Bridging Physical and Digital Traffic System Simulations with the Gulliver Test-Bed*

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Abstract. We propose a cyber-physical platform that combines road traffic simulation, network simulation, and physically simulated vehicles to facilitate extensive testing on various levels of vehicular systems. Our design integrates physical and digital vehicle simulation into a common development and testing environment. This paper describes the platform design and presents prototypical implementations that use Simulator of Urban Mobility (SUMO), TinyOS Simulator (TOSSIM), a 3D sensor simulation environment, and a test-bed of miniature vehicles called Gulliver. As a prototypical implementation, we demonstrate the development of cooperative applications, and by that we achieve: (a) a cyber-physical system that provides a common environment for physically and digitally simulated vehicles, (b) a platform to interface communication between physically and digitally simulated vehicles, and (c) the ability to tailor testing scenarios in which some system components are simulated digitally and some physically.

The suggested design provides flexibility, cost efficiency, and scalable testing opportunities for future vehicular systems. Furthermore, the proposed system is able to support novel steps towards intelligent transportation systems for smart cities.

1 Introduction

Modern vehicular systems require extensive testing to ensure the safety and reliability of active safety and driver assistance systems. New ideas and first concepts of new systems that rely heavily on data from the surroundings are not

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only time-consuming but also resource-intense with respect to testing equipment and proving grounds. Thus, designers of vehicular systems often use simulation tools for validating and testing systems behavior before carrying out the needed and often costly test-runs in proving grounds. Currently, universities and public research and engineering institutes are faced with the challenge to get access to testing ground facilities, and are most often out of the development and prototyping cycle. Therefore, we consider an inexpensive test-bed of miniature vehicles named Gulliver [18] for validating new ideas in vehicular systems. [1] In this paper, we present a cyber-physical platform that bridges between physical and digital simulations, such that a small set of physically simulated vehicles can coexist with a larger set of digitally simulated vehicles in a common testing environment. This enables simpler and faster development and testing of proof-of-concept prototypes, such as driver assistance mechanisms and traffic control, in addition to experiments of a larger scale, where traffic phenomena can be observed and investigated on physically simulated vehicles. We expect the proposed platform to influence the development and testing of full-scale vehicles in testing grounds used to validate purely digitally simulated results.

The physical simulation part uses the Gulliver platform, which is a test-bed of miniature vehicles that facilitates the validation of new ideas in vehicular systems. The miniature vehicles have on-board sensors and radio and are capable of autonomous driving. The vehicles can be remotely accessed to upload their routes and their movement through a route is traced and visualized. The network simulations are performed using TinyOS Simulator (TOSSIM), a discrete event simulation tool used in wireless sensor network simulations [15]. We use a microscopic traffic simulation tool, namely Simulator of Urban Mobility (SUMO) [11], for digital road traffic simulations. For digitally simulating raw sensor data, we use a 3D simulation environment described in [4]. Having the ability to bridge these physical and digital simulators provides a platform that can give researchers powerful tools for testing and evaluating new ideas. Fig. 1 depicts the proposed platform.

1.1 Related Work

Cyber-physical systems target varying areas from water distribution modeling [16], to medical applications [12], and data center performance and energy management [6], to name a few. Several works have studied digital vehicular systems by considering digital road traffic and network simulators [1, 2, 8, 21]. While these works can benefit from digital simulations before their physical deployment, the lack of physical validation in these works limits applications development to digital models of the physical world. Considering only a physical test-bed, as in [25], to demonstrate new ideas is often very complicated due to a number of constraints that one has to account for at the beginning of the development phase. We propose a way to simplify the development and testing process.

