread for our course portfolio in Section II. In the same section, we present each education application and depict the students' feedback and how this changed the respective application. After that, we present our lessons learned from the past years in Section III. Finally, we conclude our findings in Section IV.

II. Educational Application

A. *Umbrella Concept*

The user base of the CPM Lab comprises three distinct target groups, each with unique capabilities and objectives. Undergraduate students, typically entering with foundational programming knowledge, seek to enhance their understanding of programming paradigms, focusing on concepts like shortest paths, scheduling, and optimization. Graduate students share similar objectives but with more advanced skills, enabling them to tackle complex control challenges. Postgraduate students possessing in-depth knowledge of planning and control, prioritize practical experimentation in real-world scenarios to test various CAV applications.

Our university's guidelines for undergraduate and graduate-level courses emphasize the varying depth of process dimensions, employing Bloom's Taxonomy as defined

TABLE I

BLOOM'S TAXONOMY COGNITIVE PROCESS DIMENSIONS LISTED IN ASCENDING ORDER BASED ON [19].

Dimension	Description
Remember	Retrieve relevant knowledge from long-term memory.
Understand	Construct meaning from instructional messages, including oral, written, and graphical communication.
Apply	Carry out or use a procedure in a given situation.
Analyze	Break material into constituent parts and determine how parts relate to one another and to an overall structure or purpose.
Evaluate	Make judgments based on criteria and standards.
Create	Put elements together to form a coherent or functional whole reorganize elements into new pattern or structures.

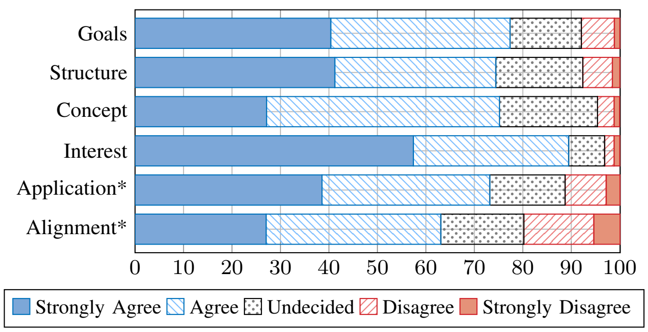

Fig. 1. Course evaluation based on approximately 260 questionnaires. The students rated: provision of clear goals, structure of the learning material, concept of the course, personal interested in the course, application of knowledge, and alignment of content to the accompanying lecture. * Questions from practice sessions based on more then 100 questionnaires.

by Table I. Undergraduate courses focus on the lower process dimensions "Remember", "Understand", and "Apply". In contrast, graduate and postgraduate courses expand to "Analyze", "Evaluate", and "Create". Incorporating these terms into course descriptions ensures alignment with the required cognitive skills: foundational understanding and practical application for undergraduates and problem analysis, mathematical derivation, problem evaluation, and solution assessment for graduate and postgraduate courses.

RWTH Aachen University conducts biannual evaluations via questionnaires to maintain course quality and adherence to guidelines. As shown in Fig. 1, these evaluations provide insight into the students' perspectives. Around 90 % express high or very high interest in the courses, while elements such as course structure, clear objectives, and the overall concept garner positive evaluations from 70 % or more of the students, rated as good or very good. These results confirm the favorable reception of our pratice-driven course concept.

In the upcoming sections, we will: (i) Describe individualized educational applications designed for specific target groups. (ii) Share insights derived from questionnaires received from approximately 260 students. (iii) Outline the course modifications made over four years and demonstrate how these changes are reflected in the feedback. (iv) Summarize the conclusions drawn, consolidated as lessons learned in Section III.

