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CPM Academy: A Remote Platform for Teaching Current Topics in Connected and Automated Vehicles*

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Abstract— **Bridging the gap between expensive real-world testing and inaccurate simulations, self-driving labs provide new opportunities for education and research in the field of connected and automated vehicles (CAVs). However, self-driving labs also have limited accessibility, requiring either travel or replication. To overcome these limitations, the Cyber-Physical Mobility (CPM) Lab at RWTH Aachen University offers publicly available remote access (CPM Remote). CPM Remote is a web framework that provides an easy introduction to CAVs and, together with the connection to the physical lab, a direct reference to reality. However, simply providing a platform is usually not enough to engage users. Therefore, we presented an application example called CPM Olympics, which was developed for researchers.**

In this paper, we present a second application example called CPM Academy. It is tailored for practice-oriented education and therefore designed and developed for students. The CPM Academy follows a didactic approach with various gamification elements and features a level-like structure built around a realistic scenario in the form of a package delivery service. In this way, the CPM Academy enables the study of various current topics in the context of CAVs, including control engineering, motion planning, and decision making. In addition, automated feedback and benchmarking help to engage students and improve the algorithms developed.

The CPM Academy is freely accessible and is already being used in a teaching course at RWTH Aachen University.

I. OPEN MATERIALS

Remote access to the CPM Lab is available at `www.cpm-remote.de`. This is where the CPM Academy as well as the CPM Olympics can be accessed for free.

II. INTRODUCTION

A. MOTIVATION

Self-driving labs for connected and automated vehicles (CAVs) bridge the gap between simulation and real-world testing. They are a valuable tool for researchers and lecturers alike due to their model-scale design, lower acquisition and maintenance costs, and ability to provide more accurate driving physics and hardware constraints than pure simulation environments. We presented our self-driving lab, the Cyber-Physical Mobility (CPM) Lab at RWTH Aachen University, in 2021 [1]. Since then, it has been continuously extended and used in various areas of education and research.

To make the CPM Lab available to everyone, regardless of location or financial means, we have created CPM Remote, remote access to the lab that was made publicly available in 2022 [2]. In addition to several quick start examples, we implemented an application in CPM Remote to provide a direct and fast start with a concrete set of tasks. This resulted in a competition called CPM Olympics [3]. This application is based on real-world datasets and was created for researchers to develop and quantitatively compare algorithms for CAVs. Accordingly, the CPM Olympics tasks are challenging and require state-of-the-art research. However, by isolating and decomposing the individual problems, a different target group can be addressed.

This paper presents a novel extension to CPM Remote in the form of an educational framework called CPM Academy. This application provides an opportunity for students to practice and improve their basic knowledge of algorithms and typical computer science problems, such as graph algorithms and combinatorial optimization problems. Furthermore, the provided content deals with several problems covering control engineering, motion planning, and decision making. Hands-on courses like the CPM Academy are often missing in the academic environment, where content is taught mainly from a theoretical point of view and without a practical connection to the real world. For example, in data structures and algorithms courses, various algorithms for computing shortest paths in graphs are taught, but the actual effect in a complex system can be difficult to grasp. With our application, students are able to test their implementation directly via CPM Remote and experience the impact of runtime or path optimizations live on the vehicles in the lab. To combine different common problems from control engineering and computer science in a meaningful way, we chose the scenario of a package delivery service. This scenario combines many problems, such as Bin Packing [4] or the Traveling Salesman Problem [5], directly in a real-world context and places a strong emphasis on motion planning and decision making because the resulting high-level controller must be designed to avoid collisions.

To increase the didactic value of the CPM Academy, we investigated the requirements arising from the educational domain and the students. This resulted in a framework that uses various gamification elements such as points, achievements, and levels to reinforce the motivation and learning success of the students. Furthermore, we implemented a feedback routine in the form of benchmarking to enable users to evaluate and improve their performance.

