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SVEA: an experimental testbed for evaluating V2X use-cases

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Abstract— **In this paper, we present a hardware and software testbed designed for evaluating vehicle-to-everything (V2X) use-cases. From platooning to remote driving, there are many proposals to use V2X communication to solve sustainability or safety issues in transport networks. However, researchers mostly evaluate their proposals in only simulation studies, since setting up real, full-scale field tests can often be prohibitively expensive or time-consuming. The open-sourced Small Vehicles for Autonomy (SVEA) testbed is built around a communication software stack and a 1/10th-scale automated vehicle platform suitable for both cost-effective and time-efficient experimentation with V2X use-cases. The testbed is designed to support evaluation in a wide range of conditions, such as heterogeneous networks or vehicle fleets. To illustrate the suitability of the SVEA testbed for studying V2X use-cases, we detail and implement three use-cases: platooning, adaptive speed regulation from a road-side infrastructure camera, and remote-driving by a human operator sitting in a control tower. Finally, we conclude the paper with a discussion on the use of the platform so far and future development plans.**

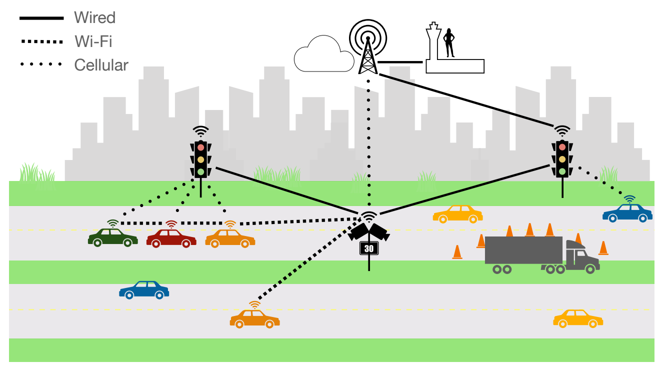

Fig. 1. An example of a heterogeneous V2X context that the SVEA testbed supports. The illustrated network consists of V2V, V2I, and V2N communication over wired, Wi-Fi, and cellular connections.

I. Introduction

Recently, automation efforts have vastly improved the safety and efficiency of individual vehicles. However, to improve the safety and efficiency of the overall transport network, vehicles will need to cooperate with other vehicles, road-side infrastructure, and network resources. Vehicles will need to utilize V2X communication networks. Currently, there is a wide variety of proposals using V2X communication to improve different aspects of transport networks. Notably, there are several proposals (e.g. [1]–[5]) using communication between groups of cooperating vehicles to form vehicle platoons, which can improve the safety, fuel-efficiency, and throughput of highways. Moreover, there are proposals (e.g. [6]–[8]) using a vehicle's network connection to allow remote human drivers to assist the vehicle during automation failure, improving the resilience and safety of transport networks.

In addition to platooning and remote driving, there are numerous solutions utilizing combinations of vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) communication. For example, researchers propose the use of V2V communication for making a to-be-overtaken vehicle transparent to the overtaking vehicle, allowing the overtaking vehicle to maneuver safely [9]. In [10], the authors use both V2V and V2I communication to minimize fuel consumption and emissions from vehicles approaching an intersection. There are several proposals utilizing purely V2I communication to minimize the queue length, overall fuel consumption, and traffic flow in intersections [11]–[13]. Outside of intersection applications, there are also road-side unit (RSU) solutions for automatic incident detection [14] to improve road safety and content streaming [15] to enable the dissemination of important content to driving vehicles. Furthermore, [16] combines V2V, V2I, and V2N communication into one architecture to support general incident event services. There are formulations that also include vehicle-to-pedestrian communication where vehicles communicate with the mobile phones of pedestrians. However, vehicle-to-pedestrian communication is not currently supported by the SVEA testbed; thus, we will leave it out of this paper.

Despite the potential of V2X communication, the majority of work done on V2X architecture design is only validated in simulation and not real hardware. Among the mentioned V2X proposals, researchers have evaluated [2], [3], [5], [9]–[12], [14], [15] in only simulation, while only [1], [4], [8], [13], [16] are evaluated on real hardware, meaning only around a third of the mentioned proposals have been tested in realistic conditions. We attribute this distribution to the fact that hardware experiments for V2X use-cases are currently prohibitively expensive and time-consuming.

