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Qi Zhu
Northwestern University
qzhu@northwestern.edu

Bo Yu
PerceptIn
bo.yu@perceptin.io

Ziran Wang
Purdue University
ryanwang11@hotmail.com

Jie Tang
South China University of Technology
cstangjie@scut.edu.cn

Qi Alfred Chen
University of California, Irvine
alfchen@uci.edu

Zihao Li
Purdue University
zihao@purdue.edu

Xiangguo Liu
Northwestern University
XiangguoLiu2023@u.northwestern.edu

Yunpeng Luo
University of California, Irvine
yunpel3@uci.edu

Lingzi Tu
Southwest Jiaotong University
linzitu@outlook.com

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Foundations and Trends® in Electronic Design Automation

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

Q. Zhu *et al.*. *Cloud and Edge Computing for Connected and Automated Vehicles*. Foundations and Trends® in Electronic Design Automation, vol. 14, no. 1-2, pp. 1–170, 2023.

ISBN: 978-1-63828-303-4

Foundations and Trends® in Electronic Design Automation

Volume 14, Issue 1-2, 2023

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Foundations and Trends® in Electronic Design Automation, 2023, Volume 14, 4 issues. ISSN paper version 1551-3939. ISSN online version 1551-3947. Also available as a combined paper and online subscription.

Contents

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Qi Zhu[1], Bo Yu[2], Ziran Wang[3], Jie Tang[4], Qi Alfred Chen[5], Zihao Li[3], Xiangguo Liu[1], Yunpeng Luo[5] and Lingzi Tu[6]

[1] *Northwestern University, USA; qzhu@northwestern.edu, XiangguoLiu2023@u.northwestern.edu*

[2] *PerceptIn, USA; bo.yu@perceptin.io*

[3] *Purdue University, USA; ryanwang11@hotmail.com, zihao@purdue.edu*

[4] *South China University of Technology, China; cstangjie@scut.edu.cn*

[5] *University of California, Irvine, USA; alfchen@uci.edu, yunpel3@uci.edu*

[6] *Southwest Jiaotong University, China; linzitu@outlook.com*

ABSTRACT

The recent development of cloud computing and edge computing shows great promise for the Connected and Automated Vehicle (CAV), by enabling CAVs to offload their massive on-board data and heavy computing tasks. Leveraging the Internet of Things (IoT) technology, different entities in the intelligent transportation system (e.g., vehicles, infrastructure, traffic management centers, etc.) get connected with each other, thus making the entire system smarter, faster, and more efficient. However, these advances also bring significant challenges to public authorities, industry, as well as scientific communities. In terms of system design and control, current cloud and edge architecture of CAVs need to be refined or even redesigned to better function under uncertainties in demand, and to better cooperate with

Qi Zhu, Bo Yu, Ziran Wang, Jie Tang, Qi Alfred Chen, Zihao Li, Xiangguo Liu, Yunpeng Luo and Lingzi Tu (2023), "Cloud and Edge Computing for Connected and Automated Vehicles", Foundations and Trends® in Electronic Design Automation: Vol. 14, No. 1-2, pp 1–170. DOI: 10.1561/1000000058.

existing conventional vehicles and infrastructure. From the performance assessment perspective, models and simulation tools based on artificial intelligence and big data have been widely developed for validation and evaluation of cloud computing and edge computing, but the validity of these models needs to be re-examined with field implementations.

Finally, while the increasing connectivity among vehicles and infrastructures may help improve their perception of the environment and enable coordinated decision making, it also presents new challenges to ensure system safety and security, with inherent disturbances to wireless communication networks and also the inevitably larger attack surface that may be exploited by malicious attacks. In this tutorial, experts from academia and industry will introduce the trends and challenges of applying cloud and edge computing for CAVs, highlight representative works in the literature and discuss their limitations, present new promising solutions, and outline future directions in research and engineering. Particular focus will be given to methodologies and tools for building digital twin frameworks with cloud and edge computing for CAVs, quantitative and formal analysis for ensuring CAV safety under disturbances and uncertainties, system-level CAV security threat landscape and defense solution space, and experiences from practical deployment of cloud and edge computing for CAVs.

1

Introduction

Autonomous driving (AD) has seen tremendous progress over the last two decades, propelled by the advancement of neural network-based machine learning techniques and their usage throughout system stages such as perception (Qian *et al.*, 2022), prediction (Jiao *et al.*, 2022; Jiao *et al.*, 2023a; Jiao *et al.*, 2023b), and planning (Liu *et al.*, 2022f; Liu *et al.*, 2023c; Liu *et al.*, 2023a). Significant progress has been made to improve AD performance in various traffic scenarios, including challenging ones such as unprotected left turns, highway merging, and lane changing. Meanwhile, connected vehicle (CV) technologies using vehicular ad-hoc networks enable information sharing among vehicles and surrounding infrastructures (Kenney, 2011; Zheng *et al.*, 2016b). This provides a great complement to the perception and prediction capabilities of individual vehicles, e.g., by sharing out-of-sight information or future motion plans that cannot be accurately predicted.

