CPM Remote: A Remote Access to a Scaled Experimental Testbed for Connected and Automated Vehicles

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Abstract

Small-scale testbeds are used in research and development to provide a controlled setting for testing new concepts. They are affordable and can be duplicated, making them useful for both education and research purposes. To address the limitations of small-scale testbeds, particularly their accessibility, we introduce CPM Remote, a web-based platform that provides real-time access to the Cyber-Physical Mobility (CPM) Lab, a scaled testbed at RWTH Aachen University. This innovative approach eliminates the need for users to travel, purchase, or reconstruct physical testbeds. CPM Remote incorporates a built-in editor, a simulation environment, and a real-time interface to the CPM Lab, extending accessibility to a global audience. Users have the flexibility to conduct their own experiments or choose from two ready-to-use applications, enabling them to actively engage with the field of Connected and Automated Vehicles (CAVs).

The educational application, CPM Academy, offers students an immersive learning experience by presenting a package delivery service scenario to develop algorithms within the context of CAVs. For research purposes, we introduce CPM Olympics, an annual competition that offers participants real-world scenarios to benchmark their motion planning algorithms. In our evaluation of the platform and its applications, we carried out multiple user studies and a technology acceptance analysis to pinpoint potential areas for enhancement. The feedback from each study was considered during the development of CPM Remote to enhance its feature set and usability. Based on the successfully conducted iterations of the CPM Academy and CPM Olympics, we demonstrate how CPM Remote bridges the gap between simulations and costly real-world tests, democratizing access to experimental research infrastructure.

Zusammenfassung

Modellabore dienen in Forschung und Entwicklung als kontrollierte Umgebungen zur Erprobung neuer Konzepte. Aufgrund ihrer Kosteneffizienz und Reproduzierbarkeit sind sie sowohl für Bildungs- als auch Forschungszwecke von Nutzen. Um die Einschränkungen, die mit bisherigen Modellaboren einhergehen, zu überwinden, präsentieren wir CPM Remote. Hierbei handelt es sich um eine webbasierte Plattform, die Echtzeitzugriff auf das Cyber-Physical Mobility (CPM) Lab, ein Modellabor an der RWTH Aachen, bietet. Dieses Konzept erspart Nutzern die Notwendigkeit zu reisen, Testumgebungen zu erwerben oder diese neu aufzubauen. CPM Remote umfasst einen Editor, eine Simulationsumgebung und eine Echtzeitschnittstelle zum CPM Lab, was die Zugänglichkeit für ein weltweites Publikum ermöglicht. Nutzer können ihre eigenen Experimente durchführen oder aus zwei sofort einsatzbereiten Anwendungen wählen, um sich mit dem Bereich vernetzter und automatisierter Fahrzeuge zu beschäftigen.

Für Bildungszwecke bietet die CPM Academy den Studierenden ein didaktisch aufbereitetes Lernerlebnis. Ein Paketzustellungszenario ermöglicht es den Studierenden, Algorithmen im Kontext vernetzter und automatisierter Fahrzeuge zu entwickeln. Zudem bieten wir Forschenden einen jährlichen Wettbewerb, die CPM Olympics, an. Hier können Teilnehmende reale Szenarien nutzen, um ihre Bewegungsplanungsalgorithmen zu evaluieren. Bereits während der Entwicklungsphase von CPM Remote wurden verschiedene Evaluationen durchgeführt, darunter mehrere Benutzerstudien und eine Technologieakzeptanzanalyse, um potenzielle Verbesserungsbereiche zu identifizieren. Das Feedback aus diesen Bewertungen wurde aktiv in die Weiterentwicklung von CPM Remote einbezogen, um sowohl den Funktionsumfang als auch die Benutzerfreundlichkeit zu optimieren. Mit dem CPM Lab und CPM Remote kombinieren wir die Vorteile von Simulationen und Praxistests, indem wir kostengünstiges und gleichzeitig realitätsnahes Testen ermöglichen. So wollen wir den Zugang zur experimentellen Forschungsinfrastruktur zu demokratisieren.

Contents

Acronyms

AI-DO AI Driving Olympics.

CAVs Connected and Automated Vehicles.

CPM Lab Cyber-Physical Mobility Lab.

DDS Data Distribution Service.

E2E End-to-end.

GNSS Global Navigation Satellite Systems.

IPS Indoor Positioning System.

LaaS Lab as a Service.

MOOC Massive Online Open Course.

STEM Science, Technology, Engineering and Math.

SWE Software Engineering.

TAM Technology Acceptance Model.

TSP Traveling Salesman Problem.

Chapter 1

Introduction

In the rapidly advancing domain of Connected and Automated Vehicles (CAVs), research and development have traditionally been anchored in either simulations or real-world experiments. Each has its own strengths and weaknesses, painting a complex picture of the testing landscape. Simulation environments are essential for testing and validation, but they often face challenges in accurately representing the real world [42]. Related to the challenges of computational modeling, these simulations struggle to capture details such as changing weather patterns or unpredictable pedestrian behavior. As they strive for greater accuracy, especially with the complexities of physics, the demands on computing power and hardware increase significantly. On the other hand, real-world experiments, despite their direct applicability, come with significant costs and overhead, sometimes making them prohibitive for iterative testing and development [73].

Small-scale testbeds have emerged as a promising solution to bridge the gap between these two approaches. These testbeds provide a controlled environment that balances the benefits of simulation and real-world experimentation. They offer reproducibility, a critical aspect of scientific experimentation, while reducing development and maintenance costs compared to full-scale testing. In addition, small-scale testbeds are tailored to specific use cases, streamlining the testing process and making it more efficient.

The Cyber-Physical Mobility (CPM) Lab [48] serves as a testbed for exploring the potential of CAVs. Within this facility, we have a fleet of 20 vehicles called µCar, each built to a 1:18 scale. They operate in a designated 4x4.5m area. Despite their small scale, these vehicles are engineered to mimic realistic driving physics, notably incorporating the Ackermann steering mechanism [81]. For navigation, the µCar rely on an indoor positioning system consisting of a ceiling-mounted camera designed as an alternative to traditional Global Navigation Satellite Systems (GNSS). The CPM Lab's infrastructure supports both centralized and distributed computing. In addition, users have the flexibility to design and implement their own test scenarios using programming platforms such as C++ and MATLAB.

However, small-scale testbeds do have limitations. One notable limitation is the extent of their feature sets. For instance, they tend to focus on specific use cases and support only certain programming languages, leaving gaps in their domain coverage. Another significant constraint is accessibility. To overcome this challenge, various testbeds have adopted different approaches to facilitate access. Some provide detailed blueprints for users to build their own testbeds [36, 49], while others are available for purchase [75]. Some may require physical travel to the testbed location [14, 49], while others offer remote access options [100]. Remote access is particularly attractive due to its minimal logistical requirements, making it a low-barrier solution that can engage a broader user base in the subject matter. Nevertheless, it is important to recognize that, despite its convenience, a remote access cannot fully replicate the tangible experience of being physically present in a testbed.

In this thesis, we present CPM Remote, a novel remote access solution for the CPM Lab and demonstrate its effectiveness in expanding access to the domain of CAVs to users worldwide. We show how this approach can bridge geographical boundaries and enable a more diverse and inclusive engagement with CAV research and experimentation. CPM Remote can also serve as an example for other scaled testbeds that might want to open their platforms to a broader audience. With its two applications, CPM Academy for education and CPM Olympics for research, it encourages broader participation in the study and development of CAV technologies and fosters collaborative advances in the domain.

1.1 Objectives and Contributions

Central to this thesis's contributions is the concept of remote access for small-scale testbeds. This approach aims to bridge geographical and infrastructural gaps. By making research and educational platforms universally accessible, we strive to facilitate advancements in CAVs, promoting a global community of informed learners and innovators. The following points outline the primary contributions of this work, emphasizing its dedication to fostering global accessibility in CAV development. We:

» Conducted a thorough examination of the current small-scale testbeds focusing on how they support the advancement of CAVs, emphasizing their accessibility to effectively promote their potential [64].

» Designed and established a remote access interface to the CPM Lab, enabling users to interact with both the hardware and software via a web interface [60].

» Introduced a user-centric web framework that harnesses cloud computing, eliminating the need for users to have advanced hardware. The platform is fully responsive, ensuring compatibility with all browsers [60].

» Undertook a detailed user analysis to tailor applications, aiming to engage distinct user groups effectively with the platform [63, 86].

» Implemented CPM Academy, a dedicated application for students presenting them with contemporary CAV challenges. A unique gameified package delivery service is implemented using state of the art didactic methodologies [61].

» Implemented CPM Olympics, an annual event tailored for researchers. It provides a set of reproducible and accessible real-world problems aimed at facilitating knowledge exchange in motion planning algorithms for CAVs [62].

» Conducted multiple user studies on the CPM Remote platform by executing two iterations of both CPM Academy and CPM Olympics. Valuable user feedback was accumulated and integrated to enhance CPM Remotes usability [59].

1.2 Thesis Outline

This thesis unfolds in the subsequent manner: In Chapter 2, we provide an exhaustive analysis of existing small-scale testbeds, emphasizing their role in CAV development and spotlighting their accessibility challenges. Chapter 3 introduces our main contribution: the creation of a user-centric, web-based remote access interface for the CPM Lab, highlighting its design and capabilities. Chapter 4 starts with a comprehensive user analysis, detailing the insights gathered and their implications for platform customization. Furthermore, it introduces CPM Olympics, a platform geared towards researchers, aiming to promote knowledge exchange in the CAV domain. In Chapter 5, we present the CPM Academy and its gamified approach, tailored specifically for student engagement. Chapter 6 deals with the technical implementation of CPM Remote. Chapter 7 reflects on the feedback and findings from the user studies conducted on the CPM Remote platform, underscoring iterative improvements and future potential. Finally, Chapter 8 concludes this thesis and provides an outlook for future work.

1.3 Bibliographic Notes

This thesis incorporates elements from earlier publications and also benefits from the input of graduate students who conducted their theses under the supervision of the author. In this section, we present a comprehensive list of the relevant publications and graduate theses. For the publications [60, 61, 62, 64, 63], the author is the main contributor to the core concepts, the evaluation concept, and the paper content. Additional authors have contributed to the implementation, execution of evaluation ideas, and review of the manuscript. A comprehensive summary of this thesis is planned to be written and submitted to the journal IEEE Robotics & Automation [59].

Peer-reviewed Publications as Main Contributor

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Further Publications

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Graduate Theses

[1] Phillip Ahlers. 'Unifying Result Delivery for Real-World and Simulated Experiments in CPM Remote'. BA thesis. RWTH Aachen University, 2023.

[9] Jan Brüggenjürgen. 'Development of an Automation Interface for the Remote Access Branch of the CPM Laboratory'. BA thesis. RWTH Aachen University, 2021.

[17] Daniel Coban. 'A Concept for a Web-based Simulation Environment of a Testbed for Networked and Autonomous Vehicles'. BA thesis. RWTH Aachen University, 2020.

[18] Daniel Coban. 'Analysis and Improvement of Software Quality and Security of the CPM Remote Project'. MA thesis. RWTH Aachen University, 2022.

[28] Niels Freitag. 'Improving User Feedback Mechanisms for Real-World Experiments in CPM Remote'. BA thesis. RWTH Aachen University, 2024.

[34] Lucas Hegerath. 'CPM Academy: A Remote Platform for Teaching Current Topics in Autonomous Driving'. BA thesis. RWTH Aachen University, 2022.

[35] Almut Herzog. 'Analysis and Improvement of Usability for the CPM Remote Project'. MA thesis. RWTH Aachen University, 2023.

[39] Lasse Jacob. 'CPM Olympics: A Manoeuvre Planning Competition for Networked and Autonomous Vehicles'. BA thesis. RWTH Aachen University, 2023.

[50] David Klüner. 'Development of a Search-based Motion Planner for Networked Non-holonomic Vehicles'. MA thesis. RWTH Aachen University, 2023.

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CHAPTER 2

Preliminaries and Related Work

2.1 Introduction

The recent years have seen a notable increase in the development and deployment of small-scale testbeds in the field of CAVs [11]. These specialized testbeds play a crucial role in research and experimentation, driving progress in areas like robotics, artificial intelligence, and control systems. A key feature shared by these varied testbeds is their reliance on the sense-plan-act paradigm. This paradigm outlines the core functions of an autonomous vehicle. This chapter aims to provide an exhaustive analysis of existing small-scale testbeds, particularly spotlighting the methods employed by these platforms to enhance accessibility and interoperability. Our review strictly follows the sense-plan-act paradigm, thereby ensuring a structured and uniform approach to the analysis. Through this lens, we aim to understand the architecture and operational dynamics of these testbeds more comprehensively. This work has been conducted in collaboration with the creators of 7 testbeds, broadening the scope of insight into their design and deployment strategies.

2.2 Small-scale Testbeds

In this section, we outline our approach for studying and comparing small-scale testbeds. We shared our results on `www.cpm-remote.de/testbeds` to keep the information accessible and easy to update for everyone interested. In our analysis, we made an effort to derive specific characteristics for each one of these domains – sense, plan, and act. These characteristics serve as criteria that encapsulate key functional aspects of the testbeds. For instance, under the *sense* domain, parameters might include the types of sensors used, with a distinction made between onboard sensors, which are directly mounted on the vehicle, and sensors that are integrated into the testbed's infrastructure. Similarly, detailed parameters are identified for the *plan* and *act* domains.

With these domain-specific characteristics, we can methodically describe and discuss each small-scale testbed, subsequently enabling a side-by-side comparison with each other. It is crucial to note that this comparison is analytic in nature; we solely intend to delineate the differences and similarities between testbeds, abstaining from any judgments regarding their quality or value. Our goal is to present an objective, and comprehensive portrayal of existing small-scale testbeds. Such an approach not only aids in understanding the unique and common features among various testbeds. It also serves as a valuable resource for researchers seeking to select a testbed appropriate for their specific research needs or to identify potential areas for improvement in existing platforms.

In the subsequent sections, we will investigate each of the identified testbeds, analyzing their structure and functionality within the sense-plan-act paradigm, and highlight their methods for ensuring accessibility to users.

2.2.1 A Survey on Small-Scale Testbeds for Connected and Automated Vehicles and Robot Swarms

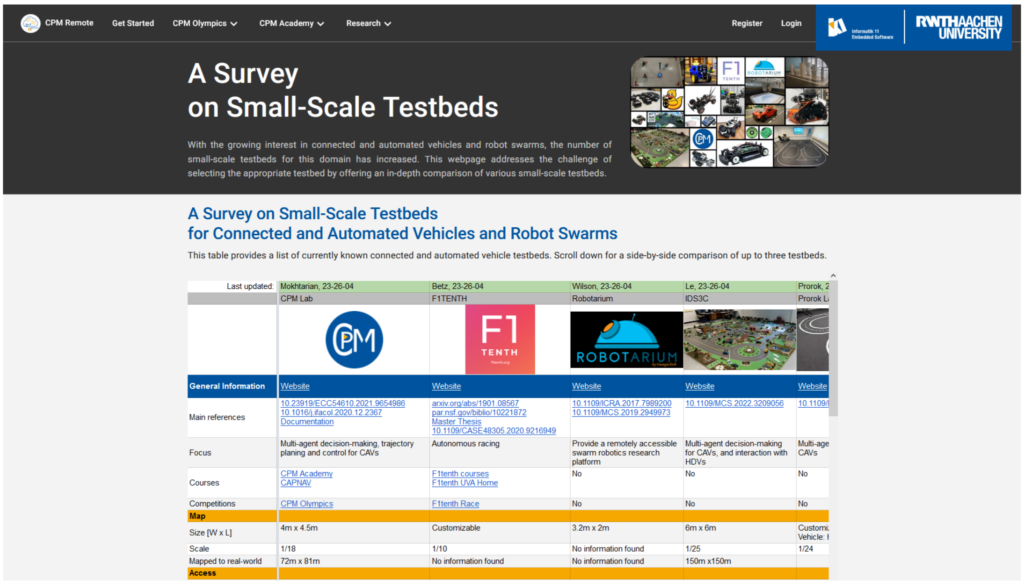

Figure 2.1: A screenshot of the publicly accessible webpage [4], which includes all investigated testbeds.

The main outcome of this survey is an online table that has been designed to display the various aspects of these testbeds. This table contains over 60 unique characteristics. Each row in the table is dedicated to a specific characteristic, while each column represents an individual small-scale testbed. This design allows for a better understanding of each testbed's capabilities, features, and specialities.

This survey was grounded in a rigorous literature research. Through this research, we identified 17 distinct testbeds. The information we gathered about each of these testbeds was then methodically integrated into our table. During the writing of this thesis, the table includes the CPM Lab [48], IDS3C [14], Duckietown [75], F1TENTH [70], Robotarium [100], Cambridge Minicar [36], CHARTOPOLIS [97], Go-Chart [43], Pheeno [99], Chronos [12], Miniature Autonomy [94], ORCA [54], MiniCity [10], SAMS [88] Cyber-Physical Systems Lab [33], UPBOT [19] , MCCT [23].

Recognizing the value of firsthand insights, we reached out to the developers and maintainers of these testbeds, inviting them to verify the information we had gathered. We also encouraged them to contribute any additional insights or details they believed were relevant. This collaborative approach was met with enthusiasm, and a majority of them participated, ensuring that our table was both more accurate and comprehensive. Figure 2.1 shows a screenshot of the public webpage [4] including our table.

One of the key characteristics we included in our table pertained to the general accessibility of these testbeds. Accessibility is crucial, as it dictates how easily researchers and students can engage with or replicate these testbed setups. The results of our survey yielded favorable findings: A significant majority of these testbeds are designed with accessibility in mind. They adopt various strategies to ensure this:

1) Blueprints and Construction Plans:
   While some testbeds offer detailed blueprints and construction plans, enabling enthusiasts to recreate the setup in their own environments, it is important to acknowledge that this can present an initial challenge due to the complexity involved in replicating such a configuration.

2) Ready-to-use Setups:
   Recognizing that not everyone has the time or resources to start from scratch, some testbeds provide pre-built, ready-to-use setups for purchase.

3) Simulation Enviroments:
   Several testbeds offer simulation tools that mimic the real-world setup, allowing users to test and experiment without needing physical access. However, it is important to note that these tools don't include all the benefits of a real-world setup, as they may not fully replicate the complexity and nuances of the actual testbed.

4) Remote Access:
   Combining the advantages of the previously mentioned methods, a remote access emerges as the most user-friendly solution. It offers the convenience of being both cost-free and effortless to set up while encompassing the benefits of a real-world testbed. Of course, it is important to recognize that this shift of convenience from the testbed creators to the users implies that the establishment of a reliable remote access system demands significant development and maintenance efforts.

In the following section, we will explore the various approaches adopted to enhance testbeds' accessibility, specifically focusing on two prominent examples: Duckietown and the Robotarium. Through these testbeds, we will illustrate their chosen methods of accessibility, providing insight into how such platforms are made more user-friendly and available to a broader audience.