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[1] The Gulliver test-bed web-site is accessible via `http://www.gulliver-testbed.net/`

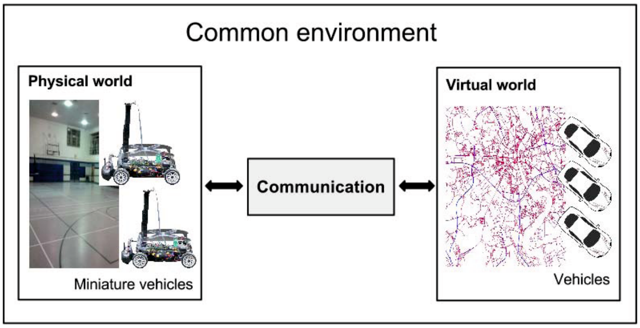

Fig. 1. Illustration of the Gulliver test-bed as a cyber-physical platform, where physical and virtual worlds communicate in a shared environment

The authors of [10] consider bridging digital and physical simulations, where full-scale vehicles are used on public roads. The work in [10] is limited to collecting and replaying empirical data traces for radio channel analysis. Furthermore, we note the costs of test ground facilities and their lack of availability for a broad range of research institutes. We are not the first to study combined digital and physical simulations, e.g., [9, 19, 20], we are the first to consider a platform in the context of experiments that consider traffic behavior, in addition to the simulation of the vehicular systems and networks.

1.2 Our Contribution

We propose a cyber-physical platform that brings together road traffic simulation, network simulation, and physically simulated miniature vehicles to facilitate rapid application development and extensive testing. The platform is based on the Gulliver test-bed in a way that integrates digitally and physically simulated miniature vehicles into a common environment, see Fig. 2.

In the proposed platform, the physical and the virtual worlds must be able to interact. The proposed platform includes the ability to generate maps so that physically and digitally simulated vehicles perceive the same surroundings. Moreover, a digital representation of each physically simulated vehicle is presented in the virtual world. This facilitates interaction among digitally and physically simulated vehicles. This is done by a communication middleware that facilities a bridge between simulators and the test-bed.

The result presented in this paper shows how to use the Gulliver test-bed for faster development and simpler testing of proof-of-concept prototypes and allow experiments that consider more vehicles than the test-bed's physically available vehicles. We review a number of case studies that exemplify the development process of different applications, such as autonomous driving, adaptive cruise control, crash avoidance, virtual traffic light and more. In each case study, we highlight our development steps and provide details to how we simplify the development environment (see Section 3).

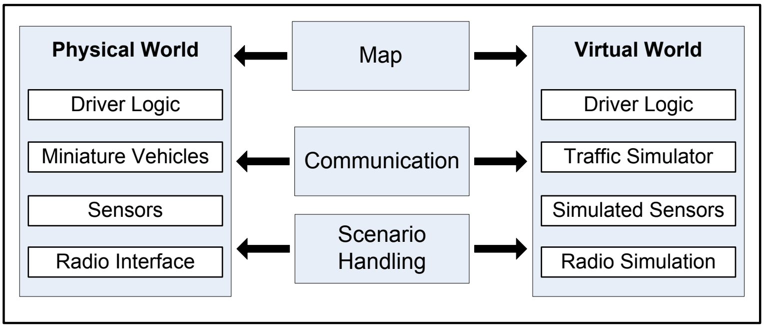

Fig. 2. Detailed logical overview of the proposed cyber-physical platform

2 The Gulliver Test-Bed

The tested includes a system of N vehicles, where each vehicle, $v_i \in V$, is represented by a digital vehicle, $v_i \in V_{ds}$, and possibly also by a physically simulated one, $v_i \in V_{ps}$. We note that each physically simulated vehicle, $v_i \in V_{ps}$, has also digital representation, $v_i \in V_{ds}$, in the virtual world.

2.1 Mapping and Consistency

We use a two-dimensional map for positioning. The map consists of roads that are defined as vectors (*segments*) interconnected via nodes to create a road network. We use the microscopic traffic tool, Simulator of Urban Mobility (SUMO) [11], which uses XML files to define scenarios and road maps. This feature is used to let each physically simulated vehicle, $v_p \in V_{ps}$, navigate through the same map like the simulated vehicles, $v_d \in V_{ds}$.