However, a number of challenges significantly impede the application of AD and CV techniques in realizing connected and automated vehicles (CAVs) in practice. Some of the major challenges include (1) taking full advantage of these techniques to maximize system performance in various applications and scenarios, (2) reducing additional costs to deploy these techniques, including software and hardware cost, system maintenance and upgrade (Zheng *et al.*, 2016a; Zhu and Sangiovanni-Vincentelli, 2018), (3) ensuring system safety considering environmental uncertainty and disturbance, as well as the difficulty in analyzing neural networks (Zheng *et al.*, 2017a; Zheng *et al.*, 2019; Zhu *et al.*, 2020; Zhu *et al.*, 2021), and (4) defending possible cyber and physical attacks on CAVs (Liu *et al.*, 2023d).

Addressing these challenges and adopting AD and CV techniques require significant computational resources, which could be challenging to deploy on future production vehicles due to the additional cost, energy overhead, hardware maintenance difficulty, etc. The advancement of cloud and edge computing (Varghese *et al.*, 2021; Sánchez *et al.*, 2022; Gross *et al.*, 2022) provides an appealing way to overcome the computational resource limitations of individual vehicles. CAVs can communicate with edge devices that are roadside units (RSUs) and leverage the RSUs' affiliated local sensors and servers, and may also communicate with cloud devices that are far away and can connect to the internet for more information. Tasks with high resource demands and without real-time requirements, e.g., neural network model training, can be uploaded to the cloud, while tasks with moderate resource demands but requiring real-time communication, e.g., perception of the environment and coordination with other vehicles, can be handled by edge computing. Individual vehicles only need to equip the necessary hardware to maintain normal operation and ensure safety when edge and cloud computing are not available occasionally.

Many works have shown that the AD pipelines may perform poorly in long-tailed traffic scenarios (e.g., extreme weather conditions) and are vulnerable to various input noises and attacks such as blemished traffic signs or dirty patches on the road (Chen *et al.*, 2019b; Sato *et al.*, 2021; Zhang *et al.*, 2022). Some methods and frameworks are proposed to enhance the robustness and security of individual modules (Yang *et al.*, 2020; Jiao *et al.*, 2023b; Jiao *et al.*, 2023a) and the AD pipeline (Jiao *et al.*, 2021) of a single autonomous vehicle.

Edge and cloud computing can significantly improve system performance, safety and security by effective collaboration among vehicles and infrastructures. For instance, with the shared information from CAVs, we can build a Sybil attack detection system (Luo *et al.*, 2021) based on a credibility-enhanced temporal graph convolutional neural network to defend the transportation system against Sybil attacks. At the same time, a cyber-physical credibility framework based on blockchain technology and vehicles' physical sensing capabilities can be maintained to build trust for connected vehicles (Liu *et al.*, 2021h), enabling quick reaction to attacks in a large-scale vehicular network with low resource overhead. Initial studies of such techniques have demonstrated effectiveness in defense against spoofing attacks, bad-mouthing attacks, and Sybil and voting attacks.

System efficiency can be maximized by allocating different tasks to cloud servers, edge devices, or individual vehicles. However, there are some open design challenges. For example, uploading long-tailed training examples to the cloud can build a robust and general model for vehicles in different areas, which can save effort in modeling training, safety and security verification. However, it leads to performance, privacy and security concerns. A general model does not necessarily perform better than a model trained with local traffic data. Individual vehicles may not want to publicize their daily travel trajectories, and even only a small amount of malicious training data can contaminate the model training in the cloud. Another example is collaborative perception with assistance from edge devices. Real-time local maps can be generated on edge devices by collecting shared information from individual vehicles, which can improve system safety, especially in occluded and complex scenarios. However, sharing raw data from Lidars and cameras costs lots of communication resources. Sharing processed information, e.g., detected objects, will lead to challenges in reaching a consensus on these objects and their positions, and each vehicle needs to equip corresponding computational devices.

In the following sections, we will discuss opportunities and challenges for CAVs with cloud and edge computing, as well as present promising solutions to address these challenges and enhance system performance, efficiency, safety and secruity. In particular, Section 2 presents a mobility digital twin framework at the transportation level for enabling edge and cloud computing for CAVs. Section 3 discusses insights in practical deployment of edge and cloud computing in CAVs. Sections 4 and 5 present software and hardware architecture designs for edge and cloud computing, respectively, that facilitate CAVs. Finally, Section 6 discusses safety and security challenges for cloud- and edge-enabled CAVs and presents potential solutions.

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