2.2.2 Duckietown and Robotarium

Duckietown [75] places a significant emphasis on perception, particularly in the self-localization of their distinctive *Duckiebot* within the test environment. The Duckiebot is engineered with a suite of sensors, allowing it to autonomously navigate and understand its surroundings. This vehicle uses a differential drive system, which makes its vehicle dynamics more similar to those of a robot than to a vehicle with Ackermann steering [81], a mechanism used in automotive applications to ensure that all wheels turn at appropriate angles during cornering.

Additionally, Duckietown strongly prioritizes educational research. It serves as an important element in academic programs and has been incorporated into a wide range of university courses internationally. It is the central component of their Massive Online Open Course (MOOC) [1], making its educational impact far reaching and accessible. Additionally Duckietown hosts a competition known as the AI Driving Olympics (AI-DO)[2]. This competition is designed to foster innovation, collaboration, and a competitive spirit among participants, furthering research and development in robotics and autonomous systems.

Duckietown has made efforts to ensure their testbed is accessible to a broad spectrum of users. One significant step in this direction is their development of a simulator based on the OpenAI Gym framework [16]. This simulator allows users worldwide to freely download and install the software, providing them the opportunity to experiment with the Duckietown environment without the need for physical hardware. In addition to their digital offerings, Duckietown also provides physical testbeds for users looking to engage with tangible hardware. They offer a variety of bundles for sale, accommodating different user needs and budget constraints. These bundles vary extensively, with packages ranging from $ 300, suitable for individuals or small-scale setups, to setups that can go up to $ 100,000 for institutional applications. This approach ensures that various users, from students to researchers and universities, can tailor their purchase to their specific needs and financial capacity.

The Robotarium [77] presents a unique approach within the landscape of small-scale testbeds, with a distinct focus on the planning aspect of the sense-plan-act paradigm. Un-

[1]https://duckietown.com/mooc/

[2]https://duckietown.com/research/ai-driving-olympics/

like Duckietown, which emphasizes local perception, the Robotarium leverages a global motion caption system to precisely localize their vehicles, known as GRITSBots. The primary challenge, therefore, pivots from perception to the complex task of coordinating multiple vehicles, ensuring, for instance, that they remain collision free.

Remarkably, of all the testbeds investigated in our survey, the Robotarium stands out as the only one offering a remote access. This feature significantly broadens its accessibility, allowing users from around the globe to interact with the testbed [100]. After setting up the necessary software, users can submit their experiments online. One of the key distinctions between our approach and the Robotarium lies in the setup process. Unlike the Robotarium, CPM Remote eliminates the need for any setup by integrating the entire development environment directly into the website. Furthermore, it is important to mention that there may be a waiting period before users receive the results of their experiments. This delay is due to high demand and scheduling constraints.

Additionally, their remote-access capability provides also a valuable educational resource. Lecturers worldwide utilize it to enhance their courses, providing students with practical, hands-on experience in a sophisticated robotics environment without the logistical and financial burdens of setting up a local testbed [7]. This approach underscores the Robotarium's dedication to breaking barriers in robotics education and research, fostering a more inclusive, accessible, and practical learning experience.

Duckietown and the Robotarium exemplify the impact of making testbeds accessible on a global scale, particularly in the field of CAVs. Their initiatives have demonstrated that when barriers to entry are lowered, there is a significant surge in engagement from enthusiasts, scholars, and researchers worldwide. This global engagement is not just a testament to the growing interest in CAVs and Robots but also a reflection of the effective outreach strategies these platforms employ.

Both Duckietown and the Robotarium have utilized the power of competitions and academic courses to foster deeper engagement with their respective platforms. Competitions like Duckietown's AI Driving Olympics present challenges that stimulate innovative problem solving and technical prowess among participants. Similarly, the integration of these testbeds into academic curricula, as seen with the Robotarium's remote access for educational purposes, offers practical, hands-on learning experiences. These approaches enhance the learning process and also cultivate a community of learners and innovators who contribute to the collective knowledge and advancement of CAVs.

In conclusion, by minimizing the inhibition threshold for engaging with a testbed and by offering structured challenges and learning opportunities, platforms like Duckietown and the Robotarium significantly accelerate progress in the domain of CAVs. More importantly, they play a crucial role in the personal and professional development of individuals in the field. Each of the testbeds, we have investigated in the survey, including examples like Duckietown and the Robotarium, exhibits its own distinctive focus, underscoring the vast and multifaceted nature of the CAVs domain. It is evident that with such a broad spectrum of research topics within this field, it is a huge challenge for a single testbed to comprehensively encompass all possible areas. In the upcoming section, we will introduce the CPM Lab, a testbed that focuses on motion planning for CAVs. Utilizing scaled vehicles, the CPM Lab's primary objective is to support the development and validation of algorithms designed to navigate and make decisions in complex traffic scenarios. In the following, we will discuss how this platform can significantly foster research and education in the domain of CAVs.

2.3 Cyber-Physical Mobility Lab

Figure 2.2: A snapshot of the Cyber-Physical Mobility Lab showcasing 15 vehicles on the map. Furthermore, a server rack housing an Intel NUC for each vehicle, a digital twin displayed on the TV screen, and a manual driving steering wheel.

The Cyber-Physical Mobility Lab [48] is primarily designed for multi-vehicle motion planning and control of CAVs. The CPM Lab operates with 1:18 scale vehicles, named μCar. These vehicles are localized within the testbed environment through a ceiling-mounted camera system that tracks LEDs mounted on the vehicles, ensuring precise movement and coordination within the testbed's physical space.

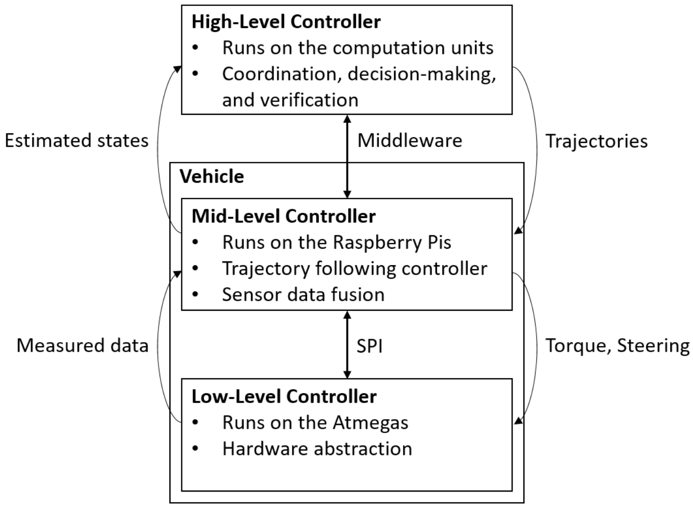

Figure 2.3: The three-layered architecture of the CPM Lab. Each layer is responsible for a separate task, which eases changes in hardware and software [47].

One of the CPM Lab's unique features is its integration of a digital twin concept, allowing the extension of physical test scenarios by including simulated vehicles. This fusion of real and virtual components allows for more comprehensive testing and simulation, enhancing the testbed's capacity to model complex traffic scenarios and test algorithmic solutions in a diverse set of conditions. As illustrated in Figure 2.3, the software architecture of the CPM Lab is structured across three layers [47]. The low-level controller, deployed on an Arduino, manages direct control over the motors and the servo, handling the vehicles' actions. The mid-level controller, hosted on a Raspberry Pi onboard the vehicle, oversees communication with the network, serving as a bridge between the vehicle's operational controls and the high-level decision-making processes. Furthermore it implements the trajectory following controller. The high-level controller, which is designed for algorithms and installed on Intel NUCs, is located within the testbed but is not installed on the vehicles due to weight constraints. It performs the complex task of decision-making and motion planning. In addition, a deterministic computational model has been integrated into this architecture, enhancing the experiment's reproducibility, particularly critical for the experimental and development processes in the CPM Lab.

Communication within the CPM Lab is facilitated through the Data Distribution Service (DDS), a publish-subscribe protocol known for its robustness and real-time data delivery capabilities [74]. Both are essential for the seamless interaction between the testbed's various components.

Despite the CPM Lab's extensive documentation and its commitment to open-source principles, it is important to note the complexity and expense involved in replicating this setup. Every aspect of the testbed, from its hardware components to its intricate software architecture, requires a significant investment of resources.

The CPM Lab is already part of the academic curriculum at RWTH Aachen University, offering both master's and bachelor's courses [3] that allow students to engage directly with current topics in the CAV domain. These courses are tailored to impart knowledge on the latest topics within the CAV domain, all while fostering hands-on experience that sharpens students' problem solving and project management skills. However, it is important to note that the number of participants able to engage with the CPM Lab is limited. This constraint is due to various factors, which we will discuss in detail in the following sections, underscoring the challenges and potential avenues for expanding access to this learning environment.

2.3.1 Accessibility of the CPM Lab

The CPM Lab faces several challenges regarding accessibility. One constraint is that the testbed can only accommodate one experiment at a time. This limitation means different groups cannot use the testbed simultaneously, which significantly restricts its availability to multiple users.

The typical workflow in the CPM Lab involves a cycle which consists of running an experiment, analyzing the results, conceiving enhancements, coding these improvements, and then running the experiment again. This iterative process, while crucial for in-depth research and development, results in substantial periods where the testbed is reserved by a single group but no active experimentation is taking place. Given that the testbed is a valuable and shared resource, this operational pattern limits the number of groups that can be accommodated per day. Additionally, increased participation would inevitably escalate the need for supervision, thereby expanding the logistical and financial expenditures. The testbed's operation is further constrained by its opening hours; for instance, it remains non-operational throughout the night, creating a span of time when no experiments are conducted, despite the potential demand.

For interested researchers or students residing outside of Aachen, Germany, the location of the CPM Lab presents a significant hurdle. The necessity for physical presence and the travel involved can be significant obstacles to potential users. This geographic limitation was further exacerbated during the recent COVID-19 pandemic, which led to a period of underutilization of the CPM Lab due to safety restrictions.

These constraints underscore the necessity for solutions to enhance the accessibility and maximize the utilization of the CPM Lab. Addressing these challenges will be crucial in leveraging the full potential of such facilities in research and education. In the following chapter, we will introduce an approach designed to address these limitations: a web-based remote-access system for the CPM Lab, aiming to extend its reach and utility for a broader audience, while enabling a more efficient use of the testbed's resources.

[3] `https://cpm.embedded.rwth-aachen.de/education/`

2.4 Summary

In conclusion, this chapter has provided a analysis of small-scale testbeds in the realm of CAVs. Through a systematic survey based on characteristics derived from the sense-plan-act paradigm, various testbeds were examined. In this chapter, the focus lay on a general characteristic named accessibility. Examples such as Duckietown and the Robotarium exemplify how initiatives to enhance accessibility can foster global engagement and facilitate educational endeavors. However, challenges remain, as highlighted by the case of the Cyber-Physical Mobility Lab, which faces limitations in experiment capacity and geographical accessibility. To address these challenges, a proposed web-based remote-access system for the CPM Lab aims to broaden its reach and optimize resource utilization, ultimately advancing research and innovation in the field of CAVs.

Chapter 3

CPM Remote

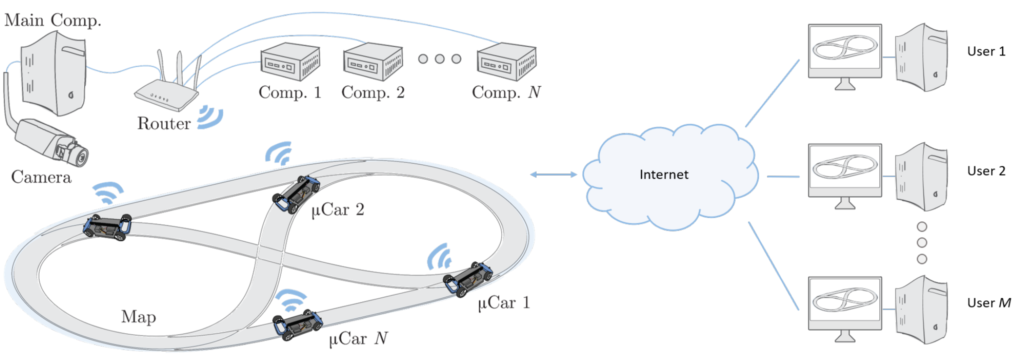

Figure 3.1: Schematic overview of CPM Remote: This image illustrates how various components within the testbed are linked via the internet, enabling users worldwide to remotely access and interact with the testbed.

3.1 Introduction

In this chapter, we present our innovative approach to broadening access to the Cyber-Physical Mobility Lab. Our ambition is to overcome geographical and technical constraints, democratizing access for researchers and students globally through a remote access. This endeavor aims to lower the barriers of entry by simplifying engagement and enhancing usability, and also seeks to sustain user interest and motivation through engaging tasks and a user-friendly environment.

Central to this concept, as depicted by Figure 3.1, is the provision of a remote access to the CPM Lab, characterized by two distinct types of access: real-time access, facilitating rapid prototyping and interactive engagement, and submission-based access, designed for more efficient, queued utilization of testbed resources. This dual-access approach ensures a balance between immediate, hands-on experimentation and organized, systematic use of the testbed's capabilities.

Key to reducing the entry barrier is the reduction of complexity and enhancement of usability. Our strategy encompasses three primary goals (G):

G1) No Installation Overhead:
We recognize that installation processes can pose significant hurdles. To counter this, we are leveraging web technologies to deliver a platform that requires no installation. The adoption of web applications eliminates overhead, making initial setup instantaneous and effortless.

G2) Self-contained Functionality:
To further streamline the user experience, we have integrated the most relevant tools directly within the platform. This leads to a *Code and Play* interface, incorporating essential elements such as an editor and a simulation environment within the web application. This not only centralizes the experience but also removes dependencies on third-party applications, ensuring a smooth workflow.

G3) Democratizing Hardware Requirements:
Simulation environments often impose substantial demands on user hardware. Our solution harnesses the power of cloud computing, transferring the computational load from the user's device to our servers. By doing so, we democratize access, ensuring that the platform's utility is not dictated by the computational capacity of the user's hardware.

Furthermore, safety and security (S) which is crucial in the operation and integrity of the CPM Lab's infrastructure, is also at the forefront of our conceptual design. To safeguard the system, we initiate several measures:

S1) Pre-execution validation of experiments ensures they are collision-free and confined within the testbed's operational boundaries.

S2) We impose limits on the cloud resources allocated per user to prevent potential abuse.

S3) Rigorous cybersecurity protocols are integrated to shield the platform from threats, maintaining the integrity and confidentiality of the research.

Through these efforts, our concept stands as a robust, user-oriented solution, ready to welcome users worldwide to the CPM Lab. In the next section, we present the development cycle, implemented based on the goals and principles just listed.

3.2 Development Cycle

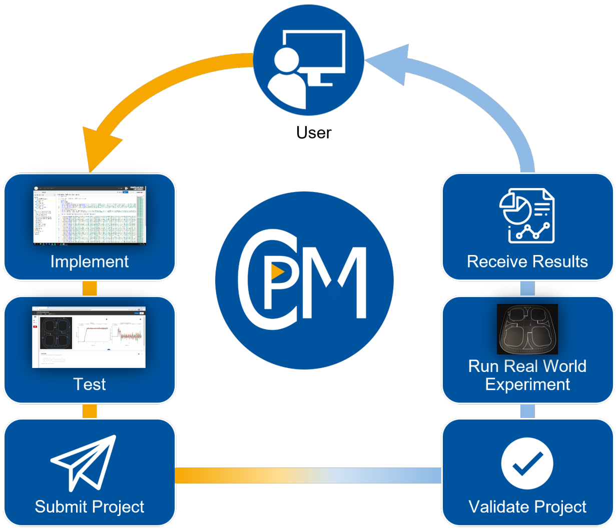

Figure 3.2: The CPM Remote Development Cycle: A schematic representation of the six-phase process users engage with when conducting experiments on the CPM Lab.

This section outlines the six steps that compose the CPM Remote development cycle, an iterative process illustrated comprehensively in Figure 3.2. These steps are designed to streamline user interaction with the CPM Lab, facilitating a smoother, more efficient approach to coding, testing, and deploying within the CPM Lab.

1) Coding Editor:
   The *Code and Play* paradigm has the potential to significantly enhance productivity by reducing the complexity typically associated with extensive development chains. To make engagement with the code as effortless as possible, we have integrated a built-in editor. As indicated by Figure 3.3, this editor equips users with essential features such as syntax highlighting and autocompletion, ensuring that the initial coding phase is both intuitive and efficient.

2) Simulation Environment:
   Leveraging the digital twin of the CPM Lab, users can test their developed code in a simulation environment. Given the close resemblance of this simulation's vehicle behavior to the real testbed, a substantial portion of the preliminary development can be executed within this virtual environment. It includes scenario visualizations, as seen in Figure 3.4, and the ability for users to generate live tables and plots during the experiment, providing immediate insights into their data.

3) Submission:
   This step serves as the gateway to the real testbed. Users are required to configure

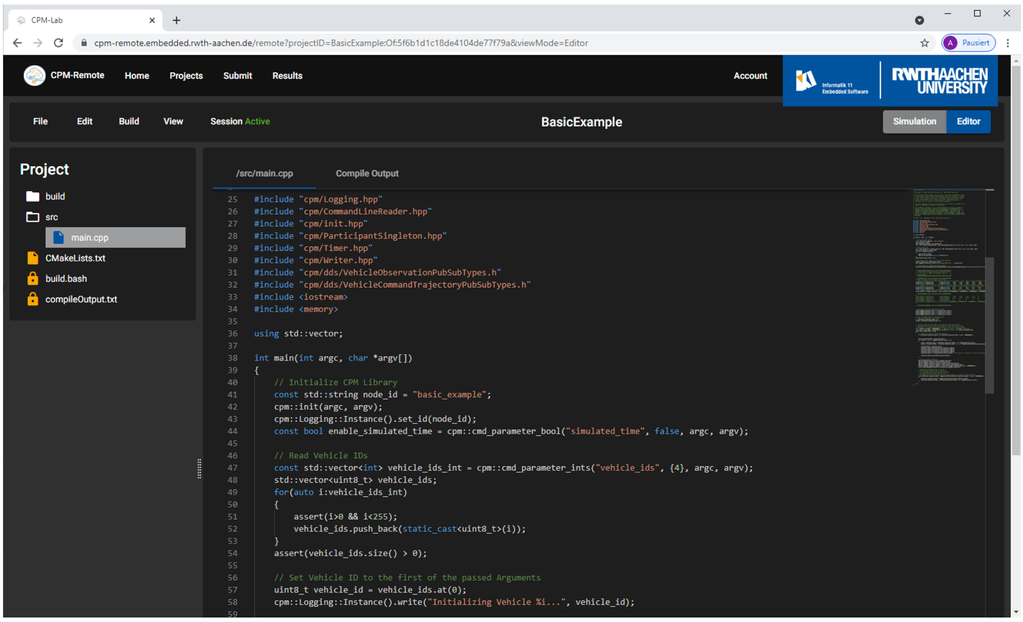

Figure 3.3: Integrated Code Editor in CPM Remote.

their experiments by specifying parameters such as the number of vehicles, their initial pose (position and orientation), and the experiment's duration.

