Towards Collaborating Semi-Autonomous Vehicular Systems

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1. Introduction

The research challenges and the application domain we have chosen to illustrate our CPS agenda is ***Semi-Autonomous, Collaborative Vehicular Systems***. We envisage a network of human-driven, semi-autonomous and fully autonomous cars moving in a transportation network in a safe and efficient way.

The research described here relies on two earlier efforts: our work on a CPS: Medium program "Autonomous Driving in Dense, Mixed Traffic Environments" and our collaborative work with Honda on Safety for Intersection Access. The research agenda has three thrusts that our prior experience has led us to select:

1. We concentrate on **"collaboration"** as a basic problem in autonomous (semi-autonomous) and totally "human-driven" CPS entities in a cohabited world. In order to have an integrative issue, one has to have a basic concern and application area to direct the research. We investigate the setting of semi-autonomous ground vehicles in an environment (street traffic) where some portion of cars make decisions themselves, securely exchange information with others and try to understand the behavior of non-communicating vehicles, to lead to safe and reliable traffic flow.
2. We underline **"scalability"** as a key concern. Indeed, our review of present research on CPS has led us to believe that most of the approaches do not lend themselves well to be scaled to the true applications scope which will involve thousands to millions of participant entities (physical systems or portions of code). We address scalability by focusing on **hierarchical structures** which can be induced by a design architecture or naturally arise due to the time-domain behavior or the information/computation flows and constraints inherent in the application. We consider grouping CPS entities as teams, convoys, regions, etc.
3. We have chosen **"testability"** as an underlying criterion for our application area of roadway transportation as we investigate scalable design methods for collaborative behavior in CPS. We will specifically develop a new approach we have introduced: Using a partially or entirely virtual environment to investigate the effect of introducing autonomous entities into a real world, and thus do testing in a safe way.

With the above three thrusts, our CPS research agenda addresses the synergy of coordination, real-time computation and communication, control, security, and human behavior.

Although the research issues that can be explored are motivated by important challenges that have come to light during our prior work in autonomous vehicles, the application domain described in this position paper is more ambitious. It will address the distribution

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of control for individual and groups of vehicles and the safety and security problems that may arise. It will cover wireless information exchange among multiple vehicles and the inevitable variability in human driver behavior. The focus questions we can address in this effort include:

1. How well can the CPS architectures that lead to acceptable control behavior for relatively simple scenarios be made to scale up to scenarios that are qualitatively similar but far more complex and taxing in terms of the decision-making requirements?
2. What is the best method/tool to estimate whether all computational tasks to be performed by a CPS, including those with real-time deadlines and interactions, will meet performance goals. How can these estimation results be used to modify the CPS design if it does not lead to adequate performance? What is the best computer architecture to map each type of computation? How do we include network latencies in these estimates?
3. How can we estimate, track and predict the behavior of multiple vehicles on the road and at the same time generate recommended vehicle actions at a sufficiently acceptable latency to be useful?
4. How can we integrate different concerns such as safety, security and collaboration and test them in a meaningful CPS environment?

In each of these related areas of research, it is clear that fundamental progress on core principles, foundations, methods, and tools will serve a vastly larger community of CPS researchers and developers than those working in the particular application domains of autonomous vehicles. At the same time, progress toward future vehicles is of huge long-term importance to the US economy, the nation's transportation infrastructure and energy independence. A more detailed research plan could address these challenges in an integrated fashion by combining the complementary expertise of the researchers, leveraging our prior collaborations.

2. Vision

We envision a future where most, if not all, vehicles on both highways and urban streets are connected through wireless communication links, have on-board GPS, and have access to map databases. In the near term most vehicles will have access to the compute-power and real time data provided by the "cloud". This somewhat unstructured resource will gradually be balanced with a more structured hierarchy of local and remote capabilities. This structured/unstructured cyber-side will also be observable in the physical-side. Inevitably, there will be an era during which a number of these vehicles will be driven fully autonomously, with their local sensors supplemented at times with data through the communication links; whereas some will still be driven by human drivers, with possible aids from devices providing suggestions, inducements and warnings.

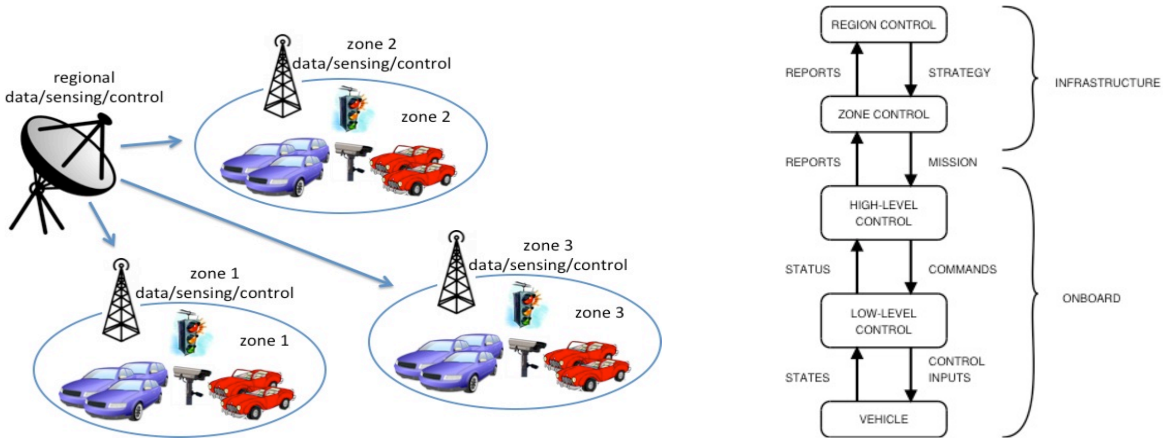

Figure 1. A general communication and data transmission architecture for ground-transportation.

By *autonomous* we mean that steering, throttle, and brakes will all be under local computer control, but even more critically, all higher-level decision making will be also done by the vehicle. Cooperation in fully autonomous driving is limited, so another intermediate stage we envision is the development of team formations with groups of interacting vehicles (as in convoys/platoons) or through the directives of coordinating agents. The CPS model to be developed will handle all these intermediate stage situations, as well as the final fully integrated stage. We will thus assume an overall communication and data transmission architecture as given in Figure 1. Although we will use the above as our primary application scenario, the theory, tools, and design approaches will be applicable to most interacting CPSs with mobile entities in a semi-structured environment. For example, applications to service robots in hospitals, factory floors, or homes, or in rescue operations in disaster areas can be imagined as potential targets.

3. Methodology and Subproblems

In previous work, our system development philosophy has taken us through a cycle of performance checking through simulation environments, to laboratory scale testing with multiple wheeled robots, to vehicle based outdoor tests in controlled layouts and test-tracks. As our tools develop, we will follow the same path here. However, our focus on scalability requires new and different verification and testing approaches.

Possible research subtopics as they relate to the three main thrusts described earlier are listed below to promote further discussion:

- Investigation of Hybrid-State Systems as a central modeling paradigm for cyber-physical interactions
- Classification of collaboration types, group coherence and decomposition analysis for collaborative driving
- Computational and security-related explorations on both the single vehicle and vehicular networks as cyber entities
- Studying the benefits and limitations of partial and full virtualization on cyber-physical system testing, on the specific example of collaborative driving.