The first step is to define the map in a *Map Client*, which is provided by the Gulliver test-bed. The map client provides a Graphical User Interface (GUI) that allows construction of scenarios and road networks. Once the map is defined, the GUI automatically generates XML files, which are used directly by SUMO. Note that the GUI uploads the same map to every physically simulated vehicle. During simulation, SUMO has a representation of every physically simulated vehicle, $v_p \in V_P$, in the platform. This facilitates several benefits apart from a common map, such as an on-going overview of the simulation in SUMO-GUI and the possibility to create detailed logs.

2.2 Radio-Based Ranging for Indoor Localization

The miniature vehicles determine their position by filtering internal data, such as the distance traveled and the steering angle, vehicle's current heading provided by the magnetometer, and external data in the form of the distance measured to a predefined anchor using Kalman filter. The external data is provided by a high precision positioning system that uses PulsON 410 RCM as radio-based ranging for indoor localization. [2] It consists of three stationary positioning modules, which are placed in the test area. The distance between the modules is measured and fed to the map client, which defines the grid. The use of three modules provides the ability to define a 2-dimensional grid. A positioning module is then attached to every physically simulated vehicle. The modules communicate at 4.3 GHz and perform two-way time-of-flight ranging technique for obtaining their ranging measurements. Using these measurements the vehicles perform triangulation and receive their position. This approach provides precision in few centimeters, however it is subject to communication delays. Therefore, we have devised a dedicated medium access algorithm [23], and used internal input parameters from vehicle actuators to provide an estimation of vehicle position, e.g., dead reckoning [7]. We combine the benefits from both approaches, see [23] for details.

2.3 Miniature Vehicles for Physical Simulation

We use an open-source platform of miniature vehicles that consists of 1:8 and 1:10 scale miniature vehicles [18]. All vehicles are equipped with IR-distance and ultrasonic sensors for collision avoidance and some exhibit also monocular vision systems. High precision positioning system [23] provides vehicles with their absolute location on the map. The vehicles are fitted with several computer systems, namely an engine controller, a main board that connects and commands peripheral subsystems, MicaZ mote [22] that provides radio communications and either a mini-ITX based PC with an attached WiFi card or an ARM-based PandaBoard ES board. The mini-ITX based PC as well as the PandaBoard ES provide several convenient abilities, such as video streaming, remote upload of maps and binaries to the vehicle, and the possibility for a human driver to remotely control the vehicle through the use of a joystick. This data is sent over WiFi to a server program running on the vehicle.

Currently, the test-bed includes eight miniature vehicles that are available for physical simulation, but so far this number is limited mainly by the fact that the system is at its prototypical stage. The number of vehicles that is available for digital simulation is bounded mainly by memory and processing constraints of the simulation server.

2.4 Vehicles for Digitally Simulation

Digitally simulated vehicles enhance the test-bed scale by considering a greater number of vehicles than the physical ones. They also provide an ability to simplify the software development and testing processes, as the case studies show (Section 3). Some of the digital simulation is generated by the Simulator of Urban Mobility (SUMO) [11]. SUMO allows the use of a variety of variables for defining the driving quality. The system connects SUMO to a sensor networks

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[2] `http://www.timedomain.com/p400.php`

simulator, TinyOS Simulator (TOSSIM) [15], in order to facilitate radio environment simulation. In TOSSIM, a digitally simulated node is created for every vehicle in SUMO. The digitally simulated nodes hold properties such as position, speed, and map related information (*segment*). These properties are provided by SUMO via the TraCI interface [26], and are used in generating radio link gains among nodes in TOSSIM. By having vehicles being represented as nodes in TOSSIM, the vehicles' radio communication can be simulated. The access to variables, such as position and speed, together with radio communication ease the implementation of several driver assistance mechanisms within TOSSIM that affect traffic behavior in SUMO.

The digitally simulated vehicles can also be equipped with functionalities similar to the one in the physically simulated ones. The examples of functionalities that we consider are based on radio communication and implementations of driver assistance mechanisms, such as adaptive cruise control and collision avoidance. We note that the exact set of digitally simulated vehicles that have these abilities can be defined in a way that resembles testing of new technologies on the open road, where prototype vehicles coexist with legacy ones. Furthermore, some digitally simulated vehicles have the ability to provide raw sensor input data for camera, ultra sonic, infrared, single layer laser scanner sensor, to name a few.