4) Validation:
To safeguard the testbed, the CPM Remote infrastructure runs each submitted experiment to check for potential collisions and ensure that the vehicles remain within the designated area. Such measures are pivotal to guard both the hardware and software components of the testbed. Users are informed via email about the approval or rejection of their experiments based on these criteria.

5) Execution:
The actual running of the experiments is handled by a local application within the CPM Lab. The necessary conditions include the testbed being operational and the vehicles positioned at their starting points. A *go-to formation* algorithm is employed before each experiment to ascertain this setup. Experiments from various users are queued and executed sequentially to minimize idle time and optimize the testbed's usage.

6) Results:
Upon completion, data from the experiments, including a video recording and a database containing detailed recordings, are gathered. These results are then uploaded to the server, and users are notified via email, enabling them to analyze the outcomes and iteratively refine their experiments.

Figure 3.4: Simulation Environment Interface: A visual representation of the CPM Lab's digital twin, showcasing the real-time simulation of vehicle behavior and scenario visualization.

With this development cycle, we aim to provide an integrative, userfriendly, and efficient mechanism for users to not just implement, but also execute, validate, and review their experiments in the context of CAVs.

3.3 Real-time Remote Access

The previously discussed development cycle for CPM Remote provides a systematic way to execute experiments, but depending on the testbed's current utilization, it can take several days to receive results. For projects that require a quicker turnaround or more immediate feedback, we offer an alternative: real-time access to the CPM Lab.

Users can schedule an appointment to gain real-time access, allowing them to deploy and monitor experiments instantaneously. However, this real-time access does bypass the validation step, so it's recommended predominantly for those who are already experienced with the platform to ensure the protection of the testbed's equipment.

As the experiment runs in the real testbed, users can observe its progress via a webcam. The CPM Remote's simulation view is repurposed during this access mode, where instead of displaying simulated data, it presents the real-time data from the testbed. This provides users with an immersive experience, as they can simultaneously watch and analyze their experiment as it unfolds. Figure 3.5 provides a visual representation, capturing a screenshot of an experiment in progress using real-time remote access.

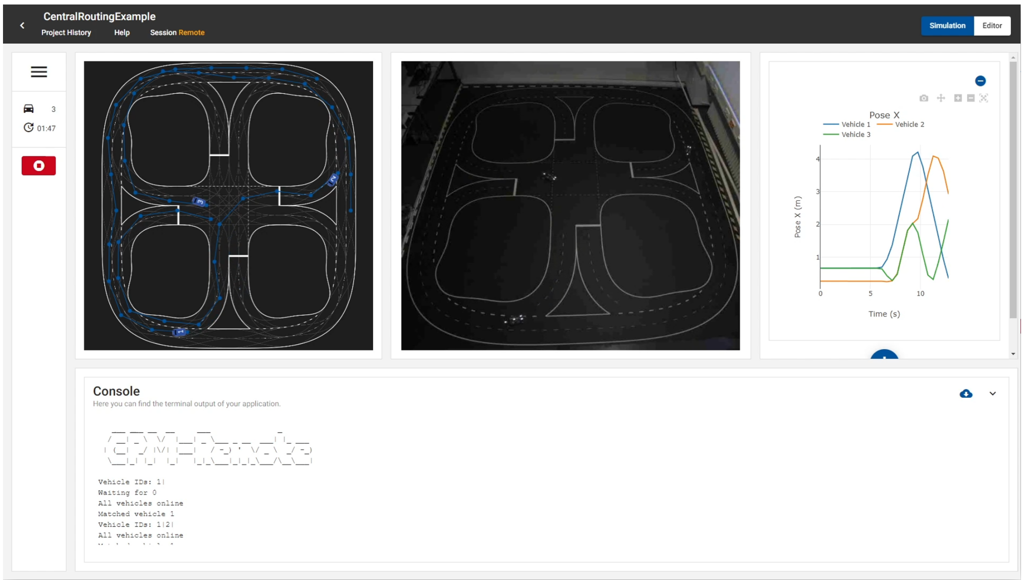

Figure 3.5: Real-time Remote Access Interface: A screenshot capturing an experiment conducted in the CPM Lab, with live data visualization and webcam feed for immediate observation and analysis.

3.4 Use-Case Examples

The CPM Lab has been deeply integrated into the research and educational activities. On the research front, notable investigations such as "sequential convex programming methods for real-time optimal trajectory planning in autonomous vehicle racing" [87] have been investigated. Moreover, the nuances of distributed trajectory planning have also been explored extensively within the confines of the CPM Lab [46]. In the realm of education, courses [86, 63, 61] are built around the features and capabilities of this testbed.

With the introduction of CPM Remote [60], the rich features of the CPM Lab are now open to an expanded audience. Our intention is not just to provide access, but to inspire and catalyze engagement among researchers and students alike. To achieve this, we conceptualized and executed two distinct applications: the research-oriented CPM Olympics [62] and the education-oriented CPM Academy [61]. Each application was crafted following an exhaustive user analysis, ensuring they are closely aligned with the interests of the target user groups. This thorough analysis facilitated the derivation of requirements that shaped the final applications.

In the subsequent chapters, we present the details of these innovative applications. The next Chapter 4 will introduce the CPM Olympics, followed by a comprehensive presentation of the CPM Academy in Chapter 5, highlighting their contributions to the field of CAVs and their impact on research and educational practices.

3.5 Summary

In this chapter, we discussed the innovative approach of providing remote access to the CPM Lab, a strategic concept that democratizes research and education in the context of CAVs. By introducing a comprehensive development cycle and real-time access capabilities, we have significantly lowered the barriers to entry, allowing global users to engage with complex CAV tasks efficiently. This chapter concludes with the presentation of practical use cases, underscoring the potential of remote access in research initiatives like the CPM Olympics and educational endeavors through the CPM Academy. This progression enhances the accessibility of the CPM Lab and also paves the way for advancements in the field of CAVs.

Chapter 4

CPM Olympics

4.1 Introduction

In the dynamic field of research on computational problems, competitive platforms not only act as stages for technological and intellectual contests but also play crucial roles in fostering innovation and progress, particularly in the development of connected and automated vehicles. This chapter provides a detailed examination of the CPM Olympics [62], a structured competition platform established specifically for research teams working in the domain of decision-making and motion planning for CAVs. The initiative's primary focus is to address, challenge, and stimulate solution-oriented research in this rapidly advancing field.

In the Seciton 4.2 of this chapter, we identify the specific target group for the CPM Olympics: research teams specializing in CAVs motion planning. It is essential to have a comprehensive understanding of this group's unique requirements, as it explains the foundational structure and objectives of the competition. One of the critical needs identified is the necessity for real-world datasets that mirror the complexity and dynamics of modern autonomous transportation systems. Accordingly, the subsequent Section 4.3 methodically addresses the datasets available for such research. The criteria for dataset selection are explained, with a focus on the importance of real-world scenarios. By prioritizing realistic scenarios, the competition ensures that challenges are practical and relevant to the current state of CAV technology. The chapter then progresses to the actual concept in Section 4.4, offering an in-depth look at this innovative competition. The concept is broken down into three distinct stages, each designed to test, challenge, and expand the research teams' capabilities and understanding.

Finally, this chapter concludes with a detailed presentation of the two iterations of the CPM Olympics of 2022 and 2023. Section 4.5 presents the concept by detailing practical aspects such as the timeline, sponsorship, and rules, and delves further into operational specifics, providing insights into the planning and execution phases. By exploring these components, the section strives to offer a clear and comprehensive understanding of the competition's framework and organizational dynamics.

4.2 Target Group

The CPM Olympics is tailored to meet the diverse needs of researchers and research teams operating in the context of CAVs while recognizing the variance in expertise within this community. These individuals or teams, though differing in their levels of knowledge and experience, are united by a common thread — a vested interest in the domain and a collective, abstract pursuit to advance the state of the art in motion planning for CAVs.

Given the specialized nature of this field, it is presumed that our target group possesses foundational knowledge in motion planning for CAVs. Additionally, engagement with our platform necessitates proficiency in programming, specifically in C++. These prerequisites ensure that participants can fully engage with and benefit from the competition's offerings.

To accommodate this spectrum of expertise, the competition is engineered with a modular setup, offering varying degrees of complexity. This strategic design ensures that experts find the challenges intellectually stimulating, while novices are not overwhelmed, promoting inclusivity and engagement across all skill levels. The modular system is pivotal, ensuring that each participant, irrespective of their expertise level, finds a path of engagement, allowing for a progressive improvement in complexity that resonates with their skill set.

Relevance is another critical factor in maintaining participant interest and ensuring the competition's applicability to real-world scenarios. Challenges presented within the CPM Olympics are designed to uphold a strong connection with real-world applicability, having a clear, traceable link to real-world situations. This approach not only enhances the competition's relevance but also motivates participants by highlighting the tangible impact and potential real-world applications of their research efforts. In the context of connected and automated vehicles, numerous datasets are available that contain recordings of real-life situations. The subsequent section is dedicated to explaining the process behind our dataset selection.

4.3 Data Selection

The strategic use of datasets plays a crucial role, particularly in training and testing algorithms. These datasets, classified based on their coordinate systems, can either be focused on a specific road segment or centered around a single ego vehicle. The latter is mainly used in the development and testing of automated driving functions or environmental perception by enabling developers to adjust algorithm behaviors through the replay of identical inputs. For the purposes of the CPM Lab, our focus gravitates toward datasets

Table 4.1: Comparative overview of evaluated datasets.

Data Set	Pedestrians	Bicycle	Cars	Bus	Trucks	Motorcycle	Size
BIWI [76]	✓						✓
Crowds [53]	✓						✓
CITR [101]	✓						✓
DUT [101]	✓						✓
highD [51]			✓		✓		
inD [8]	✓	✓	✓	✓	✓	✓	✓
Interaction [102]			✓				✓
Ko-PER [92]	✓	✓	✓		✓		✓
NGSIM [96]			✓		✓	✓	
rounD [52]	✓	✓	✓	✓	✓	✓	✓
Stanford [82]	✓	✓	✓				✓
VRU [30]	✓	✓					✓

characterized by an environment-centric coordinate system. This preference is attributed to the stationary coordinate system's adaptability to the testbeds environment, neglecting the need for compensating egomotion.

In our quest for the most suitable datasets, we conducted a comprehensive evaluation of 12 publicly available collections, each featuring a fixed coordinate system and an aerial perspective. These datasets were reviewed to ascertain their compatibility with our testbed's requirements, ensuring they contribute effectively to creating realistic traffic scenarios for CPM Olympics participants. An overview of these datasets is presented in Table 4.1. The selection criteria require that each dataset meets four essential conditions to qualify for consideration.

1) Scalability to CPM Lab dimensions:
   The area of interest within the dataset must be compatible with the CPM Lab's scale. Specifically, the testbed is designed at a 1:18 scale, with a physical map measuring 4m x 4.5m, corresponding to a real-world area of 72m x 81m .

2) Inclusion of diverse road users:
   At a minimum, datasets must include vehicles. However, those containing multiple classes of road users are preferred, as they offer a more comprehensive view of real-world traffic interactions.

3) Presence of naturalistic interaction:
   It is essential that the datasets demonstrate naturalistic interactions among road users. This criterion ensures that the scenarios used in the competition authentically mirror the complexities and unpredictabilities found in real-life traffic environments.

4) Availability of sufficient recordings:
   There must be a sufficient quantity of recordings in the dataset, allowing for the extraction of multiple scenarios. This variety is crucial in presenting a well-rounded competition, challenging participants across a broad spectrum of situations.

After an evaluation based on these parameters, only three datasets — Ko-PER [92], inD [8], and rounD [52] — met the criteria. Upon further assessment, inD and rounD emerged as the superior choices, collectively offering over 16 hours of recordings. Unlike Ko-Per, these datasets include a broader spectrum of road participants, thereby providing a more holistic and diverse range of scenarios for the CPM Olympics. Thus, inD and rounD were selected for their extensive and varied content, fulfilling our outlined conditions and promising a rich resource for the competition's challenges.

4.3.1 Integration in CPM Remote

Integrating real-world scenarios into CPM Remote necessitated the development of a specialized application, which we named and published as *Dataset Converter*[1]". This application allows to navigate through the recordings, pinpoint a specific time period, and extract the relevant information formatted as XML for streamlined processing. Each scenario extraction is comprehensive, encompassing data regarding all road users throughout the selected timeframe. This approach ensures clarity on the precise trajectory of each vehicle within the scenario, an essential aspect for accurate replication and analysis.

However, a challenge arises from the potential complexity of these scenarios. Depending on their duration, some scenarios may encompass significantly more vehicles than the 20 available in the CPM Lab. To navigate this limitation and accurately simulate these dense traffic scenarios, we created a system to reuse vehicles that have exited a scenario. This was achieved through the implementation of a *ring road* system encircling the intersections and roundabouts. This allows vehicles to dynamically enter and exit the scenario, simulating a continuous flow of traffic. The ring road is instrumental in repositioning vehicles at various entry points, enabling them to re-enter the scenario authentically, mirroring real-world traffic patterns.

To illustrate this integration, Figure 4.1 depicts a rounD scenario incorporated within the dimensions of the CPM Lab. This visual representation highlights the additional road segments, marked in red, which are tactically implemented to facilitate the reuse of vehicles. This system ensures our ability to replicate densely populated traffic scenarios within the constraints of the CPM Lab.

With the conditions now optimized to integrate inD and rounD scenarios within the CPM Lab, our focus shifts to the next phase: crafting challenging tasks based on this setup. The subsequent section delves into the methodology employed to transform these datasets

[1] `https://github.com/embedded-software-laboratory/Dataset-Converter`

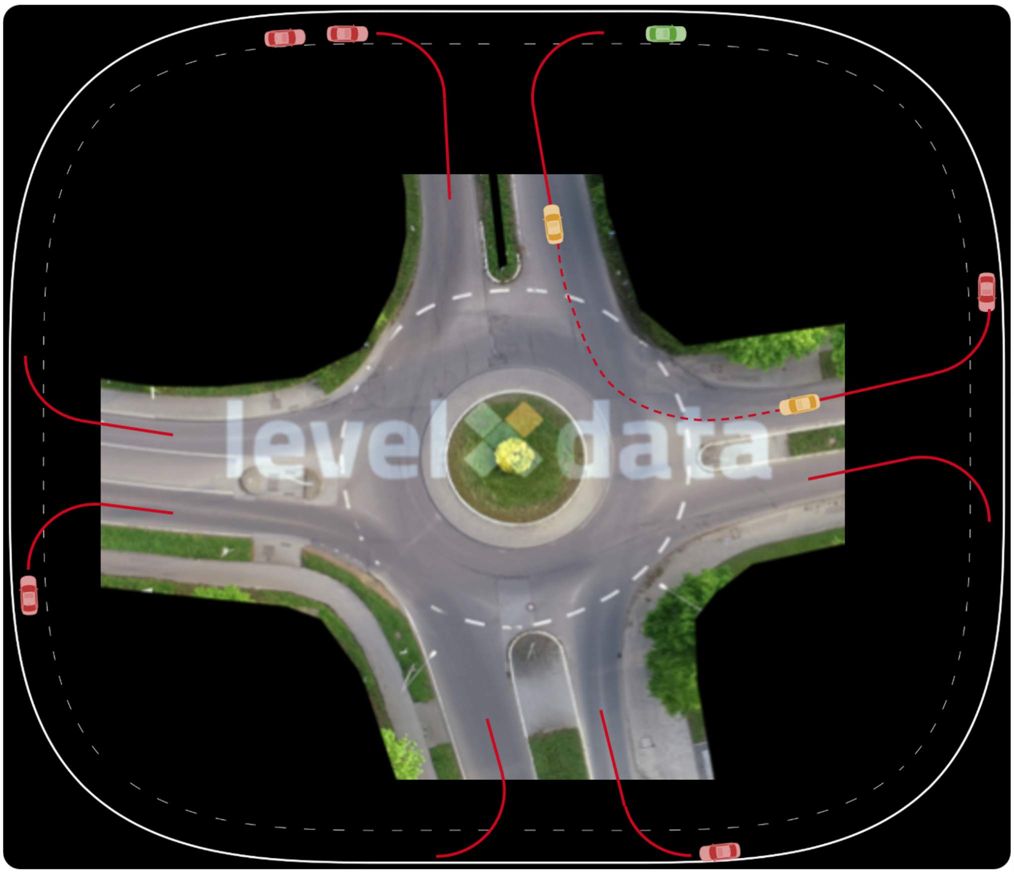

Figure 4.1: Representation of a rounD [52] scenario integrated within the CPM Lab's boundaries, highlighting additional road segments (in red) for vehicle reuse.

into a robust competition framework, outlining the steps and considerations that guide the creation of engaging and meaningful competition scenarios.

4.4 The Competition

The foundational concept of the CPM Olympics is rooted in a unique observation: real-world scenarios extracted from our chosen datasets consistently feature collision-free trajectories. This indicates that for every set of vehicles recorded, there exists a trajectory through which they navigated from an entry point to an exit point without any collisions with other road users such as pedestrians or bicyclists.

Furthermore, the datasets provide valuable insights into the nuances of these trajectories. They reveal the duration of each trajectory and also details about dynamic states: instances of acceleration, deceleration, and the relative distances maintained with other

Figure 4.2: Integration of a real-world scenario in CPM Remote, highlighting the boundary (white rectangle) and transition zones (yellow areas) between system-managed and user-managed planning areas.

road users. By strategically omitting the information concerning the actual trajectories taken by these vehicles, we introduce the possibility for competitors to explore alternative, potentially more efficient trajectories through the scenarios. Given the established solvability of these scenarios, participants are not only challenged in a concrete setting but also presented with a tangible benchmark in comparison to solutions previously executed by human drivers.

Figure 4.2 displays a screenshot of a fully integrated scenario within the CPM Remote platform. A distinctive white rectangle can be observed surrounding the roundabout, signifying the boundary between the system planner and the user's planning area. The yellow area represent the transition zones. Here, the system planner introduces a new vehicle to the user, accompanied by data regarding its desired exit point. The challenge for the user is planning trajectories between these points. This setup, depending on the scenario's specific dynamics, can pose significant challenges, especially when uncontrollable road users are present.

To facilitate users in the development of their motion planning algorithms, we offer a code skeleton alongside a variety of scenarios, each reflecting different levels of complexity. This approach is designed to accommodate a wide range of competencies and to progressively deepen users engagement with the domain of motion planning for CAVs. In the next sections, we will present three distinct stages of the CPM Olympics.