B. Undergraduate Students

The first application is an annual software development course tailored for undergraduate students, spanning a single semester. We divide the students into small groups of four to five students each. This course exposes students to real-world challenges they must solve in a scrum [20] setting. They engage in the development of a package delivery service, addressing various NP-hard problems, including the renowned traveling salesman problem. In contrast to other courses in the curriculum, which emphasized conceptual understanding, our bottom-up [21] approach prioritizes the practical implementation and application of theoretical paradigms. The current course iteration categorizes these problems into nine levels of increasing difficulty, employing a didactic approach grounded in gamification principles [22]. This strategy facilitates progress assessment by the course supervisor, based on the levels attained by each team. At the time of writing, a total of 119 students took the course.

The course's objectives have remained centered on creating a package delivery service across different semesters, but the course format has evolved. Initially, we tasked the students with coding the delivery functionality from scratch, without a provided code skeleton, and conducted on-campus testing in the CPM Lab. This approach presented two major challenges. First, the CPM Lab has limited physical space, and only one team at a time can conduct tests. Second, the supervisor must check the student's progress manually.

Amid the covid-19-pandemic, course format adaptations were prompted by restrictions on on-campus meetings and the availability of a pre-release version of CPM Remote. Testing and development transitioned to CPM Remote, accompanied by the provision of a basic code skeleton to guide students' work. The course continued to enroll 20 students, organized into teams of five students each. Evaluations from this year suggested a decline in course ratings across the board. However, it is challenging to attribute this solely to a drop in course quality, as less than half of the students completed the questionnaires.

The latest revision introduced the CPM Academy [23] in 2021. We enrolled 30 students in 2021 and 35 students in 2022, as a level-based system and automated feedback simplified student management and reduced the need for supervision. Despite the increase in student numbers per semester, we had yet to reach the limitations of CPM Remote. CPM Remote, functioning within a cloud environment, provides scalable capacity, ensuring that the platform itself does not impose any real restriction on the number of participants. Instead, limitations stem from the supervisor's ability to effectively oversee a larger number of participants. Students are now required to achieve specific goals to progress to the next level, and supervisors no longer need to manually assess students' progress, allowing for the increase to 35 in the latest iteration.

When comparing the evaluation results between the initial term in 2019 and the most recent regular term in 2022, no significant differences emerged in the evaluations. This observation led us to the conclusion that, for undergraduate students, there are no discernible advantages associated with on-campus work. Quite the opposite, students explicitly highlighted in their feedback their preference for the flexibility afforded by CPM Remote. This flexibility allows them to work from any computer, at any location worldwide, and at any time, aligning with their preferences and schedules. Moreover, students particularly appreciate receiving clear objectives without being constrained to specific solutions.

In the academy, students progress through nine levels, each serving specific educational objectives. The introductory level, level one, provides students with a foundational understanding by introducing the code base and providing them with a navigation function for CAVs. It emphasizes the cognitive skills of “Remember” and “Understand”.

In levels two and three, students are tasked with implementing collision avoidance algorithms, where they must dynamically control the vehicle to prevent collisions. They have the flexibility to choose avoidance strategies, such as braking, evading, or rerouting, introducing a dynamic control challenge in response to real-time scenarios. As the levels progress to four through six, the focus shifts to optimizing package delivery, resembling the Multiple Online Traveling Salesperson Problem. Control complexities raises from simple pickups in level four to incorporating packet counts and vehicle size limitations in levels five to six. Each level adds intricacy to the optimization problem, demanding more and more sophisticated control strategies. Moreover, the entire problem necessitates online problem-solving, as package properties are randomly determined during runtime, emphasizing the need for adaptive and dynamic control solutions. The course culminates in levels seven to nine, where vehicles face fuel consumption and refueling requirements, while packets are assigned profit and deadlines. These new variables target the “Apply” and “Analyze” dimension, thereby deepening their understanding of the problem.

In summary, our evaluation of the undergraduate course yielded several key insights: (i) Students favor flexibility over constant on-campus work, valuing the ability to manage their time independently. (ii) Students value collaborative group work and using tools like Gitlab. (iii) Students appreciate the real-world applicability of the course content. (iv) The structured level system, with clear objectives and progress monitoring, is well-received. (v) Students find value in observing their working solutions reach key milestones in the physical testbed. (vi) Despite annual documentation improvements, students express concerns about its sufficiency.