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They typically involve several full-sized vehicles, a test track, and road-side infrastructure. Moreover, during initial field tests, researchers often find that use-cases validated only in simulation suffer from a sim-to-real gap. To address this sim-to-real gap from the simulation side, there are efforts to develop more realistic wireless communication simulators that emulate the uncertainties of wireless communication (e.g. [17], [18]). While these simulators offer the capabilities to test algorithms with more realistic communication conditions, the algorithms ultimately still need to be tested on real hardware. To address the sim-to-real gap from the hardware side, institutions around the world have developed inexpensive scaled-down vehicle platforms, which allow for initial evaluation of localization and control algorithms for applications such as racing [19]–[21]. Although there is still a gap between a scaled-down and a full-sized vehicle, scaled-down connected vehicles exhibit several similar challenges of full-sized connected vehicles that are not well represented in simulation, such as the integration of communication hardware, vehicle and communication modeling errors, and the simultaneous effects of realistic disturbances to communication, localization, and control. While the platforms presented in [19]–[21] enable experimentation for single vehicle use-cases, the software provided with these vehicle platforms do not support V2X experimentation, especially within heterogeneous communication networks, such as the one drawn in Fig. 1. Thus, we find it important to develop and release an inexpensive, scaled-down testbed that can be used to study V2X use-cases.

A. Contribution

The main contribution of this paper is an integrated testbed with both software for testing V2X use-cases within heterogeneous communication networks and hardware for evaluating the use-cases with a variety of real sensors and actuators. To the extent of the authors' knowledge, there are no open-source experiment testbeds that allow for the evaluation of V2X use-cases on inexpensive hardware. Explicitly, the contributions of this paper are as follows:

1) we present a robust communication software stack that enables V2X communication within heterogeneous communication networks,
2) we overview the design choices behind our vehicle platform that supports experimentation with V2X use cases,
3) we detail and implement three use-cases that demonstrate the use of the SVEA testbed for tasks that require V2V, V2I, and V2N communication.

The remainder of the paper is organized as follows. In Section II, we provide an overview of the SVEA testbed and elaborate on the design of both the software and hardware components. In Section III, we present use-cases that indicate how the SVEA testbed can be used to evaluate V2X architecture proposals. In Section IV, we present experimental results from implementing the three use-cases to elucidate the type of results that can be expected from the SVEA testbed. Finally, in Section V, we discuss the impact of the platform and future development plans.

II. SVEA Overview

The core components of the SVEA testbed are the V2X communication software stack and the vehicle platform. Similar to the now-deprecated software used in [16], our V2X communication software stack is designed to be general enough to support any peer-to-peer (P2P) communication that might be needed in V2X use-cases. Moreover, the software stack is developed to support heterogeneous networks consisting of wired, Wi-Fi, and cellular (4G, 5G, or beyond-5G) connections with a combination of the ITS-G5 (IEEE 802.11p) and C-V2X (3GPP) perspectives, since both will likely be utilized in the future [22]–[26]. The hardware is developed modularly to easily support wide varieties of embedded computers and sensor suites. Overall, the SVEA testbed is designed to support the development of automated driving systems under V2X communication and the construction of heterogeneous vehicle fleets. For more implementation details and resources, we refer the reader to the testbed's website: https://svea.eecs.kth.se.

A. V2X Communication Software

In this section, we provide an overview of our V2X software stack. Specifically, we focus on the establishment of V2X architectures, based on P2P communication, that provide real-time streaming of binary and video data over the internet. In terms of hardware, the only requirement is a module which provides internet access. This can be a wired, Wi-Fi, or cellular connection (4G, 5G, or beyond-5G). We depict the relationship between the V2X software stack and the hardware platform in Fig. 2. On the vehicle platform, our V2X software stack runs on the high-level computer and utilizes the wireless module to establish V2X communication.