2.5 Radio Communication

Inter-vehicle communication allows vehicles to exchange useful data among themselves. Radio communication is enabled via motes that are TinyOS portable, such MicaZ [22], which use direct sequence spread spectrum for transmitting data at 2.4 GHz. Our experiments sometime use Chameleon-MAC [13, 14], which employs the scheduled approach when accessing the communication medium, rather than the random access approach, such as Carrier Sense Multiple Access (CSMA). This choice is explained by CSMA's unbounded delay in high contention periods, which leads to high packet drop as shown in [5, 24]. Chameleon-MAC serves also as the bases for vehicles to synchronize via TDMA frame alignment, see the Grasshopper algorithm [17].

The common environment created by the proposed design promotes communication across the digital and the physical simulation domains. We implement a repeater to provide this functionality. The repeater captures messages from the radio environment and injects them into simulated vehicles within sender's range. Moreover, when a simulated vehicle is transmitting to a physically simulated vehicle, the message is injected into the repeater, which then broadcasts it over the radio.

2.6 Middleware for Communication Handling

To connect the different subsystems of the proposed design a middleware for *Communication Handler* (CM) was implemented, see Fig. 3. The communication handler maintains a link to every subsystem during a simulation run. It works

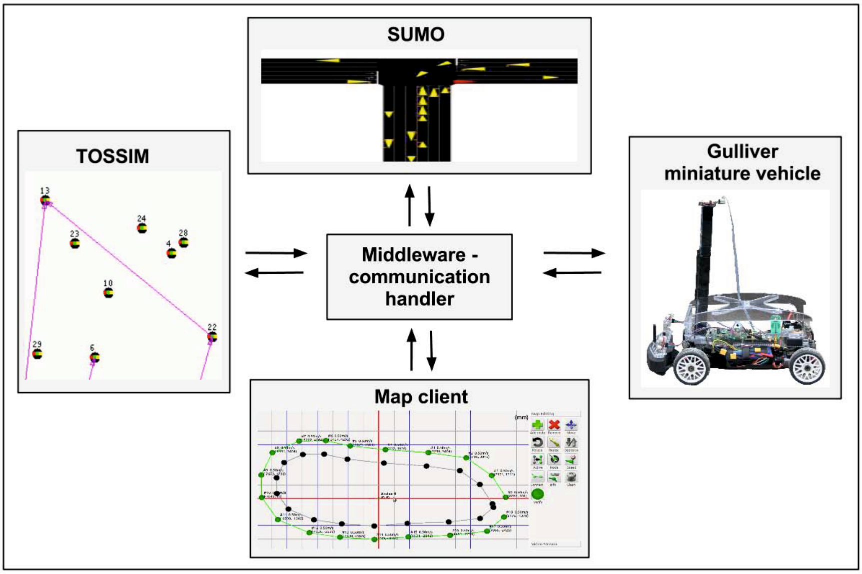

Fig. 3. The proposed platform design with arrows demonstrating communication within the system

like a packet forwarding router, where packets are sent based on a set of rules, e.g., different packets are to be sent to different destinations. The connections to different subsystems are set up in the following manner:

- CM's link with SUMO uses the traffic control interface TraCI [26], which allows control over SUMO's digitally simulated vehicles during simulation.
- CM's link to TOSSIM is based on the *serial-forwarder* (SF) extension, which enables bidirectional communication to nodes within the TOSSIM environment. In practice, the SF is a TCP server that delivers packets to nodes in TOSSIM based on their node ID. Communication in the other direction works in a similar way; broadcasted packets are sent to the SF and later received by CM.
- CM's link to the physically simulated vehicles uses a physical MicaZ mote connected, via USB, to the PC that is running the simulation. The MicaZ node works as a two-way repeater, sending packets received from the physical radio to CM, and packets from the CM to the physical radio, see the Broadcasting Unit box in Fig. 4.