The resulting application is freely accessible via CPM Remote, providing a quick start with a low barrier to entry. The CPM Academy can be used by other lecturers and

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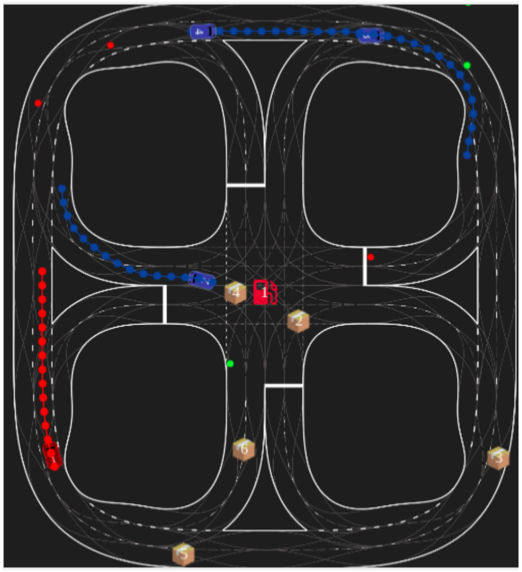


Fig. 1. Simulation view of level 7 of the CPM Academy. Blue vehicles are controlled by the user and red vehicles are passive road users. The overall goal is to collect and deliver the displayed packages.

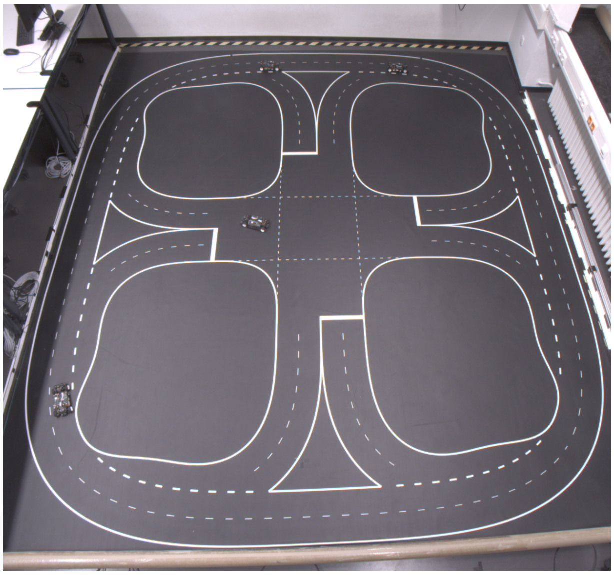


Fig. 2. CPM Lab view of level 7 of the CPM Academy at the same timestamp as in Figure 1.

private persons without further adjustments. However, the framework is customizable and can be extended by other scenarios for a different focus. We are currently actively using the CPM Academy in our 5th-semester undergraduate lab course. In our case, primarily computer science students participate in this course, but its content is also suitable for specializations in automation engineering and mechanical engineering. This can be influenced, for example, by a shift in focus from algorithm implementation to vehicle control guided by the respective supervisor.

B. *CONTRIBUTION OF THIS PAPER*

This paper describes the CPM Academy, an introductory course for the development of CAVs. This course is publicly available and already embedded in the bachelor program at RWTH Aachen University. Users can start immediately with the CPM Academy via CPM Remote, receive feedback at every development step, and have the opportunity to not only expand their programming skills but also gain insight into the field of CAVs. The special feature of this course is its direct relation to the CPM Lab and thus to reality. Figure 1 and 2 show a snapshot of a CPM Academy scenario, from different perspectives. Users are able to see their ideas turning into reality and experience real-world effects on their algorithms.

In this paper, we discuss the learning objectives and describe the requirements that lead to the presented concept. As we have already implemented this course three times, we are able to present and discuss a small study conducted with users. The feedback from each semester has been used to refine the presented concept.

C. *RELATED WORK*

In recent years, a growing number of self-driving labs have been established. Although they vary greatly in structure, purpose, and accessibility, they generally have concrete application areas in the context of education and research. This section presents labs that have developed an educational application in domains similar to the CPM Lab.

Duckietown [6] is a self-driving lab that started as an open-source project at the Massachusetts Institute of Technology in 2016. It features a playful design and self-driving vehicles (Duckiebots) that navigate through Duckietown, the model city environment consisting of streets, intersections, and traffic signs. Although the application area has some similarities to the CPM Lab, Duckietown focuses on computer vision and perception, while the CPM Lab focuses on motion planning and decision making of CAVs. Duckietown does not offer remote access to the physical lab, but hardware can be purchased, with various kits ranging from $430 to $10,000. This hardware is also needed to set up the Duckietown Massive Online Open Course (MOOC) [7], which is freely available on the web. The course focuses on computer vision, object recognition, and localization. Several universities such as the Université de Montréal [8], ETH Zurich [9], and the Toyota Technological Institute in Chicago have adopted this course. This course already enabled more than 700 students from 10 countries to participate in a Duckietown lab. Several studies conducted in Duckietown courses have confirmed the educational value of the self-driving lab. For example, Tani et al. [10] found that using Duckietown in their course with 27 participants increased student engagement and collaboration, as well as an independent work ethic.

