Position Paper: Safety Hybrid Control with Intention Inference for Semi-autonomous Cyber-Physical Transportation Systems

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1 Motivation/Background

Cyber-physical systems (CPS) consist oftentimes of modularized, networked and environment coupled control systems, yet without a need for a large amount of communication. For such systems, some important, yet at times overlooked issues, are the presence of coupling effects and the lack of knowledge of the control inputs of other systems. To consider these effects, the intention and mode of operation of other systems, as well as any induced disturbance inputs to each system due to their coupled interactions need to be inferred from noisy measurements. This inference problem of the hidden intention or mode of operation is naturally followed by a second challenge—to guarantee safety requirements and to achieve control performance criteria based on the inferred set of the most probable modes. In particular, control approaches that are robust to uncertainties in mode estimation due to mode identifiability issues need to be developed to tackle such problems. The above challenges can be conveniently considered within the framework of *hidden mode hybrid systems* (HMHS, see, e.g., [1, 2] and references therein) with unknown inputs, in which the system *state* dynamics is described by a finite collection of functions. Each of these functions corresponds to an intention or *mode* of the hybrid system, where the mode is unknown or *hidden* and mode transitions are autonomous (i.e., there is no direct control over the switching mechanism that triggers the discrete events). There are a large number of applications, including urban transportation systems considered in this project, in which it is not realistic to assume knowledge of the mode or it is simply impractical or costly to measure the mode.

In the United States of America alone, over 30,000 people die in road crashes each year and about 40% of those accidents occur at intersections. With this in mind, we choose to focus on improving the safety of (semi-)autonomous vehicles at intersections by including the inference of the intention and inputs of other vehicles. Thus, the following is proposed as the goal of this project: *Development of fundamental theory and computationally efficient algorithms for intention inference and safety hybrid control of cyber-physical transportation systems.* Methods that will be explored in this study are *simultaneous state, input and mode estimation* of HMHS using recursive filters and Bayesian hypothesis testing, as well as *safety hybrid control* with mode inference uncertainties.

2 Proposed Research/Work

We propose to cast the collision avoidance scenario of vehicles at an intersection as an intention inference and control problem of hidden mode hybrid systems (HMHS), given by:

$$\begin{aligned} (\dot{x}, \dot{q}) &= (f_q(x, u, d), 0) & (x, u, d) &\in C_q \\ (x, q)^+ &= (g_q(x, u, d), \delta_q(x)) & x &\in D_q \\ y &= h_q(x, u, d) \end{aligned} \tag{1}$$

where $x \in \mathbb{R}^n$ is the continuous state (positions and velocities), $q \in Q := \{1, 2, \ldots, N\}$ the discrete state or *mode* (intention of other vehicles), $u \in U_q \subset \mathbb{R}^m$ the known control input (input of own vehicle), $d \in \Delta_q \subset \mathbb{R}^p$ the unknown disturbance or noise input (input of other vehicles, as well as process and measurement noises) and $y \in \mathbb{R}^l$ the output measurements. The novelty of this approach lies in the modeling of the intention of other vehicles as a hybrid mode, q, of the closed loop system without restricting the control input trajectories of the other vehicles, d, to a finite set. This is an improvement to existing approaches that model intention with a small finite set of motion models of the other vehicles for computational tractability [3] or simply as braking or accelerating [1]. An example for an intention in our HMHS framework is when another vehicle at an intersection is oblivious to the presence our vehicle, in which case the unknown control input $d \in \Delta_q \subset \mathbb{R}^p$ is uncorrelated with the states of our vehicle. This unfortunately can be poorly represented by a finite set of control actions. By classifying intentions as hybrid modes instead of motion models, we can also reduce the number of hypotheses when using multi-model estimation approaches.

The chosen approach will combine methods such as interacting multi-model estimation and related approaches with our previous work on simultaneous state and input estimation [4] to carry out simultaneous state, mode and unknown input estimation (i.e., the estimation of positions and velocities of all vehicles), as well as the intention and the input of the other vehicles which are not directly measured. Specifically, we will look into the identifiability of the hybrid mode or intention for the system of vehicles at intersections using Bayesian hypothesis testing approaches. When there exists ambiguity between different modes or intentions (e.g., if we can only narrow down the probable intentions to be either stopping or being overly cautious), we will find necessary and sufficient conditions for set identifiability (i.e., such that the true mode is always in the estimated set of most probably modes). Moreover, when the mode or intention is only set identifiable, hidden mode feedback control approaches similar to [1, 2] will be developed to deal with mode estimation uncertainties for the purposes of collision avoidance and warning systems.

3 Potential Impact in/to Cyber-Physical Systems

For cyber-physical transportation systems, this project will provide a more efficient approach for intention inference and safety hybrid control for the purpose of assisting drivers and avoiding collisions. With this approach, the intention of each driver need not be broadcast to other vehicles at an intersection, removing the need for vehicle-to-vehicle communication or a central controller. The proposed approach utilizes the hidden mode hybrid system framework, in which the hidden hybrid mode represents the (potentially changing) intention of a vehicle, while each mode in turn encompasses a possibly infinite set of input trajectories. Through this study, we will gain an understanding of issues associated to intention/mode inference such as identifiability and set identifiability. Then, with the awareness of the intention of other vehicles at an intersection, feedback control can be devised to guarantee safety without resorting to overly conservative measures.

An emphasis will be made on the generality of the tools developed for mode inference and feedback hybrid control such that they are broadly applicable to hidden mode hybrid systems. These developed methodologies can be extended to a large number of cyber-physical systems such as smart electric grids and healthcare devices where the same uncertainties in intention and disturbance inputs arise when the modularized systems interact with each other (e.g., where a local operator or controller lacks knowledge of the intention and inputs of other systems to which it is coupled or networked). Such systems include human-in-the-loop applications and systems that are susceptible to disturbances and subsystem failures.

Bibliography

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