4.4.1 Three-Stages Approach

When organizing the CPM Olympics, the goal is to find a balance between encouraging ongoing involvement and encouraging participation within set timeframes. The result is the following three-stage approach:

Stage 1: Training Phase The first phase is dedicated to training. For this purpose, 16 training scenarios have been extracted, with eight scenarios from the rounD dataset and another eight from the inD dataset. Each scenario runs for a duration of 60 to 70 seconds. The complexity of the scenarios varies, with the number of simultaneous road users ranging from 2 to 16. The higher the count of road users, especially those not under direct user control, the more complex the scenario. The aim during this stage is to encourage participants to construct algorithms capable of handling a wide range of traffic situations.

Stage 2: Submission Phase The submission phase, constrained to a two-week period, serves as the coordinated event of the CPM Olympics. During this phase, participants are introduced to 13 new scenarios. These are shorter in duration, focusing on one or two specific traffic situations. This structure allows participants to fine-tune their algorithms and submit their motion-planners for evaluation. To ensure the integrity and thoroughness of the evaluation, we use an extra 12 hidden scenarios for benchmarking submissions. This prevents solutions from becoming overly tailored to known scenarios. Additionally, each year when the CPM Olympics is conducted, a total of 25 new scenarios are introduced, ensuring ongoing freshness and challenge.

Stage 3: Presentation Phase The final stage is centered around presentation. In alignment with each CPM Olympics, a workshop is scheduled at a conference where winners are given the opportunity to present their solutions. This phase serves a dual purpose: it generates awareness and fosters a scholarly exchange of knowledge and experiences within the community, contributing to the collective understanding and advancement in the field of motion planning for CAVs.

This approach provides a platform for showcasing skill and innovation while also facilitating continuous learning, adaptation, and knowledge transfer.

4.4.2 Benchmark of Motion-Planners

To effectively measure the performance of algorithms submitted during the CPM Olympics, it is essential to establish well-defined benchmarks. These benchmarks not only evaluate the fundamental capabilities of an algorithm but also assess its efficiency, safety, and overall comfort. Thus, after each scenario, benchmarks are calculated and displayed. As highlighted in Seciton 4.4, the datasets utilized contain trajectories driven by humans, all of which successfully reach their destinations without collisions. This successful trajectory sets a fundamental benchmark: any algorithm developed must, at a minimum, be capable of collision-free motion planning. To further embed real-world applicability and ensure safety within the CPM Lab environment, an additional mandatory criterion is the maintenance of a safety distance of at least 1.5 m to other road users.

Beyond basic safety and regulatory compliance, the performance of an algorithm in the CPM Olympics is assessed based on a composed score calculated for each scenario. This score considers multiple facets of driving that are critical in evaluating the efficiency of motion planning algorithms:

1) Speed:
   Measured by the duration it takes for each vehicle to drive from its starting point to its final destination.

2) Efficiency:
   Assessed through the frequency of braking and acceleration events along a vehicle's trajectory.

3) Comfort Driving:
   Quantified by examining the acceleration and deceleration, ensuring the algorithm promotes smooth driving transitions.

4) Comfort Distance:
   Evaluated based on the proximity to other road users, with higher scores awarded for maintaining a greater distance (up to a limit of 5 m).

The exact computation of these components is detailed in Equations 4.1 to 4.4.

$$\text{Speed} = \frac{t_i}{t_{ref}} = t_i \cdot \frac{v_{max}}{s_{ref}}, \tag{4.1}$$

where t_i is the vehicle's travel time, t_{ref} the real world vehicle's travel time and s_{ref} the shortest distance (calculated with dijkstra algorithm using the middle lane of the roads) to the destination. s_{ref} is not normalized since a score greater than one is potentially possible through a deviation from the middle lane. v_{max} is the maximum speed of the vehicles in the CPM Lab.

$$\text{Efficiency} = \frac{a_{max}^2 - \overline{a}^2}{a_{max}^2}, \tag{4.2}$$

where $\overline{a}$ is the average acceleration of the vehicles and a_{max} the maximum acceleration possible in the CPM Lab.

$$\text{Comfort Driving} = \frac{j_{max}^2 - \overline{j^2}}{j_{max}^2}, \tag{4.3}$$

where j_{max} is the maximum jerk possible and $\bar{j}$ is the average jerk of the vehciles.

$$\text{Comfort Distance} = \frac{\overline{d_{\leq 4}} - d_{min}}{d_{max} - d_{min}}, \tag{4.4}$$

where d_{max} is the maximum comfort distance (5 m) and d_{min} is the minimum comfort distance (1.5 m).

Collectively, these individual metrics contribute to a total score, giving a holistic view of an algorithm's performance. The aggregation of these scores is expressed with the following equation:

$$\begin{aligned} \text{Score} = \ & 0.3 \cdot \text{Speed} \\ & + 0.3 \cdot \text{Efficiency} \\ & + 0.2 \cdot \text{Comfort Driving} \\ & + 0.2 \cdot \text{Comfort Distance}. \end{aligned} \tag{4.5}$$

The weighting in this equation is introduced to ensure that algorithms are not solely optimized for speed, potentially compromising on safety and driving comfort. Instead, it encourages the development of balanced algorithms that simulate realistic, safe, and efficient driving behaviors related to, or surpassing, human-driven standards.

4.5 The Annual Competition

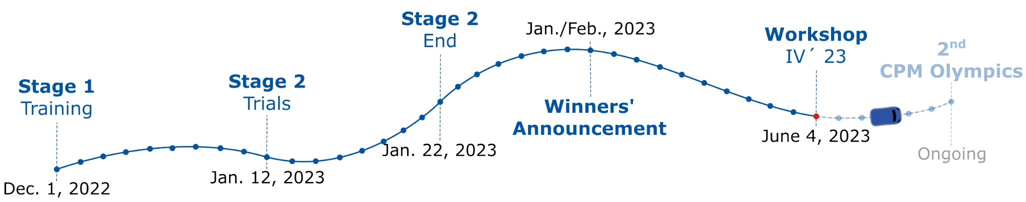

Figure 4.3: Comprehensive timeline of the CPM Olympics 2022, detailing key phases and milestones.

The first CPM Olympics was held in 2022. Recognizing the significance of raising awareness and stimulating active participation, we undertook efforts to secure a sponsorship. Given the topical nature of motion planning within the domain of CAVs, sponsorship was successfully obtained for the first and subsequent edition of the competition. The following sections will elucidate the timeline, prize distribution, and the detailed regulations governing the CPM Olympics for both editions 2022 and 2023. An integral part of the annual CPM Olympics' is the retrospective evaluation of each event. Section 7.2.1 is dedicated to this aspect, featuring a detailed review of participant engagement and feedback

4.5.1 CPM Olympics 2022

The event kicked off with its first stage (training phase) in December 2022, as illustrated in Figure 4.3. Preceding this launch, promotional activities were conducted via social media platforms and academic lectures to generate interest and inform potential participants about the competition.

By mid-January, the onset of the competition's Stage 2 started, introducing a rigorous 10-day challenge designed to test the participants' limits and innovative capacities. The competition was structured to allow individuals or groups to participate, thereby encouraging collaborative problem solving and individual ingenuity.

The 2022 edition of the competition was financially supported by FEV.io, a private company and industry partner, which contributed a total of €3,000 to the prize pool. The distribution of prizes was allocated as follows: €1,500 for the winner, €1,000 for the second place, and €500 for the third place. Integrity in submissions was of paramount importance; thus, a plagiarism checker was employed to confirm the originality of each implementation, ensuring no repeat strategies were awarded.

Following Stage 2, winners were promptly identified and invited to present their solutions at the IEEE Intelligent Vehicles Symposium 2023, held in Anchorage, Alaska, USA. This symposium included a dedicated workshop where discussions centered around the top three methodologies, offering insights and fostering knowledge exchange within the intelligent vehicles community.

4.5.2 CPM Olympics 2023

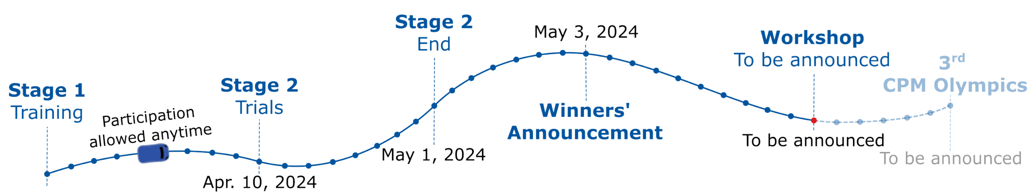

Figure 4.4: Comprehensive timeline of the CPM Olympics 2023, detailing key phases and milestones.

At the time of writing this thesis, preparations for the CPM Olympics 2023 are in progress, with the event currently being in Stage 1. We extracted 25 new scenarios, which will be published in April.

Reflecting on the insights gained from the previous year, we have made adjustments to enhance the experience and boost participation. Notably, the duration of Stage 2 has been extended, effectively doubling the time frame compared to the CPM Olympics 2022, as illustrated in Figure 4.4. This amendment was made in response to participants' feedback, highlighting the need for more time to refine their algorithms and strategies. Additionally, we have enriched the training scenario set for the second CPM Olympics by incorporating the test scenarios from the previous year, providing a broader and more diverse range of situations for participants to practice and strategize.

In a continual effort to nurture community engagement and scientific dialogue, the concluding workshop and winner presentations are invited to the IEEE Intelligent Vehicles Symposium 2024 on Jeju Island, Korea. One notable enhancement this year is the opportunity to contribute workshop papers, thereby creating a formal record of their innovative solutions and approaches. This contribution will serve as a tangible testament to their work and also as a valuable addition to the collective knowledge in the field of motion planning for CAVs.

Furthermore, another company INFORM GmbH, will be sponsoring the CPM Olympics 2023, doubling the previous year's prize pool to a total of €6,000. In a bid to encourage wider participation and reward more competitors for their contributions, we made the decision to allocate the prize money across a broader spectrum of top performers. The distribution will be as follows: €2,000 for the first place, €1,500 for the second place, €1,000 for the third place, €750 for the fourth place, €500 for the fifth place, and €250 for the sixth place. Through this more inclusive reward structure, we aim to foster a more engaging and competitive environment, encouraging a greater number of participants to immerse themselves in the challenges and rewards that the CPM Olympics present.

4.6 Summary

In this chapter, we presented the competition CPM Olympics, beginning with an analysis of our target group whose preferences underscored the necessity for a competition deeply rooted in real-world scenarios. This emphasis guided our choice of datasets, leading to the integration of specific selections into our CPM Lab, which are reflective of the complex and diverse nature of actual traffic environments.

Central to the CPM Olympics is the concept of motion planning in response to these real-world challenges, where participants' solutions are compared with the decisions made by human drivers in identical situations. Our benchmark extends beyond mere safety considerations, probing into the comfort level of the journey, assessing factors such as the smoothness of acceleration and deceleration, and the maintenance of a safety distance around vehicles.

The competition structure was unfolded through a detailed exposition of the three-stage approach: the training phase, submission phase, and presentation phase. This format was chosen to maintain a sense of urgency and focus during the competition, while still encouraging continual engagement throughout the year. Each stage serves a distinct purpose, from skill honing and algorithm development, to solution submission and scientific discourse, cumulatively contributing to the competitors' growth and the advancement of the field.

Concluding the chapter, we provided insights into the timelines, sponsorship arrangements, and the specific rules governing the CPM Olympics of 2022 and 2023. These details not only offer transparency regarding the competition's operation but also serve to highlight the commitment of both the participants and sponsors in fostering innovation and learning.

Chapter 5

CPM Academy

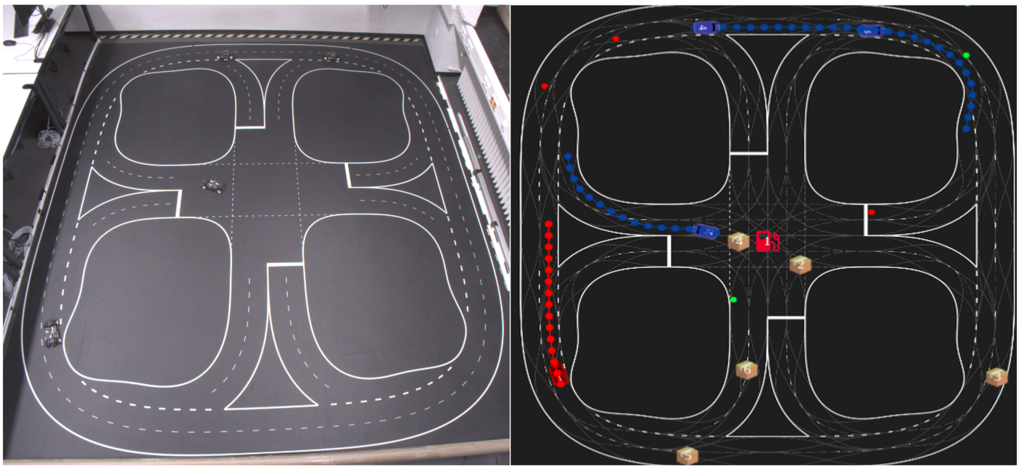

Figure 5.1: Comparison of real-world (left) and simulation (right) view of CPM Academy's level 7: featuring spawned packages, gas station, system-controlled vehicles (in red) and user-controlled vehicles (in blue).

5.1 Introduction

The domain of CAVs is rapidly evolving, making it challenging for newcomers to navigate. Consequently, it is important to guide and facilitate students' engagement with this domain in a structured and supportive manner. One of the primary challenges in this endeavor is providing motivating, practical, and hands-on tasks suitable for those with a limited knowledge base in the field. Addressing this challenge is the focus of this chapter, which introduces the CPM Academy [61]. This initiative is specifically tailored for students from

Science, Technology, Engineering and Math (STEM) studies who have demonstrated an interest in both programming and the CAVs domain.

Following the pattern of our previous chapter on the CPM Olympics, we begin with an exploration of the target group in Section 5.2. The CPM Academy is designed as a platform for students to engage with current topics in CAVs, simultaneously enhancing their programming and project management capabilities. This chapter presents the comprehensive development process, spanning from an analysis of the target group to the incorporation of didactic methods, resulting in the course design detailed in Section 5.3. Currently, the CPM Academy has been integrated as a bachelor's course within our academic curriculum. Furthermore it is open to the wider public for all interested individuals.

5.2 The Didactic Approach

As CPM Remote expands into education, we expect an extension of its user group. We are now additionally targeting STEM students, especially those in the advanced stages of their bachelor studies. Our choice of this group is based on some prerequisites: students should have a basic understanding of programming, data structures, algorithms, and project management. Ideally, they should be familiar with C++ or at least another object-oriented programming language. Also, having knowledge of common algorithmic challenges in computer science, such as the traveling salesman problem [15] or the bin packing problem [41] would be advantageous.

Our course is designed to fit into a single semester. Considering students are also taking other courses at the same time, we were mindful of how much content we include. Hence, we have carefully structured the work packages and learning objectives to fit within these constraints.

Beyond the content itself, we have given significant attention to our teaching methods and overall didactic strategy. Establishing clear learning objectives is important to ensure students understand expectations and evaluation criteria. Providing feedback is an integral aspect of the process. As a result, students receive performance insights following the completion of each work package

To keep students engaged and motivated, we made our course materials both relevant and interactive. The CPM Academy is built around a package delivery service, which is a state-of-the-art use case in today's transportation system. We have also incorporated gamification, using game elements in a non-game context, to boost engagement and motivation, making the learning process more effective and enjoyable [21, 45, 84]. In the upcoming section, we will present the CPM Academy's design and discuss how our outlined requirements shaped its concept.

5.3 Course Concept

In our effort to create a comprehensive and engaging curriculum with the CPM Academy, we centered our approach on the scenario of a package delivery service. This choice was informed by the service's capacity to be broken down into several interconnected work units. Importantly, this scenario is grounded in rigorous research, as highlighted by studies like [55, 6, 27]. Such a framework facilitates the exploration of various challenges, such as the Traveling Salesman Problem (TSP) [15], Bin Packing [41], Online Scheduling [79] and motion planning. We will delve deeper into these problems in the subsequent Section 5.3.1.

Understanding that the CPM Academy is primarily designed for academic environments and spans a single semester, its structure mirrors that of a typical semester. To break it down: a semester is six months, with two months reserved for exams. After accounting for a month-long break, an introductory week for the Academy, and two weeks of conclusion, we are left with roughly nine weeks. Informed by research, such as [29], that explains the benefits of iterative workflows, we divided our curriculum into nine work packages. These packages are designed for group work, and the group size can be adjusted based on the course's credit weight.

To sustain student motivation throughout the nine weeks, we have integrated gamification elements into our curriculum, starting by designating our work packages as *levels*. Drawing inspiration from gaming conventions and the foundational principles of gamification by [95], these levels allow students multiple attempts, promoting improvement. Completing a level unlocks the next, and notably, standout solutions can unlock the next two levels, emphasizing the gamification principle of *progression* to enhance student engagement.

In order to ensure a smooth introduction to the CPM Academy, we offer a sample project. Requiring only minor modifications, this project tackles the first level, giving students an immediate sense of achievement and mitigating initial challenges. The quality of student solutions is assessed at each level. We use gamification elements like *scores*, *achievements*, and *stars*, as described by [95]. Our feedback system includes achievements, which define a basic solution standard, and stars, which rate the solution across various metrics. Depending on their performance, students can earn up to three stars, providing a visual representation of their solution's quality. To further engage students, we have interconnected all levels with a *storyline*, a recognized gamification strategy. Our narrative chronicles a start-up's journey in launching an express delivery service, navigating the challenges that arise as they grow.

5.3.1 Level Design

The CPM Academy's curriculum is built on a series of increasingly complex challenges, spread across nine distinct levels. These levels introduce and explore the nuances of the

Figure 5.2: Overview of the CPM Academy's level design, showcasing the progressive introduction of challenges and concepts in package delivery systems

package delivery service, engaging students in real-world scenarios that underscore the significance of decision-making, optimization, and planning. Following is a walkthrough of the challenges and learnings encompassed in each level:

1. Introduction to CPM Remote:
   At this initial stage, students are introduced to the CPM Remote interface. They receive a detailed code frame, which explains the various methods to control vehicles. Although a task is provided which can be solved using the given example project, the main focus lies in comprehending the code structure and familiarizing oneself with the framework.

2. Collision Detection and Avoidance:
   Students are expected to implement effective collision detection and a rudimentary approach to collision avoidance. This functionality becomes crucial for running subsequent experiments in the CPM Lab. They have the autonomy to choose between two collision avoidance strategies: by braking or swerving. We implemented the CPM Routing library, which includes a feature for forecasting vehicle positions, thus advising the use of a priority-based avoidance method. The crux of this level emphasizes the prevention of vehicle collisions and underscores the essence of sound decision-making and motion planning.

3. Introduction of System-Controlled Vehicles:
   In this phase, system-controlled vehicles are added as new participants in the scenarios. Students need to treat these vehicles as passive agents and develop algorithms that prevent collisions without altering their predetermined routes [2].