Another self-driving lab that has some overlap with the CPM Lab is the Scaled Smart City of the University of Delaware (IDS3C) [11]. IDS3C replicates a real-world smart city, focusing on vehicle-to-everything communication and energy use. This lab is also embedded in their educational courses as it provides hands-on experience in CAVs and incorporates current research [12]. Duckietown and IDS3C demonstrate the demand and acceptance for this type of course. However, the course structure differs depending on the accessibility of the lab. While Duckietown and IDS3C require travel or replication, the following lab provides remote access.

The Robotarium [13] is a robotics lab at the Georgia Institute of Technology. Although it focuses on a different domain than the CPM Lab, it has similarities in terms of accessibility. Both labs implement remote access. While the CPM Lab uses a fully web-based solution, the Robotarium requires a local installation.

Like Duckietown, the Robotarium is already actively used in education. The Georgia Institute of Technology offers several courses based on the Robotarium, such as Cyber-Physical Design and Analysis [13]. Several other universities also use the Robotarium in their courses, such as the Université Paris-Saclay in a course on ”Control of Multiagent Systems for the Implementation of Formation Algorithms”. However, the Robotarium itself does not offer any courses on its website, only some tutorials explaining how to control the robots and how to implement two swarming algorithms.

Courses based on the Robotarium show an exemplary realization with web-based access to a remote lab. However, these courses are limited to introductory tutorials and lecturers must design their courses. Additionally, the performance of simulations can be affected by users’ hardware. CPM Remote offers an alternative solution by enabling users to conduct experiments on its servers, thereby allowing for the use of low-end devices for development purposes. Moreover, the CPM Academy is designed to provide lecturers with a user-friendly course framework that requires no customization. Nonetheless, the modular structure of CPM Remote allows for customization of the course content.

In our previous work, we introduced the CPM Olympics, which used the CPM Remote framework to host a motion planning competition for researchers. The CPM Academy covers similar topics such as decision making, motion planning, and control engineering but with reduced complexity and a more didactic approach as it is targeted towards students.

Therefore, the concept presented in this paper is derived from the requirements of the new target group. In the next section, we will first characterize this target group and present the structural design. Subsequently, in section IV, we discuss the content of our course and present the feedback we offer to the students in section V. Finally, we evaluate our approach in section VI and summarize our findings in section VII.

III. TARGET GROUP AND STRUCTURAL DESIGN

A. TARGET GROUP

With the expansion of CPM Remote to include an educational application, the target group changes accordingly. During the concept development phase, we characterized the target group in detail. We are targeting students in the last third of their bachelor studies. This is because we require basic knowledge in several areas, including a foundation in algorithms and data structures, as well as knowledge of the most common problems in control engineering and computer science. In addition, students in the 5th and 6th semesters have learned the concepts of object-oriented programming and ideally already have experience with C++, which we use in our application. Since our course is designed for one semester and students take other courses in parallel, there are limitations to the scope of our content. Therefore, the individual work packages and learning objectives must be adapted to these underlying constraints.

In addition to the content and structural requirements, there are also requirements for the didactic structure. Clearly defined learning objectives must be formulated so that students understand what they are expected to learn and how they will be assessed. In addition, students need feedback after each work package to identify areas where they need to improve and to understand how to progress in the course. Since we want to keep students interested in our course and motivated to continue working on assignments, our learning materials are designed to be engaging and interactive. Gamification, or the use of game-like elements in non-game contexts, can be a powerful tool for increasing engagement and motivation in education [14], [15], [16]. The combination of these requirements leads to the concept presented in the next section.

B. STRUCTURAL DESIGN

For our application, we chose the scenario of a package delivery service because it can be effectively structured in several work units that build on each other. In addition, this scenario is the focus of a wide range of research [17], [18], [19] and can lead to an arbitrary number of problems that can be covered in the CPM Academy, such as the TSP, Bin Packing, or motion planning. In the next section, we provide a detailed description of the problems we chose for our course.