We note that, at this platform prototyping stage, the communication loads and the speed of the physically simulated were kept low so that the digital simulator could keep up with the physical simulator.

3 Case Studies

We show how to simplify the design, development, and evaluation process by reviewing a number of applications that we developed for the Gulliver test-bed. The applications are developed using an iterative development process. In each iteration, a prototype is developed, tested in digital simulations and validated in the physical test-bed. Validation results are then used to improve the design functionalities in the next iteration starting with digital simulations. This cyclic prototype improvement is facilitated by having a bridge between digital and physical simulations.[3]

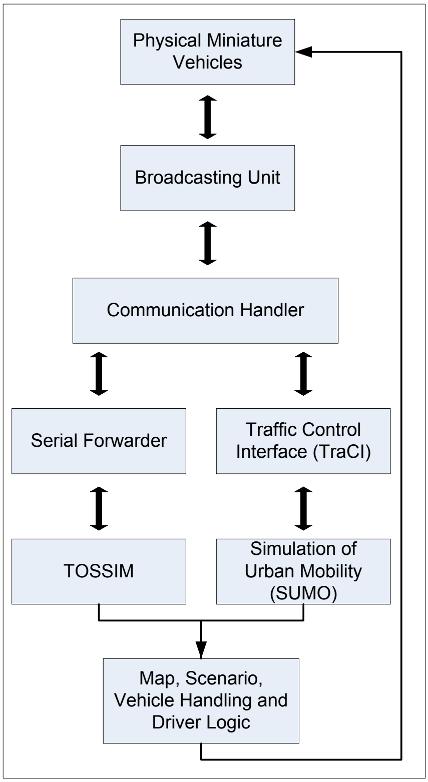

Fig. 4. Block diagram of communication between different systems components within the platform

3.1 Autonomous Driving

We consider vehicles that run applications for vision and sensor-based lane following. During operation, vehicles determine their deviation from their respective lane markings using feature detection and extraction algorithms. The algorithms are developed and evaluated in the virtualized environment, see Fig. 5, before they are integrated and validated in the physical test-bed.

3.2 Adaptive Cruise Control

This application adjusts the vehicle's cruising speed by monitoring and maintaining a safety distance to the vehicle in front. We study a (cooperative) adaptive cruise control (ACC) application that uses direct and indirect sensing information. In the case of direct sensing, a pair of ultrasonic distance sensors mounted at the front of each vehicle provides an estimated distance to the vehicle ahead. Indirect sensing uses a network protocol that frequently reports the locations of nearby vehicles. Each sensing channel is iteratively and independently tested via digital simulations, and then crossed over to the physical test-bed for validation.

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[3] See demonstration videos via `http://www.chalmers.se/hosted/gulliver-en/documents`