4. Package Delivery Service:
   The core concept of the package delivery service is introduced. Students are tasked with deciding the optimal strategies for distributing packages across various vehicles and subsequently sequencing the deliveries. This level's challenge relates to the TSP. However, with the twist of real-time target announcements, it morphs into the Multiple Online TSP [15].

5. High Throughput:
   The number of packages for delivery and the number of vehicles increase, neces-

sitating students to find more efficient motion planning techniques. The increased volume challenges previously implemented heuristics. The overarching goal of this level is to experiment with and realize the impact of enhanced methodologies on the overall system within a realistic context.

6. Weight and Dimensions Constraint:
   Drawing inspiration from real-world scenarios, packages are now endowed with specific weight and dimension parameters. Given the limited storage capacity of vehicles, students face the Bin Packing optimization problem. With fixed storage bins and real-time package announcements, the challenge results to an NP-hard decision problem [41]. Students are expected to strike a balance between the shortest possible routes and strategic bin packing.

7. Energy Consumption and Refueling:
   Energy consumption becomes a focal point in this level. Vehicles need to periodically make stops at gas stations (depicted in Figure 5.1) to replenish their energy. The existing routing algorithm requires modifications to ensure timely and efficient refueling stops.

8. Package Profit and Prioritization:
   A next challenge is introduced where packages are associated with profits. These profits are determined by their priority class and the distance between the pickup and delivery locations. Students are tasked with prioritizing high-value packages to maximize overall profit by the culmination of this level.

9. Deadlines and Delivery Timing:
   The final level introduces delivery deadlines for packages. A delay in delivering a package within its deadline negatively impacts the profit. This demands an enhanced algorithm that not only estimates the expected delivery timing but also determines the feasibility of accepting a package. The challenge is similar to the online scheduling problem [79].

The design of these levels is sequential, where each successive level builds upon the skills and concepts mastered in the preceding ones. This ensures a cohesive learning experience, allowing students to progressively delve deeper into the complexities of package delivery systems, integrating new challenges with previously acquired knowledge. Additionally, each level is equipped with its unique benchmark criteria, designed to evaluate the students solutions. The specifics of these benchmark criteria, which provide a framework for evaluation and progression, will be detailed in the subsequent section.

5.3.2 Benchmarkig Solutions

The CPM Academy is structured such that each level introduces a set of complexities building upon the last. It is not just about successfully navigating these levels, but also about how effectively one does so. To make this assessment transparent, every level comes with a benchmarking and feedback mechanism.

As elaborated in Section 5.3.1, each level lays out the criteria by which the user's solution will be assessed. This preemptive clarity ensures that users are well-informed and can tailor their strategies accordingly.

The feedback loop is twofold:

» During Execution:
At runtime of a scenario, users receive real-time feedback provided by the CPM Remote's visualization capabilities. The interface, as captured in Figure 5.1, provides a dynamic representation of the package delivery landscape – from the movement of vehicles and their planned trajectories to the placement of packages and gas stations. Beyond this, users can glean insights from a range of live data visualizations in the form of charts and tables, aiding in mid-level adjustments if needed.

» Upon Completion:
Once the level concludes, an exhaustive evaluation is conducted, both for each vehicle and the broader experimental setup. This granular approach allows for a deep dive into individual vehicle statistics while also getting a holistic view of the entire level's performance. Additionally, all raw data is accessible in tabular form and downloadable formats. Furthermore, the system retains the score, offering users a chance to compare and contrast their performances across attempts, spotlighting areas of improvement or regression.

The benchmark system is composed of two primary components: achievements and scores. Achievements represent non-negotiable criteria, serving as prerequisites for successful level completion. On the other hand, scores provide a qualitative assessment, pinpointing potential algorithmic vulnerabilities, which are computed regardless of whether the foundational achievements are secured. Notably, unlike the CPM Olympics, the Academy's scoring system compares performances against the maximal theoretical score, rather than a predefined benchmark. The achievements criteria include:

» Collision Avoidance: Ensuring no collisions occur with other vehicles or static obstacles.

» Safety Distance: A mandatory buffer of 1.5 m[1] is to be maintained with all entities on the road.

[1] 1.5 m in real-world scaled to the CPM Lab's dimensions is $\frac{1.5m}{18} = 8.3cm$

» Delivered Packages: Levels 4 through 9 necessitate the delivery of a predetermined number of packages, each level with its unique threshold.

» Balance: A testament to the effectiveness of the user's distribution algorithm, this mandates a near-even parcel distribution across user-controlled vehicles, allowing a margin of up to 20%.

In our benchmark system, each score is currently assigned equal weight. Nevertheless, the flexibility of this design permits easy adjustments in weighting, catering to scenarios where a specific metric might need greater emphasis for different courses. The aggregated score offers a personalized evaluation, spanning from 0% to 100%, gauged against the optimal solution. Furthermore, this cumulative score translates into a star-rating system. By surpassing a 50% score and meeting all requisite criteria, users earn one star. Achieving beyond 70% rewards the second star, and performances exceeding 90% are rewarded with a third star. The score criteria include:

» **Speed Score** compares the mean speed of the user vehicles to the maximum possible speed ($\frac{m}{s}$).

$$s_v = \frac{t_i}{t_{ref}} = t_i \frac{v_{max}}{s_{ref}}, \tag{5.1}$$

where t_i is the vehicle's travel time, t_{ref} the real world vehicle's travel time and s_{ref} is the shortest route to the target. v_{max} is the maximum speed of the vehicles in the CPM Lab.

» **Efficiency Score** rates the efficiency of the driven speed profiles based on the average acceleration to promote energy-efficient solutions:

$$s_e = \frac{a_{max}^2 - \bar{a}^2}{a_{max}^2}, \tag{5.2}$$

where $\bar{a}$ is the average acceleration and a_{max} the maximum acceleration ($\frac{m}{s^2}$).

» **Package Score** evaluates the delivered packages in relation to the total number of packages occurring in the level by dividing the number of delivered packages by the number of generated packages:

$$s_{pa} = \frac{n_{delivered}}{n_{generated}}. \tag{5.3}$$

» **Profit Score** replaces the package score in levels that assign a profit to packages. Furthermore, it determines sum of the profits (p_i), the user makes compared to the maximum possible profit:

$$s_{pr} = \frac{\sum_{i=1}^{n_{delivered}} p_i}{\sum_{i=1}^{n_{generated}} p_i}. \tag{5.4}$$

» **Balance Score** determines how evenly the packages were distributed among the user's vehicles based on the variance of the delivered packages per vehicle:

$$\sigma_b^2 = \frac{1}{n_{vehicles}} \cdot \sum_{i=1}^{n_{vehicles}} (p_i - \mu_{packages})^2, \tag{5.5}$$

$$s_b = \frac{L_{allowed} - \sigma_b^2}{L_{allowed}}, \tag{5.6}$$

where $L_{allowed}$ is the maximal variance allowed per level and $\mu_{packages}$ is the mean of the package profits per vehicle.

» **Utilization Score** computes the utilization of user vehicles, i.e., the time vehicles spent delivering t_{busy} at least one package in relation to the total time t_{total}:

$$s_u = \frac{1}{n_{vehicles}} \cdot \sum_{i=1}^{n_{vehicles}} \frac{t_{busy}}{t_{total}}. \tag{5.7}$$

Based on the individual scores, a **total score** is computed, which is the weighted arithmetic w_i mean of the individual scores s_i:

$$s_t = \frac{1}{n_{scores}} \cdot \sum_{i=1}^{n_{scores}} w_i \cdot s_i. \tag{5.8}$$

5.4 Summary

Concluding this chapter, we detailed the design and concept of the CPM Academy. Specifically, it was designed to enrich the educational landscape concerning connected and automated vehicles, offering students an easy entry to this complex domain. Our tailored approach aims to engage students with the technical aspects of CAVs and also to strengthen their programming skills. By using gamification elements, we created a level-based course structure that promotes continuous learning and engagement. A standout feature is our automated feedback and benchmarking system, which provides valuable insights, motivating students to improve their solutions. We successfully integrated the CPM Academy into our courses, and in Chapter 7 we will present user feedback and opinions, giving a complete view of the course's actual impact.

Chapter **6**

Implementation

6.1 Introduction

Over the course of this thesis, we implemented over 148,997 lines of code, written in 20 different programming languages. These lines are organized across seven distinct repositories, ensuring efficient management and ease of collaboration. Adhering to contemporary software development methodologies, we adopted the Agile Scrum framework [89] for this project. This approach entailed weekly development meetings that spanned nearly four years, ensuring continuous integration, iteration, and improvement of our software components.

In this chapter, we aim to provide readers with a comprehensive overview of the software architecture that emerged from this effort. Additionally, in Section 6.3.2, we will discuss CPM Routing, a central library we developed. This library serves as a foundational component for both the CPM Academy and CPM Olympics and is also designed to be a foundational building block for potential future applications in this domain.

We will conclude this chapter by discussing the comprehensive security measures we have put in place to protect our system's safety and integrity. We will also detail the thorough testing approach for CPM Remote in Section 6.4, emphasizing our commitment to creating reliable and resilient applications.

6.2 Softwarestack

The foundation for the CPM Remote platform is the MEAN Software Stack, a state of the art web development framework, encompassing MongoDB [66], Express [93], Angular [31], and NodeJS [72]. With its focus on scalability and performance, the MEAN Stack is designed for multifaceted web applications like CPM Remote [37]. Given that both frontend and backend operations in MEAN-based applications are conducted in Javascript or

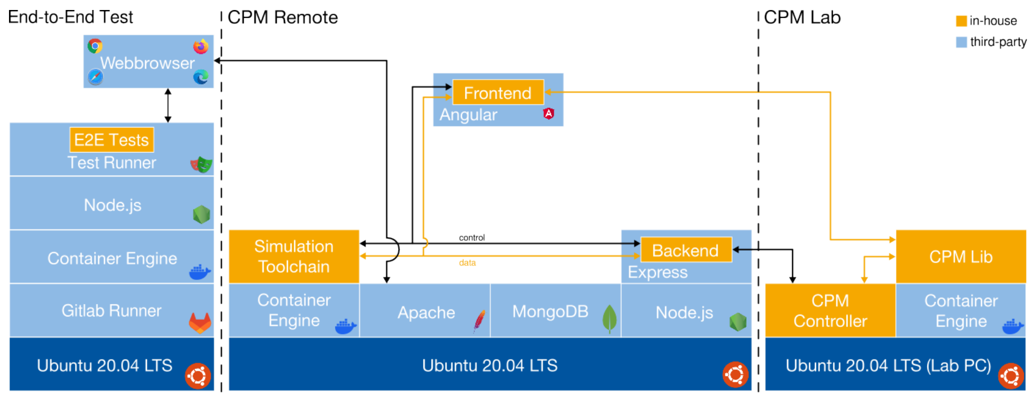

Figure 6.1: Architectural overview of the CPM Remote platform based on the MEAN software stack [65], showing the interaction between Frontend, Backend, Database, and Docker Containers.

Typescript, it enables communication between the two, while also facilitating code reuse. Additionally, the expansive library of extensions provided by NodeJS can be conveniently incorporated into the application.

As depicted in Figure 6.1, our utilization of the MEAN Stack unfolds in the following manner: The frontend, crafted in Angular, offers both public pages and private, user-specific interfaces. While the public segment includes the welcome page, FAQ, and documentation, the user-specific section provides tools and features like the project overview, coding editor, simulation interface, analysis tools, and account management. On the other side, the backend, crafted with Express, interfaces with the MongoDB database. This interaction is pivotal for obtaining user information and regulating access to individual project datasets. In addition, the backend plays a crucial role in managing the lifecycle of compilation and simulation sessions on our dedicated servers.

For our compilation and simulation environment, we adopted the containerization approach, widely revered for its capability to run multiple applications efficiently on a singular host system. Key advantages of containerization include scalability, optimal resource allocation, and isolated code execution. With modern engines capable of instantaneously initiating containers with minimal overhead [26], this method aligns perfectly with the objectives of CPM Remote. This is particularly beneficial when considering the requirement to run several containers simultaneously.

Our chosen virtualization engine for containerization is Docker [22]. These Docker containers are equipped with the essential CPM Library and other commonly used libraries necessary for user code compilation and experiment simulation. Docker is configured to allocate a fraction of our server's computational resources to each user, ensuring every user gets a consistent experience irrespective of the total number of active users. Importantly, Docker maintains a unique local network for each container, preventing any communication interference between simulation vehicles from different users' experiments.

During the simulation process, a direct connection is established between the Docker container and the Frontend via a web socket, improving communication speed and reducing latency.

In addition to the web-based application infrastructure, a local setup within the CPM Lab is crucial for managing incoming requests. As illustrated in Figure 6.1, we incorporated a component known as the CPM Controller. This component is designed to field requests coming from the web framework's backend. After receiving these requests, the CPM Controller then forwards them to the CPM Lab's software environment, specifically the *cpm_lib Toolchain*. Furthermore, to maintain the platform's integrity, we utilize a third machine, as illustrated on the far left of Figure 6.1, specifically for initiating and executing periodic End-to-end tests. Additionally, every update of CPM Remote triggers these tests, ensuring that any modifications or additions do not unintentionally introduce vulnerabilities or errors. A detailed discussion of the deployment strategies and the rigorous testing procedures is provided in Section 6.4.

6.3 CPM Libraries

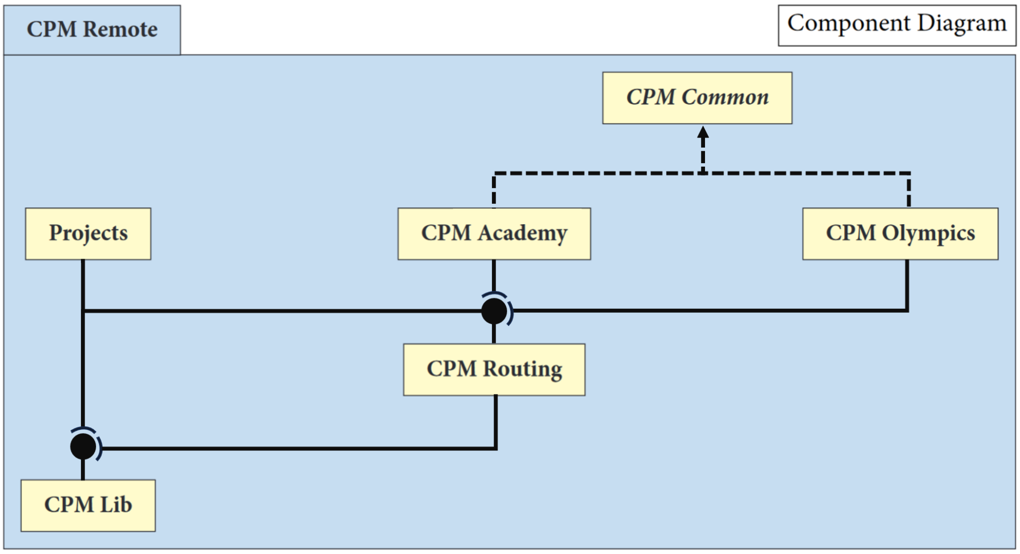

Figure 6.2: Simplified overview of the CPM Remote's software architecture showcasing the central roles of the CPM Common and CPM Routing libraries in project execution.

In the ecosystem of CPM Remote's software architecture, two central components, CPM Common and CPM Routing libraries, play a key role in supporting user interaction and project execution. Figure 6.2 illustrates the architecture used for executing projects, emphasizing the interaction of the included components. The CPM Common library plays an important role as an abstraction layer for various project types within the CPM ecosystem. These project types encompass user-initiated free projects, structured CPM Academy assignments (CPM Levels), and the tasks of CPM Olympics (CPM Scenarios).

Free projects can operate independently of the CPM Common library, as they do not require any specific scenario information. Additionally, free projects can still take advantage of the CPM Routing library, enabling them to efficiently manage their workflows and interactions within the CPM Remote ecosystem. This dual capability of interacting directly with the CPM Lib or utilizing the CPM Routing library provides users with flexibility and convenience when engaging in free projects. The upcoming sections provide a comprehensive look into both the CPM Common and CPM Routing libraries.

6.3.1 CPM Common

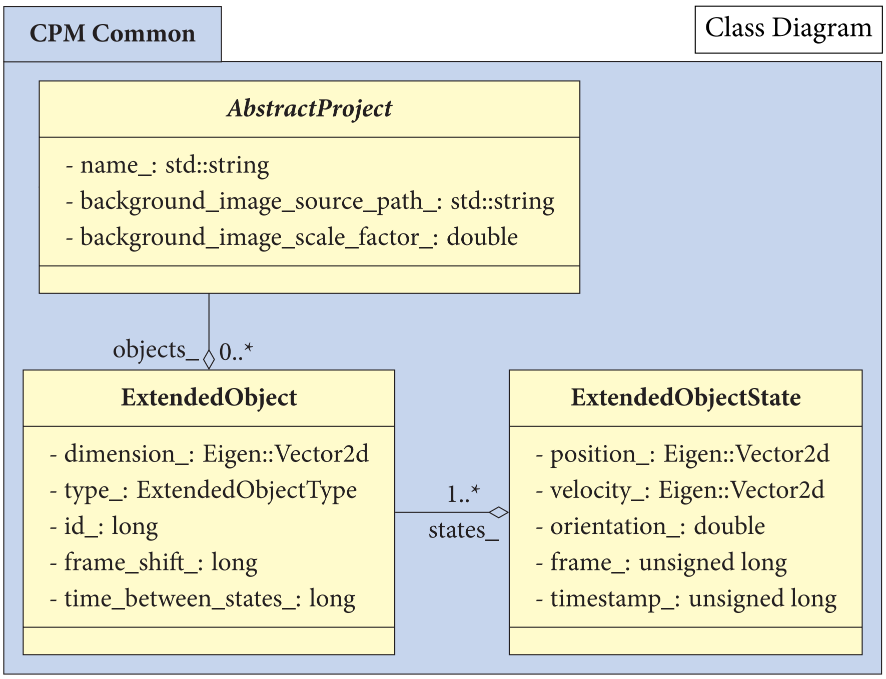

Figure 6.3: Simplified overview of the CPM Common Library structure highlighting shared properties between CPM Academy and CPM Olympics projects.

After determining the common features between CPM Academy and CPM Olympics projects, we saw a chance to make the software architecture more efficient. To simplify the creation process and establish a foundation for future projects, we extracted these shared properties and encapsulated them into the CPM Common library. An illustrative representation of the library's structure is provided in Figure 6.3.

» AbstractProject:
Acting as the foundational class for all projects, the AbstractProject includes both scenarios and levels. Every project is characterized by a distinct name and a collection of ExtendedObjects, each distinguishable within a project by a unique ID. While every project possesses a method to retrieve its runtime, the specific computation varies across projects. Therefore, this method is designated as entirely virtual to accommodate these differences.

» ExtendedObject:
This class symbolizes every object within a project. An ExtendedObject is characterized by attributes such as an ID, dimensions, type, and a collection of ExtendedObjectStates, representing the object's changing conditions over a timeline.