The number of problems that can be covered depends on the length of the course. Since the CPM Academy is mainly designed for universities and should be completed within one semester, its structure is aligned with the structure of a semester. A semester consists of six months with a two-month exam period. After deducting four weeks of lecture-free period during the semester, one week of familiarization before the CPM Academy, and two weeks of wrap-up after the Academy, there are about nine weeks left. Since iterative workflows are supposed to lead to promising results [20], we have divided our content into nine equally time-consuming work packages. These work packages are complex enough to divide the work among a group. Hence, the number of participants per group should be adjusted depending on the number of credits assigned to this course.

We model the work packages as *levels* to leverage positive gamification effects. Levels are standard elements in many games and are considered by most experts to be an integral part of gamification [21]. A level can be repeated arbitrarily often to enable students to improve their solutions. With the completion of one level, the subsequent level is unlocked. If the quality of a solution is particularly high, two subsequent levels are unlocked. This implements the gamification element of *progression*, which encourages student engagement.

To facilitate the introduction to the CPM Academy and to demonstrate the use of our framework, we provide a sample project to get started. Only minimal changes to the project are required to solve the first level. This can give students an early sense of accomplishment and prevent them from being frustrated by a high barrier to entry.

The quality of their solution is determined by the benchmarking of each level. We implement the benchmarking in the form of *scores*, *achievements*, and *stars*, all of which are typical gamification elements [21]. Our feedback consists of achievements, which enforce a minimum quality of the solution (required to pass the level), and stars, which evaluate the solution according to various metrics. These two components are then used to determine zero to three stars, which graphically represent the quality of the solution.

Finally, we use another gamification element in the form of a *story* to connect all the individual levels. According to [21], stories can also promote student engagement. Hence, we designed a story that describes a start-up company that wants to offer an express delivery service and is growing step by step while encountering several issues.

We have implemented the CPM Academy with the CPM Routing library, a new framework that simulates the levels and computes the score. For this purpose, the library which was originally developed for the CPM Olympics has been refactored and extended with new functions and interfaces. This updated framework can also be used to create custom courses with new content.

IV. LEVEL DESIGN

This section presents the implementation of the concept just described. Furthermore, the specific learning content and goals for each level are discussed. The level design aims to present the user with a new problem at each level, which can be solved with algorithms taught in undergraduate courses. Each level contains an additional challenge described by an introductory text and a concrete task. In addition, advice is given on what needs to be done before working on a level, such as implementing a new interface or researching a problem. In case of difficulties, while working on the level, we offer a collection of hidden hints that the user can reveal. Levels are designed as follows:

Level 1 introduces the user to CPM Remote. The provided code frame is explained and the different ways to control the vehicles are presented. The task is simple and can be solved with the example project, but the main focus is to get familiar with the code structure and the framework.

Level 2 already expects a working collision detection and a simple approach for collision avoidance. This is required to run the experiments in the CPM Lab starting from this level. The user is free to choose one or both of the presented approaches: Collision avoidance by braking or by swerving. Since the structure of CPM Routing allows querying all planned vehicle positions several seconds in advance, priority-based avoidance is recommended [22]. The goal of this level is to ensure that collisions between the user's vehicles do not occur and that the user understands the importance of decision making and motion planning.

Level 3 adds system-controlled vehicles as traffic participants. The user must accept the vehicles as passive agents in the algorithm and avoid collisions without being able to influence their routes [23]. This level is intended to improve collision avoidance and testing with third-party vehicles whose routes are unknown.