C. Graduate Students

The graduate-level course Control and Perception in Networked and Autonomous Vehicles (CPNAV) is our advanced class for applications in CAVs for Computer Science, Computational Engineering Science, and Automation Engineering students. This course combines theory of multi-agent decision-making with practice-driven exercises in the CPM Lab. In the lecture, we teach the Sense-Plan-Act paradigm, the basics of Model Predictive Control (MPC), and Networked Control Systems (NCS), in a top-down [21] approach, focusing on central and distributed MPC. Afterward, in our testbed, the students apply this knowledge in teams of one engineering and one computer science students in a bottom-up [21] manner. At the time of writing, 150 students took the course in total since 2019.

In the initial two course iterations, we scheduled the exercise as a two-week block following the lecture. However, student feedback from the first year revealed their preference for practical work but dissatisfaction with the block placement due to its proximity to the exam period. We moved the exercise to run in parallel with the lecture to address this issue. Since this adjustment, feedback about the placement has been consistently positive as it enables students to apply knowledge recently learned in practical settings while keeping their exam preparation time unencumbered.

In 2021, we extended the practice-driven exercise duration in the CPM Lab to eight days and introduced checkpoints for students’ progress. This extension was primarily prompted by the challenges posed by students’ low-performing hardware. Although we provide a Virtual Machine (VM) for the exercise, it often demands more computational power than some students can access. Since some students could not work outside the exercises, we extended the exercise time without increasing the content. This issue prompted us to develop CPM Remote and augment the exercise duration to ensure students have access to high-performance hardware or suitable alternatives. The addition of checkpoints ensured equitable grading based on students’ progress..

In 2022, we experimented with a new approach, offering lecture content through prerecorded videos and in-person Q&A sessions. However, student feedback indicated a preference for in-person lectures over recorded videos. Despite the option of in-person Q&A sessions, students struggled to stay motivated when relying solely on video content. As a result, we have returned to providing traditional, in-person lectures for the current iteration of the course.

We keep the number of students low for two primary reasons. Firstly, maintaining a small class size ensures that every student can access the physical testbed, a feature highly valued by students. Expanding the number of students would necessitate alternate on-site visits every other week due to physical space constraints, reducing the total time each student spends on-site. Secondly, a smaller class size promotes a closer student-lecturer relationship, which students frequently highlight as a positive aspect in our feedback. The willingness of the lecturer to engage in discussions is mentioned in eleven out of fourteen positive comments from the 2021 questionnaire. In conclusion, we observed that a limited number of students enhances engagement with the lecturer and extends practical on-site work.

The initial two days of the exercise provide an essential introduction to the testbed, emphasizing students’ understanding of the unique testbed environment and promoting independent problem-solving. This preparation serves to reduce the need for future supervisor interventions. After this, the third day focuses on model identification. While students have acquired the necessary theoretical knowledge for model identification, practical application reveals significant challenges in obtaining high-quality models from data recorded from physical systems. This experience necessitates careful consideration of data and preprocessing methods to ensure accurate motion prediction, targeting the “Analyze” dimension of Bloom’s taxonomy. The exercise descriptions present goals rather than step-by-step guidance, requiring students to synthesize knowledge from prior studies and lectures. The motion model developed on day two forms the foundation for implementing MPC on a single and multiple vehicles. Initially, students focus on controlling a single vehicle, which should adhere closely to a provided speed profile. While seemingly straightforward mathematically, this step allows students to familiarize themselves with tuning parameters in MPC and assess the quality of their motion model. The final objective is for students to construct a platoon with five or more vehicles. They commence with a central computation approach, solving the control problem as one optimization problem for all vehicles. Progressing further, they transition to a distributed computation approach, where each vehicle solves its own optimization problem while communicating with others. This final goal can be archived in multiple ways and requires students to “Evaluate” all possible solutions, spanning the “Remember”, “Understand”, and “Apply” levels as taught in the theoretical lecture.