» ExtendedObjectState:
Each object state captures a timestamp along with its position, velocity, and orientation, pinpointing the object's location at a given instant in the experiment. By evaluating this series of object states, we can illustrate and interpret the ExtendedObject's movement and behavior for the experiment's full duration.

6.3.2 CPM Routing

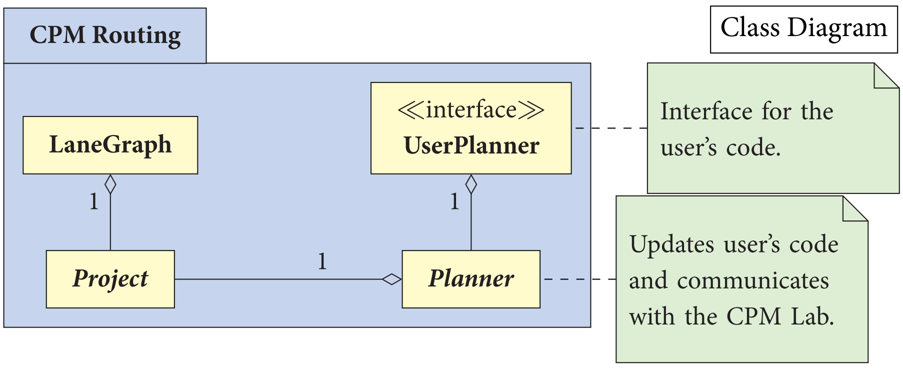

Figure 6.4: Simplified Architectural Overview of the CPM Routing Library, showcasing its four primary classes and their interactions.

The CPM Routing library is a C++ interface that acts as a bridge between the user and the simulation or CPM Lab environment. Its main purpose is to provide the user with problem definitions and essential map materials, making it easier for the user to interact with the environment. One of the main ideas behind this library was its ability to handle various task types. However, while some features of the CPM Lib were slightly reduced, the user interface was made more user-friendly. The core structure of the library consists of four primary classes, as shown in Figure 6.4:

- LaneGraph:
  This class works closely with the Lanelet2 library [78] and presents the map for the vehicles. It offers a series of important functions, eliminating the need for users to understand the details of the Lanelet2 library for basic operations. However, experienced users can also directly access the Lanelet map instance.

- UserPlanner:
  The UserPlanner serves as the primary interface for users to input and execute their code. It requires the implementation of an update function that is triggered periodically. Additionally, depending on the scenario or level, interrupt functions are called, for instance, when new vehicles appear or when obstacles are detected. This interface serves as the primary point of contact for the user.

- Planner:
  Built to handle the specific communication needs and timings for interaction with the CPM Lab, this class calls the user-defined update function and sends the determined trajectory points to the CPM Lib.

- Project:
  Initiated from the main function, this class ensures that all necessary information is ready before the UserPlanner's first update. For example, it checks that the Indoor Positioning System (IPS) recognizes all the requested µCars before the Planner starts its planning process. Both the Project and Planner are abstract classes, allowing for the creation of different project types with the CPM Routing library while relying on a shared codebase.

Once a level (CPM Academy) or a scenario (CPM Olympics) is completed, the CPM Routing library begins the corresponding evaluation based on the recorded data.

6.4 Testing and Quality Assurance

Software platforms, particularly those that are userfriendly, must meet a stringent set of quality requirements. It becomes imperative to ensure that evolving software maintains its original functionality, delivering a seamless user experience. The Testing Pyramid, a distinguished model in Software Engineering (SWE), addresses this concern. As depicted in Figure 6, the pyramid structure details three testing levels: Unit Tests, Integration Tests, and End-to-end (E2E) Tests.

- Unit Tests:
  At the base of the pyramid, unit tests are fundamental and focus on individual sections of the code. These tests verify the sum of the software's individual functionalities. Since they are crafted by developers specifically for selected code segments,

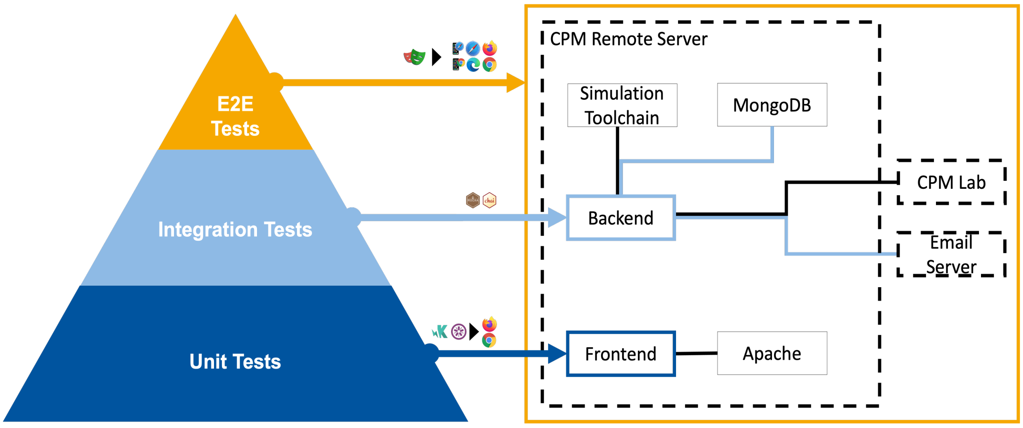

Figure 6.5: The Testing Pyramid illustrating the layers of testing and their connection to CPM Remote components.

they tend to be very robust and reliable. The primary goal here is to ensure that every piece of the software, when isolated, works as it should.

» Integration Tests:
These tests take a broader view, assessing how individual units or components of the software interact with one another. After the unit tests, these are conducted to ensure that different segments of the software cohesively work together. Integration tests can uncover issues like data flow disruptions, malfunctioning function calls, or glitches arising from combined functionalities. One of their prime benefits is detecting errors that might arise from component interfaces or miscommunications between distinct software parts.

» End-to-End Tests: These are comprehensive tests that validate the entire workflow of the application, mirroring real-world user scenarios. They check if the software, inclusive of its interactions with external systems like databases and other interfaces, functions holistically as anticipated. Typically conducted after integration tests, E2E tests are a final checkpoint before software is released to users. Though they might be more time-intensive and intricate, the importance of these tests should not be overstated.

During the early stages of CPM Remote's development, unit tests were created. However, the coverage was insufficient. Once the feature set of CPM Remote reached a plateau, a comprehensive initiative was launched to implement unit, integration, and E2E tests.

This initiative began with a analysis of the entire feature set, resulting in the definition of 154 test specifications, each designed to cover specific functionalities of the application. As of the time of this thesis, 151 of these test specifications had been transformed into test cases. Additionally, 70 test cases were automatically generated from the test specifications themselves. In total, this effort produced 221 tests, collectively providing extensive coverage of all CPM Remote functionalities.

Notably, these tests are executed across three different browsers: Chrome [32], Firefox [67], and Webkit [3]. This diverse browser testing approach ensures that the application functions consistently across various web environments, including different screen resolutions and mobile browsers with touch functionality.

The testing framework of CPM Remote primarily relies on the Playwright framework [58], which was selected after thorough research as the most suitable solution. Playwright offers several advantages, including a large and supportive community, and is developed by Microsoft, making it a state-of-the-art choice for test automation. In addition to Playwright, integration testing is performed using Mocha [71] and Chai [13]. These tests assess the backend of the application, its connection to the database, and the email server. Mocha and Chai are well-established testing tools commonly used in conjunction with the Express framework, ensuring the robustness and reliability of these critical components.

Furthermore, CPM Remote incorporates 193 unit tests, with a significant portion of these tests focusing on the Angular components of the frontend. Karma [44] and Jasmine [40] are employed to automate the execution of these unit tests, which are run in both Chrome and Firefox. This double testing approach ensures that the frontend components are thoroughly evaluated in different browser environments.

Currently, we made it a priority to encourage all developers to utilize tests, particularly E2E tests. These tests have been seamlessly integrated into the development pipeline, facilitating automated testing throughout the development process. Further details regarding the development pipeline will be discussed in next Seciton 6.4.1, providing a comprehensive view of the testing and development workflow of CPM Remote.

6.4.1 Continuous Integration and Continuous Development

CPM Remote has embraced state of the art development practices by fully dockerizing its development environment using Docker Compose. This strategic move ensures that developers work within a setup that mirrors, to a great extent, the final system that gets deployed. This congruence significantly reduces discrepancies that might arise due to environmental differences, which is a common challenge in software development.

To further facilitate the development process, aside from the official CPM Remote website[1], a mirrored version has been set up and hosted online, specifically for developers. This version, in the following referred to as *CPM Remote Dev*[2], plays an important role in ensuring that features and changes are tested thoroughly before they make their way to the official website.

[1] `https://cpm-remote.embedded.rwth-aachen.de/`
[2] `https://cpm-remote-dev.embedded.rwth-aachen.de/`

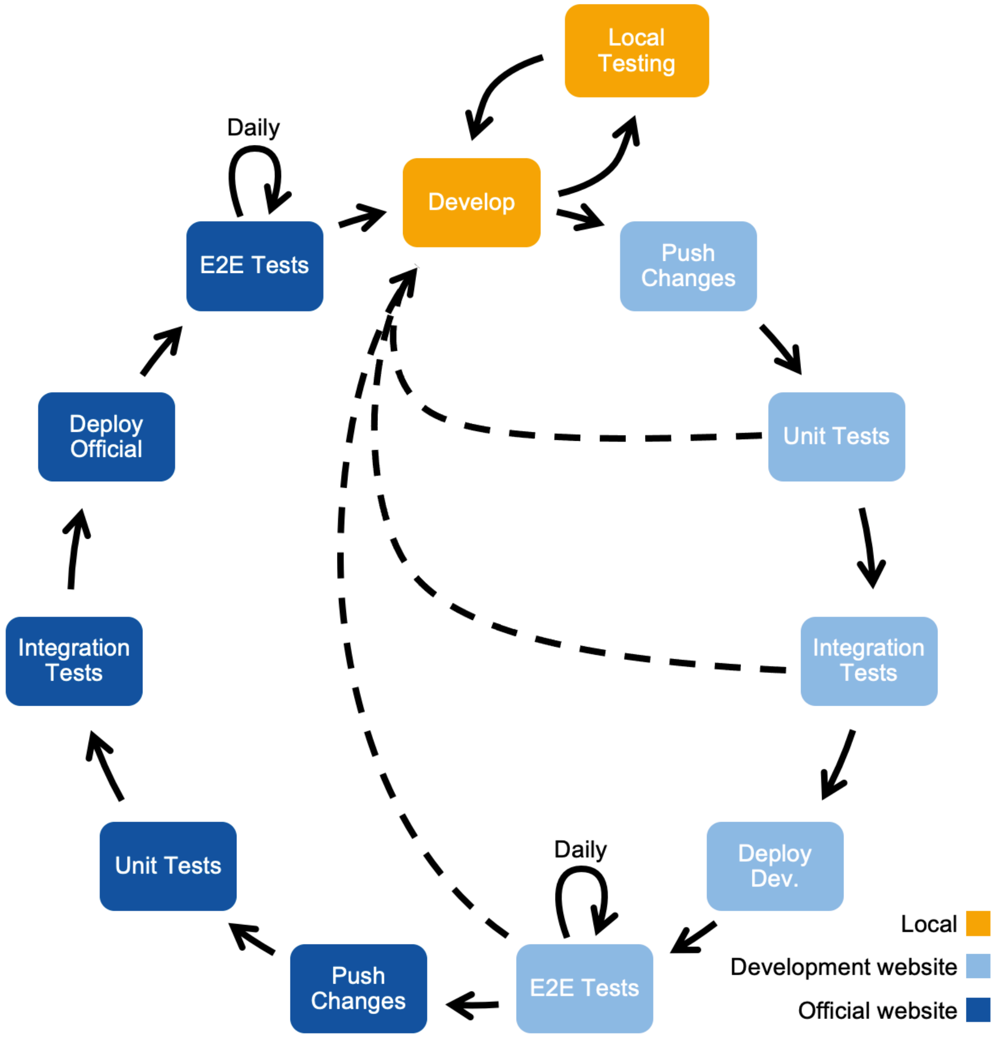

Figure 6.6: Automated testing cycle for updates in CPM Remote: From initial push to daily end-to-end tests on the official website.

Reflecting on the developmental practices prior to the introduction of the improved testing infrastructure, developers were tasked with manually testing new features on their local machines. Once the initial testing was done, the features were then deployed to CPM Remote Dev for another round of verification. Only after these two rounds of testing were successful, the changes were updated on the official site.

The recent revision of the testing infrastructure has marked a paradigm shift in how testing is approached. The process of manual testing has now been largely supplanted by automated tests. Upon pushing changes to CPM Remote Dev, a designated pipeline is triggered. This pipeline runs unit tests and integration tests in the initial phase. If these preliminary tests pass, the website undergoes deployment. Once the new version is deployed, automatic E2E tests are executed. If the test report meets the developers' approval, they can begin deploying to the official website. Subsequently, all tests are performed again on the official site. Additionally, E2E tests are conducted daily to identify possible issues. This testing cycle is depicted in Figure 6.6.

6.5 Summary

In conclusion, this chapter has provided a comprehensive overview of the implementation of the CPM Remote framework. We began by presenting our software stack in Section 6.2, which is built upon MEAN (MongoDB, Express.js, Angular, Node.js) components and the Docker framework. This foundation sets the stage for the scalable architecture that underlies CPM Remote.

Moving forward, we explored the CPM Libraries in Section 6.3, with a particular focus on the CPM Common and CPM Routing libraries. These components were strategically designed to offer a modular structure and a user-friendly interface, thereby enhancing the overall accessibility of the CPM Lab.

Furthermore, we discussed the aspect of testing and quality assurance within our framework. We presented our approach to implementing tests in accordance with the testing pyramid, ensuring thorough coverage of unit, integration, and E2E tests. Additionally, we unveiled our Continuous Integration and Continuous Deployment concept, which plays an important role in streamlining the development process of CPM Remote.

Chapter 7

Evaluation

7.1 Introduction

In this chapter, we present how CPM Remote, is perceived and accepted by its users. To begin, we present objective data in Section 7.2 to offer a foundational understanding of the platform's reach and usage.

Following this, we conducted a self-report study to explore how students perceive CPM Remote. For this purpose, we employed the Technology Acceptance Model (TAM) [20] as our theoretical framework. This model is particularly suited for understanding the factors that influence users' acceptance and engagement with new technologies.

Our investigation also encompasses a detailed analysis of the CPM Remote's applications, namely the CPM Academy and the CPM Olympics. We evaluated these applications for usability and user acceptance. Through various studies and direct feedback from users, we were able to gauge the intuitiveness and effectiveness of these applications. This feedback was instrumental in making targeted optimizations to enhance the overall user experience. These findings are presented in Section 7.3

Moreover, we studied the overall acceptance of the technology among users in Section 7.4. This part of our research aimed to identify key factors that could make the digital platform more appealing and effective. The design of this study, along with its findings, are discussed subsequently.

Finally in Section 7.5, we use the collected data and insights to discuss the contribution of CPM Remote to the scientific domain. This discussion, presented in the concluding section, synthesizes our findings to provide a coherent understanding of the impact and significance of CPM Remote in the field of connected and automated vehicles.

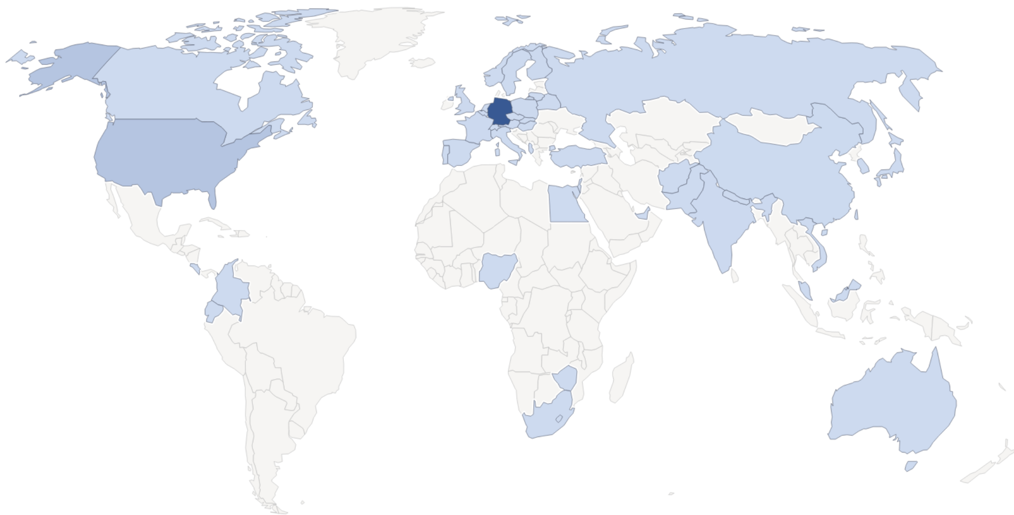

Figure 7.1: Geographic distribution of CPM Remote page visits over a one-year period, representing users from 48 distinct countries. The three shades of blue represent low (≤ 100), medium (≤ 1000) and high (≤ 2000) number of visits.

7.2 Usage Statistics

CPM Remote, as a publicly available website, allows the use of various tools to monitor its usage. Our emphasis on data privacy has influenced our decision to select Matomo, an open-source platform that facilitates local hosting [56]. Matomo ensures that all data we gather remains in our custody and is not shared with external parties.

Furthermore, we have made a decision not to store any additional cookies. Moreover, any user employing an ad blocker effectively disables our tracking capability. This significantly reduces the proportion of users we can monitor. Research indicates that almost 50% of users employ ad blockers [25]. Given that our platform is primarily targeted at the educational and research domain, the actual percentage might even surpass this estimate. While we recognize this limitation, it is a trade-off we have deliberately chosen in favor of user privacy. Nonetheless, based on the data from the users we can track, we are still able to identifiy patterns and extract meaningful statistics. The details of these insights are presented in the subsequent sections.

We initiated our deployment of Matomo in October 2022. Exactly one year later Matomo recorded a total of 5,781 page visits from 48 distinct countries. These countries are visually represented in Figure 7.1. On average, a visitor spent approximately 12 minutes and 57 seconds on the website. However, this average has a broad variance due to the inclusion of two different types of visits: brief visits for information purposes and extended visits for development and implementation tasks. Of the total visits, 13.4% were made using smartphones or tablets. The fact that CPM Remote was accessed through 224 different screen resolutions, highlights the importance of having a responsive design in modern applications. Regarding website traffic sources, 76% of users accessed the website directly. Only 11% were redirected from other websites, and 12% came via search engines.

In addition to Matomo, specific statistics can be directly sourced from our server. As of now, CPM Remote has 461 registered users. We do not mandate any particular information during registration, allowing anyone to sign up. However, based on the email addresses provided, we can determine that approximately 21% of these users are affiliated with RWTH Aachen University. In the subsequent sections, we will detail the statistics related to our two applications, CPM Academy and CPM Olympics, integrating data from both Matomo and our server records.

