Cyber-Physical Transportation Systems: Complexity, Scalability, Efficiency, and Software Design

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In this document, we outline a class of problems that we believe is general enough to encapsulate many of the current problems of interest in large-scale mobile cyber-physical systems, such as air, automotive, and rail transportation systems. In order to address these problems, we propose an input-output view aimed at establishing the robust performance of automation systems to classes of environmental or possibly adversarial actions. These problems are especially challenging since their solution requires the careful analysis of the interplay between their combinatorial and differential aspects. An algorithmic approach to the analysis and design of automation software providing provable guarantees on the system's behavior is then briefly outlined.

Dynamic Vehicle Routing Services The National Airspace, the road and rail networks, as well as local environments for specific air operations (e.g., security/military applications, disaster relief, etc.) can be modeled as a large-scale heterogeneous network of mobile and stationary agents (resp., vehicles and ground control centers). These agents are called upon by a variety of users to perform various tasks, e.g., aimed at the safe, secure, and timely transportation of people, goods, or information across a given environment. These tasks can most often be described in a purely discrete/combinatorial way; however, vehicle dynamics, environmental interactions, and safety considerations bring an additional geometric component to these tasks in terms, for example, of differential and algebraic constraints on the agents' motion, and on their ability to exchange information.

In a realistic setting, specific tasks may not be known a priori, but instead be dynamically generated over time, in a way that may or may not depend on the actual system behavior. The operation of such a system is further complicated by the fact that its characteristics cannot be captured by a static snapshot of the state of the system at a given time. Rather, the system's characteristics evolve over time, as vehicles enter/exit the system, weather evolves, failures and contingencies manifest themselves, security threats are introduced and detected.

The purpose of automation systems is to ensure, or help ensure, that the transportation network provides the best possible Quality of Service to the end users, as measured, for example, by the average or worst-case delay between the issuance of a task and its fulfillment—while providing acceptable guarantees of safety in the face of environmental or adversarial actions. In other words, efficiency must be robust to certain classes of deviations from nominal operations.

An input-output view This document briefly advocates a novel approach to the design of coordination algorithms for mobile cyber-physical systems. Instead of focusing on the ability of a given vehicle (or pre-defined group of vehicles) to perform a given arbitrary task, or to satisfy certain safety properties, we wish to look at mobile networks a shared, distributed infrastructure providing persistent, real-time dynamic routing services over a region of interest.

We believe it is important to study how the characteristics of the closed-loop system formed by the vehicles, ground operators, and automation systems, affect its ability to efficiently, safely, and securely provide the desired services. A sketch of this concept is provided in Figure

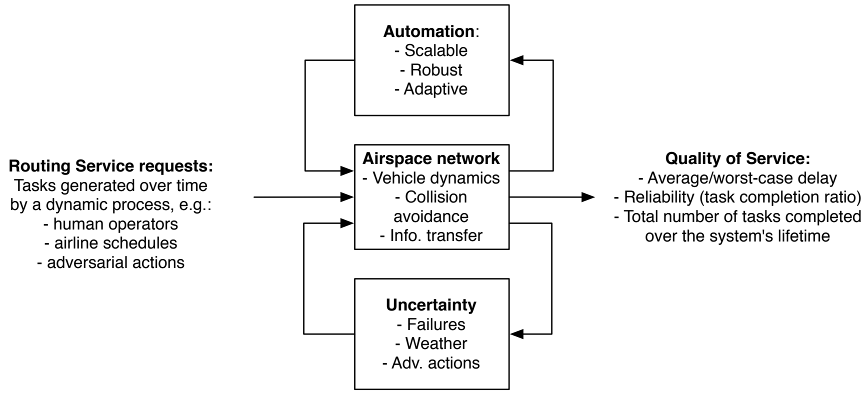

Figure 1: Sketch of the input-output view of dynamic vehicle routing services

1. For example, a fundamental question in Air Traffic Management that has received relatively little attention so far is the issue of complexity scaling with traffic volume. A measure of complexity is, e.g., the average time needed for airline flight to reach their destination; how this time changes as the number of active flights increases is not clearly understood. Similar considerations can be made in terms of the effort required of human operators in the system ("cognitive complexity"), and of the computational complexity of automation algorithms.

Other form of inputs could represent, e.g., weather or malicious actions. Outputs could represent performance and/or safety criteria. **Certification** in this context would entail (i) ensuring that outputs are within acceptable limits, for all inputs in a given class, (ii) ensuring that the system is "efficient" in some well-defined way, (iii) ensuring that safety and efficiency are robustly retained in the presence of "disturbance" inputs of various nature (iv) establishing how the scale of the system affects its performance and the outcome of the analysis.

Analysis and Design paradigms The main **barrier** in pursuing the research agenda outlined above is the poor current understanding of interplay between discrete/combinatorial task specifications and the continuous/differential nature of aircraft dynamics. In fact, the design of algorithms and software providing the desired automation capabilities—while at the same time providing an easy path to **verification and validation**—is expected to rely both on techniques from, e.g., combinatorial optimization and queueing theory, and on techniques from, e.g., optimal control and systems theory. Specific modeling components that need to be addressed include:

- *Trade-off and sensitivity analysis:* In many situations, there is a high degree of arbitrariness in selecting a performance and complexity metric that can provide an understanding of the tradeoffs involved in a problem. Average (over time, or over individual agents) and worst-case complexity measures can yield substantially different results. Complexity metrics need to capture, e.g., the tradeoffs between global and local traffic volume and operator workload, as well as a measure of robustness to uncertainty in the environment.
- *Complexity prediction:* Ad-hoc metrics developed as a proxy for workload or congestion prediction do not offer a rigorous insight into the effective complexity of a given traffic pattern. It is necessary to aim at the rigorous establishment of bounds on the *implicit* complexity of an aircraft routing scenario, and at benchmarking the complexity associated with different aircraft routing approaches with respect to such theoretical bounds.
- *Uncertainty description:* specific tasks to be performed may be determined by stochastic processes in the environment. More so, it is possible that some of the agents are deceptive and play an adversarial role. This leads to the necessity of both stochastic and

deterministic game formulations of aircraft routing problems.

In order to address the issues outlined above, new tools need to be developed combining in a novel way ideas from systems and control, robotics, combinatorial optimization, and distributed computing. Moreover, a remarkable feature of many problems in the class described above is that the complexity analysis of such decision system is substantially reduced when the number of agents is large. it is believed that the exploitation of such scaling limits may enable not only to capture tradeoffs in the complexity metrics, but also to devise tractable algorithms that can enable provably efficient aircraft routing strategies able to cope with large traffic volumes and rapidly-changing environmental conditions.

Biography Emilio Frazzoli received the Laurea degree in aerospace engineering from the University of Rome La Sapienza, Rome, Italy, in 1994 and the Ph.D. degree in navigation and control systems from the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (MIT), Cambridge, in 2001.

From 2001 to 2004, he was an Assistant Professor of aerospace engineering at the University of Illinois at Urbana-Champaign. From 2004 to 2006, he was an Assistant Professor of mechanical and aerospace engineering at the University of California, Los Angeles. He is currently an Associate Professor of aeronautics and astronautics with the Laboratory for Information and Decision Systems, Department of Aeronautics and Astronautics, MIT.

His current research interests include algorithmic, computational, and geo- metric methods for the design of complex control systems, in aerospace and other domains, and the application areas include distributed cooperative con- trol of multiple-vehicle systems, guidance and control of agile vehicles, mobile robotics, and high-condence embedded systems. Dr. Frazzoli received the National Science Foundation (NSF) CAREER Award in 2002.