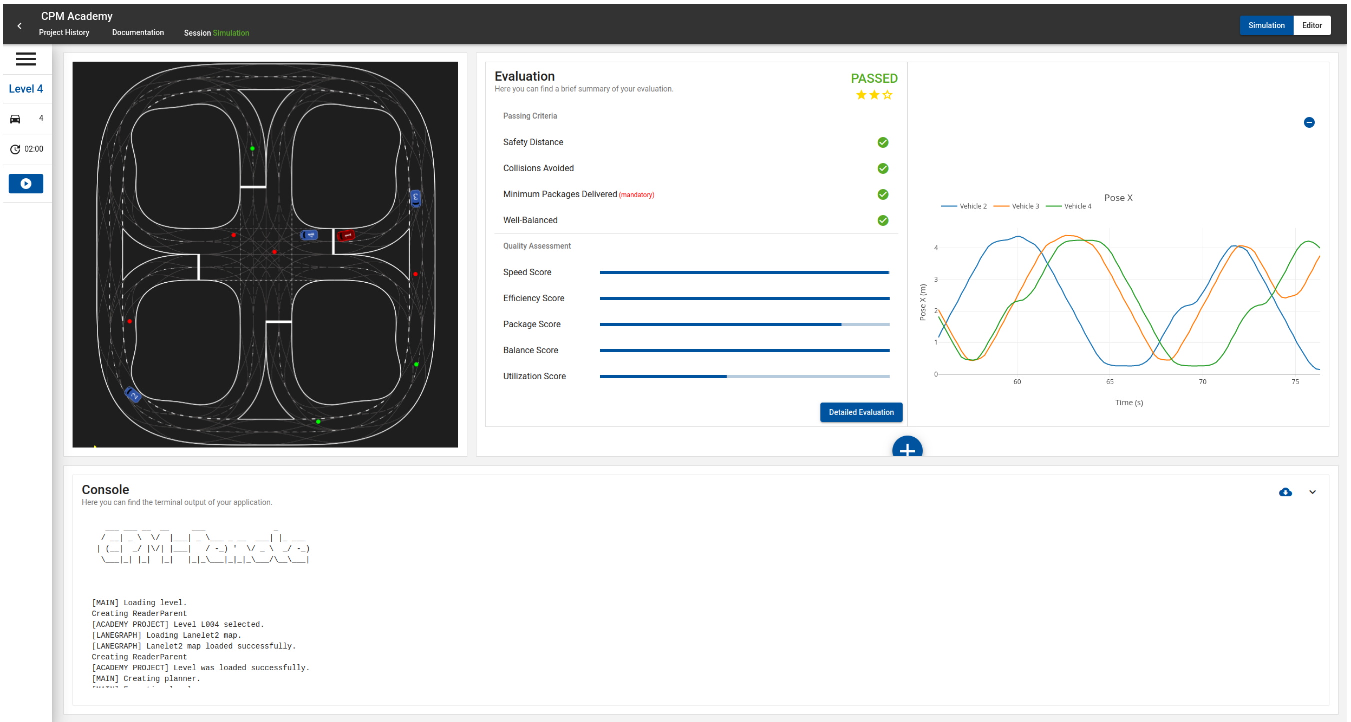
Level 4 begins with the actual development of the package delivery service. Just like in the real world, packages need to be picked up and delivered. This offers significant potential for optimization. First, users must decide how to distribute packages among vehicles. Second, the order in which the packages are delivered must be determined for each vehicle. This task is an instance of the Traveling Salesman Problem (TSP), a combinatorial optimization problem in theoretical computer science. Since the target positions are announced at runtime, it is actually a modification of the TSP, namely Multiple Online TSP [5]. Like the original TSP, this problem is NP-hard, so the optimal solution cannot be efficiently determined at runtime. Therefore, users must find an appropriate heuristic to approximate the complex problem.

Level 5 increases the number of generated packages. Thus, more efficient motion planning and picking up multiple packages at once is required to handle the increased amount of packages. The previously implemented heuristics are challenged more strongly at this level. Therefore, better heuristics have to be developed. The goal of this level is to experience the impact of an improved approach on the overall system in a realistic context.

Level 6 takes a real-world constraint into consideration. Both weight and physical dimensions must now be considered when picking up a package. Since vehicles have limited storage space, considering package sizes and weights makes the package delivery service even more realistic. The resulting problem is an instance of Bin Packing, another optimization problem. Since the number of bins is fixed, the problem is an instance of the corresponding decision problem, which is NP-hard [4]. Furthermore, since packages are announced at runtime, the problem must be solved using an online algorithm. However, the proximity of the vehicle to a package must also be taken into account, which complicates the selection of the package. The goal is to implement an algorithm that finds a tradeoff between driving distance and optimal bin packing.

Level 7 takes energy consumption into account. Therefore, vehicles must stop at gas stations periodically to replenish their energy buffer. Figure 1 shows the gas station and the packages. This constraint requires an adaptation of the routing algorithm so that a refueling stop is made at appropriate times.

Level 8 presents users with a new challenge involving the profit generated by delivered packages and package priorities. A package's profit is determined by a random



Evaluation

Here you can find a brief summary of your evaluation.