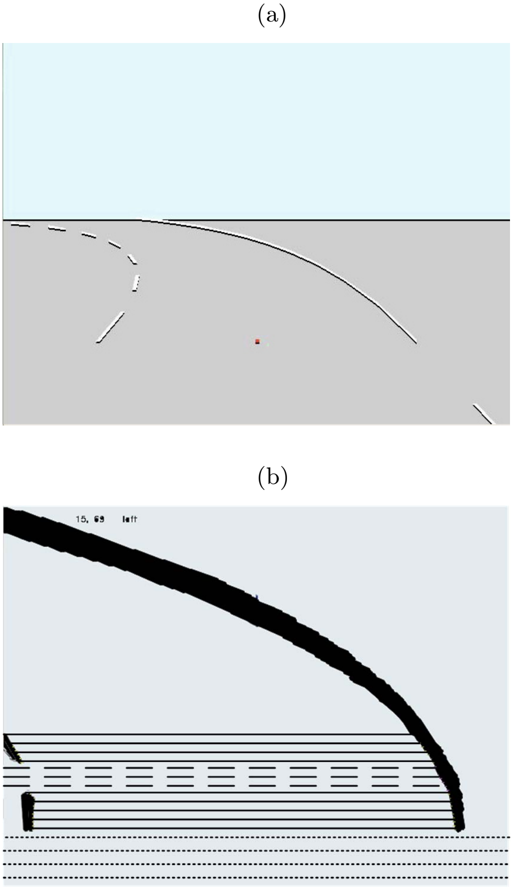


Fig. 5. Vision based approach is used to detect lane markings. (a) The input data is retrieved directly from the 3D simulation environment [4] by the virtual camera. (b) Based on virtual camera data input, lane detection algorithms are developed and tested. The horizontal lines indicate whether both left and right lane markings are detected (solid), one lane marking is detected (dashed), or none is detected (dotted).

The use of direct sensing allows the control loop to retrieve measurements within nearly constant and short delays, but with limited sensing range. The indirect sensing approach provides the control loop with longer and wider range of all nearby vehicles. However, the use of a network protocol implicates longer delays and communication interferences. We combine the benefits of direct and indirect sensing by joining the two approaches under one control loop, and use the test-bed for validation, see Fig. 6.

This case study presents the ability to independently test application components. This allows parallel validations before their integration. A sequence diagram illustrating the development and testing process of ACC is shown in

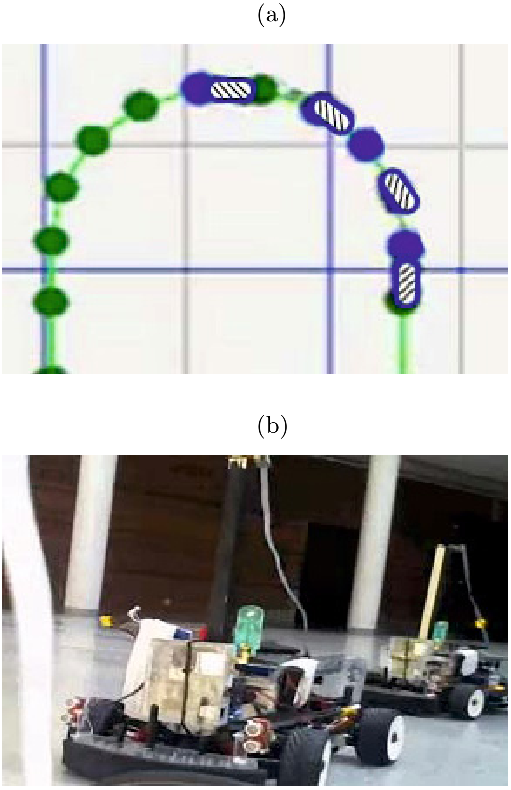


Fig. 6. (a) Map part of the application is showing physically simulated vehicles that travel on a curve while maintaining a safety distance to vehicle ahead using the developed adaptive cruise control application. (b) Rear view of leading vehicle showing trailing vehicles maintaining a safety distance.

Fig. 7. The development and testing of the application was simplified by having the possibility to bridge between digital and physical simulations.

3.3 Crash Avoidance

Testing active safety applications in non-destructive settings is crucial for the development of vehicular safety systems. We consider such experimentations using mixed approaches for digital and physical simulations. We develop a test scenario where digital and physical vehicles travel in an arena that has digital obstacles on the road. The vehicles are equipped with digitally simulated infrared distance sensors that provide the vehicles with the detection data.

In this setting, both digitally and physically simulated vehicles are allowed to drive and apply maneuvering techniques around (digital) obstacles. This setting allows crash avoidance applications that execute on the physical vehicles to be validated without the risk of crashing. Furthermore, the iterative development of

