Position Paper:
The Value of Cyber-Physical Mobility-On-Demand Systems

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Introduction

In the past century, private automobiles have dramatically changed the concept of personal urban mobility by enabling fast and anytime point-to-point travel. However, this paradigm is currently being challenged. According to United Nations estimates, urban population will double in the next 30 years. The demand for roads and parking spaces will dramatically increase, while the availability of urban land will decrease. The result is that private automobiles, with their current 5% utilization rate and 5 miles/hour average speed in urban centers, appear as an unsustainable solution for the future of personal urban mobility. Arguably, one of the most promising approaches to cope with this problem is one-way vehicle sharing with electric cars (referred to as Mobility-On-Demand -MOD-), which directly targets the problems of parking spaces, pollution, and low vehicle utilization rates. However, one-way sharing leads to vehicle imbalances, with vehicles collecting in popular destination areas (e.g. the city center) and becoming depleted in other areas (e.g. residential neighborhoods). Furthermore, such systems, while directly mitigating the problem of low vehicle utilization rates, are still unable to address system-wide congestion and throughput optimization.

The progress made in the field of autonomous driving in the past decade might offer a solution to these issues. In fact, a cyber-physical MOD system with robotic cars could eliminate imbalances within the transportation network and would enable automated system-wide coordination aimed at throughput maximization. However, the operational, economic, and societal aspects of *cyber-physical* MOD systems are still unclear: How many robotic vehicles would be needed to achieve a certain quality of service? What would be the cost for their operation? Would they decrease congestion? Such system-level problems require analysis tools at the interface between *robotics and transportation science*, which appear to be currently unavailable. More in general, the characterization of the value proposition of robotic MOD systems, which would represent one of the most complex *cyber-physical systems* ever conceived, constitutes a challenging open problem.

Research questions/challenges

As discussed above, there are virtually no tools to address the integration of system-wide coordination and autonomous driving. In this position paper, we propose the following guiding research questions to address such integration:

Analysis aspect: What are the appropriate analysis tools to address system-level questions for robotic MOD systems? Are current techniques in control theory and operations research sufficient?

Analysis aspect: Can optimal or approximately optimal solutions to MOD coordination problems be found in a computationally efficient manner? Can their solution be distributed across multiple vehicles?

Operational aspect: For a given number of robotic vehicles, what is the achievable throughput of a robotic MOD system and how does it compare with that of a MOD system with traditional cars? Would robotic cars decrease the number of cars that are needed to serve the population?

Operational aspect: What would be the customers interaction with robotic MOD systems? Should robotic MOD systems used to solve the last-mile problem or should they be used to provide point-to-point service?

Operational aspect: What gains in throughput and efficiency can be achieved with full autonomy versus partial autonomy (systems with both autonomous and human drivers)? Can human drivers be effectively coordinated through routing suggestions from on-board computers?

Operational aspect: What is the role of communication in cyber-physical MOD systems? Should all vehicles interact with a central coordinating data center, or is vehicle-to-vehicle communication more effective? Is communication even required in order to coordinate vehicles?

Economic aspect: For a given desired quality of service (e.g., elapsed time between a customer pickup request and his drop-off), what is the cost of the system and is there potential for economies of scale? How would this cost compare with that of a traditional taxi service? How would the cost compare with that of a MOD system with traditional cars that are rebalanced by human rebalancers?

Societal aspect: Would robotic cars increase the volume of traffic? Would this lead to a reduction in energy efficiency? In general, what are the sustainability benefits of robotic MOD systems?

PIs' expertise on the subject

For the past five years Dr. Pavone has been developing a systematic approach that enables the design of computationally-efficient and provably-correct coordination algorithms for robotic MOD systems. In particular he has devised rebalancing routing algorithms for the robotic vehicles [1], has performed an assessment of the benefits of "hi-tech" autonomous MOD systems versus "low-tech" driver-based MOD systems [2], and has studied fundamental limitations of performance for automated MOD systems in simple deployment scenarios [3]. Additionally, Dr. Pavone's Ph.D. work developed a comprehensive algorithm approach for the optimal coordination of mobile robotic networks in dynamic and stochastic environments [4], [5]. On the experimental side, Dr. Pavone has developed a mock urban environment comprising 15 vehicles, and is planning on deploying in March 2014 8-seat driverless shuttles providing MOD service at Stanford (see Figure 1). In general, Dr. Pavone's areas of expertise lie in the fields of controls and robotics. He is a recipient of a NASA Early Career Faculty award, a Hellman Faculty Scholar Award, and was named NASA NIAC Fellow in 2011.

Dr. Schwager has worked extensively in the area of multi-agent control and control of cyber-physical systems. His interests are in coordination and control of autonomous vehicles in urban transportation systems [2], the control and deployment of mobile sensor networks [6], multi-agent active and intelligent sensing [7], and multi-robot manipulation. He currently is PI on the CPS project "Cyber-Physical Manipulation" (CNS-1330036), and co-PI on the CPS project "Data-Driven Intelligent Controlled Sensing for Cyber Physical Systems," (CNS-1330008).

Figure 1: Left Figure: a mock urban environment where 15 small mobile robots provide on-demand service. This test bed allows the validation of dynamic vehicle routing algorithms for automated MOD systems. Center Figure: the NAVIA vehicle to be deployed at the Stanford SLAC Laboratory. Right Figure: the street at SLAC where two NAVIA vehicles will operate (the length of the loop is about 1.5 miles).

References

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