Each device in a V2X architecture is treated as an internet-of-things device belonging to possibly different networks. We connect devices on different networks by using a central server deployed as a cloud service accessible to all devices; we refer to this central server as the signaling server. The signaling server is implemented using the WebSocket protocol, which is selected because it maintains full-duplex connections over TCP connections, which is necessary for configuring the V2X architecture on-demand, while ensuring the requests and responses are guaranteed to arrive. The signaling server has two main responsibilities: (1) identity management and (2) establishing P2P connections. Our implementation of the signaling server allows for devices to join the V2X network with a unique pseudonym, such as "SVEA1" or "RSU2". By using these pseudonyms, each vehicle, RSU, or other network resources is able to request a direct, P2P connection with each other.

To establish a P2P connection, two devices who want to communicate with each other go through the following procedure. First, using their respective pseudonyms, each of the devices message the signaling server with a connection

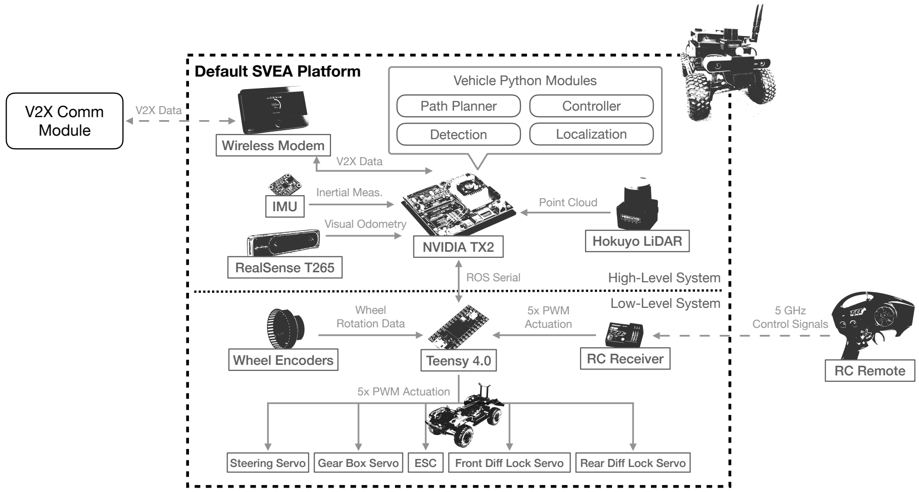

Fig. 2. An overview diagram of the different components that form the default configuration of the vehicle platform. We emphasize that the above configuration is a default configuration that works particularly well in indoor environments, due to the hardware design of the vehicle platform, the configuration (e.g. embedded computer, sensor suite, or wireless modem) can be easily changed.

request to the other device. The signaling server notifies each device of the connection request. Upon receiving a connection request, a device prepares a message containing its P2P parameters, such as its network transport addresses and media/data capabilities. Then, the signaling server facilitates an exchange of P2P parameters and Interactive Connectivity Establishment (ICE) [27] candidates between the two devices. Through this exchange, the devices are able to form the most direct P2P connection with each other, regardless of whether it is over wire, Wi-Fi, 4G, or 5G. Moreover, we have designed the software stack to be capable of publishing and subscribing to the local Robotic Operating System (ROS) [28] network onboard a device, connecting local ROS networks on vehicles, RSUs, and other networked devices to the overall V2X network through P2P connections.

Remark 2.1: The signaling server only facilitates the exchange of P2P parameters and ICE candidates, and does not handle transmission of the actual data between devices, one signaling server can easily support thousands of devices.

B. Vehicle Platform

In this section, we provide an overview of the vehicle platform in the SVEA testbed. Specifically, we focus on elaborating on the design decisions behind the different parts of the platform. As depicted in Fig. 2, the vehicle platform is split into two subsystems, a low-level system and a high-level system. The low-level system handles the distribution of power to the entire platform and implements actuation on the vehicle chassis. The high-level system manages communication, the sensor suite, and implements specified behaviors. The low-level system is purposefully set up to be static and agnostic to the high-level system. This means that the high-level functionality can be freely changed to support different applications or to emulate a heterogeneous vehicle fleet with minimal effect on the low-level system.