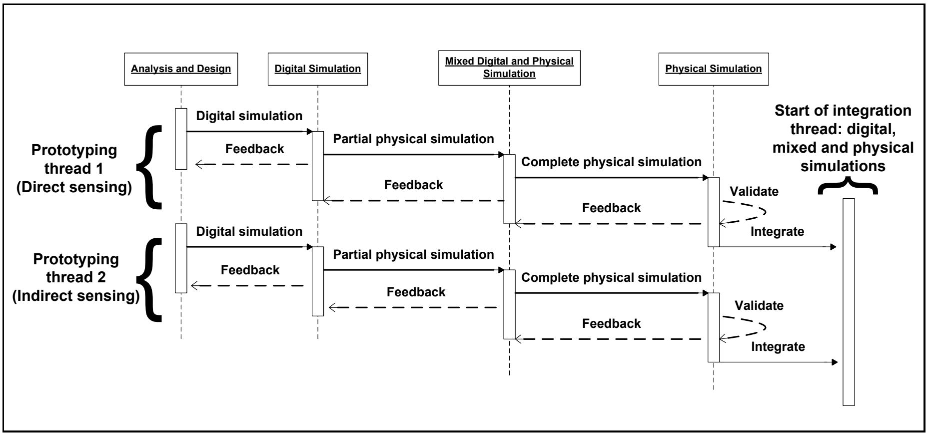


Fig. 7. Sequence diagram of ACC. Both direct and indirect sensing are developed and crossed over from digital to physical simulations in parallel by the protoyping threads. The validation feedback loops can be used for making sure that the design assumptions are covered when testing the application via digital, mixed and physical simulations. The integration thread combines both protyping threads and evaluates the resulting application.

crash avoidance applications via digital simulations, and the ability to selectively move components to the physical test-bed according to test-case needs provide flexibility and safety in validating the application.

3.4 Virtual Traffic Light

This case study considers an application for coordinated intersection crossing. The coordination is made via a distributed scheduler that the vehicles communicate over the radio. We design the scheduler such that at any time, only one direction can have a green light. This is required to prevent vehicles from crashing. Before the application can be tested, we need to validate the behavior of the network protocol. Therefore, our development process includes two parts: one where only the network protocol is validated, and the other where the system is validated. This implies that we need to have a mixed phase where we combine both physical and digital simulations under one test case.

The Gulliver test-bed allowed the application to be developed in stages. We started with a fully digital phase, where the application is only tested via digital simulations. Before validating the application in the physical test-bed, we had to validate the network protocol the delivers to the vehicles information about the traffic light state. Therefore, the next step was to use a mixed digital and physical phase that validates the network protocol of the virtual traffic light via physical simulations. In this test, the vehicle's position was given by the digital representation of the vehicles in the simulator. We then installed the entire application on the physical vehicles, but disabled the vehicle's own mobility. This phase allowed us to validate the vehicle's behavior before the full physical simulation of the application (with autonomous vehicles), see Fig. 8.

This case study demonstrates the ability and usefulness of approaches that mix digital and physical simulation components. This becomes beneficial when there is a need to validate component, such as the virtual traffic light protocol, that are suppose to prevent vehicles from crashing. By considering a limited set of physical components, we were able to exclude such risks before the application was fully used in the test-bed.

3.5 Emerging Traffic Patterns and Phenomena

A number of real-world traffic phenomena, such as shock-waves and stop-and-go traffic jams, can appear when the road contention is very high. The

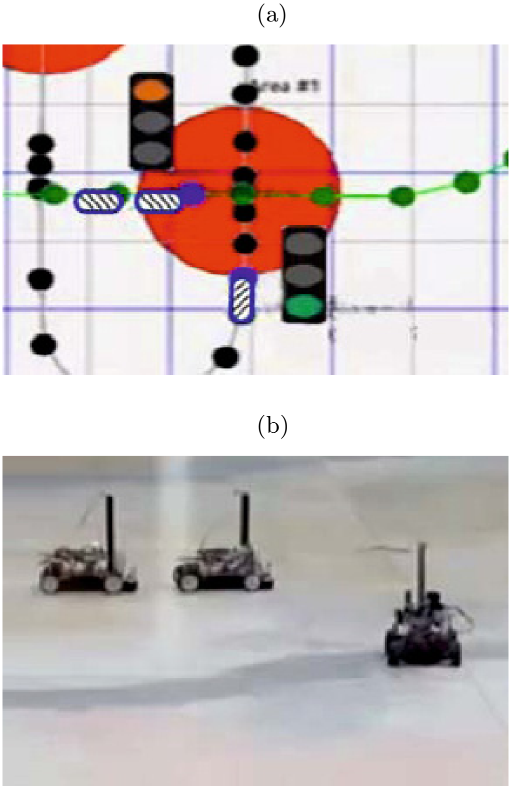
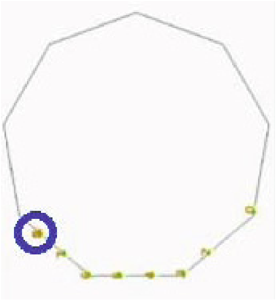