We integrated five flipped classrooms into the traditional theoretical lecture format. In these 30-minute sessions, students prepare materials, present a lecture, and guide the post-lecture discussion. Feedback from students has predominantly praised this approach, with the occasional critique centering on language barriers or minor slide inconsistencies, promptly addressed through clarifications by the lecturer. Remarkably, we have encountered minimal negative feedback regarding flipped classrooms across four years of implementation, signifying their effectiveness in fostering deeper student engagement with course materials.

In summary, our evaluation of the practical course for graduate students revealed several key findings: (i) Students like the placement of practice-driven exercises right after the theoretical lecture as it allows for direct practical understanding. (ii) Students like the interactive lecture contents like flipped classrooms and open discussions and value a close student-lecturer relationship. (iii) Students appreciate the small class sizes, close interaction with the lecturer and in-person lecture over prerecorded videos. (iv) Students like having clear goals to work towards and having intermediate goals like checkpoints. At the same time, it makes grading easier as a team’s progress can be objectively quantified. (v) Students often do not have access to sufficient hardware to execute a simulation for CAV applications. They need sufficient time with on-campus hardware or an alternative solution like CPM Remote.

D. Postgraduate Students

CPM Olympics [24] is an annual motion planning competition tailored to postgraduate students, offering a platform for benchmarking motion planning algorithms for CAV. The participants, often recent or near-graduates, exhibit diverse needs and backgrounds, making a structured, guided experience akin to the CPM Academy less feasible. Instead, at this level, participants opt in deliberately, motivated by intrinsic interest in the field. Our focus has shifted toward fostering interest in the platform itself, emphasizing the value proposition in relation to the effort invested.

The CPM Olympics distinguishes itself from comparable platforms in three key ways. Firstly, it offers a standardized set of benchmarks that facilitate objective comparisons between different solutions. Secondly, it features a growing set of real-world scenarios to challenge motion planners. Lastly, the competition rewards the best-performing solutions with cash prizes and a possibility to present their solution at a conference workshop.

The evaluation of submitted planners involves two aspects. Firstly, there are mandatory requirements like collision avoidance. Failure to meet these requirements results in a zero score for the scenario. Successfully meeting these requirements paves the way for a more detailed evaluation that assesses performance metrics such as energy efficiency and travel time. This application focuses on the highest of Bloom’s taxonomy levels, “Create”, as every scenario is different, and a single motion planner should solve all.

The inaugural CPM Olympics in 2022 featured a total prize pool of $3,000. This competition garnered 79 registrations, with active participation from nearly 30 % of users, as indicated by an average of 3.5 submitted planners per participant. The workshop was held at the IEEE Intelligent Vehicle Symposium (IV) in Anchorage, Alaska. Building on this success, the second edition doubled the prize money.

III. Lessons Learned

This section provides the lessons learned from the educational applications presented in the previous section. We address key aspects such as testbed utilization, providing web-based interfaces, scheduling of practice-driven exercises, and promoting active student interaction.

Use testbed space effectively. Our feedback and comparable literature suggest that working with simulations and occasional on-campus visits, especially at key milestones, engages undergrad students as effectively as constant on-campus work. Graduate-level courses benefit from small classes that allow constant on-campus work, especially for tasks involving direct interaction with physical robots, such as motion model creation or low-level hardware work.

Provide a platform like CPM Remote. Despite advancing hardware, many students rely on outdated or low-performing systems that hinder the execution of CAV simulations. We propose creating a web-based platform with server-side execution to overcome hardware limitations and allow students to participate in a course they would otherwise not be capable of attending.