1) Low-Level Design: The vehicle platform is built on top of the Traxxas TRX-4 all wheel drive remote-controlled car. The TRX-4 is a “Crawler” vehicle that features a two-gear transmission and differential locks on each axle. Since the transmission can switch between a low and high gear ratio, the platform is able to both drive up to speeds as fast as 3.6 m/s and crawl at speeds as low as 0.3 m/s. This wide range of speeds (particularly the low speeds) is not attainable by other platforms built on the popular Traxxas Rally or Slash models, since these models are tailored specifically for driving as fast as possible in races. Thus, due to having slow speed options, the TRX-4 is more suitable than many other models to do slow maneuvers, such as parking [29]. Connected to the TRX-4 chassis is a Teensy 4.0 with a power-board shield that was custom designed for this platform. The Teensy 4.0 is an Arduino-compatible micro-controller that acts as a programmable information hub for low-level signals. We chose the Teensy due to its higher computational accuracy and processing power over traditional Arduino boards, which is necessary for implementing low-level controllers. As shown in the lower half of Fig. 2, the Teensy controls the steering servo, gear transmission, electronic speed controller (which controls the motor), and the differential locks. By varying the gear transmission and differential locks, the dynamic capability of the vehicle can be varied, providing another opportunity to make the vehicle fleet heterogeneous.

2) High-Level Design: The high-level system of the vehicle platform consists of a central computer (an NVIDIA TX2, by default), a sensor suite (an indoor driving suite, by default), and a cellular modem (4G, by default). All three of these component groups can be varied with minimal overhead due to the standards upheld by the low-level system and the communication software module. For example, in previous works the SVEA vehicle was equipped with a 4K camera and a 5G modem to support experiments on remote teleoperation [8]. To manage the high-level system, we have developed a Python-based software library that is designed to support the use of the vehicle platform in large-scale

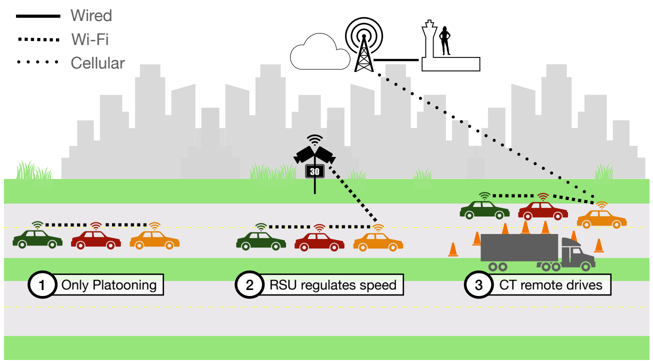

Fig. 3. We illustrate the three use-cases we will demonstrate on the SVEA testbed: (1) platoon formation control with Wi-Fi links between the vehicles, (2) RSU speed regulation with a Wi-Fi link between the platoon leader and the RSU, (3) teleoperation from a control tower (called CT in figure) with a 4G link between the control tower and the platoon leader.

experiments. The software design and paradigms deviate from the programming style prescribed by rospy, the official ROS python library, to instead emphasize object-oriented programming. This facilitates more re-use of code between different automated driving system implementations across heterogeneous vehicle fleets. For more details, we refer the reader to the repository linked on the platform's website.

III. SVEA V2X Use-Cases

In this section, we introduce three use-cases for the SVEA testbed, which are illustrated in Fig. 3. First, we present a platoon formation control use-case as a demonstration of V2V communication. Second, as a demonstration of V2I communication, we introduce a use-case where an RSU equipped with a camera regulates the speed of the platoon to the speed limit of the road segment that the camera supervises. Finally, as a demonstration of V2N communication, we detail a use-case where the platoon encounters a road block that is outside of its operational design domain and requires a human operator, who is connected over the cellular network, to teleoperate it around the road block to open road, where automated operation can resume.

A. (V2V) Platoon Formation Control

To showcase performing V2V communication with the SVEA testbed, we implement a cooperative car-following model for performing string-stable platoon formation control (illustrated in step 1 of Fig. 3). The model we will use for platoon formation and maintenance is introduced in [5], where authors prove the resulting control scheme's stability. For more technical details about the controller and its analysis, we refer the readers to [5]. In the presented cooperative control scheme, each vehicle i in the platoon communicates the spacing $s_i \in \mathbb{R}$, its speed $\dot{x}_i \in \mathbb{R}$, a specified minimum spacing η_i, the specified time headway τ_i, and its length l_i. Let x_i be the longitudinal position of the front bumper of vehicle i. Then, we define the spacing s_i to be $s_i := x_{i-1} - x_i - l_{i-1}$, where vehicle $i = 1$ is the leader of the platoon. We model the longitudinal dynamics of each vehicle i with