PASSED ★★☆

Passing Criteria

- Safety Distance ✓
- Collisions Avoided ✓
- Minimum Packages Delivered (mandatory) ✓
- Well-Balanced ✓

Quality Assessment

- Speed Score
- Efficiency Score
- Package Score
- Balance Score
- Utilization Score

Console

Here you can find the terminal output of your application.

```
  ___ ___ __  __     ___               _
 / __| _ \  \/  |___| _ \___ _ __  ___| |_ ___
| (__|  _/ |\/| |___|   / -_) '  \/ _ \  _/ -_)
 \___|_| |_|  |_|   |_|_\___|_|_|_\___/\__\___|


[MAIN] Loading level.
Creating ReaderParent
[ACADEMY PROJECT] Level L004 selected.
[LANEGRAPH] Loading Lanelet2 map.
[LANEGRAPH] Lanelet2 map loaded successfully.
Creating ReaderParent
[ACADEMY PROJECT] Level was loaded successfully.
[MAIN] Creating planner.
```

Fig. 3. A screenshot of CPM Remote's simulation view. It includes a visualization, a console, graphs, tables, and a detailed evaluation of the experiment.

assignment to one of three discrete priority classes and the distance between the pickup and delivery points. The user must now prioritize higher-priced packages to achieve the highest possible profit at the end of the level.

Level 9 introduces deadlines for the delivery of packages. If a package is picked up but not delivered on time, it negatively affects the user's profit. Thus, an extension of the algorithm is needed that estimates the time for delivery of a package and thus decides whether the package should be accepted. This problem is an instance of online scheduling [24].

V. BENCHMARKING AND FEEDBACK

Each of the levels presented in section IV contains a customized benchmarking and feedback system. In the description of each level, all evaluation criteria are already disclosed so that the user can clearly understand which metrics will be used to evaluate the solution. We provide feedback to the users in two ways: During execution and upon completion of the level. As with all projects in CPM Remote, run-time feedback is available in the form of visualizations, freely configurable graphs, and tables. Figure 3 shows a screenshot of the CPM Remote web framework. The vehicles, planned destinations, and all simulation objects such as parcels and gas stations are visualized on the map. In addition, live data provided by the vehicles is processed and displayed graphically as charts and tables.

After an experiment is completed, a detailed evaluation is computed for each vehicle individually and for the experiment as a whole. This allows the individual statistics of each vehicle to be compared to each other and the overall level. In addition, all raw data is provided in a table and for download so that the exact values and the composition of the scores are transparent to the user. The computed score is immediately available to the user and saved for future reference, allowing the user to compare progress between two attempts at a level and determine if there has been any improvements.

An evaluation is divided into two parts. The first part consists of criteria that must be met to pass a level (achievements). The second part measures the quality of the solution (scores) and assigns different scores depending on the content of the level.

A. ACHIEVEMENTS

The following criteria are mandatory to pass a level and earn the first of three stars. Some were adopted from our CPM Olympics and represent basic requirements for participation in road traffic.

- **Collision Avoidance:** There shall be no collisions between user vehicles and other road users or static obstacles.
- **Safety Distance:** A minimum distance must be maintained between all road users. We have set this distance to 1.5m.
- **Delivered Packages:** There is a minimum number of packages that must be delivered at each level that contains packages (levels 4 to 9). The amount is different for each level and is determined by the level's specific constraints.
- **Balanced:** This criterion ensures that delivered packages are evenly distributed among all user vehicles.

It allows variations of up to 20%. This requires the user algorithm to compute an efficient distribution of packages to the vehicles.

In addition, to evaluate the solution qualitatively, we compute a set of scores, which are presented in the next section.

B. SCORES

The selected scores are intended to help identifying weaknesses in the algorithm and are therefore computed even if the pass criteria are not met. Unlike the CPM Olympics, the CPM Academy does not provide a reference solution, so user scores are computed in relation to the theoretically highest possible score.