7.2.1 CPM Olympics

Table 7.1: Participation statistics for the CPM Olympics 2022 recorded from 10/01/2022 - 02/01/2023

Metric	Amount
Registrations (Stage 1)	79
Registrations (Stage 2)	19
Information page visits	2554
Participants	24
Submissions	83
Average length of stay	17:44 min
Requested sessions	4872

The primary motivation for initiating the monitoring of website traffic was the hosting of the first CPM Olympics in 2022. Table 7.1 encapsulates the key data points collected during this period. During Stage 1 of the Olympics, a phase designated for participants to enroll, we noted a surge in registration with 79 new users. Over this duration, Matomo logged 2,554 page visits. Stage 2 saw an additional 19 users joining. However, while it remains feasible to enter the competition at this period, it is considerably late to have a successful run in the contest.

During the CPM Olympics 2022, 24 participants competed. These participants collectively submitted 83 distinct solutions, translating to an average of 3.4 submissions per participant. Notably, during this CPM Olympics, the average duration of website visits surged, being nearly 5 minutes longer than the yearly average. Concurrently, there were 4,872 Olympics session requests recorded. Each of these sessions corresponds to a 10-minute window wherein simulations are run through CPM Remote.

The CPM Olympics 2022 presented participants with 25 distinct scenarios, each serving as a benchmark for the submitted solutions. Out of these 25 scenarios, 16 remained unsolved by all participants. However, while some scenarios were addressed by the majority of submissions, others were only resolved by specific solutions. The distribution of solutions across scenarios is depicted in Figure 7.2. This data suggests that some scenarios might have been overly complex, though the range of difficulty levels did allow to distinguish among the solutions. The best three solutions managed to solve 7 (1st place), 7 (2nd place), and 6 (3rd place) scenarios. The average score per scenario for these top solutions was 79% for the 1st place, 75% for the 2nd place, and 85% for the 3rd place. Although the solution in third place had a higher average score, it ranked third because the first two solutions addressed one more scenario successfully.

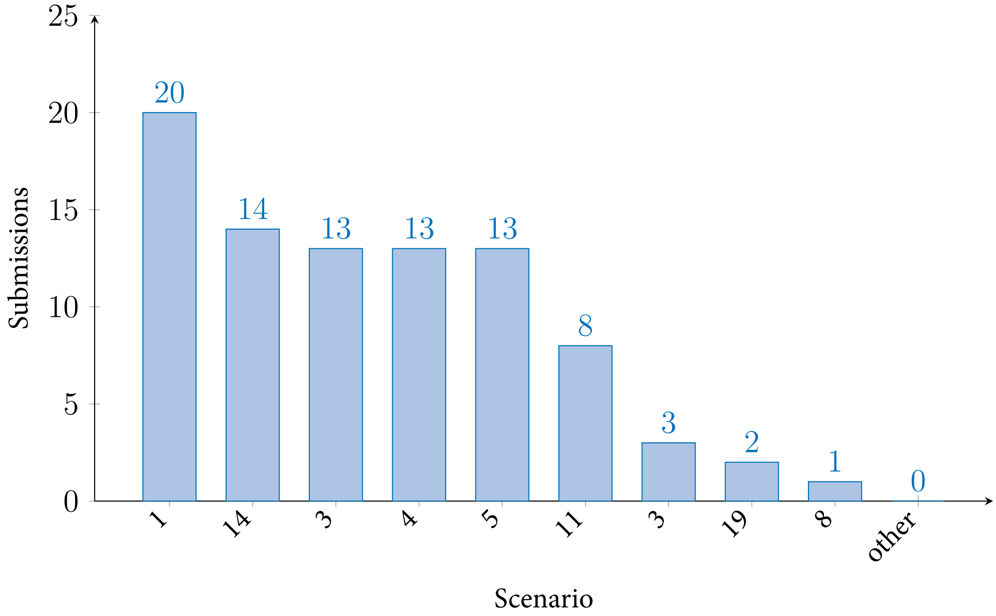

Figure 7.2: Distribution of solved scenarios across participant submissions for the CPM Olympics 2022.

After the Olympics, we reached out to participants via email, inviting them to complete a survey. This was aimed at understanding their experiences with the platform, including both its advantages and challenges. The results of this survey will be discussed in Section 7.3.

7.2.2 CPM Academy

CPM Academy, an integral part of our chairs curriculum, is conducted during the winter semester. Over the past four years, this course has undergone significant development, resulting in the concept detailed in Section 5.3. Under this framework, we have held the course three times: in the winter semesters of WS 21/22 and WS 22/23, and uniquely, in the summer term of SS23. The decision to offer the course in the summer term was twofold. Firstly, it allowed us to refine certain parameters within the package delivery scenario. Secondly, it provided an opportunity to assess the impact of the enhancements made to CPM Remote through firsthand user feedback. The results of this survey will be elaborated on in Section 7.3. Subsequent to this introduction, we will present notable statistics regarding participation in the CPM Academy.

The demand for seats in the CPM Academy course consistently exceeds our ability to supply due to constraints related to supervision. In the initial year of the course in 2019, before the implementation of CPM Remote, the capacity was constrained by the limited and sometimes inefficient utilization of the CPM Lab, allowing us to offer only 24 seats. When CPM Remote was introduced in WS 21/22, despite the interest of 110 students, we were still only able to accommodate 30. In an effort to meet the rising demand, we refined our approach, enabling us to increase the seat count to 40 in the subsequent year. However, during the exceptional summer term 23, we intentionally limited the intake to 10 seats. This decision aimed to provide intensive supervision, facilitating a deeper understanding of students' interactions with the platform. Our data monitoring began in 2022, so our primary insights are derived from the past year's activity. The 40 students from this period requested a total of 671 sessions on CPM Remote, where each session denotes a 10-minute window to test their code. The summer term, which had only 10 participants, saw 281 session requests. Given that the majority of solutions weren't collision-free, only 14 experiments were submitted to the CPM Lab for execution.

When evaluating the course feedback, comparing the initial term in 2019 (which was conducted without CPM Remote) with the 2022 term that utilized CPM Remote, no marked disparities were identified in student evaluations. This observation suggests that undergraduate students do not perceive significant advantages in on-site, in-person coursework. In fact, many students explicitly voiced their appreciation for the flexibility that CPM Remote offers. A more detailed examination of this feedback is discussed in Section 7.3.

7.3 Usability Analysis

In irregular intervals, often prompted by events such as the CPM Olympics, CPM Academy, or concerted initiatives (e.g., in the context of a student thesis) aimed at enhancing the usability of CPM Remote, users have been subjected to surveys of varying scopes and depth. This section focuses primarily on the outcomes of six distinct studies. Moreover, we will explore the research methodology employed in the most comprehensive of these studies and engage in an in-depth discussion of the findings. One of these studies was conducted as part of a master's thesis [35] under the author's supervision, with the primary objectives being to assess the current state of usability, implement improvements based on user feedback, and then conduct another survey to evaluate the impact of these enhancements.

7.3.1 Study Design

To gather comprehensive data for our assessment, we created a questionnaire based on literature in this field [5, 68, 69]. Following recommendations, we ensured that the questionnaire featured a number of open-ended questions, allowing participants the opportunity to freely express their views. The questionnaire was structured into seven categories:

(i) General: These questions cover overall impressions and participants' general experiences with CPM Remote, providing a broad perspective on usability.

(ii) Quality criteria: This section presents the finer details, examining aspects such as:

  a) Innovation
  b) Usefulness
  c) Aesthetics
  d) Comprehensibility
  e) Arrangement
  f) Consistency
  g) Dependence on external circumstances
  h) Authenticity of interaction with the (physical) CPM Lab
  i) What mood do you associate with CPM Remote?

(iii) Recognition: This category aims to assess participants' familiarity with CPM Remote and whether they can easily identify its features and functions.

(iv) Initial accessibility: These questions investigate how easily users can access and navigate CPM Remote initially, focusing on user-friendliness.

(v) Goals and workflows: Participants are asked about their specific objectives and tasks when using CPM Remote, providing insights into the platform's alignment with users' goals.

(vi) Problems and difficulties: Users are encouraged to highlight any challenges or issues they encounter while using CPM Remote, helping identify areas in need of improvement.

(vii) Additional suggestions: This category invites participants to share any additional comments, ideas, or recommendations they may have regarding CPM Remote's usability and functionality.

Prior to completing the questionnaire, participants were provided with tasks, guiding them through the utilization of CPM Remote's functionalities. This approach ensured that participants had hands-on experience with the platform before sharing their feedback. Additionally, it is important to note that at a certain stage of the study, all participants were physically present in the actual CPM Lab to interact with it directly, rather than solely relying on CPM Remote. This provided a unique opportunity to compare and contrast their experiences between the two settings.

7.3.2 Results of the Usability Analysis Study

A total of 42 individuals participated in this survey. The majority of these participants were computer science students. However, the cohort also included students from diverse academic backgrounds as well as research assistants. To facilitate clarity and avoid overemphasizing specific issues, we chose to group and summarize the feedback provided in this study. This approach allows for a more concise presentation of the findings while maintaining the integrity of the participants' responses.

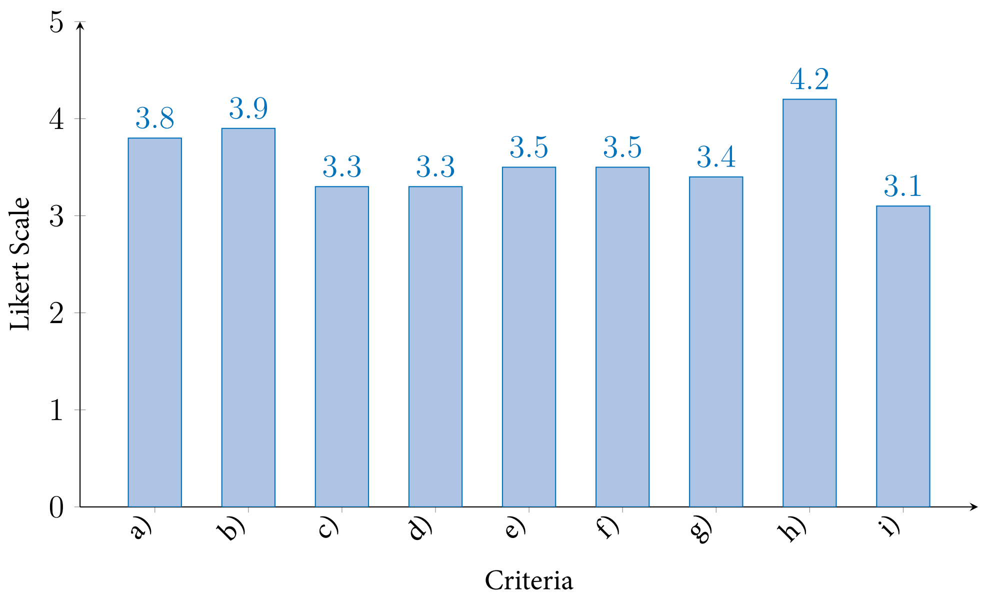

Figure 7.3: Participants' ratings of various quality criteria, as described in Section 7.3.1, on a scale from 0 (worst) to 5 (best).

Figure 7.3 displays the results of the quality criteria presented in Section 7.3.1, where participants were asked to rate various aspects on a Likert scale ranging from 0 (worst) to

5 (best). It is noteworthy that every criterion received ratings exceeding 3. However, one particular criterion, criterion h), which pertains to the authenticity of interaction with the (physical) CPM Lab, stood out with a rating of 4.2. This criterion explored participants' perceptions of remote access as a suitable interface to the real testbed. Remarkably, in a subsequent questionnaire, 40 out of 42 participants expressed a preference for the remote access, citing the additional flexibility it offers over the necessity of physically being present in the testbed.

While the overall ratings for the remaining criteria were similarly favorable, the study also identified areas with the potential for improvement. Out of this specific study, a total of 69 issues emerged. To systematically manage and address these issues, we categorized them based on Ben Shneiderman's *Eight Golden Rules of Interface Design* [90]. For example:

» We encountered 21 consistency issues, which included problems such as misleading button colors and elements that were not fully responsive.

» Additionally, there were 11 feedback-related issues where participants requested more meaningful feedback mechanisms at certain points. In response to this feedback, we implemented a feedback bar that notifies the user about errors and warnings.

» A significant portion of the issues revolved around helping users become more familiar with the website. This led to the development of a new *Get Started* page, an additional documentation for the framework and an automatic walkthrough for the website after the first login.

Each issue was assigned a priority level, ranging from feasible and relevant (priority 1) to infeasible and out of scope (priority 3). The allocation of priorities was determined by considering available resources and the overall practicality of implementing each suggestion. At the time of writing this thesis, all priority 1 and 2 issues have been successfully implemented, demonstrating our commitment to enhancing the usability and functionality of the CPM Remote platform based on user feedback.

7.3.3 Usability Analysis of CPM Academy

In the pursuit of continuous improvement and responsiveness to user feedback, we conducted surveys accompanying each iteration of the CPM Olympics and the CPM Academy. These surveys provided valuable insights from participants, guiding our focus for the ongoing development of CPM Remote.

In this section, we present feedback and evaluations from multiple course offerings. Due to the unavailability of remote access during the winter term of 2019/20, the course feedback presented here encompasses the winter term of 2020/21 with 8 participants, the

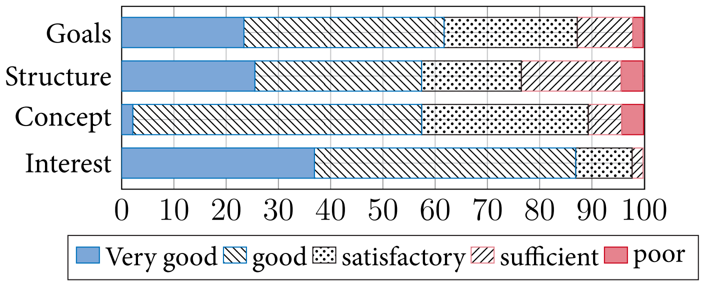

Figure 7.4: Evaluation of CPM Academy based on 63 questionnaires. The students were asked to rate: personal interested in the course, concept of the course, structure of the learning material and provision of clear goals.

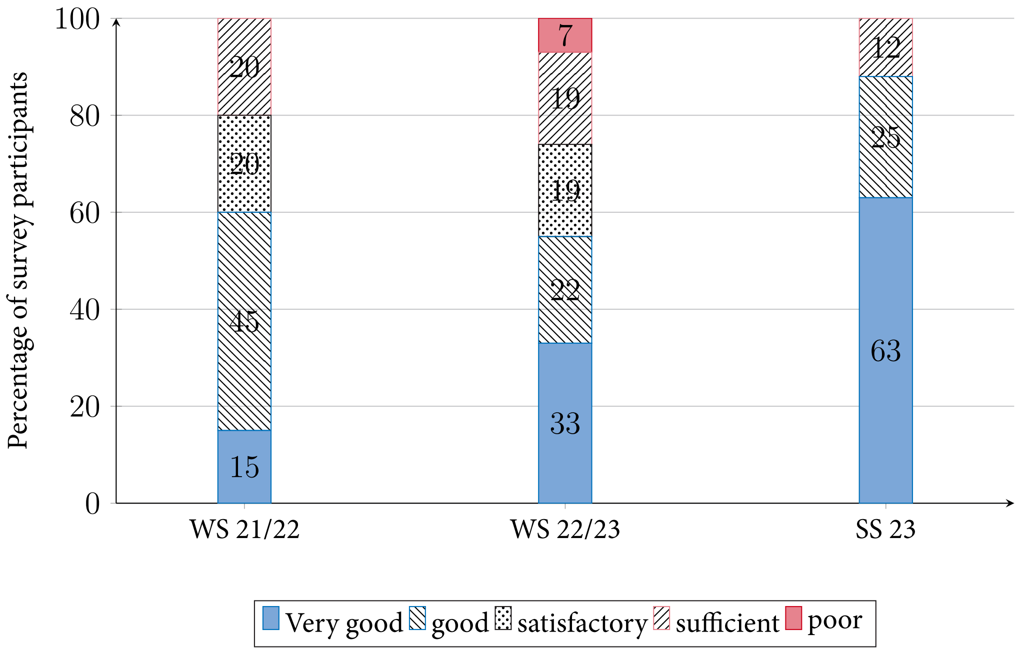

Figure 7.5: Course structure approval trends over multiple years in the CPM Academy.

winter term of 2021/22 with 20 participants, the winter term of 2022/23 with 27 participants, and the summer semester of 2023 with 8 participants. These four studies were conducted using the predefined survey template of RWTH Aachen University, encompassing various detailed questions.

Among the diverse range of inquiries, four key criteria were employed to evaluate the courses:

» Goals: Evaluates the clarity, relevance, and application of the course's central ideas.

» Structure: Examines the organization and coherence of the course materials and activities.

» Concept: Examines the methodology underlying the course content, including the supervision.

» Personal Interest: Measures the extent to which the course aligns with individual student interests and preferences.

Figure 7.4 summarizes the findings from all four studies, representing a total of 63 participants. In each of the four main criteria, over 50% of the students expressed positive rankings for the courses. Regarding *Personal Interest*, over 87% of respondents indicated that the course aligned with their interests. These cumulative insights from course evaluations provide an overview of the positive reception and alignment with participant interests within the CPM Remote offerings.

Performing a longitudinal analysis of these studies presents challenges due to various factors that could influence the results, including fluctuations in participant counts and external variables such as the recent COVID-19 pandemic. Consequently, we encountered difficulties in identifying consistent trends, whether positive or negative, with one notable exception. An encouraging trend was observed in the approval ratings for the course structure over the course of the CPM Academy. As depicted in Figure 7.5, during the first year, 15% of participants rated the course as *very good*, which increased to 33% in the second year and further surged to 63% in the last iteration. Although we highly value these quantitative indicators, our primary focus has consistently been on the open-ended questions, where participants can freely express their views and provide qualitative feedback. Through this approach, we were able to identify an average of 21 issues per survey, enabling us to continuously enhance the platform based on user feedback.

7.3.4 Usability Analysis of CPM Olympics

The survey conducted after the CPM Olympics involved a total of 10 participants. Much like the CPM Academy study, the primary aim here was to refine the concept for the next iteration, continuing our commitment to ongoing improvement.

In addition, we aimed to gain insights into the participants' backgrounds and their perspectives on the complexity of the problem. To achieve this, we included questions to ascertain whether participants possessed prior domain knowledge (70% answered no, while 30% answered yes) and to assess their coding experience (10% had less than a year, 60% had 1-5 years, and 30% had over 5 years of coding experience).