$$\ddot{x}_i = u_i + w_i,$$

where $u_i \in \mathbb{R}$ is the acceleration input of vehicle i and $w_i \in \mathbb{R}$ is an additive disturbance acting on the vehicle's acceleration. The dynamics of the leader is determined by a phantom vehicle p, which drives at a speed v_p, where the spacing in front of the platoon leader is $s_1 = x_p - x_1$ and $\dot{s}_1 = v_p - \dot{x}_1$. Practically, the phantom vehicle p can correspond to a vehicle that is driving in front of the platoon, though it is not necessary for there to be an actual vehicle in front of the platoon at all times. Then, based on [5], the longitudinal controller for each vehicle i is explicitly written as

$$\begin{aligned} u_i = k_{1,i}(s_i - \eta_i - \tau_i \dot{x}_i) + k_{2,i}\dot{s}_i + k_{3,i} \sum_{j \in \mathcal{N}_i^+} (\hat{\dot{x}}_j - \dot{x}_i) \\ + k_{4,i} \sum_{j \in \mathcal{N}_i^+} \sum_{k=j+1}^{i} (\hat{s}_k - \hat{\eta}_k - \tau_k \hat{\dot{x}}_k), \quad (1) \end{aligned}$$

where $\mathcal{N}_i^+$ is the set of vehicles in front of vehicle i that vehicle i is able to communicate with, and $k_{1,i}, k_{2,i}, k_{3,i}, k_{4,i}$ are tunable gains. $k_{1,i}$ is a constant time-headway gain, $k_{2,i}$ is a constant follow-the-leader gain, and $k_{3,i}, k_{4,i}$ are constant, positive communication gains. After each communicating vehicle broadcasts s_i, $\dot{x}_i$, η_i, τ_i, and l_i, then, using (1), we know what acceleration each vehicle in the platoon should implement in order to maintain stability within the platoon. Throughout the experiments, we will use our V2X communication module to communicate the information required for implementing the cooperative controller. Moreover, in the following two use-cases, we will continue to build off of this platooning use-case.

B. (V2I) Regulating the platoon with an RSU

In our V2I use-case, we implement a camera-equipped RSU that is placed on the side of the road to enforce adaptive speed limits. For brevity, we will not delve into the details of the design and motivation behind adaptive speed limits, however for an introduction into the potential benefits of adaptive speed limits, we refer the readers to [30]. In our case (illustrated in step 2 of Fig. 3), at time t when the RSU's camera sees the platoon passing by, the camera will register that the platoon has entered the road segment that it is regulating, and require the platoon to drive at the current speed limit v_s. In our implementation the RSU's camera will detect an ArUco marker on the platoon leader and form a P2P connection with the platoon leader. On reception of the new speed limit, the platoon leader will set the velocity of the phantom vehicle to $v_p = v_s$ and use its V2V connection with its followers to inform them of the new v_p.

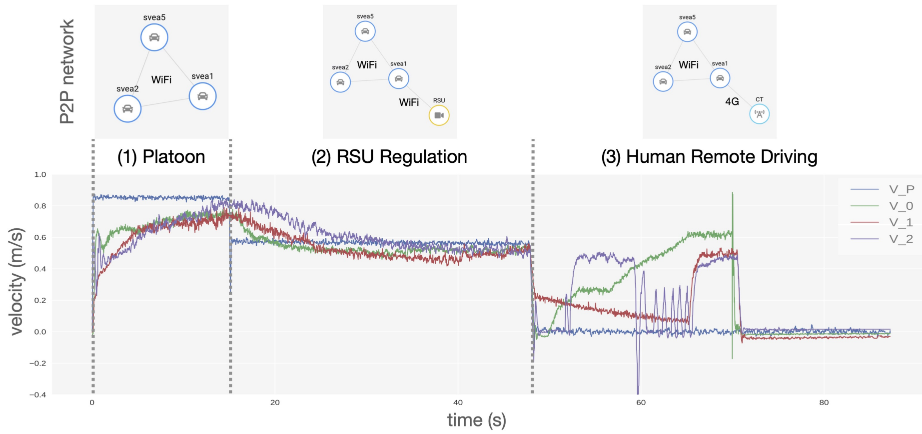

Fig. 4. The results of evaluating the platoon's string-stability throughout the three V2X use-cases on the SVEA testbed. Full experiment video footage available at https://bit.ly/SVEA_V2X.