Strategically schedule practice-driven exercises. Clustering practice-driven exercise in a block can reduce engagement and create a stressful work environment. Instead, spread placement across the semester and position the exercise right after the theoretical lecture to apply the gained knowledge.

Promote active student interaction. Use interactive elements like flipped classrooms for collaborative learning and a deeper understanding of the lecture material. Encouraging students to collaborate will help them to solve complex problems and can be further assisted by an open student-lecturer relationship.

Creating intermediate goals. Create intermediate goals like the levels in CPM Academy, the checkpoints in CPNAV, or the difference scenarios on the CPM Olympics. Students value having a clear goal and find it rewarding to pass those goals. Additionally, it makes grading easier and fair as the supervisor can objectively assess a team's progress.

Offer in-person lectures. While videos allow students to pace themselves and access course content from anywhere, our feedback has shown that they are best utilized as supplementary resources rather than the primary basis for instruction. Students may face challenges in self-motivation and have questions that require immediate answers, making in-person lectures a more effective choice.

IV. Conclusion

In summary, we showed that the CPM Lab has proven its worth as an educational resource over the past four years, while ongoing course adaptations aim to optimize the learning experience. Our implementation across diverse student groups provides hands-on experience for all education levels, starting with undergrad students and finishing with postgraduate students. We provide lessons learned for other institutes to create their course portfolio and learn from the experience we gathered. For undergrad students who come in touch with CAV for the first time, it is more important to have easy access and a guided experience with gamification aspects to increase engagement with the topic. On the other hand, for graduate students, engaging deeply with the knowledge with tools like flipped classrooms provides opportunities to target the higher taxonomy dimensions "Analyze" and "Evaluate". We could not gain such conclusions for postgraduate students as their needs and goals are too broad to cover in a single application. However, the CPM Olympics provides a tool to compare motion planners for CAVs with real-world scenarios objectively.

References

[1] M. Kloock, P. Scheffe, J. Maczijewski, A. Kampmann, A. Mokhtarian, S. Kowalewski, and B. Alrifaee, "Cyber-physical mobility lab: An open-source platform for networked and autonomous vehicles," in *2021 European Control Conference (ECC)*, 2021, pp. 1937–1944.

[2] A. Mokhtarian, P. Scheffe, S. Kowalewski, and B. Alrifaee, "Remote teaching with the cyber-physical mobility lab," *IFAC-PapersOnLine*, vol. 55, no. 17, pp. 386–391, 2022, 13th IFAC Symposium on Advances in Control Education ACE 2022.

[3] F. Foundation, "F1tenth - course documentation," 2020, accessed on Oct. 5th 2023. [Online]. Available: https://f1tenth.org/learn

[4] A. Agnihotri, M. O'Kelly, R. Mangharam, and H. Abbas, "Teaching autonomous systems at 1/10th-scale: Design of the f1/10 racecar, simulators and curriculum," in *Proceedings of the 51st ACM Technical Symposium on Computer Science Education*, ser. SIGCSE '20. New York, NY, USA: Association for Computing Machinery, 2020, p. 657–663.

[5] J. Betz, H. Zheng, Z. Zang, F. Sauerbeck, K. Walas, V. Dimitrov *et al.*, "Teaching autonomous systems hands-on: Leveraging modular small-scale hardware in the robotics classroom," *arXiv preprint arXiv:2209.11181*, 2022.

[6] S. Wilson, P. Glotfelter, L. Wang, S. Mayya, G. Notomista, M. Mote *et al.*, "The robotarium: Globally impactful opportunities, challenges, and lessons learned in remote-access, distributed control of multirobot systems," *IEEE Control Systems Magazine*, vol. 40, no. 1, pp. 26–44, 2020.

[7] L. Paull, J. Tani, H. Ahn, J. Alonso-Mora, L. Carlone, M. Cap *et al.*, "Duckietown: An open, inexpensive and flexible platform for autonomy education and research," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, 2017, pp. 1497–1504.