Fig. 8. The virtual traffic light application running on the test-bed. (a) The map client monitors and displays the current position of vehicles as they approach the intersection. (b) The miniature vehicle at the intersection as seen on test-bed.

(a)



(b)

Fig. 9. (a) Digital vehicles traveling counter-clockwise on a single lane road, where the last (circled) vehicle is physically simulated. (b) The physically simulated vehicle is imposed to move according to the stop-and-go phenomenon in test-bed.

investigation of such phenomena is imperative when examining applications, such as the virtual traffic light and cooperative cruise control, that have safety-critical and contention concerns. For example, a shock-wave can surprise the driver and impose an emergency brake. Cooperative cruise control mechanisms can assist with meditating the shock-wave propagation.

Thus far, such phenomena were studied via microscopic (digital) analytical simulation tools such as SUMO [3]. One may aim to produce such phenomena with miniature vehicles. Such experiments could be costly and complicated because they will involve hundreds of miniature vehicles. Gulliver's approach overcomes this difficulty by taking a mixed approach for physical and digital simulation, where some of the simulated vehicles are physically present in the test-bed, while a large number of vehicles are digitally simulated.

We consider both digital and physical simulation of vehicles. A physically simulated vehicle can be either autonomous or controlled via the digital simulator. The experiment demonstrates this ability using a circular single lane road, where a physically simulated vehicle is controlled by its digital image. The physically simulated vehicle follows a number of digitally simulated vehicles that travel counter-clockwise, see Fig. 9.

As the contention on the road created by the digitally simulated vehicles increases, the physically simulated vehicle is imposed to move according to the produced stop-and-go phenomenon. We note that a number of autonomous physically simulated vehicles can follow the controlled one and move according to the stop-and-go phenomenon.

This case study shows that the mixed physical and digital approach can cause physically simulated vehicles to move according to the digitally generated traffic phenomenon. Given this ability, we can then use physically simulated vehicles to investigate the behavior of safety critical applications with traffic phenomena by considering simple and inexpensive testing environment.

4 Conclusions

Vehicular systems require extensive testing in the digital domain before they are validated with physical experiments. This paper proposed an inexpensive cyber-physical platform that bridges digital and physical simulations in order to simplify the development and testing environment of vehicular systems. The proposed platform facilitates iterative testing, where lessons learned from each iteration are used to improve the application starting from digital simulations.

By reviewing case studies of applications that were developed using the proposed platform, we were able to demonstrate our mixed digital and physical simulation approach. According to the application needs, the platform allows some components to be digital and others physical. For example, applications of high speed object avoidance can be tested in a mixed simulation, where physically simulated vehicles maneuvers around objects that are digitally simulated. This mixed approach is extended to demonstrate that real world traffic phenomena, such as shock-waves and stop-and-go traffic jams, can be generated using mixed digital and physically simulated vehicles that navigate through the same map. This facilitates the investigation of safety critical applications that are related to collision avoidance in the context of different traffic phenomena. One may also add intelligent balloon vehicles to the test-bed to validate safety critical applications. Outcomes learned from using miniature vehicles can then be used with full-scale vehicles on testing grounds.

The designed platform opens new possibilities for validating new ideas for traffic situations in complex systems. Gulliver long-term goals include decreasing the gap between full-size and miniature scale vehicles in order to provide an even more flexible and low-cost test-bed.

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