C. (V2N) Teleoperating the platoon over the network

In recent years, there has been growing interest in the use of vehicle control towers for managing and supervising connected, automated vehicles. Currently, in order to handle unexpected issues, experimental automated vehicles typically have an on-board safety driver. However, since having an on-board safety driver severely limits the economic scalability of automated vehicles, there are proof-of-concepts in development to support exception-handling on automated vehicles with remotely connected human operators [6]–[8]. These remote operators would sit in control rooms from which they can monitor the status of and teleoperate vehicle fleets.

The remote teleoperation scenario we will consider is as follows. Illustrated as step 3 in Fig. 3, the platoon comes across a truck that has pulled into the shoulder of the road due to a malfunction. The truck driver has put out cones to denote where vehicles cannot drive anymore due to the truck's presence on the shoulder. Since the cones block most of the platoon's current lane, the platoon halts and requests support from a human operator because the platooned vehicles' operational design domain specifies that they are not allowed to autonomously drive into lanes of oncoming traffic. Then, in this scenario, a human operator connects to the leader of the platoon and teleoperates it past the obstruction. The followers in the platoon laterally follow the teleoperated leader, while continuing to maintain platoon formation using (1).

IV. Experiments

In this section, we present the results of implementing and evaluating the three use cases on the SVEA testbed. The main objective is to show that the SVEA testbed can support the use-cases described in Section III. We show this by illustrating the string-stability of (1) in the context of the three V2X communication use-cases. In this paper, we do not analyze the network performance of the P2P communication in detail, but will explore this in future work. As is indicated in Fig. 3, we implement the three use-cases as a sequence of events along one stretch of road. In particular, we prepared three of our vehicle platforms (referred to as "svea1", "svea2", and "svea5") to form the platoon, one Nvidia Jetson Nano equipped with a 4K camera to be the speed-regulating RSU, and a laptop connected to a Logitech steering wheel and pedals to act as the CT. All three vehicles are equipped with the default hardware configuration shown in Fig. 2. We additionally equip the leader vehicle of the platoon with a fisheye camera to give the remote human operator visual feedback throughout teleoperation. We implement the platooning controller on the three vehicles and manage the P2P network using our V2X software stack. The results of running the full system is shown in Fig. 4, where we plot the velocity profiles of the three vehicles throughout the three use-cases and visualize the corresponding P2P network during each use-case. In the first stage, the vehicles get up to speed together to form a platoon using V2V communication. Then, just as the platoon reaches the current speed limit of 0.8 m/s, through V2I communication, the RSU lowers the speed limit to 0.6 m/s. The platoon reduces speed and maintains stable speeds. The platoon eventually reaches the road block, where it requests assistance from the human operator. The human operator teleoperates the leader of the platoon (in green in Fig. 4) and brings the vehicle past the road block. Notably, as the human teleoperates, the platoon becomes unstable and the follower vehicles begin braking, since the human does not drive according to (1).

V. Discussion

The SVEA testbed allows for the evaluation of V2X use-cases on real, but inexpensive, hardware. We have designed our V2X software module in the testbed to be agnostic to the communication mediums being used in experimentation and facilitate the creation of P2P communication channels across heterogeneous networks. Furthermore, we have designed the vehicle platform to be modular in hardware and software to assist the development of an automated vehicle fleet. Already, the testbed has been used for experimentation in previous work: [8], [29], [31], [32], where the design of the

V2X software module and vehicle platform were critically important for the conducted experiments. The testbed is currently being used to support the implementation and evaluation of shared situational awareness or cooperative perception applications, such as the one presented in [33]. Finally, when evaluating V2X use-cases, researchers often want to understand and measure different quality-of-service aspects across the communication network, thus we are currently working on adding new features to the testbed that will allow users to measure important metrics such as latency, bandwidth, hand-over times, and packet loss.

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