- **Speed Score** compares the mean speed of the user vehicles to the maximum possible speed ($\frac{m}{s}$).
$$s_v = \frac{t_i}{t_{ref}} = t_i \frac{v_{max}}{s_{ref}}, \tag{1}$$
where, t_i is the vehicle's travel time and s_{ref} is the shortest route to the target.
- **Efficiency Score** rates the efficiency of the driven speed profiles based on the average acceleration to promote energy-efficient solutions:
$$s_e = \frac{a_{max}^2 - \bar{a}^2}{a_{max}^2}, \tag{2}$$
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 amount of packages occurring in the level:
$$s_p = \frac{n_{delivered}}{n_{generated}}. \tag{3}$$
- **Profit Score** replaces the package score in levels that assign a profit to packages. Furthermore, it determines the profit the user makes compared to the maximum possible profit:
$$s_p = \frac{\sum_{i=1}^{n_{delivered}} p_i}{\sum_{i=1}^{n_{generated}} p_i}. \tag{4}$$
- **Balance Score** determines how evenly the packages were distributed among the user's vehicles based on the variance of the delivered packages per vehicle:
$$\sigma_b^2 = \frac{1}{n_{vehicles}} \cdot \sum_{i=1}^{n_{vehicles}} (p_i - \mu_{packages})^2, \tag{5}$$
$$s_b = \frac{b_{allowed} - \sigma_b^2}{b_{allowed}}, \tag{6}$$
where p_i is the profit 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 at least one package in relation to the total time:
$$s_u = \frac{1}{n_{vehicles}} \cdot \sum_{i=1}^{n_{vehicles}} \frac{t_{busy}}{t_{idle}}. \tag{7}$$

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

$$s_t = \frac{1}{n_{scores}} \cdot \sum_{i=1}^{n_{scores}} w_i \cdot s_i. \tag{8}$$

In the current implementation, all scores are equally weighted. However, the weighting can be easily adjusted if a particular metric should be emphasized in other courses. The total score represents an individual evaluation between 0% and 100%, based on the best possible solution.

In addition, the total score results in zero to three stars. The number of stars directly depends on the total score: from 50% upwards and all criteria passed, the user receives one star, from 70% upwards the second star, and for solutions with a score above 90% also the third star.

VI. EVALUATION

The course, based on the concept of the CPM Academy in combination with the CPM Lab, is now in its 4th year [25]. Each year, at the end of the course, anonymous evaluations are conducted to improve the quality of the course. In addition to standard university questionnaires, we created customized surveys to examine specific questions and the acceptance of our online lab. In this chapter, we present our most recent small-scale study that examines the feasibility and acceptance of this course.

A. PARTICIPANTS

We conducted the study in a practical course for bachelor students of computer science at RWTH Aachen University, which we offered in the winter semester of 2022. A total of 33 students participated in the course, divided into 9 groups. Most of the students were in their fifth to seventh semester. All of the participants reported that they had previous experience with object-oriented programming languages, with 58% of the students reporting that they had between one and five years of experience. However, 83% of the students had no prior knowledge of automated driving and motion planning. While all participants were physically located near the lab, they accessed the lab remotely using CPM Remote.

B. RESULTS

In the final survey, 32 out of 33 students stated that the CPM Academy was a suitable platform to gain insight into the domain of CAVs and that they were able to improve their programming skills with the help of the CPM Academy. The description of the different levels and the structure of the CPM Academy were rated as ”good” to ”very good”. The overall concept was also rated ”good” to ”very good” by 95% of all students. However, it was also noted that the existing documentation could be improved. In addition, some students missed a C++ debugging tool within the online IDE provided by CPM Remote. Every year, we use feedback to improve the course.

VII. CONCLUSION

This paper extends CPM Remote with an application example that can be used in control engineering and computer science education and offers students the opportunity to apply theoretical knowledge in the field of CAVs.

In the first part of this paper, we identified the requirements for the development of the CPM Academy that emerged from the educational application domain. In particular, we focused on a didactic approach and presented gamification as a means to increase student motivation and learning success.

The second part deals with the concept of the CPM Academy, which was designed based on the previously identified requirements. We developed a game-like structure of sequential levels that are unlocked step by step. After a short introduction, each level presents the user with a new problem that can be solved using algorithms introduced in undergraduate courses.

Our automated feedback and benchmarking system provides customized feedback for each level. Due to the relevance of feedback in the classroom, a unique system was created using gamification to award students with scores and achievements based on various metrics.

As the course progressed, it became clear that the amount of support needed by each student group varied considerably. While some groups solved all nine levels almost independently, other groups needed help at a very early stage. Nevertheless, our small study showed that our application is very well suited for teaching topics in control engineering and computer science. Therefore, we will continue to employ, maintain, and enhance this course in our teaching. It's conceivable that we might introduce new levels with varying levels of difficulty or focus, catering to different use cases or majors.

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