[8] B. Chalaki, L. E. Beaver, A. I. Mahbub, H. Bang, and A. A. Malikopoulos, "A research and educational robotic testbed for real-time control of emerging mobility systems: From theory to scaled experiments [applications of control]," *IEEE Control Systems Magazine*, vol. 42, no. 6, pp. 20–34, 2022.

[9] N. Buckman, A. Hansen, S. Karaman, and D. Rus, "Evaluating autonomous urban perception and planning in a 1/10th scale minicity," *Sensors*, vol. 22, p. 6793, 2022.

[10] S. Karaman, A. Anders, M. Boulet, J. Connor, K. Gregson, W. Guerra *et al.*, "Project-based, collaborative, algorithmic robotics for high school students: Programming self-driving race cars at mit," in *2017 IEEE Integrated STEM Education Conference (ISEC)*, 2017, pp. 195–203.

[11] B. Balaji, S. Mallya, S. Genc, S. Gupta, L. Dirac, V. Khare *et al.*, "Deepracer: Autonomous racing platform for experimentation with sim2real reinforcement learning," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2020, pp. 2746–2754.

[12] T. Tiedemann, L. Schwalb, M. Kasten, R. Grotkasten, and S. Pareigis, "Miniature autonomy as means to find new approaches in reliable autonomous driving ai method design," *Frontiers in Neurorobotics*, vol. 16, p. 846355, 2022.

[13] R. Shadiev and S. Yi, "A systematic review of uav applications to education," *Interactive Learning Environments*, vol. 0, no. 0, pp. 1–30, 2022.

[14] G. A. Casañ, E. Cervera *et al.*, "The experience of the robot programming network initiative," *Journal of Robotics*, vol. 2018, 2018.

[15] J. Cañas, D. Martín-Martín, P. Arias, J. Vega, D. Roldán-Álvarez, L. García-Pérez *et al.*, "Open-source drone programming course for distance engineering education," *Electronics*, vol. 9, no. 12, p. 2163, 2020.

[16] P. Scheffe, J. Maczijewski, M. Kloock, A. Kampmann, A. Derks, S. Kowalewski, and B. Alrifaee, "Networked and autonomous model-scale vehicles for experiments in research and education," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 17 332–17 337, 2020, 21st IFAC World Congress.

[17] M. Kloock, P. Scheffe, I. Tülleners, J. Maczijewski, S. Kowalewski, and B. Alrifaee, "Vision-based real-time indoor positioning system for multiple vehicles," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 15 446–15 453, 2020, 21st IFAC World Congress.

[18] A. Mokhtarian and B. Alrifaee, "CPM Remote: A remote access to the cpm lab," in *2022 8th International Conference on Control, Decision and Information Technologies (CoDIT)*, vol. 1, 2022, pp. 1124–1129.

[19] L. W. Anderson and D. R. Krathwohl, *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives: complete edition*. Addison Wesley Longman, Inc., 2001.

[20] A. Jurado-Navas and R. Munoz-Luna, "Scrum methodology in higher education: Innovation in teaching, learning and assessment." *International Journal of Higher Education*, vol. 6, no. 6, pp. 1–18, 2017.

[21] R. Sun, *Bottom-Up Learning and Top-Down Learning*. Boston, MA: Springer US, 2012, pp. 479–481.

[22] K. Kapp, *The gamification of learning and instruction: game-based methods and strategies for training and education*. John Wiley & Sons, 2012.

[23] A. Mokhtarian, L. Hegerath, and B. Alrifaee, "CPM Academy: A Remote Platform for Teaching Current Topics in Networked and Autonomous Driving," 2023, accepted in IEEE Conference on Decision and Control.

[24] A. Mokhtarian, S. Schäfer, and B. Alrifaee, "CPM Olympics: Development of scenarios for benchmarking in networked and autonomous driving," in *2022 IEEE Intelligent Vehicles Symposium (IV)*, 2022, pp. 9–15.