Figure 7.6 illustrates how the participants rated the complexity of the scenarios presented in the CPM Olympics 2022. These ratings align with the statistics we previously presented in Section 7.2. Specifically, 4 participants regarded the scenarios as fair, 5 participants found them complex, and one participant deemed them too complex. From this survey, we

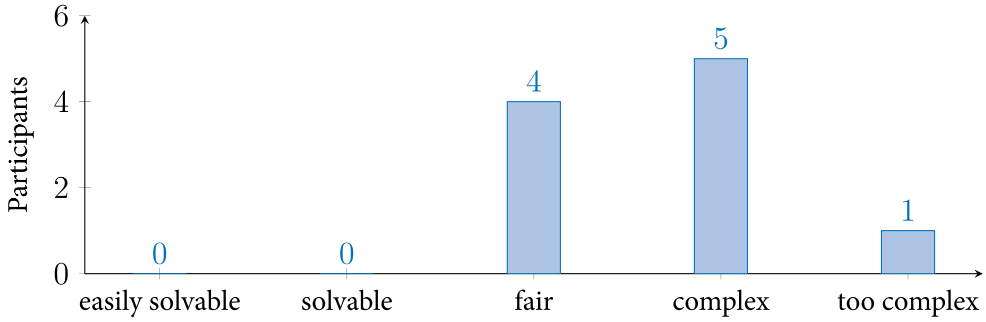

Figure 7.6: Participants' ratings of the complexity of scenarios presented in the CPM Olympics 2022.

were also able to identify and derive actionable issues for further improvement. Combining the feedback and issues identified across the six studies presented in this section played a important role in shaping the CPM Remote concept, which we presented in Chapter 3. However, these studies were primarily conducted to refine the concept of CPM Remote and identify usability issues. In the following section, we will shift our focus to exploring user acceptance of this method for engaging with a small-scale testbed, utilizing the Technology Acceptance Model [20] known as UTAUT 2 [98]. In Section 7.5, we examine the feedback received from all investigations and their substantial impact on the evolution of the CPM Remote concept.

7.4 Technology Acceptance

Technology Acceptance Models (TAMs) play a pivotal role in understanding how users come to accept and use a technology [20]. These models seek to unveil the determinants of technology acceptance, allowing developers and researchers to anticipate potential barriers and enablers to adoption. Among various TAMs, the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) stands out due to its comprehensive nature, integrating multiple constructs that capture the essence of user acceptance, particularly in consumer technology contexts [98].

Given the innovative nature of the CPM Remote project, it was imperative to identify the key factors that would drive its acceptance. UTAUT2, with its inclusion of constructs like Performance Expectancy, Effort Expectancy, Social Influence, Facilitating Conditions, Hedonic Motivation, and Habit, seemed a fitting choice. However, for the context of our study, two components from the original UTAUT2 model were excluded: Price Value, since the CPM Remote framework is offered without cost, and Gender, which was not investigated in this research. An illustration of the model is provided in Figure 7.7. In this section, we present the findings from our study with 32 participants, highlighting the key factors from UTAUT2 that influence the acceptance of the CPM Remote project.

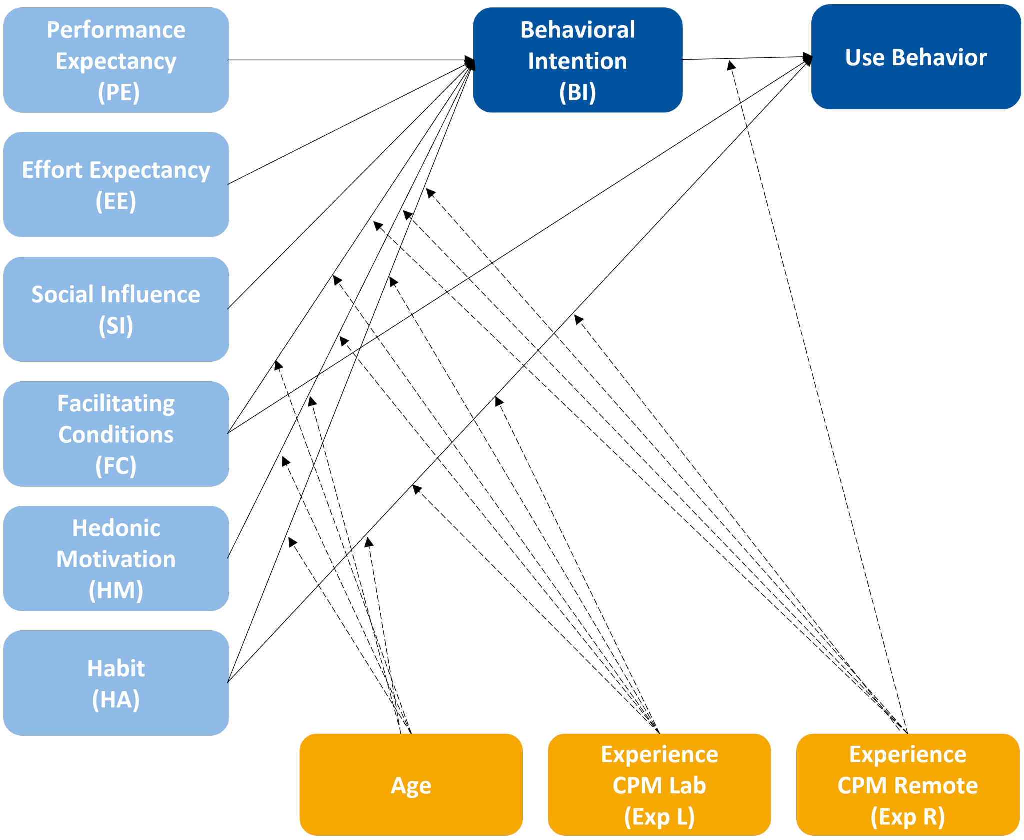

Figure 7.7: The adapted UTAUT2 model for evaluating user acceptance of the CPM Remote project.

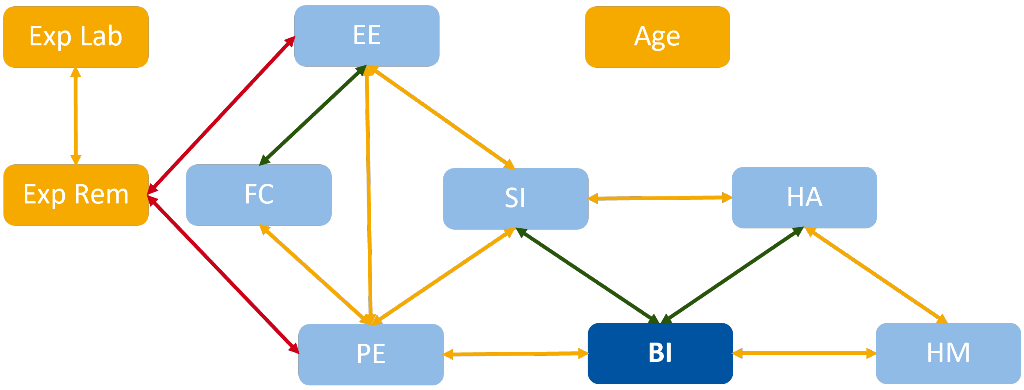

Figure 7.8: UTAUT2 model visualization representing correlations in CPM Remote project acceptance. Red lines indicate negative, green lines strong positive and yellow moderate correlations.

	PE	EE	SI	FC	HM	HA	BI	Age	Exp R	Exp L
PE	100									
EE	58.5	100								
SI	58.7	54.3	100							
FC	66.5	75.1	44.3	100						
HM	37.5	28.6	44.9	44.5	100					
HA	41.5	21.8	62.2	25.6	50.7	100				
BI	53.4	39.7	78.9	37.1	55.8	76.1	100			
Age	3.1	-1.0	14.6	-8.8	3.0	4.6	4.6	100		
Exp R	-62.8	-52.6	-28.87	-47.2	-36.75	-18.6	-24.3	-8.9	100	
Exp L	-45.3	-34.6	-30.9	-39.2	-37.1	-31.92	-28.8	11.4	57.08	100

Table 7.2: Detailed values in % of the UTAUT2 correlation Mmatrix for CPM Remote acceptance. Strong correlations (≥ 75) highlighted green and moderate correlations (≥ 50) highlighted yellow.

The study involved a diverse group of participants from the academic sector, with ages ranging from 17 to 55. This group included both students and research associates. From the data gathered, we implemented the UTAUT2 model, resulting in the collection matrix depicted in Figure 7.8, with detailed values presented in Table 7.2. Within this matrix, we emphasized strong and moderate correlations for clarity. In the following we will discuss the key findings and provide possible interpretations. It is important to note that the correlations identified here are not indicative of direct causation. These correlations are interpreted based on the responses and data obtained from the questionnaires conducted with the participants.

» Influence on Behavioral Intention:
The most significant correlations to behavioral intention for CPM Remote were Social Influence (79%) and Habit (76%). Given the participants' academic backgrounds, there is a belief that peer adoption or institutional recommendation of CPM Remote would influence their intention to use it. The correlation with Habit speaks to the nature of human behavior; individuals who are familiar with a tool often prefer to keep using it.

» Effort Expectancy and Facilitating Conditions:
A relationship emerged between Effort Expectancy and Facilitating Conditions. From follow-up survey notes, it became clear that as facilitating conditions improve, users expect less effort in adopting the technology. At a glance, this might seem obvious, but it underlines the significance of effective onboarding and comprehensive documentation in mitigating perceived effort. An interesting observation was the lack of a correlation between Effort Expectancy and Behavioral Intention. This may

be because participants feel they have few alternatives, leading them to see the effort as a necessary part of the process, especially if CPM Remote offers a unique way to access such a testbed.

» Effects of Experience with CPM Remote:
As participants became more familiar with CPM Remote, they expected greater effort in its use, a trend also observed with Performance Expectancy. This increased expectation was attributed to the Dunning-Kruger effect [24]. The deeper participants delved into the platform, the more they recognized the complexities of the domain and its applications, such as the CPM Academy and Olympics.

» Real Lab Experience & CPM Remote:
A correlation emerged between the experience in the actual CPM Lab and the experience with CPM Remote. Participants felt that by using the remote platform, they were indirectly getting to know the physical CPM Lab. This aligns with the primary goal of CPM Remote to overcome the physical constraints of accessing the testbed.

The study underscores a general acceptance of the CPM Remote technology among participants. However, to further enhance this acceptance and facilitate seamless adoption, certain areas require focused attention. Emphasizing a good onboarding process can assist users in navigating the initial stages of engagement more effectively. Comprehensive documentation can address uncertainties and diminish perceived effort, ensuring a smoother user experience. Furthermore, integrating elements that foster intrinsic motivation becomes pivotal. This motivation can be amplified by clearly communicating the platform's capabilities and showcasing its benefits upfront. By offering a transparent view of what the platform can achieve and the advantages it brings, users can be more intrinsically motivated to engage. By addressing these areas, the potential of the CPM Remote project can be better realized.

7.5 Discussion

This section presents an analysis of key insights from three components of the CPM Remote project: The Remote Access, CPM Olympics, and CPM Academy. These show the effectiveness, acceptance, and impact of these components in the context of promoting teaching, research, and engagement in the field of CAVs.

CPM Remote has proven to be a success, as evidenced by the high number of registered users (461) and page visits (5,781) within its first year. The functionality of remote access to the CPM Lab has been well-received, offering a viable alternative to physical presence in the testbed. The usability analysis and technology acceptance investigation affirm that

CPM Remote is perceived as an appropriate and suitable solution. This outcome is significant as it extends the benefits of a state-of-the-art small-scale testbed to a broader audience, facilitating engagement in CAV-related activities. The positive response from users, as indicated by many surveys, underscores the value of this offering. However, usability analyses have highlighted areas for improvement. Users have expressed the need for additional features, such as better debugging capabilities, that are currently missing on the platform. Furthermore, feedback suggests that documentation could be enhanced to provide clearer guidance for users, and overall performance optimizations are warranted to further enhance the user experience. These insights indicate that while CPM Remote has made significant strides, there is still room for grow.

CPM Olympics, in its first year, saw 24 active participants, marking a promising beginning for the competition. The task of raising awareness and fostering engagement for such an event can be quite challenging. Thus, this initial participation rate can be viewed as a successful start. Building upon this positive momentum, we remain committed to continuous platform improvement based on valuable user feedback. The platform evaluation has provided insights into factors that can enhance engagement and reduce entry barriers, offering a clear direction for future development efforts. CPM Olympics has effectively established itself as a challenging competition that generates interest in the field of motion planning. As a result, preparations for the next iteration are currently in progress.

CPM Academy offers a course that resonates well with students due to its strong alignment with their interests and the practical relevance of the course content. The structured level system, featuring clear objectives and progress monitoring, has garnered positive feedback. Students appreciate the opportunity to witness their working solutions achieve milestones in the physical testbed. Moreover, students value the flexibility offered by CPM Remote, which allows them to manage their time independently instead of being tied to constant on-site, in-person work. The option for collaborative work through CPM Remote is also highly regarded by students. While there have been annual documentation improvements, some students have expressed concerns about its sufficiency. We take these concerns seriously and are actively working to address them.

7.6 Summary

In conclusion, this evaluation chapter underscores the success of the objective to provide global access to development tools for connected and automated vehicles through the establishment of a remote access solution. The insights gathered from the assessment of various components within the CPM initiative, including the Remote Access, CPM Olympics, and CPM Academy, collectively demonstrate the efficacy of these efforts in promoting engagement, research, and education in the domain of CAVs. The positive user responses, active participation rates, and valuable feedback all contribute to the overall achievement of the goal to extend access to CAV development on a worldwide scale.

This statement is substantiated by the evaluation presented in this chapter. We justified this assertion through a multifaceted approach, drawing upon various sources of data. In Section 7.2, we provided quantitative support by showcasing user statistics, demonstrating the substantial user engagement and interest in CPM Remote. Furthermore, in Section 7.3, we presented the qualitative aspects of usability through user studies, presenting the practicality and user-friendliness of the system. The examination of technology acceptance in Section 7.4 further reinforced the viability of the remote access solution by investigating its acceptance and appropriateness to users. Our discussion of key findings in Section 7.5 elaborated the data and insights from these sections, ultimately leading to the conclusion that the goal of providing worldwide access to CAV development through remote access was indeed realized. The combined evidence from user statistics, usability studies, and technology acceptance assessments strongly reinforces the overarching conclusion that confirms the success of the CPM Remote Project in accomplishing its goals.

Chapter **8**

Summary and Future Work

8.1 Conclusion

Small-scale testbeds have proven to be valuable for research and development in the domain of connected and automated vehicles. This thesis focused on addressing the accessibility challenges associated with these testbeds. A comprehensive literature review discussed various approaches to improve the accessibility of small-scale testbeds and concluded that remote access is the most convenient solution from a user perspective. In response to these challenges, CPM Remote was developed to provide direct, real-time access to our small-scale testbed, the CPM Lab. Recognizing that simply offering remote access might not fully engage users, we developed two applications: CPM Olympics and CPM Academy. CPM Olympics is an annual competition aimed at researchers, presenting tasks that mirror real-world challenges, while CPM Academy is an educational tool that guides users through the different aspects and functionalities of the CPM environment with a didactic approach.

The technical implementation of the platform and its applications was achieved using the state-of-the-art MEAN stack, allowing integration into a browser-based interface. Over three years, a team of 21 developers wrote more than 148,997 lines of code across seven repositories under the author's supervision. The project management was streamlined using the agile software engineering framework Scrum. Additionally, to foster a more modular software architecture, two libraries, CPM Common and CPM Routing, were implemented. These provide an abstraction layer for scenario definitions, facilitating more convenient application development in the future. Ensuring the robustness and reliability of CPM Remote was a crucial aspect of this work. The thesis detailed the extensive testing measures in place, such as Unit Tests, Integration Tests, and End-to-end Tests. The testing approach evolved over time, shifting from a focus on unit tests to covering all layers of testing. This comprehensive testing strategy ensured the platform's effectiveness across different browsers and user scenarios.

The platform's effectiveness was evaluated through several methods. Usage statistics in the first year showed a large user base (461) and over 5700 page visits, indicating high engagement. User studies conducted after each iteration of CPM Olympics and CPM Academy provided valuable feedback for continuous improvement. A comprehensive user study demonstrated the usability of CPM Remote, with a significant majority of participants favoring remote access for its flexibility. The overall technology acceptance of CPM Remote was also investigated using the UTAUT2 model, which showed general acceptance of this approach and identified key factors influencing user acceptance. This thesis aimed to show how CPM Remote provides accessibility to a small-scale testbed, contributing to the field of CAVs through technical innovation and user-focused applications for education and research.

8.2 Future Work

Frameworks such as CPM Remote are always in a state of ongoing development and improvement. There is a continuous need to refine aspects like user experience, the range of features, and overall performance. After reaching a notable level of quality with CPM Remote, our focus is now evolving to encompass wider goals. This shift in focus includes a significant emphasis on enhancing the visibility and understanding of the platform and its capabilities. Recognizing the value of CPM Remote, it's important for us to work towards its wider recognition. Consequently, we are dedicating efforts to foster awareness in both academic research and educational settings, aiming to maximize the platform's reach and impact.

In the research community, awareness can be increased through publications, presentations at conferences, and active participation in relevant workshops and symposiums. Additionally, forming collaborations with other research institutions and industry partners can provide opportunities to showcase the capabilities and benefits of CPM Remote. These collaborations can also offer valuable feedback and suggestions for further improvements and innovations.

In the education sector, integrating CPM Remote into university curricula can significantly boost its visibility. Developing course materials and workshops that utilize CPM Remote can offer students hands-on experience with the platform, thereby increasing its adoption and familiarity among the next generation of researchers and developers. Furthermore, outreach programs and partnerships with educational institutions can help in embedding the platform's usage in various academic programs.

Building on the integration of CPM Remote into university curricula, a key focus is to provide more accessible learning resources. This effort encompasses the creation of detailed tutorials, instructional videos, improved documentation, and Hello World examples specifically designed for the platform. By enriching the educational materials, the goal is to streamline the initial experience with CPM Remote, making it more approachable and engaging, particularly for individuals new to this field. These resources will not only support academic courses and workshops but also enhance self-directed learning and exploration of the platform. This strategy aligns with the broader objective of fostering widespread familiarity and ease of use among researchers and developers.

To further advance CPM Remote's development, adapting it to meet evolving educational standards is a promising direction. As new standards emerge, particularly those focused on managing online testbeds as dynamic and interactive learning resources [38], integrating CPM Remote with these frameworks could be highly beneficial. Specifically, conforming to the Lab as a Service (LaaS) model could make CPM Remote more relevant for educational purposes and also improve its compatibility within the digital education landscape.

Despite the completion of this thesis, the maintenance and improvement of CPM Remote, along with the CPM Lab, will continue. The second iteration of CPM Olympics has already started, showcasing the ongoing commitment to fostering research through practical and challenging tasks. Additionally, our educational courses will maintain the CPM Academy. Furthermore, we remain committed to actively promoting CPM Remote, aiming to further support and stimulate research and education in the domain of connected and automated vehicles.

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